

Effect of Freestream Turbulence on Flow Structure Around

Slanted-Back Ahmed Body

By

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Abstract

This study examines the influence of freestream turbulence (FST) intensity on the spatiotemporal flow dynamics around an Ahmed body with two distinct leading edge geometries: rounded (RL) and squared (SL), both featuring a slanted rear angle of $\alpha = 25^\circ$. Time-resolved particle image velocimetry (TR-PIV) was employed to analyze the flow at a Reynolds number of $Re = 0.17 \times 10^5$ (based on freestream velocity and body height), with FST intensities of 1.5% (baseline), 5.0%, 10.0%, and 15.0%, generated using regular and fractal grids. Results show that the squared leading edge enlarges the recirculation bubble over the roof but does not affect the wake recirculation length. It also suppresses downwash in the wake, reducing shear layer interactions and wake vortex shedding frequency.

For both geometries, increasing FST intensity consistently reduced the size of the roof recirculation bubble due to an earlier shear-layer reattachment. Conversely, the wake recirculation bubble length remained largely independent of FST intensity in both cases. Over the slanted surface of the RL geometry, the bubble size increased with FST up to 10.0% and stabilized at 15.0%, linked to stronger correlations between the C-pillar vortex and the separated shear layer from the leading edge of the slanted surface. Turbulence statistics exhibited geometry-specific responses to FST. In the RL case, FST suppressed Reynolds stresses over the roof and in the wake, with no significant impact on turbulence levels over the slanted surface, while promoting turbulence transition through elongated streaks with higher streamwise than wall-normal velocity fluctuations. In the SL case, streamwise Reynolds stresses and turbulent kinetic energy (TKE) increased over the roof with FST, driven by energy redistribution to low-frequency motions ($St < 0.23$), whereas wall-normal and shear stress peaks showed minimal sensitivity. In both body

configurations, TKE in the wake region was suppressed due to diminished wall-normal Reynolds stresses and disrupted vortex interactions.

Frequency spectra and Spectral Proper Orthogonal Decomposition (SPOD) analysis revealed that in the RL geometry, FST suppressed dynamically important frequencies, including roof bubble pulsation, and disrupted the flapping motion and spectral coherence of wake recirculation bubbles. In the SL geometry, SPOD and quadrant-based analysis showed that FST amplified low-frequency flapping over the roof and promoted persistent C-pillar vortices that dominated the upper shear layer, disrupting classical vortex shedding in the wake. The results offer critical insights for refining aerodynamic models and developing flow control strategies tailored to real-world turbulent conditions.

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Dedication

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List of Abbreviations

Nomenclature

A	Instantaneous Reverse Flow Area
A_{mean}	Mean Reverse Flow Area
A'	Fluctuation of Reverse Flow Area
B	Width of Ahmed body
C	Length of Cylindrical Struts
C_g	Distance Between Model Underside and Ground Surface
C_ϵ	Energy Dissipation Rate Coefficient
$C_{\epsilon 0}$	Equilibrium Energy Dissipation Rate Coefficient
$C_{\epsilon'}$	Proposed Energy Dissipation Rate Coefficient
C_p	Mean Pressure Coefficient
d	Diameter of Cylindrical Struts
D	Water Level in the Test Section
D_f	Fractal Dimension
d_p	Particle Diameter
F_u, F_v	Flatness of Velocity Fluctuations
f	Vortex Shedding Frequency
F_r	Froude Number
f_{sp}	Sampling Frequency
g	Acceleration Due to Gravity
H	Body Height
H^*	Shape Factor
h_r	Recirculation Bubble Height
J	Characteristic Turbulent Velocity Scale
k	Turbulence Kinetic Energy
k_ω	Vorticity Growth Rate
L	Length of Ahmed Body
L_r	Recirculation Length
L_u	Streamwise Integral Length Scale
L_v	Cross-stream Integral Length Scale
N_f	Number of Fractal Iterations
N_W	FFT Window Size
P_r	Probability Distribution of Reattachment Point
Q_x	Volumetric Flow Rate
Re	Reynolds number
R_{ij}	Space-time Correlation Coefficient
R_L	Length Ratio of Each Bar at One Successive Iteration
RL	Round Leading-edge Body
R_t	Ratio of Bar Thickness in One Iteration
Re_λ	Turbulence Reynolds Number
$Re_{\lambda'}$	Proposed Turbulence Reynolds Number
$Re_{\lambda 0}$	Equilibrium Turbulence Reynolds Number
Re_0	Global Reynolds Number
Re_L	Proposed Global Reynolds Number

R_{uu}	Two-point Autocorrelation of Streamwise Fluctuating Velocity
R_{vv}	Two-point autocorrelation of Cross-stream Fluctuating Velocity
St	Strouhal Number
S_D	Downwash Strength
S_k	Stokes Number
S_u', S_v'	Skewness of Velocity Components
S_{xy}	Cross-spectrum Between Two Signals x and y
t_c	Convective Time Scale
t_r	Thickness Ratio
T_u, T_v	Turbulence Intensity
U_∞	Freestream Velocity
U	Streamwise Mean Velocity
U_c	Convective Velocity
U_d	Streamwise Velocity Deficit
U_e	Streamwise Edge Velocity
u	Streamwise Instantaneous Velocity
u'	Streamwise Velocity Fluctuation
$\overline{u'u'}, \overline{v'v'}, \overline{w'w'}$	Reynolds Normal Stresses
$\overline{u'v'}, \overline{u'w'}, \overline{v'w'}$	Reynolds Shear Stresses
u_{rms}	Root Mean Square of Streamwise Velocity Fluctuation
V	Cross-stream Mean Velocity
V_i	Entrainment Velocity
V_e	Wall-normal Edge Velocity
v'	Cross-stream Velocity Fluctuation
v_{rms}	Root Mean Square of Cross-stream Velocity Fluctuation
w'	Spanwise Fluctuating Velocity
W	Spanwise Mean Velocity
x	Streamwise Direction
x^*	Wake Interaction Length Scale
x_{peak}	Streamwise Distance Where Turbulence Intensity is Maximum
x_r	Mean Reattachment Point
x_s	Roof Bubble Separation Point
y	Cross-stream Direction
z	Spanwise Direction

Greek

α	Slant Angle of Ahmed Body
Λ	Spectral Coherence
δ	Boundary Layer Thickness
δ^*	Displacement Thickness
δ_ω	Shear Layer Thickness
θ	Momentum thickness
ϵ	Turbulence Kinetic Energy Dissipation Rate
η	Kolmogorov Length Scale
ϕ	Phase Angle
λ_u	Streamwise Taylor Micro-scale

λ_v	Cross-stream Taylor Micro-scale
ν	Fluid kinematic Viscosity
ρ_p	Particle Density
σ	Blockage Ratio (Solidity)
τ	Integral Time Scale
τ_p	Particle Response Time
τ_f	Characteristic Temporal Scale
μ_f	Fluid Dynamic Viscosity
ω_y	Wall-normal Vorticity
ω_z	Spanwise Vorticity
Ψ_ω	Spanwise velocity fluctuation (POD mode)

Acronyms

CFD	Computational Fluid Dynamics
CMOS	Complementary Metal Oxide Semiconductor
DNS	Direct Numerical Simulation
FFT	Fast Fourier Transform
FM	Flapping Motion
FST	Freestream Turbulence
GHG	Greenhouse Gas
HF	High Frequency
Jpdf	Joint probability density function
KH	Kelvin Helmholtz
LDV	Laser Doppler Velocimetry
LES	Large-eddy Simulation
LF	Low Frequency
LSB	Laminar Separation Bubble
MF	Medium Frequency
Nd: YLF	Neodymium-doped Yttrium Lithium Fluoride
pdf	Probability Density Function
PIV	Particle Image Velocimetry
POD	Proper Orthogonal Decomposition
PSD	Premultiplied Spectral Density
RANS	Reynolds Averaged Navier Stokes
RL	Rounded Leading Edge
SAR	Super Abrasion Resistant
SL	Squared Leading Edge
SPOD	Spectral Proper Orthogonal Decomposition
SVD	Singular Value Decomposition
THEL	Turbulence and Hydraulic Engineering Laboratory
TKE	Turbulence Kinetic Energy
TR-PIV	Time-resolved Particle Image Velocimetry

Declaration

The outline of this thesis follows the “sandwich format”. It merges five individual papers prepared for publication in peer-reviewed journals. Chapter 1 contains an introduction about the problem statement and the thesis contributions; Chapters 2 to 6 are manuscripts containing an abstract, introduction, methods, results, and discussion; Chapter 7 provides the conclusions of the work and recommendations for future research directions.

Chapters 2 to 5 are papers that have already been published, and Chapter 6 was prepared to be submitted for publication in a peer-reviewed journal. The contribution of **Sagharichi, A.** consisted mainly of conceptualization; data collection; data analysis; writing; resources; editing, and preparing the first drafts of manuscripts. My supervisor, Dr. Mark F. Tachie, supervised the research, including constant feedback during the different phases of my data collection, conceptualization, review, and editing. My Co-author (Dr. Seyed Sobhan Aleyasin) contributions in Chapter 3 consisted of investigation, review, and editing.

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Chapter 1: Introduction

1.1 Background and Scope

A bluff body is defined as a body that, when subjected to a fluid flow, the flow streamlines deviate and separate over a substantial part of it (Forouzi Feshalami et al., 2022). Many physical phenomena, such as flow separation, reattachment, vortex shedding, and wake formation, can be observed in separated flow around bluff bodies (Derakhshandeh & Alam, 2019). These phenomena are fundamental to understanding aerodynamic performance, as they dictate the formation of complex flow structures that contribute to drag, lift, and stability in engineering applications. Bluff bodies find diverse engineering applications, including the transportation industry, where they serve as a simplified model for on-road vehicles. The flow around on-road vehicles is intricate, exemplified by significant separation and development of wakes, ultimately contributing to high aerodynamic drag (Tunay et al., 2014; Liu et al., 2021). This drag is a critical factor in vehicle efficiency, as it directly impacts fuel consumption and emissions, making the study of bluff body flows a cornerstone of automotive engineering research aimed at sustainable transportation solutions.

The aerodynamic performance of on-road vehicles is increasingly critical in the context of global environmental challenges and economic pressures. The rapid increase in oil prices over recent years underscores the pressing need to develop innovative methods to minimize the aerodynamic drag of on-road vehicles. According to Environment and Climate Change Canada and Natural Resources Canada's 2023 report on fuel consumption, Canadians typically spend \$1962 annually on fuel for every 20000 kilometres driven. According to Hucho & Sovran (1993), over 50% of the total fuel consumption of a typical car running on a highway is due to the aerodynamic drag.

Additionally, every 10% reduction in aerodynamic drag on on-road vehicles (large heavy-duty trucks and trailers) translates to a fuel consumption saving of about 7% (Bellman et al., 2010). Thus, a significant amount of fuel cost savings can be obtained by reducing the aerodynamic drag of on-road vehicles. The reduced fuel consumption also implies fewer emissions discharged by vehicles, which are now one of the major contributors to air pollution associated with greenhouse gas (GHG) emissions, global warming, and the occurrence of extreme weather events. On-road vehicles also contribute more than 30% of carbon dioxide and other greenhouse gas emissions through fuel consumption (Bellman et al., 2010). Concerns about global warming and increasing fuel costs over the past decades have highlighted the need for more aerodynamic and environmentally friendly designs of on-road vehicles. Achieving such designs necessitates a comprehensive understanding of the flow dynamics surrounding on-road vehicles, which is a prerequisite for optimizing the shapes of on-road vehicles and implementing active flow controls to reduce aerodynamic drag (Joseph et al., 2011). These environmental and economic imperatives drive the need for advanced research into flow dynamics, particularly under conditions that reflect the turbulent environments encountered in real-world driving scenarios.

The complexity of vehicle aerodynamics arises from the interaction of turbulent flows with vehicle geometry, leading to phenomena such as flow separation, reattachment, and the formation of unsteady wakes. These flow features are influenced not only by the vehicle's shape but also by the characteristics of the incoming flow, particularly freestream turbulence (FST). Understanding how FST modulates flow structures around vehicles is essential for developing robust aerodynamic models that can predict performance accurately under diverse operating conditions.

1.2 Ahmed Body

The practice of employing simplified models is widespread in on-road vehicle aerodynamics. These models typically represent scaled-down, simplified bluff bodies that feature some of the essential aerodynamic characteristics of actual on-road vehicles. Over the years, they have served predominantly for validation and providing insights into fundamental aspects of the flow characteristics around on-road vehicles (Ahmed et al., 1984; Howel et al., 2023; Sakurai, 1985). Notable examples of such models include the Ahmed body (Figure 1.1a), the Windsor body (Figure 1.1b), and the Willy body (Figure 1.1c). Over time, the level of detail incorporated into these aerodynamic models has exhibited variation, leading to the emergence of two primary groups: simple bluff bodies and more intricate vehicle models, as identified by Le Good and Garry (2004). Typically, the level of model details is inversely correlated with the generality of the results. In academic research, simplified bluff bodies are more popular for these reasons. Although these models are simplified, the wake flow generated around them allows researchers to analyze the fundamental aerodynamic characteristics of an on-road vehicle without the added complexity caused by the detailed body shape. One of the simplest but most widely adopted bluff bodies for the study of automotive aerodynamics is the Ahmed body, introduced by Ahmed et al. (1984). The Ahmed body's widespread adoption stems from its ability to replicate key aerodynamic features such as flow separation, wake formation, and vortex shedding while maintaining geometric simplicity, making it an ideal platform for both experimental and computational studies.

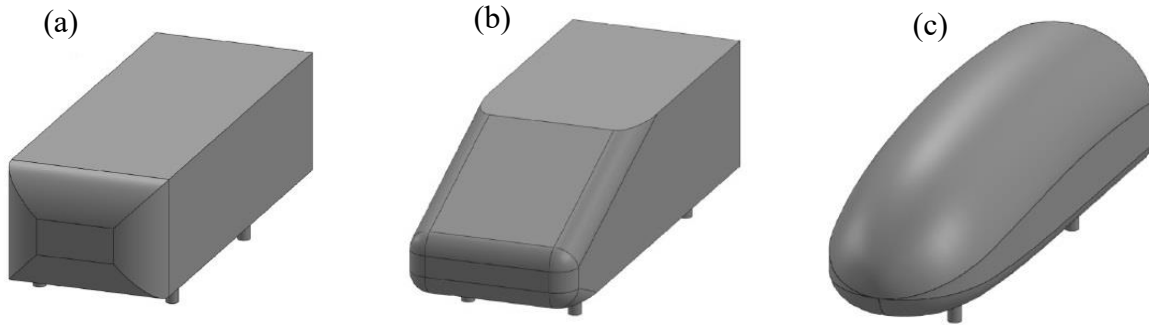


Figure 1.1 Illustrations of three different simplified automotive aerodynamic models: squared-back Ahmed body (a), Windsor body (b), and Willy body (c) models (Booysen, 2021)

The Ahmed body is characterized by a rounded frontal area that facilitates flow separation, an extended mid-section to enable the reattachment of separated flow, and a rear slanted surface, featuring an adjustable slanted surface angle (α) to mimic the flow effects over various setups (Figure 1.2). The slanted surface angle of the Ahmed body varies from $\alpha = 0^\circ$ to 40° . When the angle is set to $\alpha = 0^\circ$, the model transforms into the squared-back version of the Ahmed body, replicating the aerodynamic characteristics associated with squared-backed vehicles such as transport trucks and delivery vehicles (Booysen et al., 2022). The body is supported by four legs, elevating it from the ground to simulate the tires and the vehicle's distance from the road. The length (L), height (H), and width (B) of the original Ahmed body are 1044 mm, 288 mm, and 389 mm, respectively (Ahmed et al., 1984). These geometric features allow the Ahmed body to capture the essential flow physics of real vehicles.

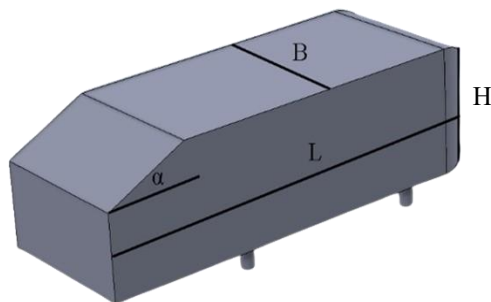


Figure 1.2 Illustration of slanted-back Ahmed body

Ahmed et al. (1984) conducted the first experimental investigation of the flow around the slanted-back Ahmed body. The investigation involved measurements of pressure and velocity to characterize mean flow topology. Since then, both numerical and experimental investigations have been conducted to characterize the flow structure around the Ahmed body (Vino et al., 2005; Grandemange et al., 2013; Krajnović, 2014; Zhang et al., 2015; Liu et al., 2021). Figure 1.3 shows the typical flow structure around Ahmed body with $\alpha = 25^\circ$. In this figure, the approach flow separates from the leading edge and lateral surfaces and evolves downstream as hairpin structures. The wake region consists of a recirculation bubble over the slanted edge, and a pair of counter-rotating vortices, which are referred to as C-pillar vortices, are shed from the side edges of the body. Numerous experimental and numerical studies at various crossflow planes downstream of the Ahmed body revealed the existence of a low-pressure zone in the form of a counter-rotating recirculation torus behind the vertical base (indicated by upper and lower recirculation bubble) which separates from the slanted and bottom surfaces (Wang et al., 2013; Zhang et al., 2015; Liu et al., 2021). These flow structures are highly sensitive to the geometry of the leading edge and the turbulence characteristics of the incoming flow, making the Ahmed body an ideal test case for studying the interplay between vehicle design and environmental flow conditions.

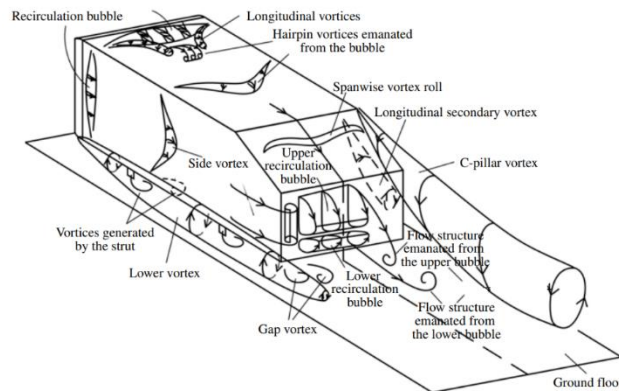


Figure 1.3 Mean flow structure around Ahmed body (Zhang et al., 2015)

The Ahmed body's versatility allows researchers to manipulate parameters such as the slant angle, leading-edge shape, and ground clearance to study their effects on flow behaviour. This thesis focuses on the slanted-back Ahmed body with a slanted angle of $\alpha = 25^\circ$, a configuration known to produce complex wake dynamics relevant to hatchback and sedan vehicles.

1.3 Motivation of the Research

Most of the previous studies that examined the flow dynamics around Ahmed bodies were conducted at FST intensities ($T_u = u_{\text{rms}}/U_\infty$, where $u_{\text{rms}} = \sqrt{\overline{u'^2}}$ is the root-mean-square of the streamwise fluctuation velocity u' , $(\cdot)$ denotes time averaging, and U_∞ is freestream velocity) of less than $T_u = 2\%$ (Tunay et al., 2014; Venning et al., 2015; Zhang et al., 2018; Siddiqui and Agelin-Chaab, 2022; Venning et al., 2022). Indeed, turbulence levels in open-road and wind gust conditions can vary from $T_u = 2\%$ and 16% (Saunders & Mansour, 2000; Passaggia et al., 2021; Burton et al., 2021), highlighting a significant disparity between laboratory conditions and the turbulence levels experienced in real-world driving. Additionally, the on-road integral length scale (L_u , representing the dimension of the energy-containing eddies in the incoming flow) varies between $L_u = 0.3H$ (when surrounded by other cars) and $L_u = 3.5H$ (on open roads and in light winds), where H is the typical height of on-road vehicles (Saunders and Mansour, 2000). This underscores the necessity for refined experiments at elevated FST levels (i.e., $T_u > 2\%$) to understand their impacts on the flow dynamics around on-road vehicles. The discrepancy between laboratory and real-world turbulence levels limits the applicability of existing research to practical vehicle design, as high FST can significantly alter flow separation, vortex shedding, and wake structures, affecting aerodynamic performance.

A handful of previous studies on the role of turbulence on the flow dynamics around the Ahmed body simulated elevated turbulence levels using smooth- and rough-wall turbulent boundary layers (Aleyasin et al., 2021). As such, it is difficult to isolate the direct influence of turbulence from the mean shear (velocity gradient) of the boundary layers. Additionally, studies in which grids were used to generate high turbulence levels focused mainly on mean pressure distribution and bistability phenomena (Wang et al., 2020; Burton et al., 2021) or drag and mean velocities around a squared-back Ahmed body (Passaggia et al., 2021). The only study on the effect of turbulence intensity on flow structure around the slanted-back Ahmed body focused on the vortex shedding frequency characterization around the body (Zhang et al., 2015). While these studies have advanced our understanding of flow around the Ahmed body, there is a need for detailed insight into the spatiotemporal flow dynamics. This thesis addresses this gap by employing passive grids to generate controlled FST levels ranging from 1.5% to 15.0%, allowing for a systematic investigation of turbulence effects without the confounding influence of boundary layer shear. Furthermore, the use of high-resolution time-resolved particle image velocimetry (PIV) enables a detailed analysis of both mean and unsteady flow characteristics, providing a richer dataset than previous studies that relied on point measurements or coarse numerical simulations.

The motivation for this research is twofold: first, to bridge the gap between laboratory experiments and real-world driving conditions by studying the Ahmed body under high FST levels that mimic on-road turbulence; second, to explore how leading-edge geometry interacts with these turbulent flows to influence spatiotemporal flow characteristics around the body. By combining advanced experimental techniques with comprehensive flow analysis, this study aims to provide actionable insights for vehicle designers seeking to reduce drag and emissions, contributing to the development of more sustainable transportation solutions.

1.4 Research Objectives

The objective of the research is to understand the effects of FST level and leading-edge shape (squared and rounded) on the spatiotemporal flow dynamics around slanted-back Ahmed bodies with a slant angle $\alpha = 25^\circ$. To achieve elevated FST levels, one regular grid and two fractal grids were deployed at the inlet section of a water channel to generate a wide range of turbulence intensities and integral length scales ($T_u = 5.0\%$ to $T_u = 15.0\%$ and $L_u = 0.29H$ to $L_u = 1.07H$) and the results are compared with the baseline turbulence level of $T_u = 1.5\%$ (without grid installation). Particle image velocimetry is used to perform velocity measurements in the flow around the bodies. The effects of FST on the turbulent statistics and transport phenomena are analyzed in terms of the mean velocities and Reynolds stresses. The effects of turbulence on the vortical structures are analyzed by using two-point correlation, proper orthogonal decomposition (POD), and reverse flow area, and their temporal characteristics will be assessed using frequency spectra and Spectral proper orthogonal decomposition (SPOD). These objectives are designed to provide a holistic understanding of how FST, from statistical properties to coherent structures, has implications for both fundamental fluid mechanics and applied automotive engineering.

Specifically, the research seeks to: (1) quantify the impact of leading-edge shape on flow separation and wake dynamics under low turbulence conditions; (2) investigate how elevated FST levels modify these flow characteristics across a range of realistic turbulence intensities; and (3) elucidate the underlying mechanisms driving these changes through advanced techniques.

1.5 Outline of the Thesis

The remainder of the thesis is organized as follows. Chapter 2 characterizes the turbulent flow downstream of regular and fractal grids in the absence of the Ahmed body. In addition to characterizing the freestream turbulence intensity and integral length scale in the test section

centerline, this chapter investigates the relationship between the turbulence energy dissipation rate coefficient (C_ε) and turbulence Reynolds number (Re_λ) in the streamwise and cross-stream directions downstream of passive grids using a high-resolution PIV. Readers will find a comprehensive analysis of turbulence properties, including mean velocity profiles, turbulence kinetic energy, dissipation rates, and statistical moments, establishing the foundation for the controlled flow conditions used in subsequent chapters.

Chapter 3 investigates the effect of leading-edge configuration (square and round leading shapes) on separated and reattached turbulent flow around the Ahmed body at $T_u = 1.5\%$. Readers will see detailed comparisons of flow structures for rounded and squared leading-edge Ahmed bodies, focusing on recirculation bubbles, vorticity distributions, Reynolds stresses, coherent structures, and shedding frequencies, providing baseline insights into the role of geometry in low-turbulence conditions. The effect of Reynolds number, $Re = 0.17 \times 10^5$ and $Re = 0.36 \times 10^5$ at $T_u = 1.5\%$ around the squared and rounded leading edge of Ahmed body will be discussed in Chapter 4. It will be observed how variations in Reynolds number influence flow behaviour, interact with leading-edge geometry, and affect wake dynamics.

Chapters 5 and 6 respectively assess the effect of FST on spatiotemporal flow characteristics around the rounded and square leading edge of the Ahmed body, respectively. Three FST intensities ($T_u = 5.0\%$, 10.0% , and 15.0%) were generated using regular and fractal grids, and the results will be compared with those obtained at a baseline turbulence level of $T_u = 1.5\%$ achieved in the absence of the grids. This includes detailed examinations of changes in recirculation bubble size, turbulent statistics (such as Reynolds stresses and mean velocities), and coherent structures, elucidated through two-point correlations and spectral proper orthogonal decomposition (SPOD). The chapters evaluate how FST intensity influences the connection between vortical structures at

the leading edge and those in the wake region, revealing how turbulence modulates flow separation and reattachment processes.

Finally, Chapter 7 summarizes the key findings of the thesis and outlines some recommendations for future work. Readers will see a synthesis of the experimental results, highlighting the implications for vehicle aerodynamics and suggesting directions for extending this research to other geometries and flow conditions.

This thesis is structured as a sandwich thesis, with chapters derived from journal papers, each contributing a distinct perspective on the effects of FST and leading-edge shape. The comprehensive dataset generated through high-resolution PIV and advanced analytical techniques provides a valuable resource for guiding the design of next-generation vehicles with optimized aerodynamic performance. By addressing the understudied role of high FST in vehicle aerodynamics, this work advances both fundamental fluid mechanics and practical engineering applications, contributing to the global effort to reduce vehicle emissions and improve energy efficiency.

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Chapter 2: Analysis of Non-Equilibrium Turbulence Dissipation Downstream of Regular and Fractal Grids in an Open Channel Flow

2.1 Abstract

This study investigates the relationship between the turbulence energy dissipation rate coefficient (C_ϵ) and turbulence Reynolds number (Re_λ) in the streamwise and cross-stream directions downstream of four passive grids using a high-resolution particle image velocimetry (PIV) in an open channel. The grids include two regular square grids with 35% and 48% blockage ratios and two fractal square grids with 32% and 41% blockage ratios. PIV measurements were performed in the production, peak, and decay regions, and the data were analyzed in terms of mean velocity, turbulence intensities, small- and large-scale isotropy, velocity gradient tensor invariants, turbulence length scales, and the energy dissipation rate coefficient. The results in the production region and peak location in the cross-stream direction conform to a non-equilibrium scaling for turbulence energy dissipation rate. It is also shown that the turbulence dissipation rate coefficient ($C_{\epsilon'}$) in the production region and peak location of both regular and fractal grids can be related to a newly proposed local Reynolds number ($Re_{\lambda'}$) and global Reynolds number (Re_L) by the relations $C_{\epsilon'} \propto Re_L^{-0.4} / Re_{\lambda'}$ and $C_{\epsilon'} \propto Re_L^{-0.2} / Re_{\lambda'}$, respectively. This scaling differs from the traditional non-equilibrium equation that relates the local and global Reynolds numbers and energy dissipation rate coefficient ($C_\epsilon \propto Re_0^{1/2} / Re_\lambda$) along the grids' centerline.

2.2 Introduction

Grid turbulence is an important topic in the turbulence research community, as it best represents homogeneous isotropic turbulence (Yao et al., 2021). Besides its fundamental importance, turbulence-generating grids are also used in diverse engineering applications, for instance, as turbulators to enhance thermal mixing (Hoi et al., 2019; Laizet & Vassilicos, 2012), in fluidic energy harvesting (Ferko et al., 2019), impinging jets for efficient enhancement of heat transfer (Cafiero et al., 2021), and spoilers for mitigating vortex shedding and acoustic emissions (Nedić & Vassilicos, 2015).

Grid turbulence can be produced using passive (regular and fractal) or active grids. These grids have been studied extensively over the past decades (Gad-el-Hak & Corrsin, 1974; Poorte & Biesheuvel, 2002; Nagata et al., 2013; and Azzam & Lavoie, 2023). Staicu et al. (2003) conducted measurements downstream of three-dimensional fractal structures resembling branching trees. Subsequently, Biferale et al. (2004) and Mazzi & Vassilicos (2004) conducted numerical simulations of turbulence generated by fractal and multiscale grids. These efforts were followed by an investigation of turbulence generated by regular and fractal grids by Hurst & Vassilicos (2007), who examined 21 different grids. These investigations showed that, regardless of the grid geometry, the flow downstream of the grids is characterized by an inhomogeneous and anisotropic region in the vicinity of the grids, where turbulence is produced, followed by a turbulence peak and a decay region where the flow is approximately homogeneous and isotropic. These studies also demonstrate that the highest level of homogeneity is achieved in the decay region of square fractal grids with satisfactory large-scale isotropy values of $u_{\text{rms}}/v_{\text{rms}} \in [1.1, 1.3]$, where $u_{\text{rms}} = \sqrt{u'^2}$ and $v_{\text{rms}} = \sqrt{v'^2}$ are root-mean-square of the streamwise (u') and cross-stream (v') fluctuation

velocities, respectively. The development of turbulence behind single-square grids has been compared to turbulence generated by regular and fractal grids. It has been shown that a fractal square grid can produce higher turbulence levels in the near-field region compared to the single square grid, and the presence of small fractal iterations leads to elevation of turbulence intensity in the production region, while in the decay region, it results in fast recovery from the initial inhomogeneity (Zhou et al., 2014).

The scaling of the turbulence dissipation rate coefficient (C_ε), equation 2.1 also plays an important role in shaping a fundamental understanding of turbulence.

$$C_\varepsilon = \varepsilon L_u / u_{\text{rms}}^3 \approx \text{constant} \quad (2.1)$$

Here, ε is the turbulence kinetic energy (TKE) dissipation per unit mass, and L_u is the streamwise integral length scale. Equation 2.1, often referred to as 'equilibrium scaling,' presupposes that the mechanism of energy transfer between different scales of turbulence motions is in a state of equilibrium (Goto & Vassilicos, 2016; Chen et al., 2021). This concept forms the basis for formulating turbulence models in Reynolds-averaged Navier-Stokes (RANS) equations, as it offers a direct approach to estimating the turbulence kinetic energy dissipation rate (Pope, 2001). Sreenivasan (1995) conducted a comprehensive analysis of experimental data for multiple turbulent shear flows, including the wake of a sphere and cylinder, mixing layer, as well as round and plane jets, and found that C_ε exhibits Reynolds number independence when the turbulence Reynolds number ($\text{Re}_\lambda = \lambda_u u_{\text{rms}} / \nu$, where ν is fluid kinematic viscosity) exceeds 100. The streamwise Taylor microscale can be approximated by (Pope, 2001):

$$\lambda_u = \sqrt{2u_{\text{rms}}^2 / \left(\frac{\partial u'}{\partial x} \right)^2} \quad (2.2)$$

The energy dissipation rate can be estimated under the assumption of isotropy, as outlined in Pope (2001) and Isaza et al. (2014):

$$\varepsilon = 15 \nu u_{\text{rms}}^2 / \lambda_u^2 \quad (2.3)$$

It follows from equations 2.1 and 2.3 that the equilibrium scaling can be expressed as equation 2.4, which indicates that there is a direct relationship between L_u/λ_u and Re_λ .

$$L_u/\lambda_u = (C_\varepsilon/15) \text{Re}_\lambda \approx \text{constant} \quad (2.4)$$

It is noted that the equilibrium turbulence dissipation scaling is not valid during the initial stage of turbulence decay (Mazellier & Vassilicos, 2010; Valente & Vassilicos, 2015). Indeed, Valente and Vassilicos (2015) observed that in the initial decay region of regular and fractal grids, the energy spectra exhibit a distinct power law with exponents similar to Kolmogorov's $-5/3$ scaling. The study by Zhou et al. (2016) investigated the spatial evolution of turbulence generated by a single square grid, focusing on the development of helical behaviour and the emergence of a $2/3$ power-law in the energy spectrum. Their findings suggest that the observed $-5/3$ energy spectra in grid-generated turbulence are associated with the interactions of large-scale structures. Similarly, Zhou et al. (2019) showed that in the near-field region behind two side-by-side square cylinders, the emergence of a well-defined $-5/3$ energy spectrum is intimately associated with extreme events that are pronounced non-Gaussian velocity fluctuations caused by strong large-scale vortex shedding. In the initial decay region, the turbulence dissipation rate coefficient does not adhere to a constant value described in equation 4. Dairay et al. (2015) employed both direct numerical simulation and hot-wire anemometry and reported that C_ε is not constant but decreases with increasing turbulence Reynolds number. Later, Vassilicos (2015) indicated that, C_ε varies with both the global (Re_0) and local (Re_λ) Reynolds numbers as follows:

$$C_\varepsilon \propto \text{Re}_0^{m/2} / \text{Re}_\lambda^n (\neq \text{constant}) \quad (2.5)$$

Here, the empirical exponents $m \approx n \approx 1$ and $\text{Re}_0 = U_\infty t_0 / \nu$ is Reynolds number based on the incoming freestream velocity (U_∞) and the grids' (largest) bar thickness (t_0). This observation, also made in the flow downstream of active grids (Zheng et al., 2023), is referred to as the 'non-equilibrium turbulence dissipation scaling.' The non-equilibrium scaling has been further validated in studies of turbulent/non-turbulent interfaces (Zhou & Vassilicos, 2017).

The non-equilibrium scaling has found widespread application in both homogeneous and inhomogeneous turbulence, including turbulent boundary layers (Obligado et al., 2022), free jets (Cafiero & Vassilicos, 2019), and the wake of a slender body (Ortiz-Tarin et al., 2021). Despite the widespread applicability of equation 2.5, the precise values of the exponents (m and n) are a subject of debate. Bos & Rubinstein (2017) obtained $m = n = 15/14$ for regular and fractal grids under the assumption that the flow is homogeneous and isotropic, and introduced a new scaling as follows:

$$C_\varepsilon / C_{\varepsilon 0} \propto (\text{Re}_\lambda / \text{Re}_{\lambda 0})^{-15/14} \quad (2.6)$$

where $C_{\varepsilon 0}$ and $\text{Re}_{\lambda 0}$ are the equilibrium values of C_ε and Re_λ . Chen et al. (2021) argued that these values can be influenced by inhomogeneity. Zheng et al. (2021) demonstrated that the scaling proposed by Bos & Rubinstein (2017) holds in the flow downstream of active grids with an equilibrium value of $C_{\varepsilon 0} = 0.81$, which is in good agreement with 0.87 (Puga et al., 2017) and 0.82 (Kang et al., 2003) reported for active grids.

It has been shown that non-equilibrium turbulence dissipation scaling holds along the centerline of passive and active grids (Hearst, 2015; Zheng et al., 2023). However, the production region of

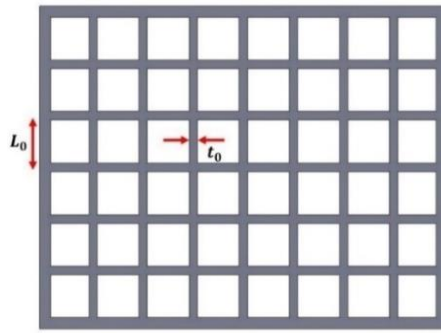
grid turbulence has not received as much attention as the decay region. Specifically, the universality of the relationship between C_ϵ and Re_λ in the cross-stream direction in turbulent flows characterized by inhomogeneity and anisotropy has not yet been established. To address this knowledge gap, analyses of turbulence statistics and scaling of the dissipation rate coefficient along the centerline and cross-stream direction, spanning the production region, peak location, and decay region of regular and fractal grids, are reported. The rest of Chapter 2 is organized as follows: Section 2.3 describes the experimental procedure, results and discussion are presented in Section 2.4, and conclusions are summarized in Section 2.5.

2.3 Experimental Procedure

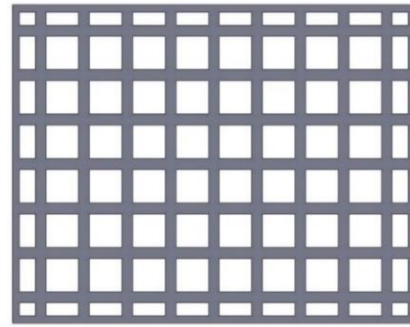
2.3.1 Test Facility and Grids

The experiments were conducted in an open recirculating water channel with a test section of length, width, and height of 6000 mm, 600 mm, and 450 mm, respectively. To facilitate optical access and flow visualization, the side walls and floor of the water channel were fabricated from 31.8 mm Super Abrasion Resistant® clear acrylic. The flow was driven by a 30 kW variable-speed drive motor pump through a flow conditioning unit before entering the test section. The flow conditioning unit consists of perforated plates, hexagonal honeycombs, and mesh screens of different sizes and has a contraction ratio of 4.88:1. Four grids consisting of two square regular grids and two square fractal grids were fabricated from stainless steel sheets and installed at the inlet of the test section. The thickness of all grids is 6.35 mm, and schematics of the grids and their geometric specifications are presented in Fig. 2.1 and Table 2.1, respectively. The parameters defined in Figs 2.1a and 2.1c are discussed as follows: t_0 is the spanwise thickness of the largest bar in the fractal grids (or the bar thickness of the regular grids), t_2 is the spanwise thickness of the smallest bar in the fractal grids, $t_r = t_0/t_2$ is the thickness ratio, L_0 and L_2 are the maximum bar

length (the regular grid's bar length) and the minimum bar length in fractal grids. In Table 2.1, T^2 is the cross-section dimension of the grid, N_f is the number of fractal iterations, and S is the number of patterns in each iteration. R_t is the thickness ratio of each bar at each successive iteration, and R_L is the length ratio of each bar at each successive iteration. The fractal grid design follows a square shape, incorporates $N_f = 3$ iterations of fractal patterns, and is considered space-filling as the fractal dimension, $D_f = 2$ (Hurst & Vassilicos, 2007; Seoud & Vassilicos, 2007). σ represents the blockage ratio (solidity) of grids, defined as the ratio of the grid-covered area to the total cross-sectional area of the test section. As can be seen from the table, the grid F41 has a thickness ratio of $t_r = 17.0$ and a blockage ratio of $\sigma = 41\%$ while for F32, $t_r = 9.50$ and $\sigma = 32\%$, the same blockage ratio studied by Valente & Vassilicos (2011). $x^* = L_0^2/t_0$ is the wake interaction length, which provides a measure of the streamwise distance from the grids to the location where the wakes arising from the largest bars meet each other on the centerline (Mazellier & Vassilicos, 2010).



(a) R35



(b) R48

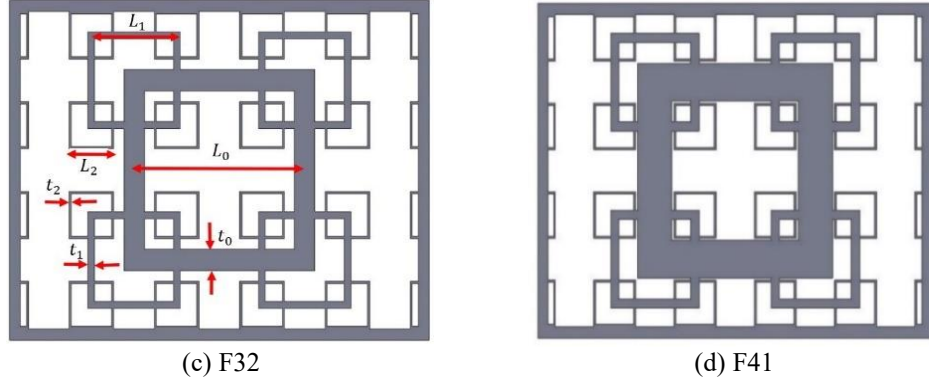


Figure 2.1 Schematic of square regular and fractal turbulence-generating grids

Table 2.1 Fractal and regular grids' specifications

Parameters	R35	R48	F32	F41
T^2 (mm ²)	585×450	585×450	585×450	585×450
N_f	-	-	3	3
S	-	-	4	4
t_r	1	1	9.50	17
R_t	1	1	0.32	0.24
R_L	1	1	0.50	0.50
L_0 (mm)	72	62.85	238	238
L_1 (mm)	-	-	119	119
L_2 (mm)	-	-	59.50	59.50
t_0 (mm)	12	15.75	28.50	51
t_1 (mm)	-	-	9.25	12.37
t_2 (mm)	-	-	3	3
t_0/L_0	0.17	0.25	0.12	0.21
x^* (mm)	-	-	1987.51	1110.67
σ %	35	48	32	41

2.3.2 Test Condition and PIV Measurement Procedure

In all experiments, the water level was maintained at 435 mm, which is 15 mm below the grids' top horizontal bar. The freestream velocity measured at the test section centerline was $U_\infty = 0.24$ m/s. The corresponding global Reynolds numbers were $Re_0 = 3000, 3937, 7125$ and 12750 for R35, R48, F32 and F41, respectively. For the water channel without the inlet grids, the boundary layer thickness on the floor at 1737 mm downstream of the channel inlet, which corresponds to $x/L_0 = 7.3$, was measured to be $\delta = 15.2$ mm. Hence, it was concluded that boundary

confinement from the channel floor does not significantly affect the results presented in this manuscript. The streamwise turbulence intensity, measured at the channel centerline when the grids were not installed, was $T_u (=u_{rms}/U_\infty) = 1.5\%$. Outside the boundary layer, the streamwise turbulence intensity was uniform to within $\pm 0.85\%$ along the channel centerline and $\pm 0.75\%$ in the cross-stream direction.

The velocity vectors within the flow field were measured using a PIV technique. Silver-coated hollow glass spheres with a mean diameter of $d_p = 10 \mu\text{m}$ and density of $\rho_p = 1400 \text{ kg m}^{-3}$ were introduced into the flow as seeding particles. To assess the ability of the particles to follow the flow accurately, the Stokes number (S_k) of the particles was determined by comparing the particle response time (τ_p) to the characteristic temporal scale in the flow (τ_f). The particle response time is determined as follows:

$$\tau_p = \frac{d_p^2(\rho_p - \rho_f)}{18\mu_f} \quad (2.7)$$

where ρ_f and μ_f are the density and dynamic viscosity of the working fluid. It was found to be $\tau_p = 2.2 \times 10^{-6} \text{ s}$. The characteristic temporal scale was determined as the minimum value of $\tau_f = \sqrt{\nu/\varepsilon}$ in the near field, the values of the Stokes number were found to be $S_k \leq 3.74 \times 10^{-4}$, which are orders of magnitude lower than the critical value of 0.05 proposed by Samimy & Lele (1991) for the seeding particles to respond to changes in the flow motion faithfully.

Flow field illumination was provided by a dual-cavity, dual-head high-speed Neodymium-doped yttrium lithium fluoride (Nd: YLF) laser, each with a maximum energy output of 30 mJ/pulse. To mitigate laser distortion induced by free-surface bubbles, a 9 mm thick acrylic surface plate, measuring 585 mm in length and spanning the entire width of the section, was partially submerged beneath the laser sheet (Kumahor & Tachie, 2023; Sagharichi & Tachie, 2024). The boundary

layer thickness formed on the plate was $\delta = 6.1$ mm. Thus, the effect of boundary confinement due to the surface plate on the present results is negligible. Two complementary metal oxide semiconductor cameras, each with a resolution of $2560 \text{ pixel} \times 1600 \text{ pixel}$, were arranged side-by-side and positioned perpendicular to the side wall of the test section. The measurements were performed in the x-y plane at the test section's midspan ($z = 0$). The field of view of each camera covers an area of $288 \text{ mm} \times 180 \text{ mm}$ for regular grids and $323 \text{ mm} \times 202 \text{ mm}$ for fractal grids, with a 15 mm overlap. The digital resolution of each field of view was 8.88 pixel/mm for regular grid measurements and 7.92 pixel/mm for fractal grid measurements, respectively. A schematic of the PIV setup is provided in Fig. 2.2. The sampling frequency was set to $f_{sp} = 3$ Hz to ensure that the samples are statistically independent. Based on a convergence study for U/U_∞ , T_u , $\overline{u'^3}/U_\infty^3$ and $\overline{u'^4}/U_\infty^4$ at $x/x_{peak} = 0.5$ downstream of grid F32, 12,000 snapshots were acquired. Data acquisition and velocity vector calculation were performed using commercial software (DaVis version 10.2.1) supplied by LaVision Inc. The velocity vectors were calculated using a GPU-accelerated multi-pass cross-correlation algorithm, with an initial interrogation window of $128 \text{ pixels} \times 128 \text{ pixels}$ with 50% overlap, followed by final four passes with an interrogation window of $24 \text{ pixels} \times 24 \text{ pixels}$ and 75% overlap.

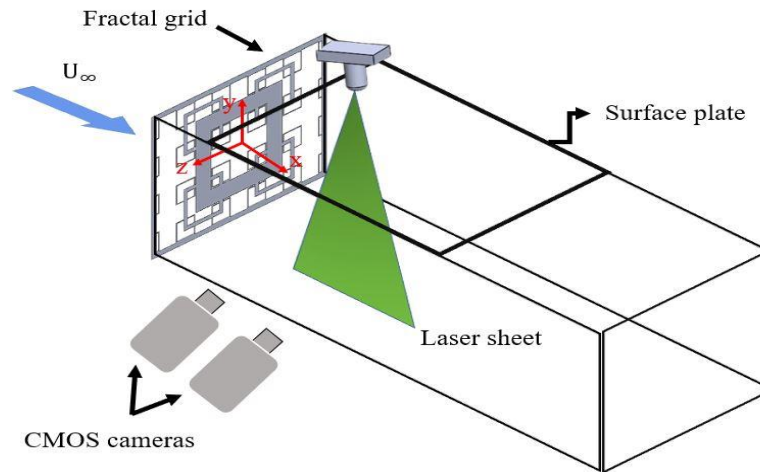


Figure 2.2 Schematic of the experimental setup, with F41 at the inlet

The spatial resolution of the PIV measurement plays a crucial role in obtaining a reliable estimate of the energy dissipation rate (Chen et al., 2021). For a reliable estimate of the TKE dissipation rate, Tokgoz et al. (2012) suggested that the ratio of the interrogation window size (Δd) to the Kolmogorov length scale $\eta = (v^3/\varepsilon)^{1/4}$, where ε was calculated using equation 2.3, should not exceed 8 if a 75% overlap of the interrogation window was implemented. It is observed from Fig. 2.3 that $\Delta d/\eta$ ranges from 2 to 5, except for a few data points between 6 and 8 for R48. Hence, the spatial resolution is sufficient for a reliable energy dissipation rate estimation.

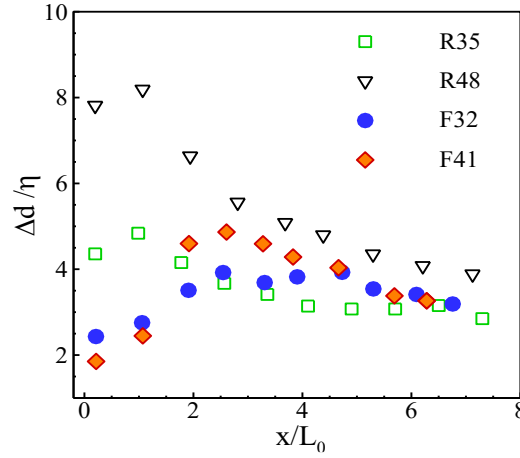


Figure 2.3 The ratio of the interrogation window size to the Kolmogorov length scale along the grid's centerline

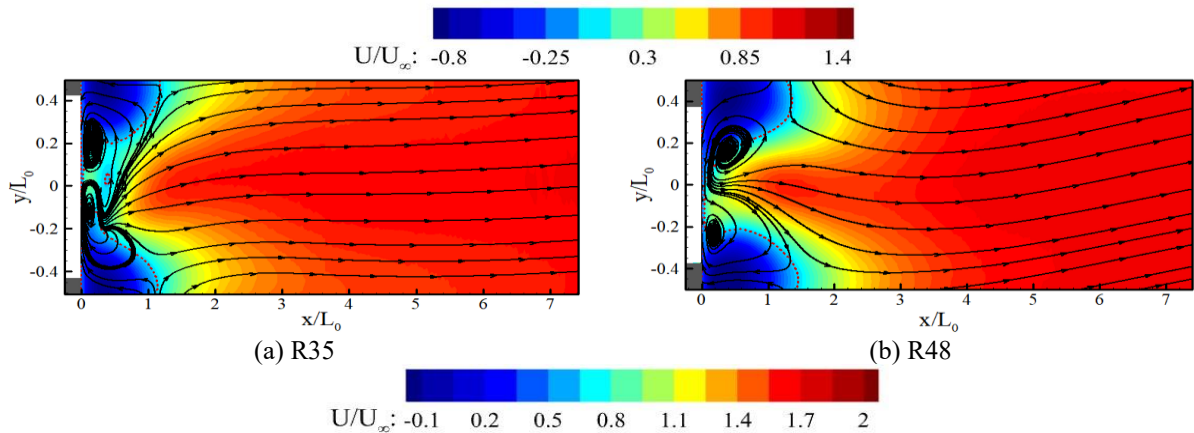
Measurement uncertainties for the streamwise mean velocity and Reynolds normal stresses were determined at a 95% confidence level using the methodology described in Sciacchitano and Wieneke (2016), Bendat & Piersol (2010), and Sagharichi et al. (2023). The maximum uncertainties in the mean velocity and Reynolds normal stresses are estimated as $\pm 0.0098 \text{ m/s}$ and $\pm 0.0002 \text{ m}^2/\text{s}^2$ respectively, downstream of the regular grids and $\pm 0.0052 \text{ m/s}$ and $\pm 0.0002 \text{ m}^2/\text{s}^2$, respectively, for the fractal grids.

2.4 Results and Discussion

This section presents an assessment of the flow characteristics downstream of the grids. Section 2.4.1 focuses on the mean velocity and turbulence intensity, Section 2.4.2 discusses isotropy, Section 2.4.3 focuses on the turbulence length scales, and a new non-equilibrium scale in the production and peak regions in the cross-stream direction is introduced in Section 2.4.4.

2.4.1 Mean Flow and Turbulence Intensity

Figure 2.4 displays the contours of the streamwise mean velocity downstream of the grids, superimposed with the mean streamlines. The mean flow downstream of the fractal grids differs significantly from that of the regular grids, with the high-velocity regions resembling jet-like wakes downstream of the grids. The flow downstream of the F41 grid exhibits greater momentum than the F32 grid, which can be attributed to the higher blockage ratio in the former case. The recirculation length (L_r), which is measured as the streamwise distance from the grid to the point where $U/U_\infty = 0$ shows that an increase in the blockage ratio of the regular grids leads to an increase in the recirculation length. Specifically, the recirculation length increases from $L_r = 1.18L_0$ for R35 to $L_r = 1.45L_0$ for R48, compared to $L_r = 1.30L_0$ reported by Gan & Krogstad (2016) for flow downstream of a regular grid with a blockage ratio of $\sigma = 44\%$.



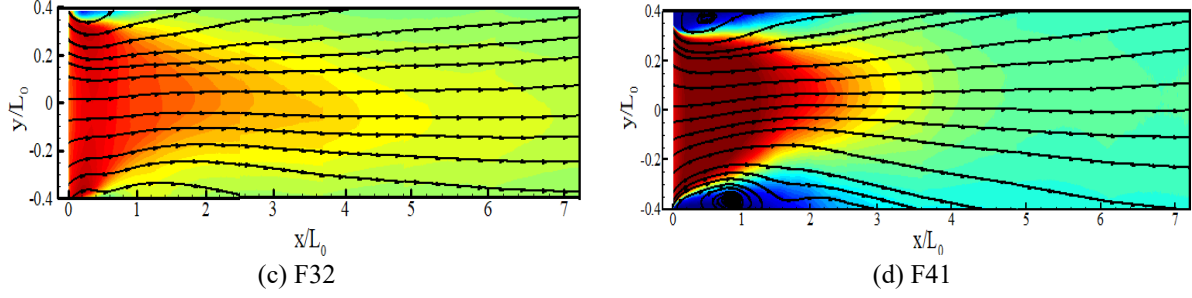


Figure 2.4 Contours of normalized streamwise mean velocity superimposed by mean streamlines. The dashed line in the (a) and (b) panels indicates the recirculation bubble

Figure 2.5 shows the distribution of the normalized streamwise mean velocity along the centerline. In this figure, streamwise locations are normalized by x_{peak} (the location where turbulence intensity peaks). The streamwise mean velocity downstream of the regular grids (Fig. 2.5a) is initially negative, followed by a rapid increase to its maximum velocity at $x/x_{\text{peak}} \approx 1.50$ (or $x/L_0 \approx 1.19$ and 1.28 for R35 and R48, respectively). For the fractal grids, the mean velocity peaks closer to the grid compared to the regular grid (Fig. 2.5b). Downstream of the peak location, the mean velocity gradually decreases from the peak value of $U_c/U_\infty = 1.5$ and 2.5 (for F32 and F41, respectively) to $U_c/U_\infty = 1$. The velocity recovery rate is faster for F41 than for F32. The present results are also in good agreement with experimental data from the literature for $x/x_{\text{peak}} \geq 2$. The difference between the present data for regular grids and the study conducted by Nedić & Tavoularis (2016) (for a grid with a blockage ratio of 35%) within the production region ($x/x_{\text{peak}} < 2$) can be attributed to the plane in which the data was collected. In the present study, the midspan of the test section where data were collected is positioned downstream of the grid bars, while the data reported by Nedić & Tavoularis (2016) were acquired within the space between the grid bars.

(a)

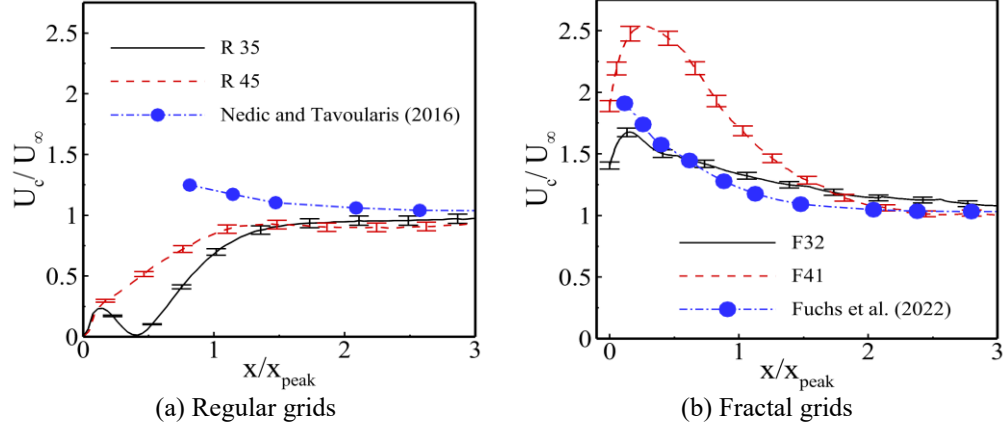


Figure 2.5 Normalized centerline streamwise mean velocity profile in comparison with the data of Nedić & Tavoularis (2016) and Fuchs et al. (2022)

Plots of the streamwise ($T_u = u_{rms}/U_\infty$) and cross-stream ($T_v = v_{rms}/U_\infty$) turbulence intensities are presented in Figs. 2.6a and 2.6b. The plots show that the streamwise locations where T_u and T_v peak is similar. Additionally, R48 and F41, which possess a higher blockage ratio compared to the F32 and R35 grids, exhibit higher turbulence intensity peaks, and the turbulence intensities peak closer to the regular grids ($x/L_0 = 0.9$ and 1 for R35 and R48, respectively) in comparison to the fractal grids ($x/L_0 = 1.9$ and 3.1 for F41 and F32, respectively). As shown in Figs. 2.6c and 2.6d, the broader production region downstream of the fractal grids, compared to regular grids, is attributed to sustained TKE production (P_k), which is maintained by successive interactions of distinct wake patterns generated by the multi-scale bars. Figure 2.7 demonstrates a good agreement between the present and previous results of Nedić & Tavoularis (2016) for regular grids and Sponfeldner et al. (2015), Weitemeyer et al. (2013) and Fuchs et al. (2022) for fractal grids.

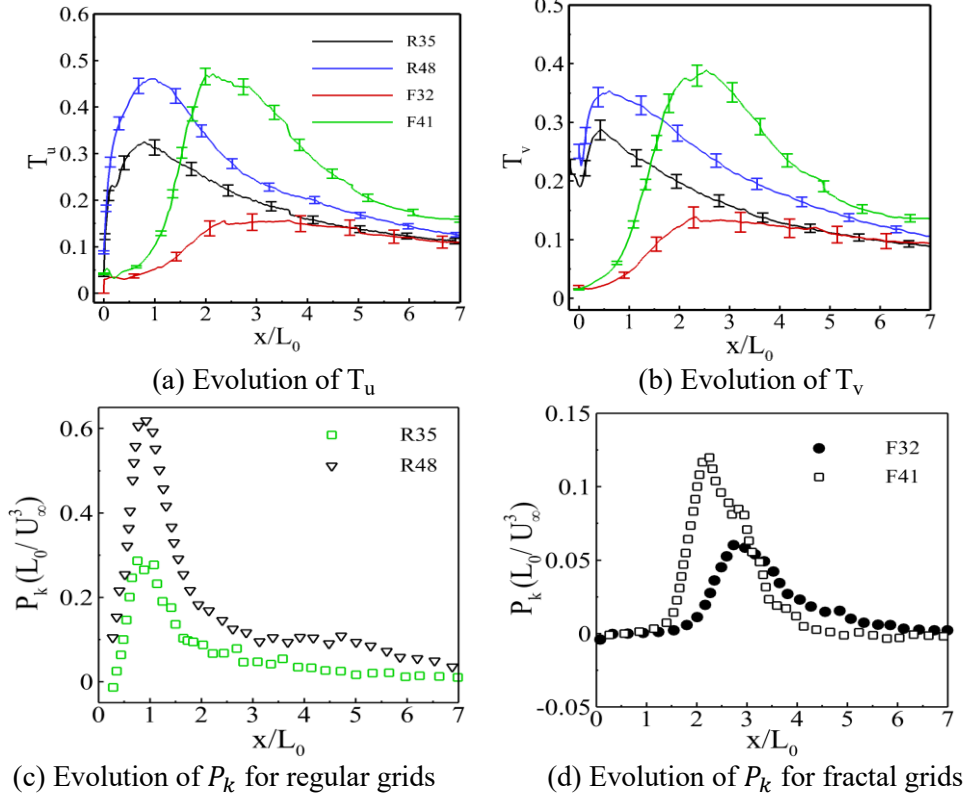


Figure 2.6 Streamwise development of T_u , T_v , and TKE production (P_k)

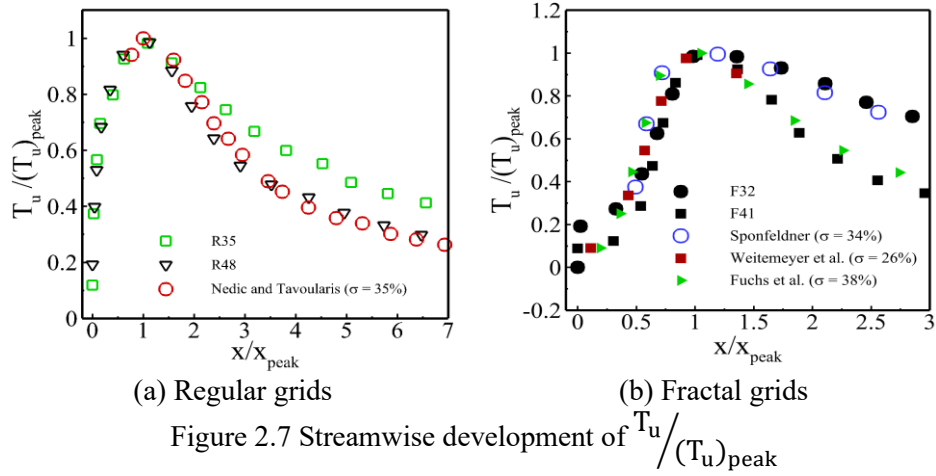


Figure 2.7 Streamwise development of $T_u / (T_u)_{peak}$

2.4.2 Isotropy

It is well-documented that the flow near the grid is inhomogeneous and anisotropic (Gomes-Fernandes et al., 2014). To assess the global (large-scale) isotropy downstream of the grids, the streamwise evolution of u_{rms}/v_{rms} is shown in Fig. 2.8. The flow in proximity to the grids exhibits significant anisotropy with values of u_{rms}/v_{rms} as high as 1.40 and as low as 0.45 in the case of the

regular grids and 1.47 and 0.96 for the fractal grids. The isotropy, however, tends to improve with streamwise distance, and for the regular grids in the decay region, it is approximately $u_{rms}/v_{rms} = 1.17$, which is consistent with values of 1.15, 1.25, and 1.25 reported for regular grids by Kang et al. (2003), Olivieri et al. (2021), and Nedić & Tavoularis (2016), respectively. In the fractal grids, this ratio lies between 1.15 and 1.20 for $x/x_{peak} \geq 1$, which is in good agreement with $u_{rms}/v_{rms} \in [1.10, 1.25]$ reported by Hurst & Vassilicos (2007) and Gomes-Fernandes et al. (2014).

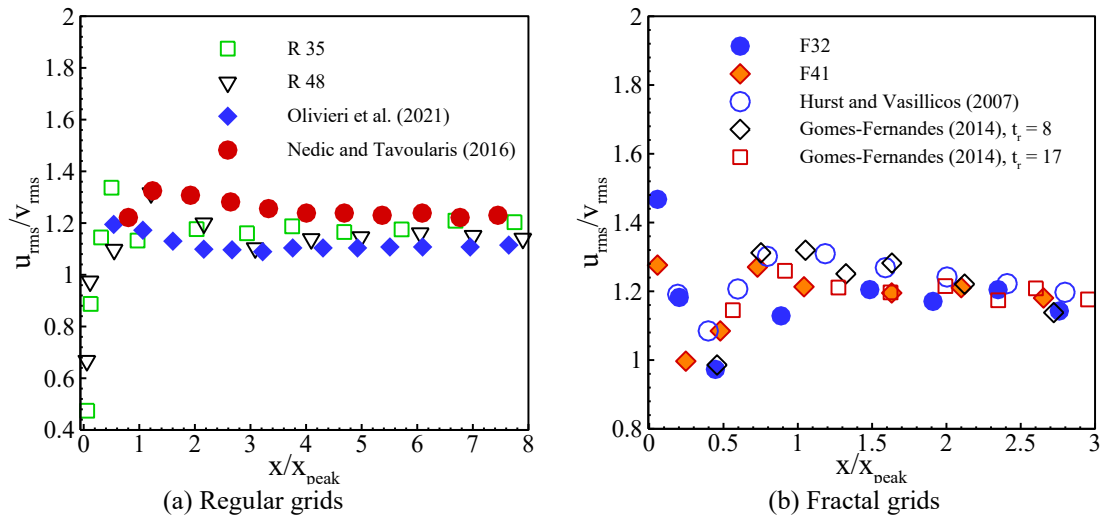


Figure 2.8 Streamwise evolution of global isotropy along the grids' centerline

The distributions of skewness ($S_{u'} = \overline{u'^3}/u_{rms}^3$ and $S_{v'} = \overline{v'^3}/v_{rms}^3$) and flatness ($F_{u'} = \overline{u'^4}/u_{rms}^4$ and $F_{v'} = \overline{v'^4}/v_{rms}^4$) of the fluctuating velocities along the centerline are examined in Fig. 2.9. Also

shown are the skewness and flatness of streamwise velocity fluctuation derivatives

($S_{(\partial u'/\partial x)} = \overline{(\frac{\partial u'}{\partial x})^3} / [\overline{(\frac{\partial u'}{\partial x})^2}]^{3/2}$) and ($F_{(\partial u'/\partial x)} = \overline{(\frac{\partial u'}{\partial x})^4} / [\overline{(\frac{\partial u'}{\partial x})^2}]^2$). If the flow is isotropic, the skewness

and flatness take Gaussian values of zero and three (Isaza et al., 2014). Hence, for comparative purposes, reference lines for $S_{u'}$, $S_{v'} = 0$ and $F_{u'}$, $F_{v'} = 3$ (which are indicated by horizontal dotted lines) are included in these plots. The figure shows that while the skewness of u' and v' for the

regular grids are approximately constant and near zero, the corresponding values of S_u' (S_v') for the fractal grids decrease (increase) in the production region and then increase (decrease) as the flow evolves further downstream. However, the largest departure from the Gaussian distribution is seen in the peak region of the F41 grid. A similar departure from the Gaussian distribution was reported in inhomogeneous flow downstream of dual-plane turbulent jets (Zhou et al., 2018). Figure 2.9a also shows that the flow downstream of fractal grids is not isotropic, yet in region $1.0 \leq x/x_{\text{peak}} \leq 1.5$, located inside the early part of the decay region. Comparing Figs. 2.9a and 2.9b reveal that S_v' approaches zero sooner than S_u' , aligning with the findings of Hearst (2015). The distributions of F_u' and F_v' are presented in Figs. 2.9c and 2.9d. For the regular grids, the distributions are Gaussian, i.e., $F_u', F_v' \approx 3$. However, the flatness for F41 and F32 deviates from the Gaussian value of 3 within $0.20 \leq x/x_{\text{peak}} \leq 1.0$. Similar extreme values in the production region of fractal grids were also observed by Nagata et al. (2013). Figures 2.9e and 2.9f reveal that the skewness and flatness of the derivative of velocity fluctuations in the decay region are approximately $-S_{(\partial u'/\partial x)} \approx 0.43$ and $F_{(\partial u'/\partial x)} \approx 5$. These values are consistent with values of 0.45 and 5.0 reported by Isaza et al. (2014) and Hearst & Lavoie (2015) for regular and fractal grids, respectively. It has been documented that in the decay region, $-S_{(\partial u'/\partial x)} \propto (F_{(\partial u'/\partial x)})^{3/8}$ (Wyngaard & Tennekes, 1970). In the present study, the values of $-S_{(\partial u'/\partial x)} / (F_{(\partial u'/\partial x)})^{3/8}$ in the decay region falls within the range of 0.21 to 0.25, regardless of grid type and blockage ratio. This range of values is in line with 0.20 to 0.25 reported for flow downstream of active grids Zheng et al. (2021).

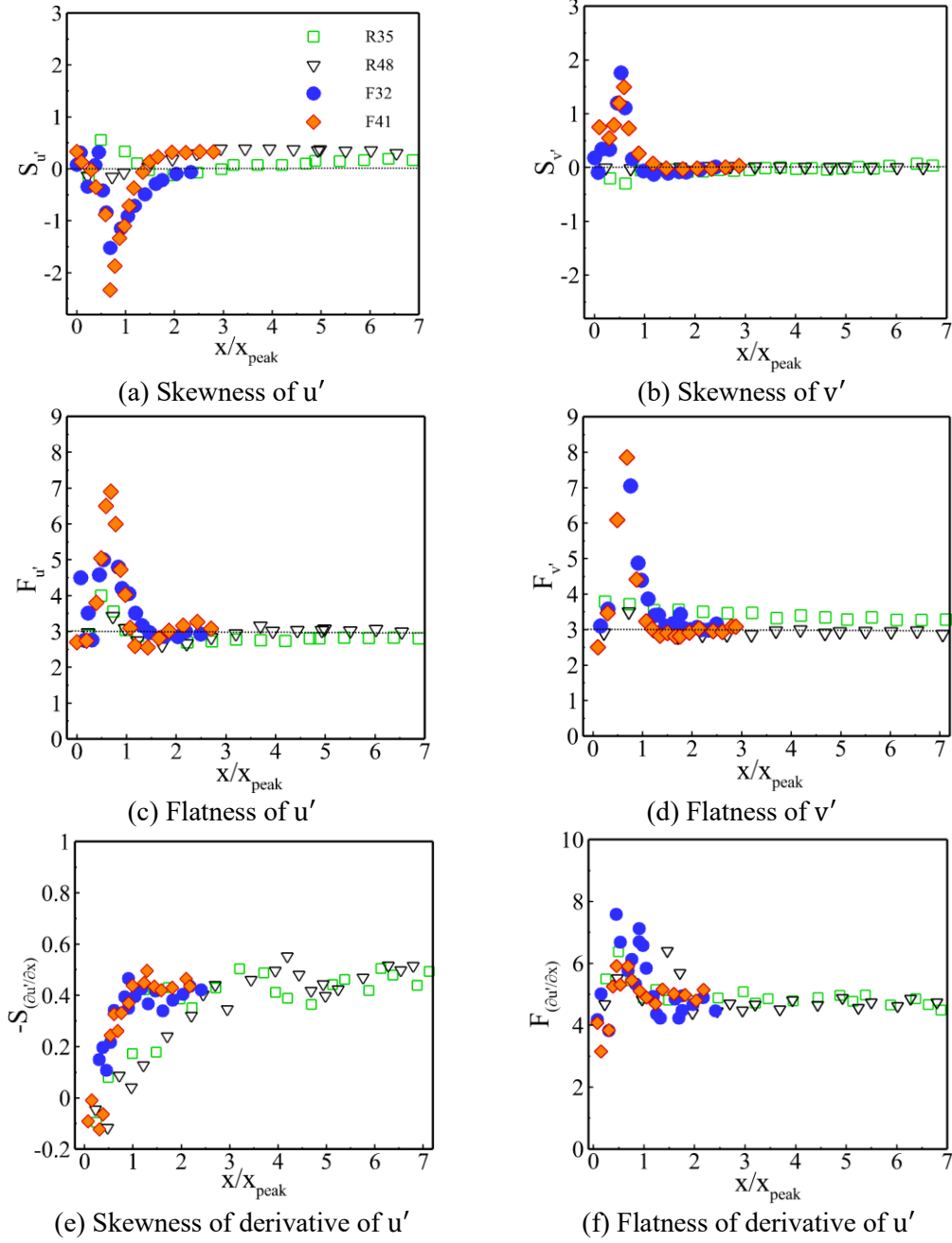


Figure 2.9 Streamwise evolution of skewness and flatness of the velocity fluctuations, and derivative of streamwise velocity fluctuation along the grid centerline

2.4.3 Turbulence Length Scales

The spatial organization of turbulence can be examined through the turbulence integral length scales. The streamwise integral length scale is calculated by integrating the spatial two-point autocorrelation function of the streamwise fluctuating velocity (Equation 2.8). The streamwise

separation between the points is represented by r_x . In equation 2.9, r_0 is defined as the distance at which the two-point autocorrelation coefficient (R_i) first crosses zero. Here $u'_1 = u'$, $u'_2 = v'$, $R_1 = R_{u'}$ and $R_2 = R_{v'}$.

$$R_i(x, y, r_x) = \frac{\overline{u'_i(x, y) u'_i(x + r_x, y)}}{\sqrt{\overline{u'^2_i(x, y)}} \sqrt{\overline{u'^2_i(x + r_x, y)}}} \quad (2.8)$$

$$L_i(x, y) = \int_0^{r_0} R_i(x, y, r_x) dr_x \quad (2.9)$$

Figures 2.10a and 2.10b show the streamwise distributions of $R_{u'}$ and $R_{v'}$ at the locations of the peak turbulence intensity, i.e., $x/L_0 = 0.85$ and 2.60 for R48 and F41, respectively. Plots for R35 and F32 are not shown since they exhibit similar trends as R48 and F41. In both cases, it is observed that $R_{u'}$ decays more slowly than $R_{v'}$, indicating that the streamwise velocity fluctuations component remains correlated over a longer distance compared to the cross-stream velocity fluctuation component. For the regular grid, the decorrelation points of $R_{u'}$ and $R_{v'}$ are relatively close in magnitude ($r_x \approx L_0$), suggesting a more homogeneous turbulence structure. Conversely, for the fractal grid, the decorrelation point of $R_{u'}$ ($r_x \approx 0.21L_0$) is about four times as high as that of $R_{v'}$ ($r_x \approx 0.05L_0$), implying a more sustained spatial correlation in the streamwise direction. This difference results from the multiscale wake interactions introduced by the fractal grid.

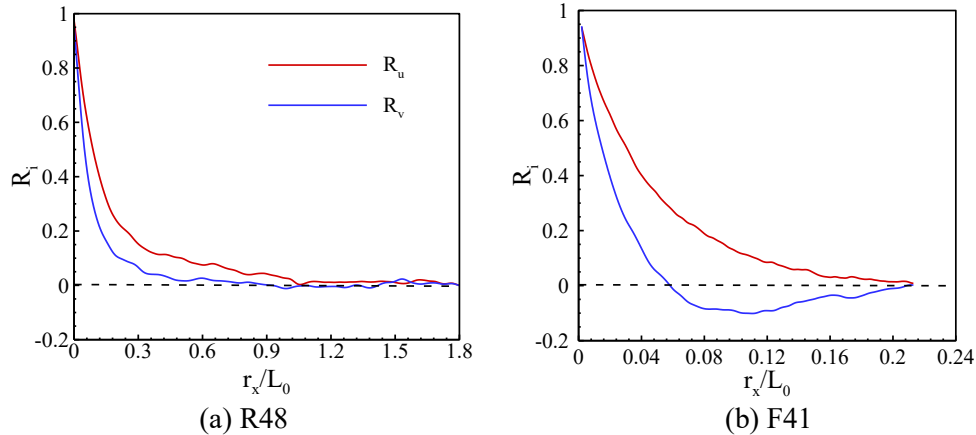


Figure 2.10 Two-point auto-correlation coefficients R_i for $i = 1, 2$ with $u_1 = u'$ and $u_2 = v'$ at peak turbulence intensity

Figure 2.11a shows the streamwise integral length scale calculated using equation 2.9 and normalized by the (largest) grid bar size (L_0) along the grids' centerline. The integral length scale for both grid types increases monotonically as the flow evolves downstream, which is in good agreement with the observation of Olivieri et al. (2021). In the decay region, the integral length scale of the fractal grids fluctuates around $L_u \approx 0.22L_0$, a trend that is consistent with the findings of Gomes-Fernandes et al. (2012) and Nagata et al. (2017). The length scale ratio L_u/λ_u along the centerline (Fig. 2.11b) is within the range of 4 to 5 for regular grids, regardless of the blockage ratio. For the fractal grids, on the other hand, there is a significant variation, with values as high as $L_u/\lambda_u \approx 8$ to 10 in the decay region, but these values are comparable to $L_u/\lambda_u \approx 9$ reported by Fuchs et al. (2022). It is also noted that the Kolmogorov length scale for the fractal grids initially decreases until $x/x_{\text{peak}} \approx 1$, where turbulence intensity peaks and then grows monotonically as it enters the decay region. This behaviour aligns with that observed behind fractal grids by Nedić & Tavoularis (2016).

For isotropic turbulence, the ratio of the streamwise to cross-stream Taylor microscale is $\lambda_u/\lambda_v = \sqrt{2}$ (Pope, 2001). The ratio of streamwise to cross-stream Taylor microscale is plotted in Fig. 2.11d, with a horizontal line representing $\lambda_u/\lambda_v = \sqrt{2}$ for reference. The results are in reasonable agreement with the theoretical value of isotropic turbulence in the decay region.

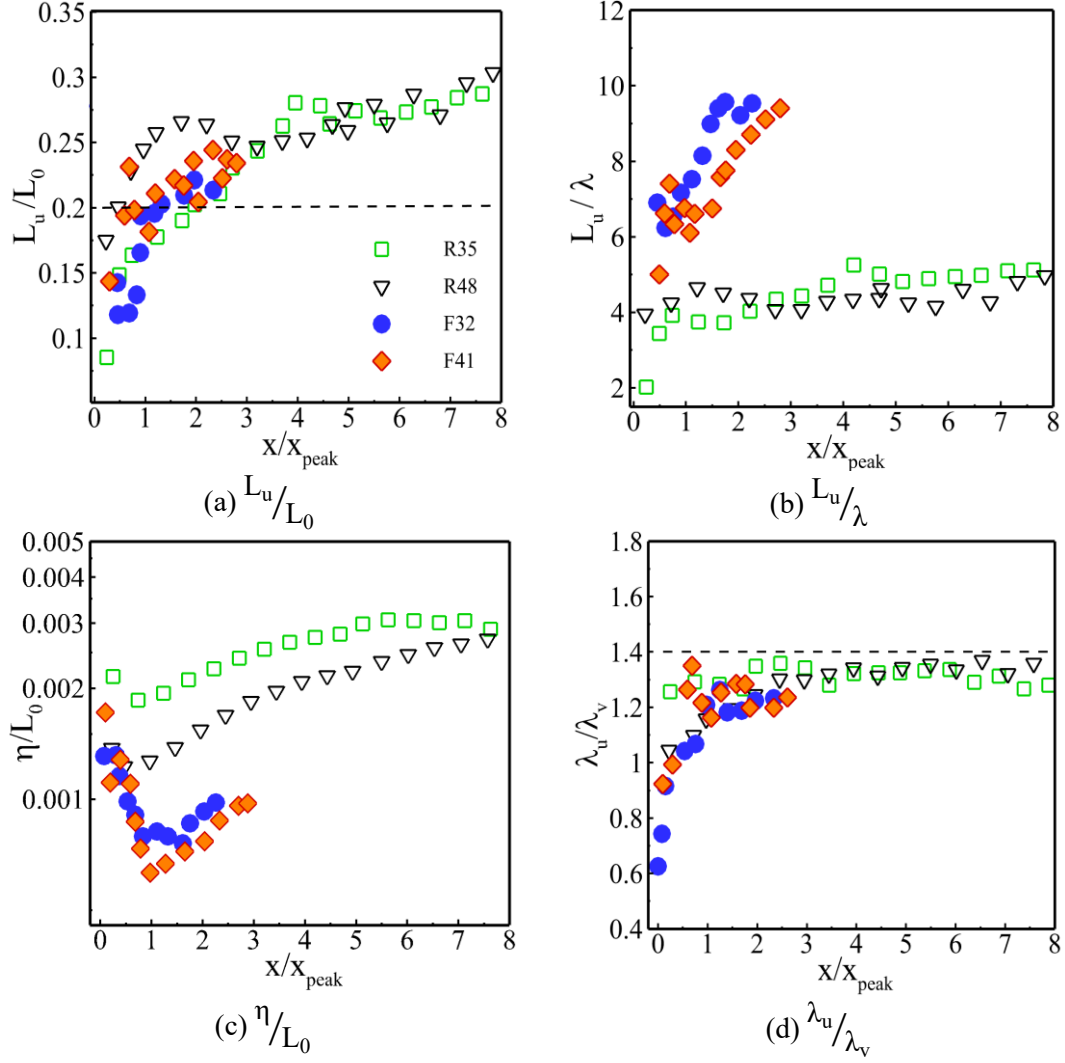


Figure 2.11 Streamwise evolution of turbulence scales along the grid centerline

2.4.4 Scaling of the Turbulence Energy Dissipation Rate Coefficient (C_ϵ)

2.4.4.1 Scaling of C_ϵ Along the Grids' Centerline

As seen in Fig. 2.11b, the ratio of L_u/λ_u is nearly constant downstream of the regular grids. This observation is significant because if this ratio remains constant, according to equation 2.4, the turbulence Reynolds number (Re_λ) should also remain constant to satisfy $C_\epsilon \approx \text{constant}$. However, an examination of the streamwise variation of the turbulence Reynolds number (Fig. 2.12) reveals

that Re_λ decreases with increasing streamwise distance. Consequently, equation 2.4 does not hold along the centerline in the decay region.

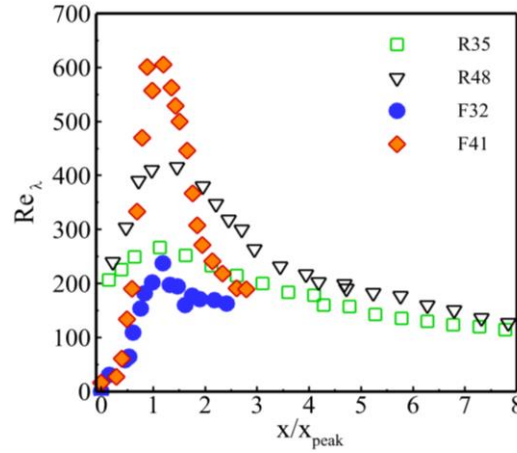


Figure 2.12 Streamwise evolution of Re_λ along the grid centerline

To investigate the dissipation and non-equilibrium characteristics in the decay region, plots of C_ε against Re_λ along the grid centerline are depicted in Fig. 2.13. Data from previous studies on both regular and fractal grids are also included for comparison. The correlation between C_ε and Re_λ and the corresponding R-squared values are determined using the least square method and are displayed on the plots. Consistent with previous studies (Nagata et al., 2017; Wang et al., 2023), the data support an inverse relationship between C_ε and Re_λ (i.e., $C_\varepsilon = A/Re_\lambda$ where A is an empirical constant) regardless of grid geometry and blockage ratio. The fits show good agreement with the data (R-squared values ranging from 0.82 to 0.96), indicating that the reciprocal relationship holds well within the range of Re_λ studied. However, it should be noted that the constants derived from these fits are specific to the range of Re_λ covered in this study, and its applicability may be restricted because the data do not span a broad enough range of Re_λ . Although the reciprocal fit $C_\varepsilon = A/Re_\lambda$ describes the data well for each grid type, it is observed that the constant A varies with the global Reynolds number Re_0 . The value for R35 and R48 grids is $A = 72$, which shows that increasing the global Reynolds number from $Re_0 = 3000$ to 3937 does not

affect the constant A. In contrast, for the fractal grids, increasing the global Reynolds number from $Re_0 = 7125$ to 12750 results in a reduction of the empirical constant from $A = 140$ to 129.

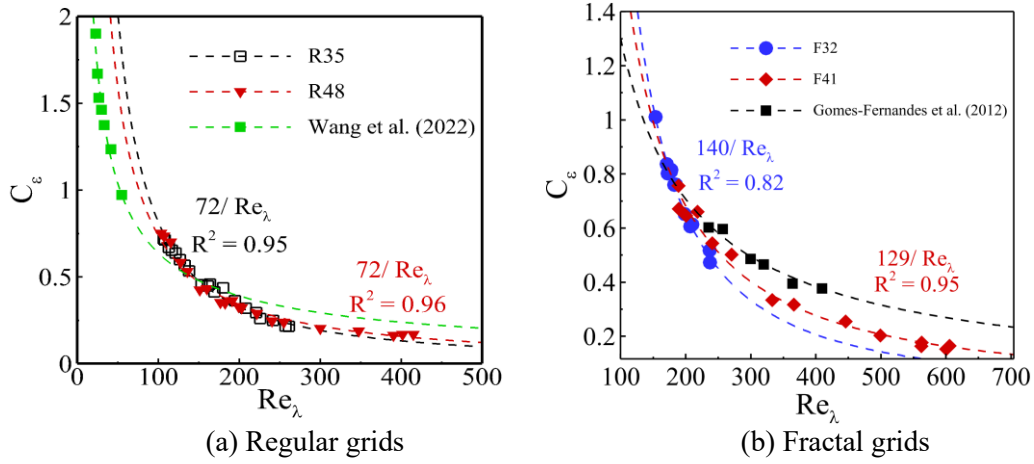


Figure 2.13 C_ε versus Re_λ along the grids' centerline

Figure 2.14a compares the present data with the theoretical data from Bos and Rubinstein (2017), represented by a dashed line. In this figure, $C_{\varepsilon 0}$ and $Re_{\lambda 0}$ are equilibrium values of C_ε and Re_λ (determined at $x/L_0 = 7$), respectively. The present data are in reasonable agreement with the theoretical data. To verify the non-equilibrium equation (Equation 2.5), $C_\varepsilon / \sqrt{Re_0}$ is plotted against Re_λ in Fig. 2.14b. Nagata et al. (2017) recommended using $Re_0 = U_\infty t_0 / \nu$ for normalization of C_ε instead of $Re_{L0} = U_\infty L_0 / \nu$. The data presented in Fig. 2.14b collapse reasonably well at higher turbulence Reynolds numbers ($Re_\lambda \geq 190$), regardless of the grid type, but deviate at lower Reynolds numbers. This suggests that C_ε remains nearly constant in the decay region for all grids. These findings support the non-equilibrium scaling (Equation 2.5) with $m \approx n \approx 1$ for all the grids.

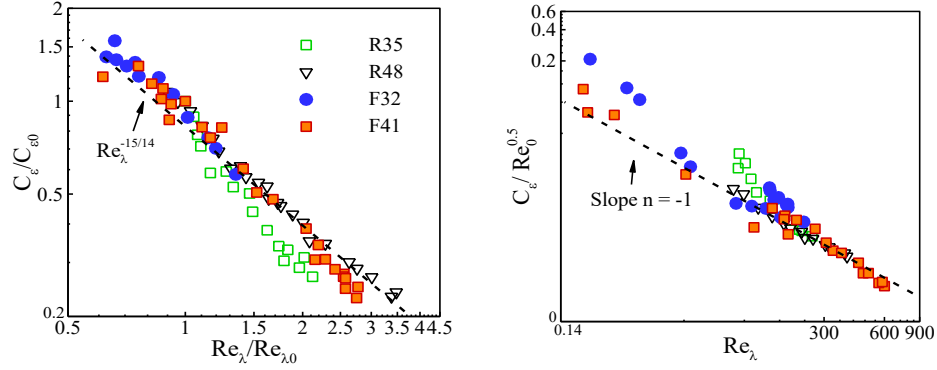


Figure 2.14 Left figure: Scatter plots of $C_\varepsilon/C_{\varepsilon 0}$ versus $Re_\lambda/Re_{\lambda 0}$ downstream of the grids. Right figure: The theoretical predictions and plot of $C_\varepsilon/\sqrt{Re_0}$ versus Re_λ . The dashed line represents $C_\varepsilon/\sqrt{Re_0} \propto Re_\lambda^n$ with $n = -1$

2.4.5 Scaling of C_ε in the Cross-stream Direction

Consideration is now turned to scaling the energy dissipation rate coefficient in the cross-stream direction. To formulate a universal dissipation scaling, the flow characteristics in the cross-stream direction are analyzed at different streamwise locations within the production region ($x/x_{\text{peak}} = 0.5$), at the peak location ($x/x_{\text{peak}} = 1$) and in the decay region ($x/x_{\text{peak}} = 8$ and 2 for the regular and fractal grids, respectively). Since the x_{peak} value occurs further downstream of the fractal grids compared to the regular grids, the chosen value of x/x_{peak} for the analysis of the fractal grids is lower than that for regular grids.

Figure 2.15 presents the probability density function (pdf) of the streamwise fluctuation velocities in the production region, peak location, and decay region. Gaussian distribution (solid line) is also plotted for comparison. The figure shows that, regardless of the grid type or blockage ratio, the distributions are non-Gaussian in the production region but nearly Gaussian in the decay region. In the production region of the fractal grids (Figs. 2.15c and 2.15d), the distributions are negatively

skewed, indicative of extreme negative fluctuation values that are more likely to occur than positive ones in the production region.

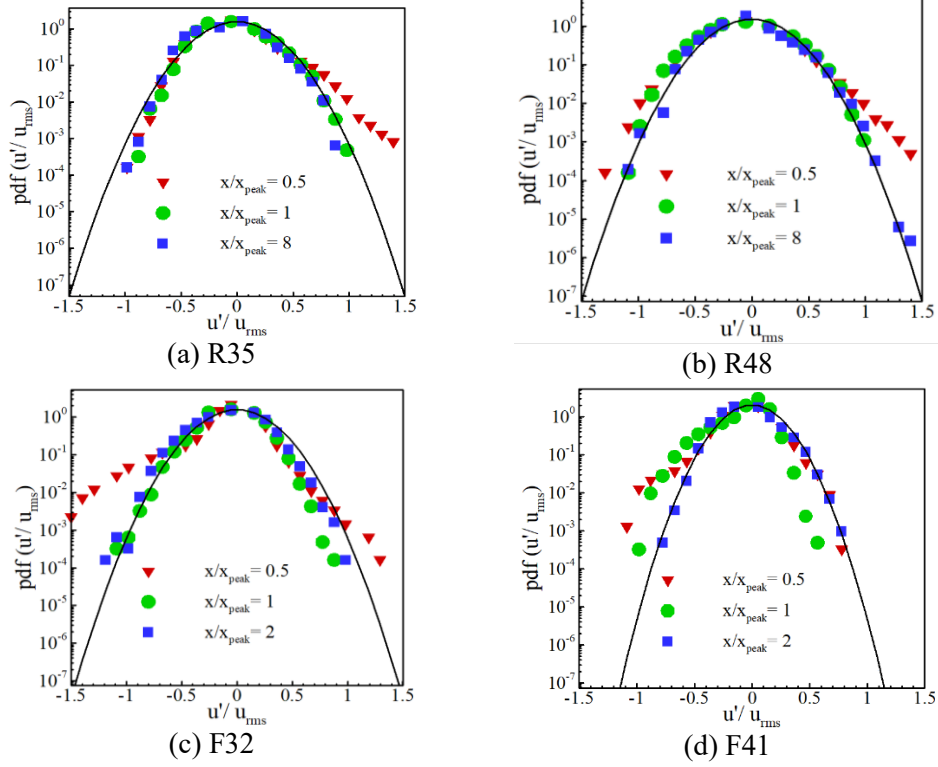


Figure 2.15 The pdf of the streamwise fluctuation velocity in production, peak, and decay region. The solid lines represent the Gaussian profile

The probability density function of the fluctuating vorticity at three streamwise locations is examined in Fig. 2.16 for R35 and F32. Due to the similarity across grid types, plots for other test cases are not shown for conciseness. As discussed by Wilczek et al. (2012), the vorticity field can be decomposed into coherent and incoherent contributions using the Coherent Vorticity Extraction (CVE) method. The coherent structures are characterized by high vorticity levels and are responsible for the non-Gaussian behavior of the vorticity field, while the incoherent contributions exhibit lower vorticity levels with Gaussian-like statistics. As shown in the figure, regardless of the grid type, the probability density function in the production region exhibits broader tails than a Gaussian distribution. This is a characteristic feature of coherent structures, which dominate in

regions of high vorticity production. These coherent structures are associated with intense vorticity events, leading to the observed non-Gaussian tails in the pdf. Conversely, in the decay region, a significant portion of the samples exhibit lower vorticity levels. Thus, the decay region is dominated by incoherent contributions.

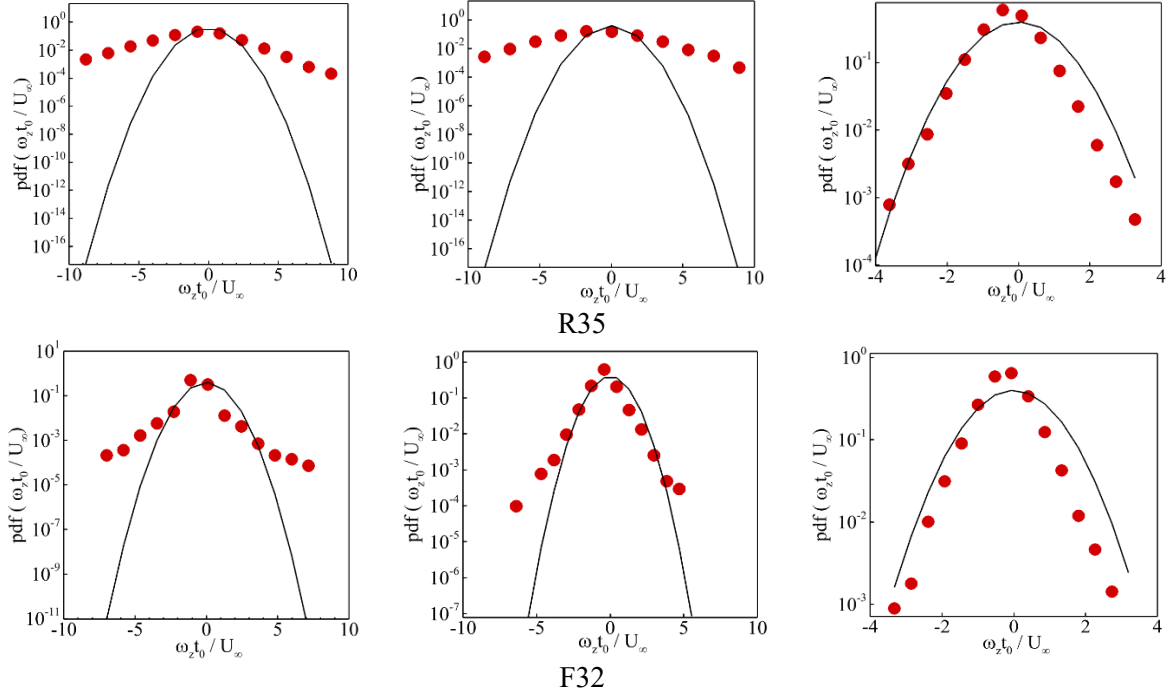


Figure 2.16 The pdf of the fluctuating vorticity for production (left column), peak (middle column), and decay region (right column). The solid lines represent the Gaussian profile

The reduced form of the fluctuating velocity gradient tensors derived from the two-component two-dimensional PIV data is used to compare the level of the local (small-scale) isotropy (Perry and Chong, 1987):

$$\tilde{\mathbf{a}} = \begin{bmatrix} \frac{\partial u'}{\partial x} & \frac{\partial u'}{\partial y} \\ \frac{\partial v'}{\partial x} & \frac{\partial v'}{\partial y} \end{bmatrix} \quad (2.10)$$

Cardesa et al. (2013) showed that the joint probability density function (jpdf) of the two invariants of $\tilde{\mathbf{a}}$, i.e., $p = -\text{tr}(\tilde{\mathbf{a}})$ and $q = \det(\tilde{\mathbf{a}})$ depicts a teapot-like form around the discriminant $q/p^2 = 1/4$.

They also demonstrated that under conditions characterized by small-scale isotropy, the relationship $\overline{pq} \approx 1.17 \overline{p^3}$ holds. Figure 2.17 shows the jpdf of p and q for the R35 and F32 grids at $x/x_{\text{peak}} = 0.5$. The plots for the other grids are similar and are therefore not shown. In the figure, the teapot-like form around the discriminant value $q/p^2 = 1/4$ is evident, consistent with the findings of Cardesa et al. (2013). However, the plot for F32 appears stretched, but that for R35 shows a noticeably higher concentration near $p = q = 0$.

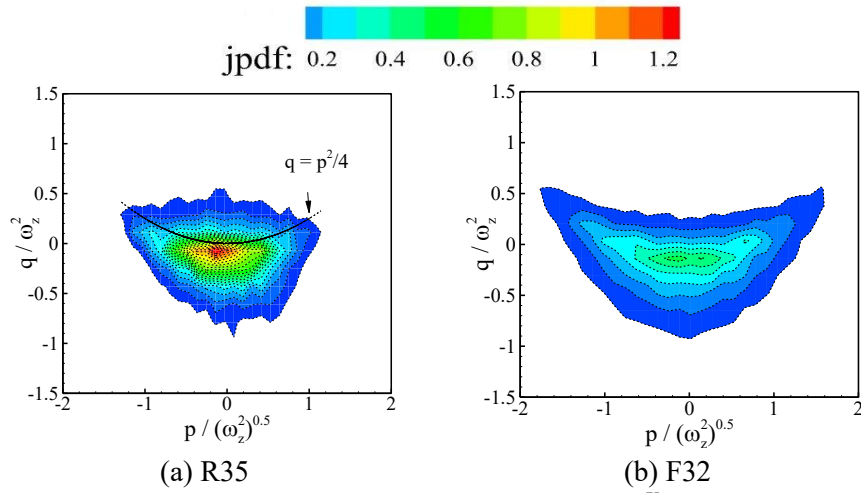


Figure 2.17 Joint pdf of p and q invariants at $x/x_{\text{peak}} = 0.5$

Table 2.2 summarizes the values of $\overline{pq}/\overline{p^3}$ at the selected streamwise locations for the different grids. The data in the table show that the condition for local isotropy ($\overline{pq}/\overline{p^3} \approx 1.17$) is not met in the production region ($x/x_{\text{peak}} = 0.5$) and at the peak location ($x/x_{\text{peak}} = 1$), and departure from local isotropy is more pronounced for the fractal grids than for the regular grids. In the decay region, on the other hand, the data for all grids indicate a close adherence to local isotropy.

Table 2.2 The ratio of $\overline{pq}/\overline{p^3}$

Point	$x/x_{\text{peak}} = 0.5$	$x/x_{\text{peak}} = 1$	$x/x_{\text{peak}} = 8$ (2)
R35	1.38	1.54	1.15
R48	0.44	0.91	1.18
F32	0.06	0.65	1.17
F48	0.36	3.02	1.21

In view of the observed anisotropy in the production region and location of peak production, following Chen et al. (2021), a new dissipation rate coefficient ($C_{\varepsilon'}$) and turbulence Reynolds number are proposed as follows:

$$C_{\varepsilon'} = \varepsilon \langle L_u \rangle / J^3 \quad (2.11)$$

$$Re_{\lambda'} = \lambda J / \nu \quad (2.12)$$

In these equations, $J = \sqrt{2/3} k$, where $k = 0.5(\overline{u'u'} + \overline{v'v'})$, and $\langle L_u \rangle$ denotes the spatial-averaged streamwise integral length scale in the cross-stream direction. Figure 2.18 shows the cross-stream distribution of $C_{\varepsilon'}$ versus $Re_{\lambda'}$ for the different grids at various streamwise locations within the production region, peak location, and decay region. In each figure, a power law ($C_{\varepsilon'} \propto Re_{\lambda'}^{-n}$), and the R-squared value for the fit is provided. It is evident that, regardless of the grid type and blockage ratio, an inverse relationship exists between the energy dissipation rate coefficient and turbulence Reynolds number in the cross-stream direction, both in the production region and at the peak location. In the decay region, $C_{\varepsilon'}$ tends to be independent of $Re_{\lambda'}$, which aligns with findings from previous studies (Takamure et al., 2019). The data show a reasonably good fit with power law, with R-squared values between 0.81 and 0.98. Even though the relationship between $C_{\varepsilon'}$ and $Re_{\lambda'}$ varies for each grid type, the power-law exponent is identical for the regular and fractal grids in the production region and peak location. As $C_{\varepsilon'}$ is dependent on the inlet flow conditions

(Antonia & Pearson, 2000), its value differs for the different grids, i.e., $C_\epsilon \approx 1.25, 0.71, 0.62$, and 0.55 for R35, R48, F32 and F41, respectively.

In search for a universal relation between the C_ϵ and $Re_{\lambda'}$ in the production region, a new global Reynolds number is proposed as follows:

$$Re_L = J \langle L_u \rangle / \nu \quad (2.13)$$

By carefully examining the equations and deriving a universal form similar to Equation 2.5, it is possible to relate C_ϵ to the proposed global Reynolds number for each grid in the production region and the peak location. Figure 19 shows the plots of $C_\epsilon Re_{\lambda'}$ versus Re_L in logarithmic scale for R35 and F32 in the peak and production regions (for brevity, plots for other test cases are not presented). The dashed line with a slope of -1 is also superimposed on the figure, demonstrating an inverse relationship between $C_\epsilon Re_{\lambda'}$ and Re_L . This relation was also observed for other streamwise locations within the production region. Based on the figure, it is concluded that the new non-equilibrium equation, $C_\epsilon \propto Re_L^m / Re_{\lambda'}^n$, holds for grids in the anisotropic and inhomogeneous regions. For the regular grid, the appropriate power exponents are $m \approx -0.4$ and $n \approx 1$, while $m \approx -0.2$ and $n \approx 1$ work for the fractal grid. The observed inverse relationship between C_ϵ , $Re_{\lambda'}$ and Re_L in the peak and production regions indicates that as the global Reynolds number (Re_L) increases (decreases), the product of the local Reynolds number ($Re_{\lambda'}$) and the dissipation rate constant (C_ϵ) decreases (increases). The proposed non-equilibrium equation provides a valuable tool to predict the dissipation rate constant in anisotropic and inhomogeneous regions. The difference in the exponent m between regular and fractal grids stems from their distinct turbulence generation mechanisms. Regular grids, which produce turbulence primarily through quasi-uniform wakes, exhibit a stronger dependence on the global Reynolds number (with $m \approx -0.4$). In contrast, fractal grids, characterized by a hierarchical arrangement of bars that generate multi-scale wakes,

distribute energy across a broader range of scales. This multi-scale interaction leads to more sustained turbulence and reduced sensitivity to the global Reynolds number, resulting in a lower exponent ($m \approx -0.2$).

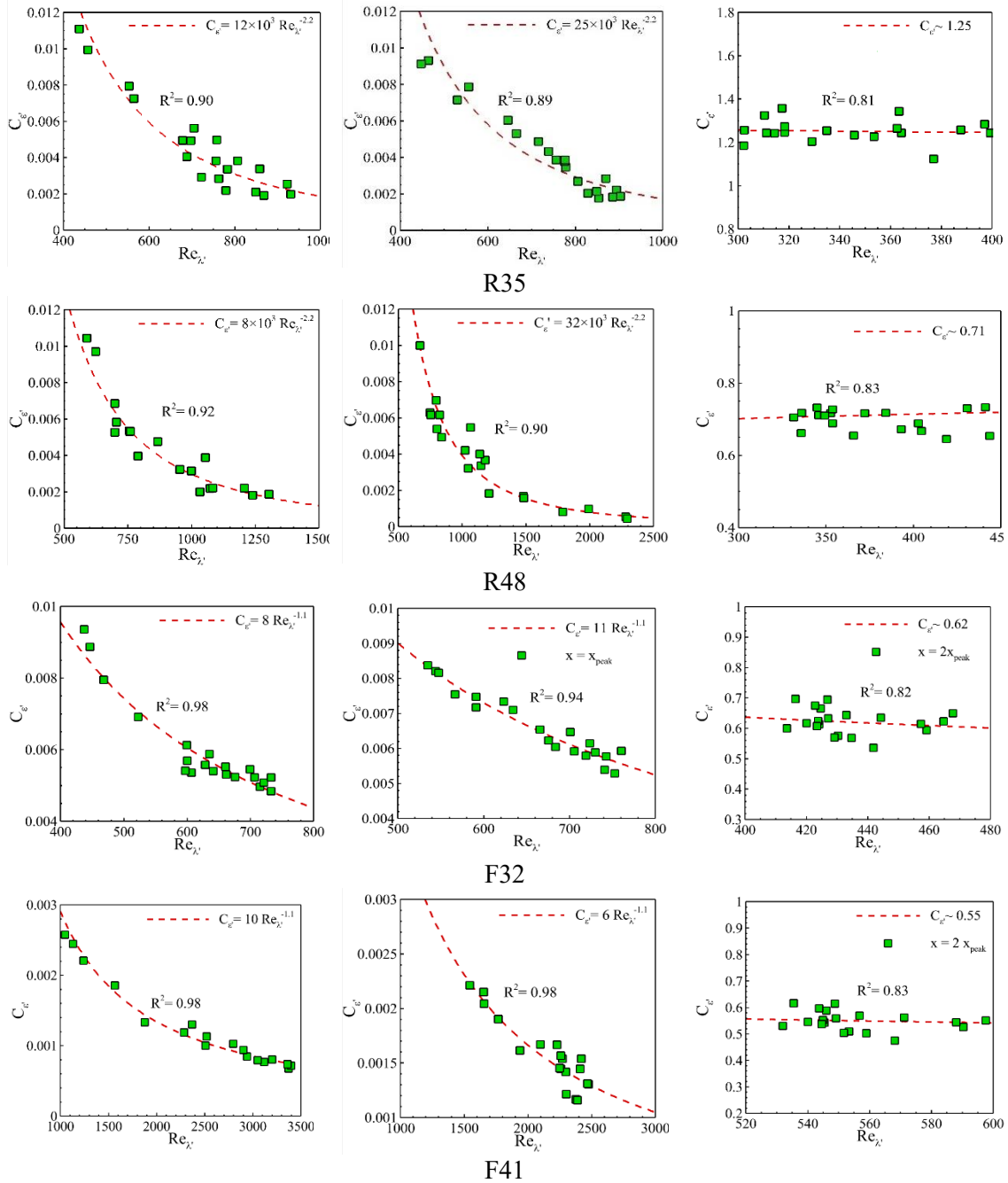


Figure 2.18 Plots of C_e versus Re_{λ} values in cross-stream direction at $x/x_{peak} = 0.5$ (left column), $x/x_{peak} = 1$ (middle column) and decay region (right column)

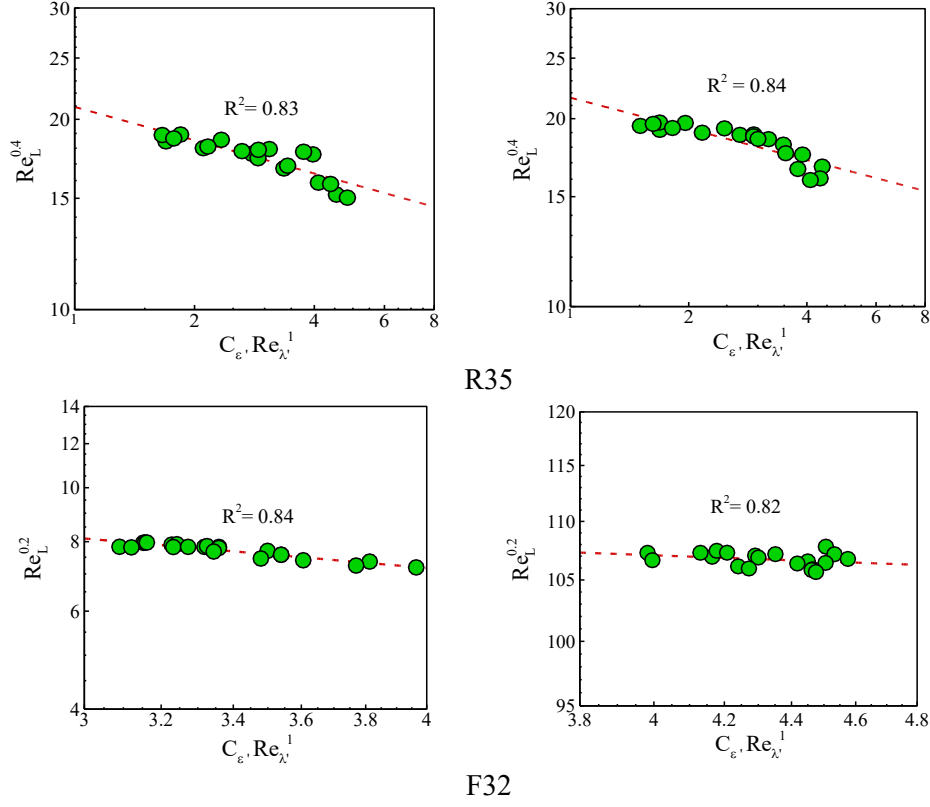


Figure 2.19 Scatter plots of $C_\epsilon Re_\lambda^n$ in relation to Re_L^m at $x/x_{peak} = 0.5$ (left column) and $x/x_{peak} = 1$ (right column). The dashed line represents $C_\epsilon Re_\lambda^n \propto Re_L^m$ with slope = -1

2.5 Conclusion

This study provided a detailed examination of turbulence downstream of passive grids using particle image velocimetry. Two passive grid types with different blockage ratios were examined, including two regular grids (35% and 48%) and two fractal grids (32% and 41%). The flow characterization was divided into two directions, along the centerline and cross-stream direction. The results along the centerline showed that grids with higher blockage ratios exhibit higher turbulence levels. The distributions of the skewness and flatness factor of the velocity fluctuations and their derivatives were Gaussian in the decay region. However, those for the fractal grids showed a significant departure from the Gaussian distribution in the production region, particularly

at a higher blockage ratio. The ratio of the integral length scale to the largest bar (L_u/L_0) increased monotonically while the ratio of streamwise to cross-stream Taylor microscale (λ_u/λ_v) remained constant in the decay region. Regardless of the blockage ratio, the ratio of turbulence length scales (i.e., L_u/λ_u) remained nearly constant in the decay region of regular grids, but the turbulence Reynolds number decreased with increasing downstream distance, highlighting the non-equilibrium characteristics in the decay region. The dissipation rate coefficient (C_ϵ) along the centerline in the decay region was not affected by a change in blockage ratio for regular grids. However, it decreased with an increase in blockage ratio in the case of fractal grids. For all grid types, an inverse relationship was observed between C_ϵ and Re_λ along the centerline. The non-equilibrium scaling, $C_\epsilon \propto \sqrt{Re_0}/Re_\lambda$, was applicable along the centerline of all grids in the decay region.

Along the cross-stream direction, an inverse relationship was observed between the turbulence dissipation rate coefficient and turbulence Reynolds number for all grid types in the production region and peak locations. The non-equilibrium scaling, $C_\epsilon \propto \sqrt{Re_0}/Re_\lambda$, was not applicable along the cross-stream direction in the production region and peak location. A new non-equilibrium scaling, $C_{\epsilon'} \propto Re_L^m/Re_{\lambda'}^n$, was proposed for the production region and peak location downstream of regular and fractal grids. While the exponent $n \approx 1$ holds for both grid types, m depends on grid type, with $m \approx -0.2$ and -0.4 for fractal and regular grids, regardless of grid blockage ratios.

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Chapter 3: PIV Analysis of Wake Characteristics of Slanted-Back Ahmed Bodies: Effect of Leading-Edge Shape

3.1 Abstract

This study experimentally investigates turbulent flow separation around a slanted-back Ahmed body with different leading-edge configurations (rounded (RL) and square (SL)) using the particle image velocimetry (PIV) technique. The Reynolds number (based on freestream velocity and body height) is $Re = 0.17 \times 10^5$. Spatiotemporal flow characteristics, including mean flow, vorticity flux, two-point correlation, reverse flow area, frequency spectra, and proper orthogonal decomposition (POD), are analyzed to elucidate the effects of leading-edge shape on separated shear layer interactions over the roof, slanted surface, and the wake region. The results show that rounding the leading edge of the Ahmed body leads to the formation of smaller coherent structures with lower shedding frequency over the roof. While the structures are still smaller over the slanted surface and the wake region of the RL body, the shedding frequency surpasses that of the SL ones. The results also show evidence of the identical shedding frequency over the roof, slanted surface, and wake region of the RL body. Detailed analyses, including convective velocities of vortices over the roof, slanted surface, and in the wake region, vary significantly between SL and RL cases, indicating distinct shedding mechanisms influenced by leading-edge geometry.

3.2 Introduction

In recent decades, environmental challenges related to greenhouse gas and climate change have driven the transport industry to improve ground vehicle performance by reducing fuel consumption. Research has shown that, for ground vehicles based on internal combustion engines, reducing aerodynamic drag can effectively reduce fuel consumption and greenhouse gas emissions (Bao et al., 2022). For example, a 20% reduction in aerodynamic drag can lead to approximately 4% fuel savings for a heavy vehicle weighing 36 tons at a highway speed of 105 km/h (Choi et al., 2014). Ground vehicles often feature a pronounced bluff design, which is primarily driven by practical functionality. This bluff shape results in various physical phenomena, including flow separation, reattachment, vortex shedding, and the formation of unsteady wakes. In this context, extensive research efforts have been dedicated to studying simplified bluff shapes with rectangular cross-sections, such as the Ahmed body (Ahmed et al., 1984) and the Windsor body (Le Good & Garry, 2004), to understand the flow dynamics around these shapes, which is a crucial step in identifying effective flow control technologies for drag reduction. Previous research has shown that the flow topology around these geometries is exemplified by three-dimensional unsteady vortical structures, including separation bubbles near the leading edge and lateral sides, spanwise vortex over the rear slanted surface, C-pillar vortex near the side edge of the rear slanted surface and toroidal structure arising from alternate shedding of the upper and lower vortices in the wake region (Ahmed et al., 1984; Liu et al., 2021). The three-dimensional wake structure in the near wake region of the body holds particular significance due to its pivotal role in generating pressure drag, which significantly impacts the overall aerodynamic efficiency and energy consumption of ground vehicles. The dynamics of the vortical structures in the wake of bluff bodies, which span a wide range of spatial and temporal scales, are quite complex and exhibit sensitivity to upstream

disturbances such as the roundness of leading and slanted edges (Delassaux et al., 2021; Bao et al., 2022).

Recent studies have investigated the impact of leading-edge roundness on the aerodynamic characteristics of bluff bodies. Rocchio et al. (2020) investigated the impact of leading-edge rounding of a 5:1 wall-mounted rectangular cylinder on the length of the recirculation bubble, the roll-up of the detached shear layer, and turbulent kinetic energy growth. Their results showed that rounding affects the roll-up of shear layers emanating from the leading edge and the growth of turbulent kinetic energy (TKE), which in turn decreases the recirculation bubble. It was reported that sharpening the leading edge induces a small recirculation bubble inside the primary (larger) recirculation bubble formed near the leading edge. Moore et al. (2019) investigated the effect of aspect ratio on the interaction between modes of instability near the leading edge and wake region and found that when the section is sufficiently long for the time-averaged flow to reattach to the surface, the influence of the wake flow and the shear layer near the leading edge is greatly diminished. The study of internal flow over a backward-facing step by Schäfer et al. (2009) revealed the presence of a dominant frequency of $St = 0.26 (= fH/U_\infty)$, where f is vortex shedding frequency, and H is step height) near the leading edge and wake region of the step, indicating a correlation between the shear-layer vortices and the oscillations of the recirculation bubbles.

The effects of slanted edge geometry on the spatial and temporal characteristics of the flow structures around the Ahmed body have received considerable research attention (Thacker et al., 2013; Siddiqui & Agelin-Chaab, 2022). These investigations demonstrated that rounding the roof/rear slant connection can effectively alleviate separation on the slanted surface and shift the low-pressure separation bubbles in the near-wake region away from the base, resulting in up to a 16% reduction in drag (Thacker et al., 2013; Rossitto et al., 2016). Delassaux et al. (2021) observed

that rounding the roof edges alters the flow topology in the wake region, resulting in a 16% reduction in drag. However, rounding the side edge of the slanted surface delays the onset of C-pillar vortices and forms larger recirculation bubbles in the wake region, leading to a 3% increase in drag (Rossitto et al., 2016). Replacing the regular rear end of the slanted-back Ahmed body with an elliptical curvature eliminates the slanted recirculation bubble and shifts the upper recirculation bubble in the wake region toward the slant surface, effectively reducing pressure drag (Siddiqui & Agelin-Chaab, 2022).

While prior research has investigated the flow structures around the Ahmed body and evaluated the effects of slanted edge shape modification on near-wake structures, the influence of the leading-edge roundness on the spatial and temporal characteristics of the three-dimensional flow structure around the body is still not fully understood. The studies by Krajnović & Davidson (2005) and Minguéz et al. (2008) reported that the small-scale Kelvin-Helmholtz (KH) vortices originating from the leading edge of the Ahmed body developed into hairpin structures as they evolved downstream. Therefore, it is anticipated that altering the leading-edge shape influences the nature of the shear layer and modifies its interaction with the three-dimensional unsteady vortical structures around the body. Nonetheless, investigations on the effects of leading-edge shape on the spatiotemporal dynamics of vortical structures over the body and their interaction with wake flow structures are limited (Easanesan et al., 2020; Aleyasin et al., 2021; Sagharichi et al., 2023). Furthermore, most of these studies predominantly focused on wake characteristics around squared-back Ahmed bodies (Grandemange et al., 2013; Chen et al., 2023). In a recent study, Aleyasin et al. (2021) experimentally investigated the effect of turbulence intensity on the wake behind a square-back Ahmed body and a cuboid using PIV. Two freestream turbulence intensity levels, $T_u = 4\%$ and $T_u = 7\%$, were examined by exposing the bluff bodies, respectively,

to an approaching turbulent boundary layer over a smooth wall and a rough wall. Due to the exposure of the body to a high turbulence level, no separation was observed near the leading edge of the square-back Ahmed body and cuboid. Their study demonstrated that modifying the leading edge of a squared-back Ahmed body from a rounded shape to a squared one results in the creation of a recirculation bubble near the leading edge of the body. Also, the dominant vortex shedding frequency in the wake region increases from $St = 0.16$ to 0.32 , as the leading edge is modified from a rounded shape to a square one. Sagharichi et al. (2023) investigated the effect of Reynolds number on turbulent flow structure around a rounded and squared-leading-edge Ahmed body with slanted-back. Results showed that for both geometries, a recirculation bubble was formed near the leading edge. Although the recirculation bubble size was independent of Reynolds number in the squared leading-edge, it decreased by 5.6% for the rounded leading-edge body as the Reynolds number was doubled. It was also reported that while vortex shedding frequency of flow over the roof of a rounded leading-edge decreases with Reynolds number, it is insensitive to Reynolds number for the squared leading-edge case.

To the authors' knowledge, a detailed investigation of the effects of leading-edge geometry on the spatiotemporal dynamics of the shear layer around the Ahmed body has not been reported. Therefore, the objective of this study is to understand the spatial and temporal characteristics of the shear layers, including the interplay between the unstable shear layers near the leading edge, the slanted surface, and the emerging vortical structures in the wake region. In this Chapter, the spatiotemporal flow characteristics over the roof, slanted surface, and the wake region of two slanted-back Ahmed bodies, one featuring a rounded leading edge and a square leading edge with slanted-back, are investigated. A high-speed PIV system is used to perform temporally resolved whole-field velocity measurements around these bodies in the x-y and x-z planes. To examine the

effects of leading-edge geometry on turbulent statistics and transport phenomena, mean velocities, vorticity flux, Reynolds stresses, and reverse flow area are analyzed. Additionally, the effects of leading-edge geometry on the temporal characteristics and vortical structures are evaluated using two-point auto-correlation, proper orthogonal decomposition (POD), spectra analysis of the velocity fluctuations, reverse flow area, and POD coefficients. The rest of the Chapter is structured as follows: Section 3.3 describes the experimental procedure, and the results and discussion on the effects of the leading edge on the flow dynamics are presented in Sections 3.4 and 3.5. The main conclusions are summarized in Section 3.6.

3.3 Experimental Procedures

3.3.1 Test Conditions

The experiments were carried out in an open recirculating water channel in the Turbulence and Hydraulic Engineering Laboratory (THEL) at the University of Manitoba. The streamwise length, spanwise width, and vertical height of the test section are 6000 mm, 600 mm, and 450 mm, respectively. The test section is fabricated from 31.8 mm thick Super Abrasion Resistant transparent acrylic plates to facilitate optical access. Two 1:4 models of the full-scale slanted-back squared (SL) and rounded leading-edge (RL) Ahmed bodies (Ahmed et al. 1984) with a rear slant angle of $\alpha = 25^\circ$ were used. The models have an overall length of $L = 261$ mm, a width of $B = 97$ mm, and a height of $H = 72$ mm, supported by four cylindrical struts of $C = 12.50$ mm length and $d = 7.50$ mm diameter, as shown in Fig. 1. The leading-edge roundedness radius is 25 mm, and the precision of the rounded leading-edge geometry is 0.50 mm. The x-coordinate represents the streamwise direction, while the y-coordinate aligns with the wall-normal direction, and the z-axis indicates the spanwise direction with the origin of the coordinate system situated at the midpoint of the lower edge of the models' vertical base (Fig. 3.1).

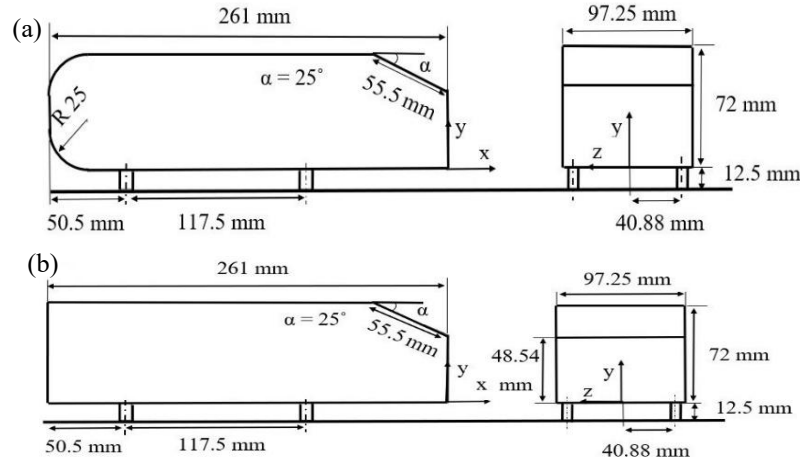


Figure 3.1 Detailed drawings of (a) rounded and (b) squared leading-edge Ahmed body

The bodies were installed on a raised floor, which is 3000 mm long, 590 mm wide, and 9 mm thick, and features a sharp leading edge. The raised floor was positioned horizontally within the test section and installed 50 mm above the ground to control the incoming boundary layer. The freestream velocity was set at $U_\infty = 0.24 \text{ m s}^{-1}$ which leads to the Reynolds number based on the body height of $Re = 0.17 \times 10^5$. The longitudinal turbulence intensity in the mid-test section was measured at $T_u = 1.50 \%$, and the boundary layer thickness at the location of the leading edge of the bodies (when the bodies were removed) was measured $\delta/H = 0.63$. Hence, the model height is located outside of the boundary layer thickness.

3.3.2 PIV Measurements

The flow was seeded by silver-coated hollow glass spheres of diameters $10 \mu\text{m}$ and specific gravity of $\rho_p = 1.4$. Flow field illumination was provided by a dual-cavity, dual-head, high-speed Neodymium-doped yttrium lithium fluoride (Nd: YLF) laser with a wavelength of 527 nm. The maximum energy output of the laser is 30 mJ/pulse. The thickness of the laser sheet was set to 1 mm. Two high-speed complementary metal oxide semiconductor (CMOS) cameras with a

resolution of $2560 \text{ pixel} \times 1600 \text{ pixel}$ were used to capture the particle images. The cameras were arranged side-by-side to cover the flow field upstream and downstream of the body simultaneously in the x-y plane at $z/H = 0$ and the x-z plane at $y/H = 0.59$ to facilitate comparison with results reported by Wang et al. (2013). In each case, 12000 images were collected in double frame mode at 3 Hz and 60000 images at 806 Hz to temporally resolve all dynamically important vortical structures. The field of view was set to $8H \times 2.50H$ and $7.68H \times 2.40H$ for the x-y and x-z planes, respectively. A schematic of the PIV setup is provided in Fig. 3.2.

The images were processed using commercial software (Davis version 10.2.1) supplied by LaVision Inc. The vector fields were computed using a GPU-accelerated multi-pass cross-correlation algorithm with an initial interrogation window of $128 \text{ pixel} \times 128 \text{ pixel}$ with 50% overlap, followed by final four passes with an interrogation window of $24 \text{ pixel} \times 24 \text{ pixel}$ and 75% overlap. This results in a vector spacing of $0.009H$ for both planes. Detailed information on the PIV uncertainty of the present measurements is available in Essel et al. (2021) and Sagharichi et al. (2023). The uncertainty in the measured mean velocity, Reynolds normal, and shear stresses at their peak values (with 95% confidence) for both time-resolved and double frame are less than $\pm 0.15 \%$, $\pm 2.5 \%$, and $\pm 2 \%$, respectively.

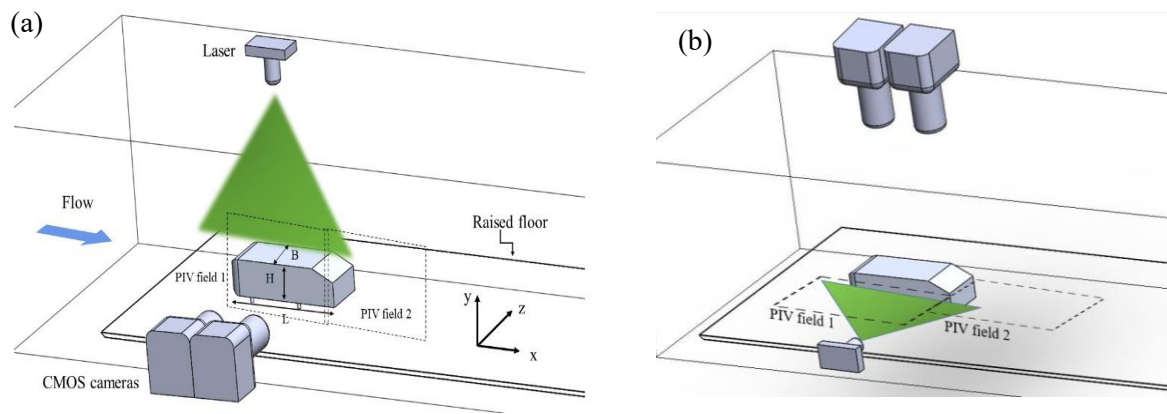


Figure 3.2 Schematic of the experimental set-up, x-y plane (a), and x-z plane (b)

In this paper, dimensions and velocity are normalized by the body height (H) and freestream velocity (U_∞) respectively, e.g., $x^* = x/H$, $y^* = y/H$, and $U^* = U/U_\infty$. SL and RL are hereafter used as representatives of the squared leading-edge and rounded leading-edge bodies, respectively.

3.4 Results and Discussions

3.4.1 Flow Characteristics in the x-y Plane

3.4.1.1 Mean Flow

Figure 3.3 shows the contours of the streamwise mean velocity near the leading edge and in the wake region superimposed by the mean streamlines. The recirculation bubbles are highlighted by the red line, which represents the isopleth $U^* = 0$. While the roundness of the leading edge provides a smooth transition of the shear layer near the RL body (Fig. 3.3c), the sharp edge of the leading edge in the SL body forces flow separation and significantly changes the pressure gradient, leading to the formation of a comparatively thicker recirculation bubble (Fig. 3.3a). As shown in Figs. 3.3a and 3.3c, a recirculation bubble formed near the leading edge. The length of the recirculation bubble for the RL and SL is $L_r = 0.87H$ and $1.83H$, respectively. The streamwise and vertical coordinates of the foci points of the recirculation bubbles are $(x^*, y^*) = (-2.55, 1.30)$ and $(-2.80, 1.07)$ for the SL and RL bodies, respectively. Figures 3.3b and 3.3d reveal two counterrotating recirculation bubbles that emanate from the slanted surface and the undersurface of the base formed in the near wake region behind the bodies. While the upper and lower bubbles are of comparable size in the SL case, the upper recirculation bubble is larger than the lower bubble in the RL case. As a result, the foci of both recirculation bubbles in the RL case are pushed closer to the ground, and the focal position of the upper recirculation bubble (F_{II}) moves closer to the body base. The change in recirculation topology in the wake region can be attributed to the higher

downwash flow emanating from the slanted surface of the RL body, as noted by Sagharichi et al. (2023). Despite the topological differences between the recirculation bubbles in the SL and RL cases, their recirculation lengths (which are measured as the maximum longitudinal length of $U^* = 0$.) in the wake region ($L_r^* = 0.53$ and 0.55 , respectively) are not significantly different.

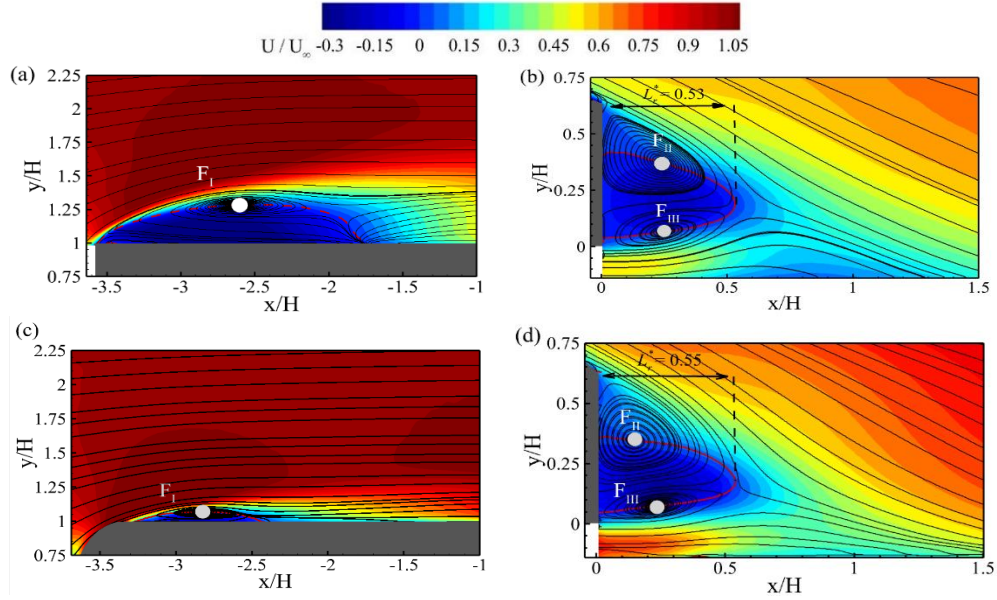


Figure 3.3 Contours of normalized streamwise mean velocity superimposed by mean streamlines for SL body at [(a), (b)] and RL body [(c), (d)]. Red lines represent $U^* = 0$

Figure 3.4 illustrates the downstream evolution of the mean spanwise vorticity flux ($F = \frac{1}{H} \int \omega_z^* dy$, where $\omega_z = (\frac{\partial V}{\partial x} - \frac{\partial U}{\partial y})$). The figure demonstrates that the vorticity flux in the immediate vicinity of the leading edge is much higher in the SL case than in the RL case. Vorticity continues to accumulate, reaching its peak at a streamwise position that coincides with F_I ($x/H = -2.9$ and -2.7 for the RL and SL cases, respectively). Further downstream, the vorticity flux decreases in magnitude with a steeper decline observed in the RL case compared to the SL case. This trend continues until $x/H = -2.4$ and -1.75 for RL and SL, respectively, where the flow reattaches to the roof in both cases. Beyond these points, the vorticity flux decreases at a slower rate until the trailing edge. In the wake region, a higher ($\approx 11\%$) vorticity flux accumulates in the upper shear layer

emanating from the slanted surface compared to the lower shear layer, regardless of the leading-edge shape. This difference can be attributed to wall proximity constraints. The higher vorticity flux over the SL body than the RL one can be attributed to the higher thickness of the shear layer in the former case. However, for each specific streamwise location, the magnitude of $\frac{\partial U}{\partial y} \gg \frac{\partial V}{\partial x}$, and these two gradients are higher over the RL compared to the SL body.

Figure 3.5 shows the contours of wall-normal Reynolds normal stress and turbulent kinetic energy ($TKE = 0.5 (\overline{u'u'^*} + \overline{v'v'^*})$). The peak values are indicated on each contour. The figures show that a thicker shear layer is induced near the leading edge of the SL body, corresponding to a larger recirculation bubble over the SL body than the RL case (Fig. 3.3). However, the leading-edge geometry does not affect the peak value of the Reynolds normal stresses and TKE over the body. In the wake region, a more extended cluster of wall-normal Reynolds shear stress and TKE can be seen, while its peak value increases from 0.03 to 0.05 for the RL body.

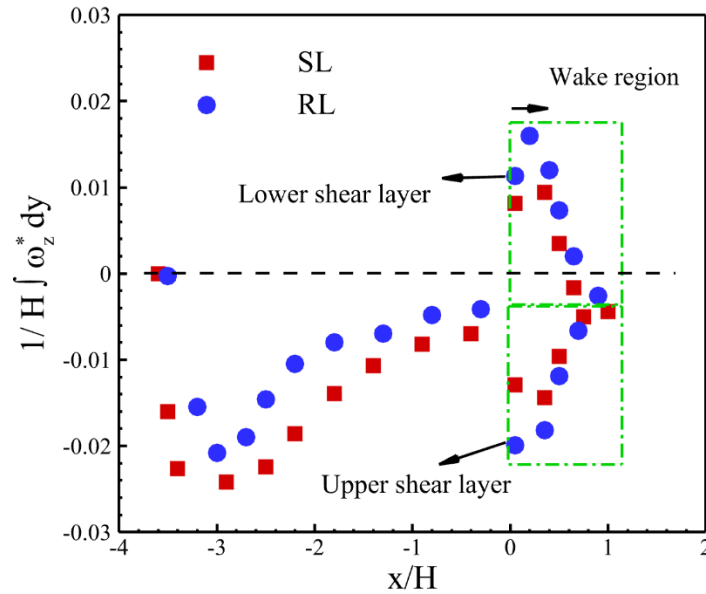


Figure 3.4 Downstream evolution of vertically averaged spanwise vorticity

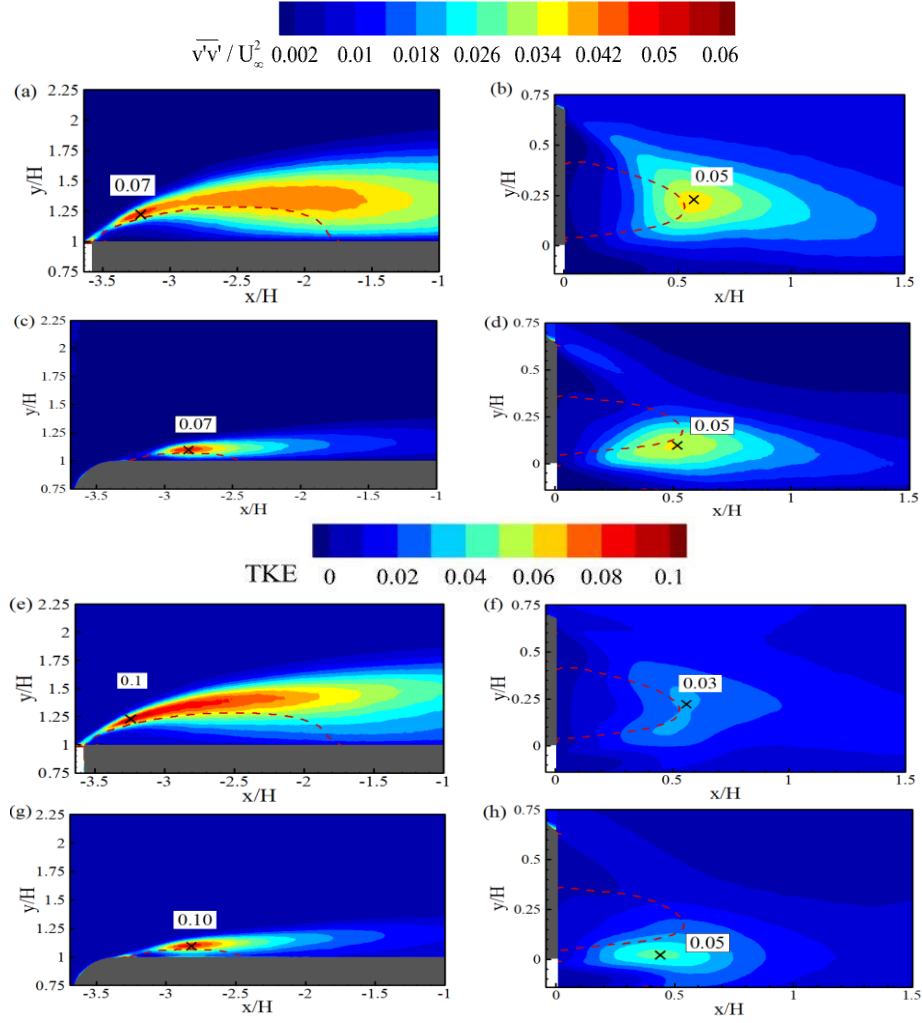


Figure 3.5 Contours of wall-normal Reynolds normal stress [(a) - (d)] and turbulent kinetic energy [(e) - (h)]. Dashed lines represent $U^* = 0$

3.4.2 Flow Characteristics Over the Body Roof

To identify and characterize the energetic vortical structure of the flow field over the roof, which affects the flow structures around the slanted surface and the wake region, proper orthogonal decomposition (POD) analysis was performed (Lumley, 1967). In this method, the instantaneous velocity field, $u_i(x, y, t)$ is decomposed as:

$$u_i(x, y, t) = U_i(x, y) + u'_i(x, y, t) = U_i(x, y) + \sum_{k=1}^N \Psi_k^n(x, y) a_k^n(t) \quad (3.1)$$

where i represents the velocity component, and $U_i(x,y)$ and $u_i'(x,y,t)$ represents the mean and fluctuation velocity, n represents the mode number, and $N = 60000$ is the number of snapshots. As can be observed, the fluctuation velocity is decomposed into a set of spatial eigenfunctions $\Psi_k^n(x,y)$ multiplied by its temporal coefficients (mode coefficient) $a_k^n(t)$. A Detailed procedure for implementing the snapshot POD method is provided by Meyer et al. (2007) and Fang & Tachie (2019).

The POD analysis was conducted within the defined masked region, where x/H ranges from -3.70 to 0 and y/H ranges from 0.96 to 2.30. Figure 3.6 illustrates the fractional TKE energy contributions of the first thirty modes. The comparison reveals lower fractional energy for the first six modes when the leading edge is rounded. The contribution from the first six modes to the total TKE is 35% and 21.7% for the SL and RL cases, respectively, which is indicative of the more energetic vortical structure over the SL roof. The figure also illustrates that the first two POD modes capture higher energy compared to the higher modes.

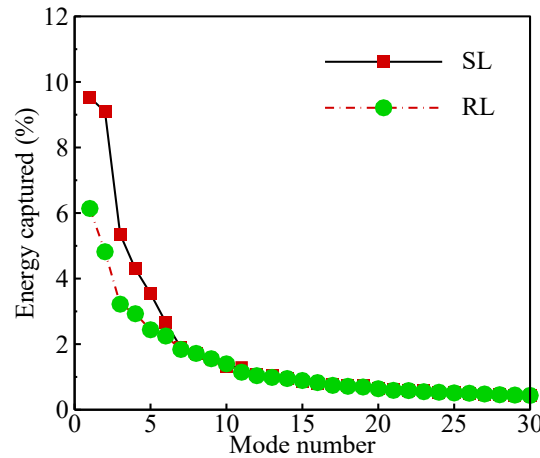


Figure 3.6 Fractional energy distribution of POD modes

The spatial distribution of wall-normal velocity fluctuation (v') in the first and second POD modes is presented in Fig. 3.7. For both cases, alternating zones of positive and negative motion, indicative of alternate vortex shedding, are observed. However, a larger cluster of velocity

fluctuations is formed over the SL body, and these clusters evolve downstream at a higher elevation than the structures over the RL roof. Comparing the spatial patterns of the first and second modes shows that their topology is similar but shifted by one-quarter wavelength (Λ , which is defined as the distance between alternating positive (or negative) structures) as noted by Riches et al. (2018), Essel et al. (2023), and Kumahor & Tachie (2023). The wavelengths of the vortices shed over the SL and RL bodies are $\Lambda = 2.04H$ and $1.40H$, respectively. The frequency spectra of the time coefficients of the first and second POD modes (Fig. 3.8) were used to determine the frequency associated with the coherent mode. It can be seen that the dominant frequencies of both modes one and two are $St (fH/U_\infty, \text{ where } f \text{ is vortex shedding frequency}) = 0.36$ and 0.33 over the SL and RL bodies, respectively. Based on these shedding frequencies ($f \approx 1.25$ and 1.14), the convective velocity of the vortices ($U_c = \Lambda f$) is estimated as $U_c \approx 0.76U_\infty$ and $0.47U_\infty$ for SL and RL cases, respectively. Based on these convective velocities and the distance between the cores of recirculation zones close to the leading edge and in the wake region for the SL and RL ($D = 0.33H$ and $0.36H$), the respective convective time scale of the coherent structures over the SL and RL roof is estimated to be $t_c = 3.30$ and 3.60 .

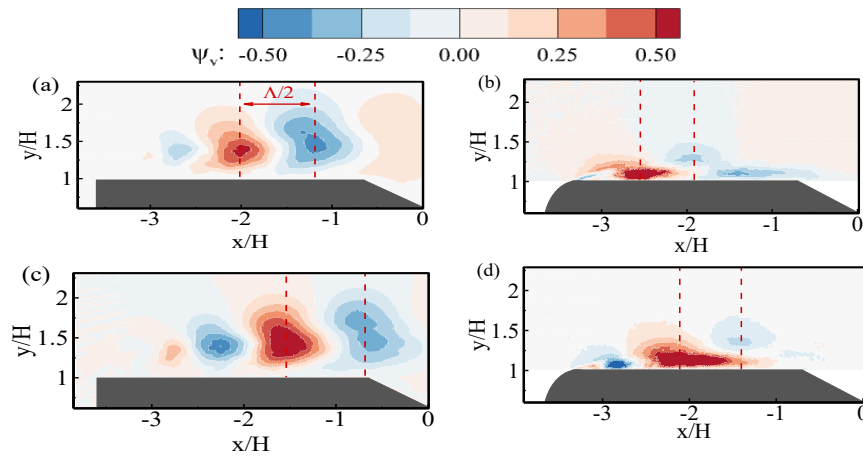


Figure 3.7 Contours of first [(a), (b)] and second [(c), (d)] POD modes over SL [(a), (c)] and RL [(b), (d)] body

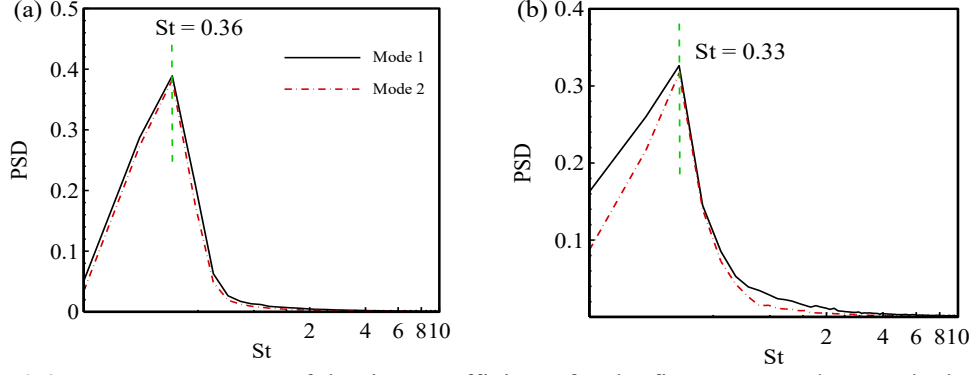


Figure 3.8 Frequency spectra of the time coefficients for the first POD mode over the body roof

3.4.3 Flow Characteristics Over the Slanted Surface

The slanted surface of the Ahmed body is characterized by a spanwise elliptic shape recirculation bubble, as indicated by (Ahmed et al., 1984; Joseph et al., 2011; Zhang et al., 2015). The influence of the leading edge on flow separation and reattachment over the slanted surface is presented in Fig. 9 using the mean streamlines. It can be observed that the separated flow attaches to the surface, and a recirculation bubble forms. The respective mean recirculation length over the slanted roof of the SL and RL body (L_{sr}/L_s , where L_{sr} and L_s are the recirculation length and slanted surface length, respectively) is 0.40 and 0.56. The latter value is comparable to $L_{sr}/L_s = 0.58$ reported by Joseph et al. (2011) for a rounded leading edge Ahmed body. In both cases, the flow separates from the trailing edge of the slanted surface and sheds into the wake region to form the upper recirculation bubble. The difference in leading edge shape alters the characteristics of the wake recirculation bubble, with the focal point of the upper recirculation bubble being shifted closer to the base of the body in the RL configuration.

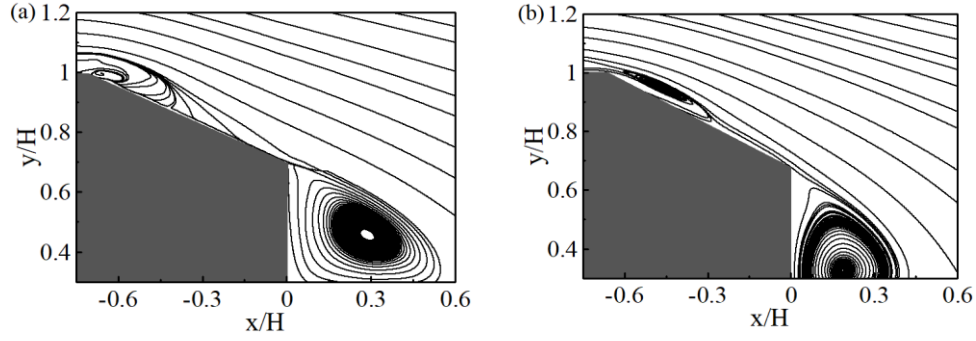


Figure 3.9 Contours of mean streamlines over the slanted surface of SL (a) and RL (b) bodies

Wall-normal profiles of streamwise mean velocity and TKE are depicted in Fig. 3.10. Fig. 3.10a shows that flow separates from the leading edge of the slanted surface ($x/H = -0.68$) and reattaches at approximately the midpoint of the slanted surface. Further away from the slanted surface, the streamwise mean velocity for the RL body is higher than for the SL body, with the difference diminishing as the flow progresses downstream. This confirms that the flow over the body is significantly influenced by the wake generated due to the flow separation from the body leading edge. Fig. 10b shows the wall-normal profiles of the TKE over the slanted surface and wake region. The TKE magnitude over the SL body is comparatively higher than the RL body. The higher TKE further from the slanted surface for the SL body coincides with a thicker shear layer, which evolves at a greater distance from the roof in the SL body, as illustrated in Fig. 3.5. The level of TKE over the RL body is negligible except in the vicinity of the slanted surface. Notably, the level of TKE for the SL body remains higher than the RL body even after the body trailing edge.

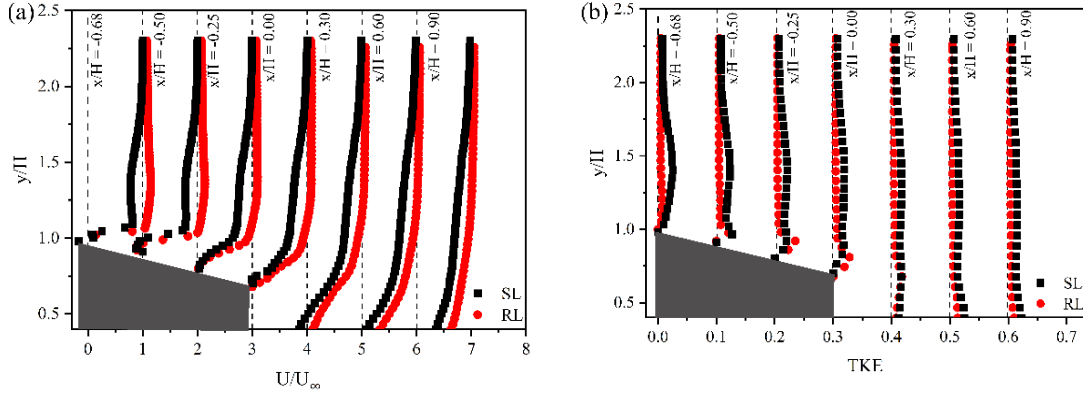


Figure 3.10 Wall-normal profiles of streamwise mean velocity (a) and TKE (b) over the slanted surface and wake region

A POD analysis of the flow over the slanted surface was conducted to investigate the effects of leading-edge geometry on the spatiotemporal characteristics of the shear layer over the slanted surface. The first POD mode contributes 29% and 26% of the total TKE energy for the RL and SL cases, respectively (not shown for brevity). This contribution decreases rapidly, reaching approximately 12% and 10% for the second mode, while the third mode captures 6% and 5% for the SL and RL body, respectively. The first POD mode contribution to the total TKE compares well with the 28% contribution observed by Thacker et al. (2013). Since there is a noticeable difference between the energy levels of the first three modes, it can be inferred that the spatiotemporal structures within these modes are different. Hence, these three modes are chosen to study the most dominant flow structure over the slanted surface and to highlight the impact of the leading-edge dynamics on that structure over the slanted surface.

Figure 3.11 shows the wall-normal spatial POD modes. Consistent with the observation made in Fig. 3.7, the POD spatial structures over the SL body are larger than those of the RL body. For both bodies, the first POD mode shows velocity fluctuations that encompass the entire recirculation bubble. A similar flow was observed by Thacker et al. (2013) over the slanted surface of the RL body and was attributed to the flapping motion of separated flow, which is exemplified

by instantaneous contraction and expansion of the recirculation bubble (Thacker et al., 2013; Fang & Tachie, 2019). Depending on the signs of its coefficient, the first POD mode represents a structure that expands or contracts the recirculation bubble over the slanted surface, as demonstrated by (Joseph et al., 2011; Thacker et al., 2013; Chiatto & de Luca, 2021). The second mode exhibits distinct structures with alternating positive and negative fluctuations, which originate from the leading edge of the slanted surface and evolve downstream. A similar observation was made by Thacker et al. (2013) regarding the spatial structure of the second POD mode around the slanted surface of the RL body and was attributed to the large-scale vortex emission (Bergmann & Cordier, 2008). The third mode can also be characterized by positive and negative structures, with a shift in space compared to the second mode, denoting the convective nature of these modes. Typically, the periodicity of positive and negative zones of extreme fluctuations from the second POD mode is utilized to define the wavelength representative of large-scale structural emissions in the flow (Mohammed-Taifour & Weiss, 2016). To characterize the scaling of these dynamics, the distance between the positive and negative structures in the second mode is measured. This value is $\Lambda/2 = 0.46H$ and $0.32H$ for the SL and RL bodies, respectively.

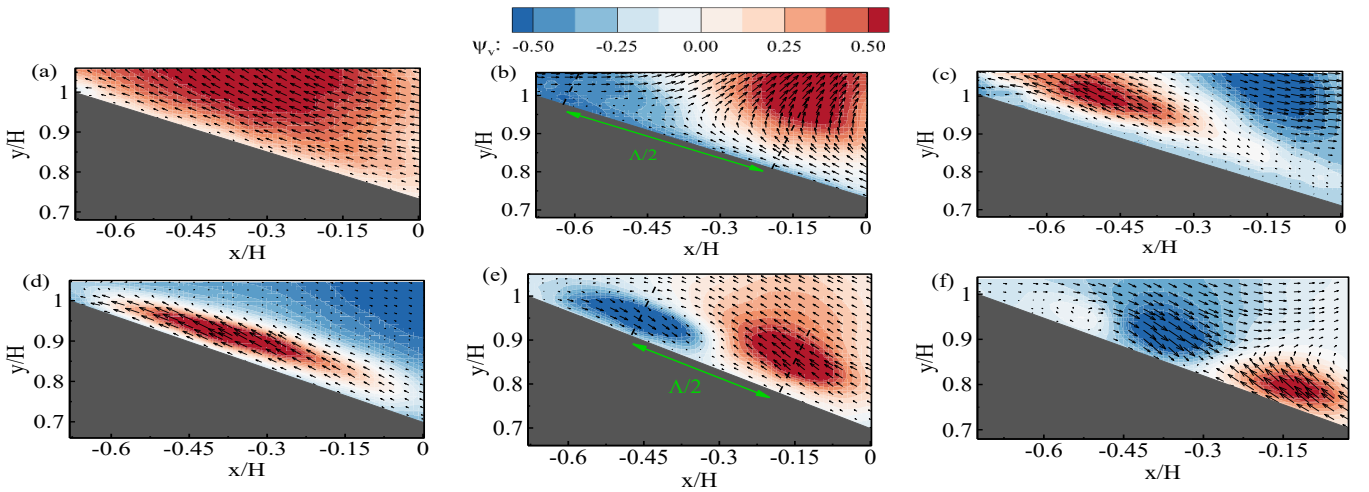


Figure 3.11 Contours of first [(a), (d)], second [(b), (e)], and third [(c), (f)] POD spatial modes over SL [(a), (b) and (c)] and RL [(d), (e) and (f)] body. For clarity, every tenth POD vector is plotted

To evaluate the periodicity of the POD structures, the premultiplied frequency of POD time coefficients for the first, second, and third POD modes is shown in Fig. 3.12. The figures present evidence of varying distinct frequencies across the slanted surface, reflecting the notable influence of the leading edge on temporal characteristics. For the SL body (Fig. 3.12a), the first mode is characterized by a dominant frequency of $St = 0.23$ (or $St_{L_{sr}} = \frac{f_{L_{sr}}}{U_{\infty}} = 0.07$), which is lower than $St_{L_{sr}} = 0.08$ over the RL body. This low frequency was previously linked to the flapping motion of the recirculation zone formed over the slanted surface of the RL body by Joseph et al. (2011), Thacker et al. (2013), and (Siddiqui & Agelin-Chaab) 2022. The second mode is characterized by a frequency of $St = 0.46$ ($St_{L_{sr}} = 0.14$), which is the harmonic frequency of $St = 0.23$ ($St_{L_{sr}} = 0.07$), and can be attributed to the large-scale vortices shed from the leading edge of the slanted surface (Fig. 11b). The frequency of flapping motion, $St = 0.23$ ($St_{L_{sr}} = 0.07$) is also evident in the second mode. The dominant frequency of the third mode increases to $St = 0.55$ ($St_{L_{sr}} = 0.16$). Notably, the spectra show a distinct frequency of $St = 0.33$ ($St_{L_{sr}} = 0.09$) characterized by weak energy in the third mode, which is comparable to the dominant frequency of coherent structures, $St = 0.36$ ($St_{L_{sr}} = 0.10$) observed over the body (Fig. 3.8a). In the case of the RL body, the first POD mode is characterized by a dominant frequency of $St = 0.33$ ($St_{L_{sr}} = 0.13$), aligning with the dominant frequency of the alternate vortex shedding of the shear layer emanating from the leading edge of the RL body (Fig. 3.8). While the flapping motion frequency of $St = 0.19$ ($St_{L_{sr}} = 0.08$) is also present in this mode, it is weaker than the energy of the frequency of alternate vortex shedding, $St = 0.33$ ($St_{L_{sr}} = 0.13$). The presence/absence of the dominant frequency of the upstream shear layer

emanating from the leading edge in the frequency spectra of the slanted surface of the RL and SL cases underscores the strong/weak correlation between the shear layer originating from the leading edge and the slanted surface of the RL/SL body. The frequency spectra of the second mode in the RL body show a broad peak with multiple frequencies, with a dominant frequency of $St = 0.52$ ($St_{L_{sr}} = 0.20$). Additionally, the dominant frequency of the third POD mode, $St = 0.66$ ($St_{L_{sr}} = 0.25$) in the RL body is also higher than that of the SL body, $St = 0.55$ ($St_{L_{sr}} = 0.16$).

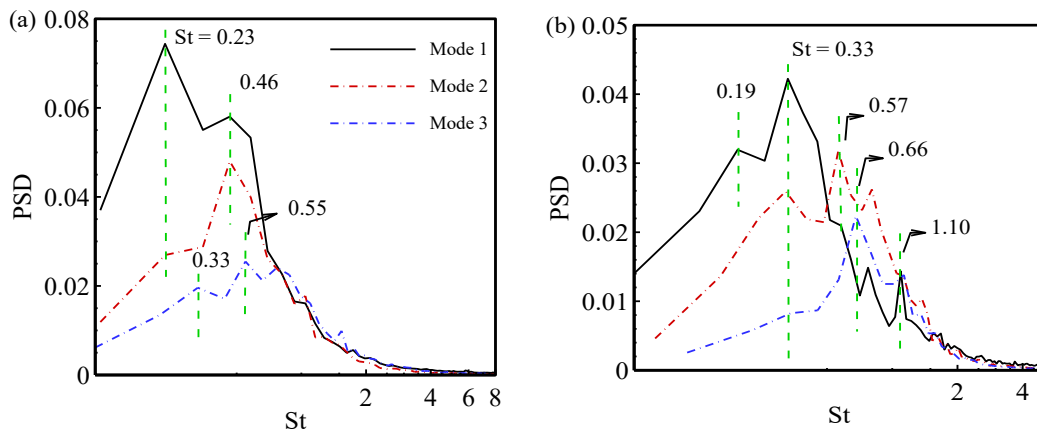


Figure 3.12 Frequency spectra of the POD time coefficients for the first, second, and third POD modes over the slanted surface for SL (a) and RL (b) Ahmed body

The convective velocity over the slanted surface of the SL and RL bodies is $U_c = 0.42U_\infty$ and $0.36U_\infty$. This suggests that the coherent structures over the slanted surface of the SL body travel faster than those over the RL body. This behaviour is consistent with the higher convective velocity observed over the SL roof ($U_c = 0.72U_\infty$ and $0.47U_\infty$ for the SL and RL, respectively).

3.4.4 POD Reconstruction

The POD analysis in the previous sections showed that the frequency of the most energetic structures (first POD mode) over the roof and the slanted surface of the RL body coincide, indicating a strong influence of the leading-edge shear layer separation on the flow dynamics over the slanted surface. To examine the physical mechanism behind the influence of the separated

shear layer from the leading edge on the flow over the slanted surface of the RL body, the flow over the roof and slanted surface are reconstructed using low-order POD modes (Perry et al., 2016; Podvin et al., 2020; Venning et al., 2022), and the mean velocity field is then added to the reconstructed fluctuating fields (Mohammed-Taifour & Weiss, 2016; Bai et al., 2019). This analysis reconstructs the dynamics of the coherent structures while masking the effect of small-scale structures. The POD reconstruction was performed using the first several modes, which recovered 40%, 50%, and 60% of TKE. The analysis (not shown for the economy of space) showed evidence of small-scale structures for cutoff energies of 50% and 60%, indicating that a threshold exceeding 50% of the cutoff energy begins to include small-scale fluctuations. Hence, a cutoff energy of 40% (first ten and twenty-five modes for the SL and RL body, respectively) was chosen for the reconstruction. The vorticity distributions of the reconstructed flow field are shown in Fig. 3.13.

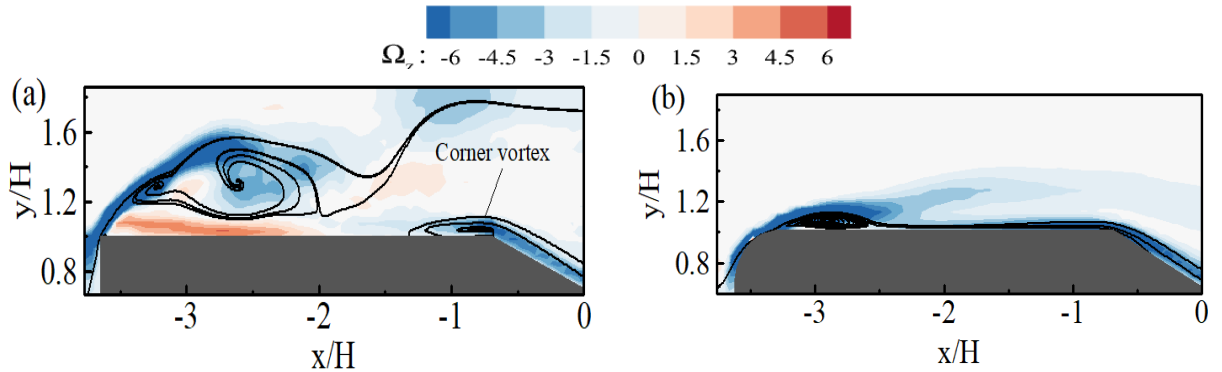


Figure 3.13 Spanwise vorticity distribution for (a) the first ten and (b) twenty-five POD modes over the body superimposed by flow field streamlines

Similar to Fig. 3.3, Fig. 3.13 illustrates the formation of a recirculation bubble near the leading edge. Figure 3.13a demonstrates that after the recirculation bubble, the flow deviates from shedding directly into the wake region. Notably, the reconstructed flow reveals the existence of a corner vortex just before the slanted surface of the SL body, which forms under the pressure difference between the roof and slanted surfaces. This vortex acts as a barrier, driving an upwash

flow and deflecting the leading-edge shear layer from interaction with those over the slanted surface. This behaviour can also be confirmed by tracing the negative (clockwise) vorticity emanating from the leading edge, which sheds away from the slanted surface. In contrast, Fig. 3.13b shows that the streamlines over the RL roof are modulated by negative vorticity emanating from the leading edge and shed into the wake region. Hence, a stronger correlation between the dynamics of the shear layer emanating from the leading edge and those over the slanted surface is expected (Moore et al., 2019).

3.4.5 Flow Characteristics in the Wake Region

To evaluate how the leading edge affects the most energetic structures and their associated frequencies in the wake region, POD was conducted for the wake region ($x^* \in [0, 2.25]$ and $y^* \in [-0.17, 1.0]$). The first two POD modes for the SL body capture 13.6% and 13.2% of TKE, while 11.8% and 10.4% are captured by the first and second POD modes for the RL body. The POD spatial structures of the first and second modes are illustrated in Fig. 3.14. The wake of the bodies is characterized by a succession of positive and negative fluctuations that emanate from the slanted surface and undersurface of the body. In both cases, positive and negative structures evolve downstream towards the ground, reflecting the influence of higher downwash flow compared to upwash flow in the wake region. Consistent with observations over the roof and slanted surface, the size of coherent structures is larger in the wake region of the SL body and more persistent in the region far from the base. Comparing the spatial patterns of the first and second modes for both cases shows that their topology is similar, and the average distance between the peaks of successive positive or negative structures in the first two modes is $\Lambda = 1.4H$ and $1.1H$ for the SL and RL body, respectively.

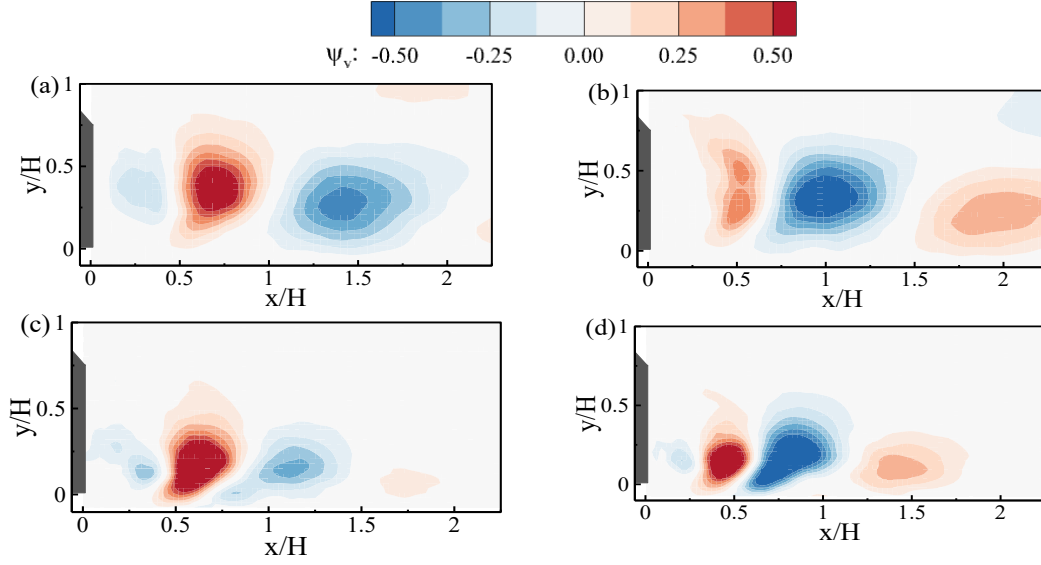


Figure 3.14 Contours of the first [(a), (b)] and second [(c), (d)] POD modes

To investigate how the leading-edge flow affects the periodic structures in the wake region, a conditional averaging analysis is performed. This analysis is based on the temporal coefficient of the first POD mode, where a sorting criterion based on the conditions ($-0.3 < a^{(1)} < -0.09$, $-0.09 < a^{(1)} < 0.09$ and $0.09 < a^{(1)} < 0.30$) was considered (See Fig. 3.15). For each condition, a low-order model was subsequently developed using the time-averaged field and the first mode, based on equation 3.2, following a method similar to that of Thacker et al. (2010) and Perry et al. (2016) and Fan et al. (2020).

$$u_{\text{LOM}}(x, y, t) = U(x, y) + \Psi^1(x, y)a^1(t) \quad (3.2)$$

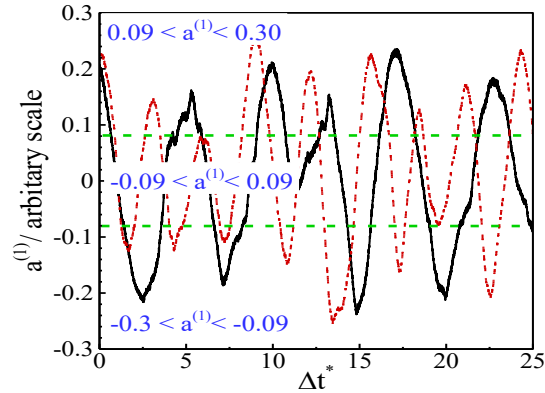


Figure 3.15 Time sequence of temporal coefficient of first POD mode. The solid and dashed lines represent SL and RL POD coefficients, respectively

The reconstructed vorticity snapshots for the three conditions are plotted in Fig. 3.16. The mean streamlines are superimposed to display the wake recirculation bubble. For both leading-edge configurations, vorticity originating from both the top slanted surface and the undersurface of the body stretches and curls towards the body as the flow evolves downstream. The positive vortices with counterclockwise rotation induce a negative (clockwise) vorticity on the ground. The figure shows that two recirculation bubbles in the wake region form a toroidal structure (refer to Fig. 3.3). In the SL case, at condition 1 (Fig. 3.16a), the two recirculation bubbles have approximately similar streamwise lengths. Under this condition, the recirculation length is $L_r^* = 0.62$, which is larger than its mean value, $L_r^* = 0.53$ (Fig. 3.3). For the second condition (Fig. 3.16b), the upper shear layer is contracted and inclined toward the base, while the lower one is stretched out downstream. Owing to the enhanced downwash flow entrained into the wake region, the upper recirculation bubble is larger than the lower one, and the recirculation length increases to $L_r^* = 0.68$. At condition 3 (Fig. 3.16c), the upper recirculation bubble enlarges and bursts while the lower shear layer contracts, and its core moves toward the base. The recirculation length decreases to $L_r^* = 0.50$ at this condition. Even though the condition sequences in the wake region of the RL case are qualitatively similar to those observed for the SL case, some important differences can be observed. For instance, the upper recirculation bubble is always larger than the lower one, which leads to the dominance of the upper recirculation bubble over the lower one. Also, no bubble bursting is observed in the upper recirculation bubble of the RL body. Tafti & Vanka (1991) demonstrated that the bubble pulsation phenomenon is linked to the entrainment of freestream flow into the recirculation bubble of a blunt flat plate, which in turn elevates its pressure and eventually results in bubble bursting once its pressure reaches a threshold. Zhang et al. (2015) argued that the pulsation in the wake region of the Ahmed body is a result of the alternating

emanation of fluid structures, driven by pressure differences between the two recirculation bubbles. Figure 3.16 shows that the separated shear layer from the slanted surface of the SL case is entrained into the upper recirculation bubble and increases the bubble pressure at conditions 1 and 2, and this persists until its pressure gradually increases to a certain value. At condition 3, the upper recirculation bubble bursts, and part of the fluid in the upper bubble is transported into the lower bubble. In the RL case, despite the alternate emanation of structures, the upper recirculation bubble never diminishes to a size smaller than the lower bubble. This suggests that as the pressure level of the upper recirculation bubble reaches a certain value, it feeds the lower bubble. However, the upper recirculation bubble maintains its high pressure. This would suggest a lower pressure difference between the upper and lower recirculation bubbles of the RL case compared to the SL case.

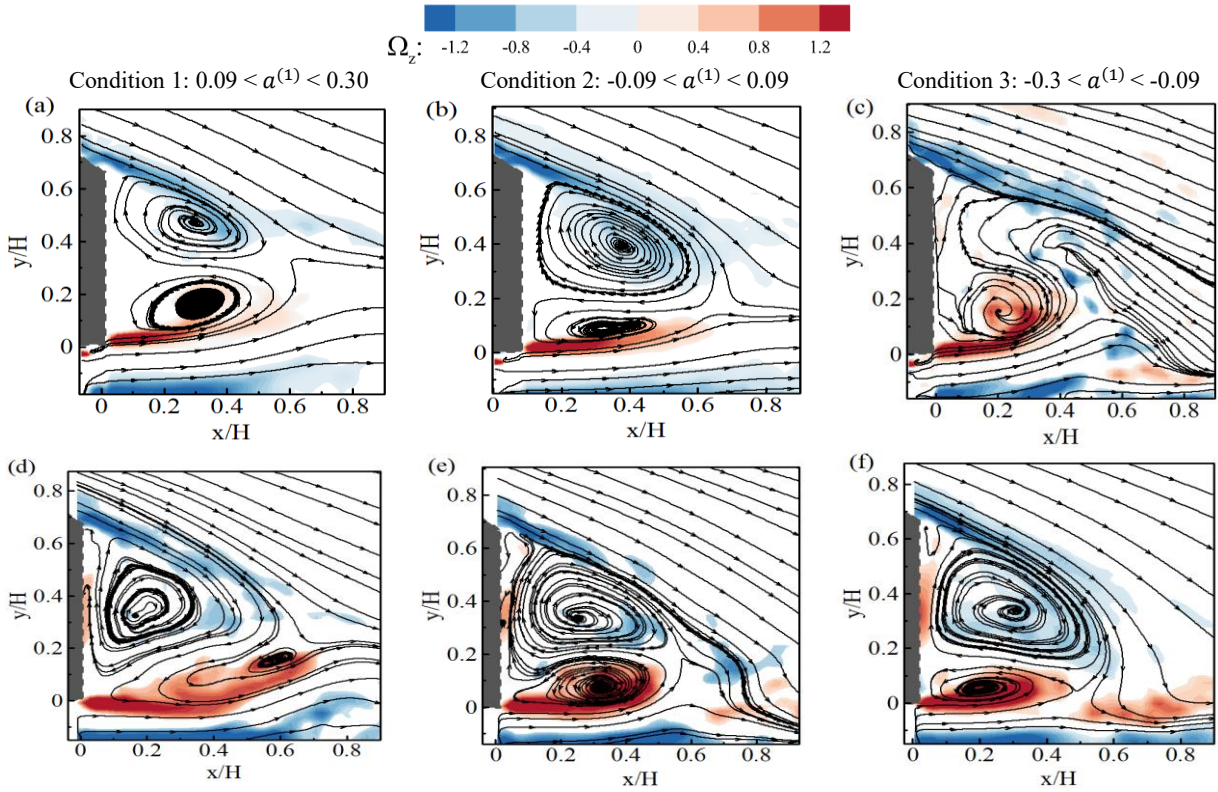


Figure 3.16 POD conditionally averaged states in the wake region of SL [(a), (b), and (c)] and RL [(d), (e), and (f)]

Figure 3.17 shows the pre-multiplied frequency spectra of the temporal coefficients corresponding to the first two POD modes. The von Kármán shedding frequencies of $St = 0.23$ and 0.33 are observable in the wake region of the SL and RL bodies, respectively. The vortex-shedding frequency of $St = 0.33$ is comparable to $St = 0.31$ observed by Tunay et al. (2014) and Zhang et al. (2015). The shedding frequency in the wake region of the RL body is identical to the dominant frequency of coherent structures observed over the roof and slanted surface (Figs 3.8 and 3.12). Indicating that rounding the leading edge influences the manifestation of the von Kármán shedding frequency around the body. The respective magnitude of convective velocity based on wavelength and associated dominant frequency in the wake region for the SL and RL is $U_c \approx 0.32U_\infty$ and $U_c \approx 0.36U_\infty$, respectively.

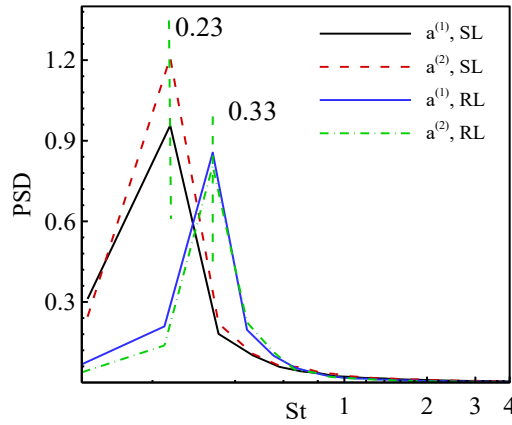


Figure 3.17 Frequency spectra of the POD time coefficients for the first, and second modes in the wake region

3.4.6 Reverse Flow Area

To evaluate the effects of the leading-edge shape on the unsteady reverse flow area behaviour, including their auto-correlation, statistical analyses of the reverse flow area near the leading edge and in the wake region were performed. The instantaneous reverse flow area is determined by

integrating the areas where $u < 0$ within a region of interest (E), as described by Pearson et al. (2013):

$$A(t) = \int_E \zeta(u(x, y, t)) dx dy \quad (3.3)$$

$$\zeta(P) = \begin{cases} 0 & P \geq 0 \\ 1 & P < 0 \end{cases} \quad (3.4)$$

The analysis was performed over $x^* \in [-3.64, -1]$ and $y^* \in [1, 2]$ over the leading edge, and $x^* \in [0, 2.24]$ and $y^* \in [-0.17, 1.05]$ in the wake region.

Figure 3.18 displays the probability density function (pdf) of the reverse flow area near the leading edge and wake region for both SL and RL cases. The pdf distribution of the SL case is quasi-Gaussian, while the distribution of the RL case is right-tailed, demonstrating the occurrence of a smaller reverse flow area near the leading edge. It is also noted that the probability of fully reattachment flow on the roof flow ($A = 0$) is higher in the RL case than in the SL case.

Table 3.1 provides a summary of the reverse flow area near the leading edge and in the wake region of both body types. Notably, the mean reverse flow area of the SL case ($(A_L)_{\text{mean}} / H^2 = 0.552$) is an order of magnitude larger than the corresponding value ($(A_L)_{\text{mean}} / H^2 = 0.053$) for the RL case. The table also reveals that the standard deviations of the reverse flow area $(A'_L)_{\text{rms}} / (A_L)_{\text{mean}}$ and $(A'_W)_{\text{rms}} / (A_W)_{\text{mean}}$ are notably higher in both regions for the SL case. The difference between the two cases is particularly pronounced over the leading-edge region.

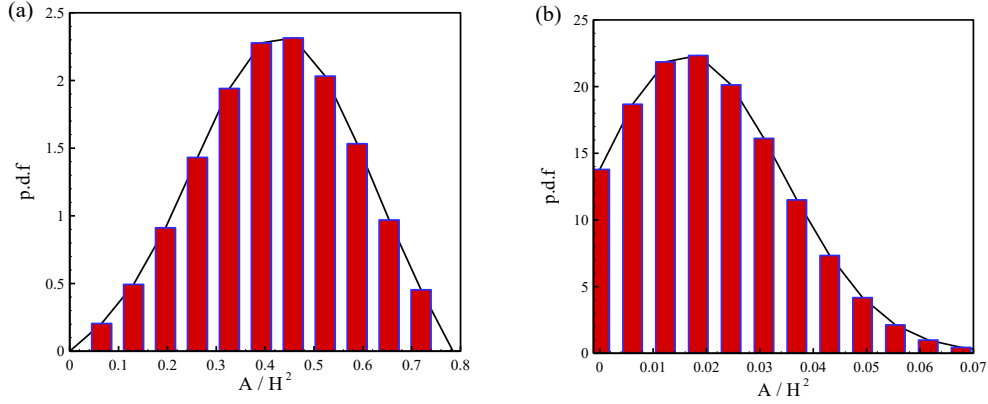


Figure 3.18 Probability density function of reverse flow area near the leading edge of SL body (a), RL body (b)

Parameters		SL	RL
Leading edge	$(A_L)_{\text{mean}} / H^2$	0.552	0.053
	$(A'_L)_{\text{rms}} / (A_L)_{\text{mean}}$	0.161	0.283
Wake region	$(A_W)_{\text{mean}} / H^2$	0.220	0.172
	$(A'_W)_{\text{rms}} / (A_W)_{\text{mean}}$	0.136	0.122

Figure 3.19 compares the time sequences of the instantaneous reverse flow area over the roof (A_L) and the coefficients of the first POD mode ($a^{(1)}$) for both test cases. The synchronization between these two temporal signals is noteworthy, and the cross-correlation coefficient between $a^{(1)}$ and A_L equals 0.70 and 0.92 for the SL and RL bodies, respectively. The premultiplied spectra of the reverse flow areas near the bodies' roofs are presented in Fig. 3.20. The dominant frequencies observed over the SL and RL bodies are $St = 0.36$ and 0.33 , respectively. These frequencies align with the dominant frequency of coherent structures obtained from the first two POD modes (Fig. 3.8). A Similar observation was made by Fang & Tachie (2019), Aleyasin et al. (2021), and Kumahor & Tachie (2023) over a forward-backward facing step, Ahmed bodies, and rectangular cylinder, respectively, and suggest that the temporal characteristics of the reverse flow area are strongly linked to the dynamics of coherent structures over the roof. The shedding frequency of $St = 0.33$ over the RL body is comparable to $St \approx 0.30$ observed over the RL body by Minguez et

al. (2008). To account for differences in body geometry and upstream flow conditions, the vortex shedding frequency was normalized by recirculation length over the roof (Kiya & Sasaki, 1985; Tafti & Vanka, 1991; Zhang et al., 2015). The vortex shedding frequency based on the recirculation length of SL and RL is $St_{xR} = 0.65$ and 0.28 , respectively. The frequency of $St_{xR} = 0.65$ compares well with $St_{xR} = 0.60 - 0.80$, which are characteristic shedding frequencies based on the reattachment length over sharp-edged bluff bodies (Kiya & Sasaki, 1985; Tafti & Vanka, 1991).

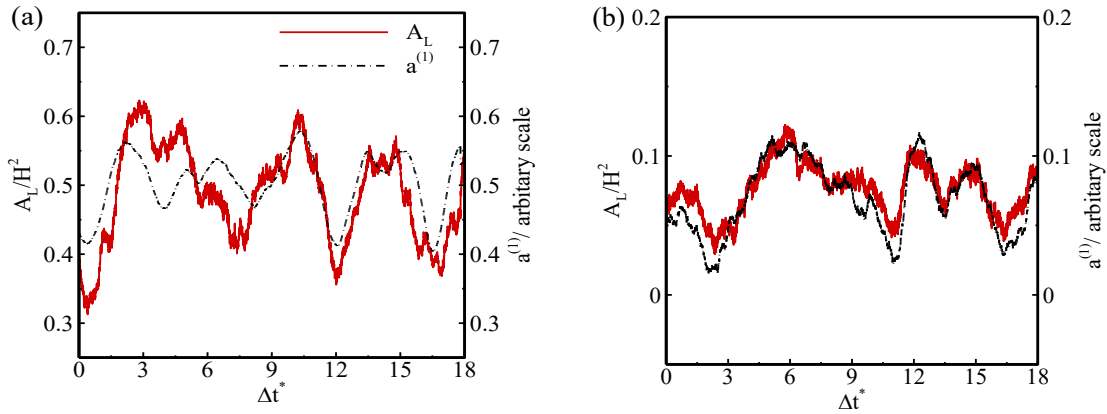


Figure 3.19 Time sequences of the instantaneous reverse flow area and the coefficient of first POD mode for SL (a), and RL (b) body

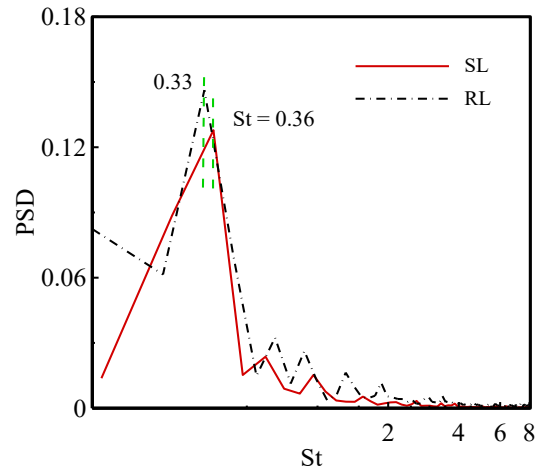


Figure 3.20 Premultiplied frequency spectra of instantaneous reverse flow area over the roof (A_L)

To assess the temporal characteristics of interactions between the shear layers emanating from the leading edge and those in the wake region, the temporal auto and cross-correlation coefficient of

the fluctuating reverse flow area (A') near the leading edge and in the wake regions is calculated as follows:

$$R_{ij}(\Delta t) = \frac{\overline{A'_i(t)A'_j(t+\Delta t)}}{(A'_i)_{\text{rms}}(A'_j)_{\text{rms}}} \quad (3.5)$$

R_{ij} would be R_{LL} , R_{WW} (for auto-correlation) and R_{LW} (cross-correlation). The distribution of R_{LL} (Fig. 3.21a) and R_{WW} (Fig. 3.21b) are periodic with $R_{LL}(0)$ and $R_{WW}(0) = 1$ at the self-correlation time (i.e., $t^* (= \Delta t U_\infty / H) = 0$). The decorrelation point near the leading edge is higher in the SL case than in the RL case. This behaviour is consistent with the observation of a higher integral time scale observed near the leading edge and wake region of the SL case compared with the RL case (Sagharichi et al., 2023). The time variation of the distribution of cross-correlations of the fluctuations of reverse flow areas shows positive and negative correlation values over time, with a decaying trend with time. Figure 3.21c shows distinct peaks at $t^* \approx 3$ and the first decorrelation ($R_{LW} = 0$) occurs at $t^* = 9$ for both cases. This significant observation indicates that the recirculation bubble in the wake region requires $t^* \approx 3$ times to respond to changes in upstream conditions induced by recirculation bubbles over the body. This value is close to the convective time scales of $t_c = 3.3$ and 3.60 obtained from the convective velocity of coherent structures over the roof (Section 3.4.2). The figure also shows that the cross-correlation of the reverse flow areas for the SL case persists for a wider range of time compared to the RL case. While a high correlation exists until $t^* = 9$ for the RL case, it significantly decreases as time progresses. For $t^* < 9$, the cross-correlation coefficient of the reverse flow area for the RL and SL cases is positive and negative, respectively. This indicates that the shrinkage of the wake recirculation bubble is associated with the enlargement (shrinkage) of the SL (RL) body. Hence, as the fluid flow approaches the RL body, the leading-edge bubble enlarges (shrinks) and with a time delay of $t^* = 3$, the recirculation

bubble in the wake region also undergoes enlargement (shrinkage). The time shift ($t^* = 3$) that results in the highest synchronization between the fluctuation reverse flow area near the leading edge and the wake region is in good agreement with the convective time scales of coherent structures, $t_c = 3.30$ and 3.60 for the SL and RL body, as discussed in Section 3.4.2. For $t^* \geq 9$, there is a higher correlation coefficient in the SL case; however, the difference is lower than that for $t^* < 9$.

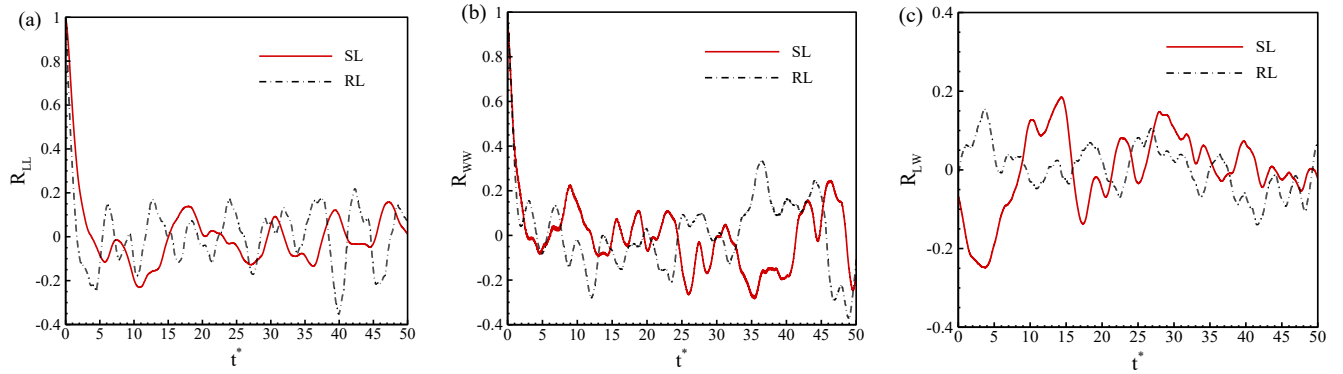


Figure 3.21 Temporal auto-correlation [(a), (b)] and cross-correlation of fluctuation (c) of the fluctuating reverse flow area over the leading edge and wake region

To assess the synchronization of the separation bubbles over the leading edge and the wake region, the probability density functions of cross-correlations of A' near the leading edge and wake region are shown in Fig. 3.22. The distribution shows a tendency toward negative correlations for the SL case and positive correlations for the RL case. This suggests that for the SL (RL) case, instances of expansion or shrinkage of the leading-edge separation bubble, occurring simultaneously with shrinkage (expansion) or expansion (shrinkage) of the wake region separating bubble, are more prevalent than the opposite scenario. The figure also demonstrates that the probability of the occurrence of cross-correlation within $-0.5 < R_{LW} < -0.1$ or $0.1 \leq R_{LW} < 0.5$ is higher in the SL case. In contrast, the possibility of the occurrence of cross-correlations within $-0.1 \leq R_{LW} \leq 0.1$ is more likely to happen around the RL case.

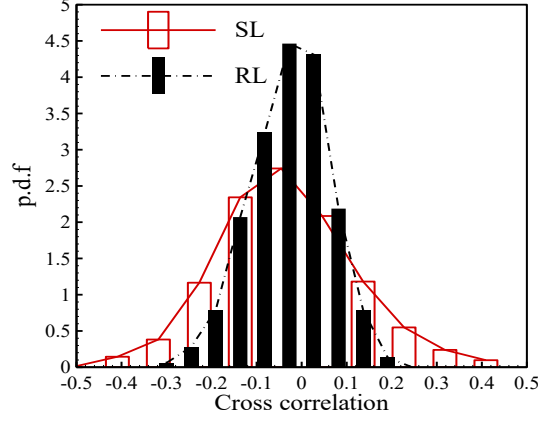


Figure 3.22 P.d.f distribution of R_{LW} around SL and RL bodies

3.5 Flow Characteristics in the x-z Plane

3.5.1 Shear Layer Characteristics

Due to the 3-D nature of the flow around the bodies, measurements in the x-z plane are used to provide additional insights into the shear layer and wake characteristics. Figure 3.23 displays the contour of wall-normal mean vorticity ($\omega_y = \partial W / \partial x - \partial U / \partial z$) around the bodies, with mean streamlines and isopleths of $U^* = 0$ and 0.5 superimposed on the plots. The figure shows the concentration of vorticity along the $U^* = 0.5$ near the leading edge and wake region in both cases. A thicker vorticity region forms near the leading edge in the SL case compared to the RL case. In the wake region, the vorticity cluster aligns with the lateral surface in the SL case but inclines toward the wake region in the RL case. Flow reattachment on the lateral surface of SL and RL cases occurs at $x^* \approx -2.50$ and -2.78 for the SL and RL cases, respectively. Figure 3.23b also shows evidence of two strip structures in the wake region of the RL case, a phenomenon also noted by Wang et al. (2013), who suggested that the outermost strip is associated with the shear layer developed over the side surface emanating from the leading edge. The negative strips in the middle are attributed to the interaction between the C-pillar vortex and the recirculation bubble originating from the slanted surface. This negative strip is also present in the wake region of the SL case, but

with lower intensity compared to the RL case, which is due to the lower elevation of the C-pillar vortex from the ground in the RL case, allowing it to be captured in the spanwise plane.

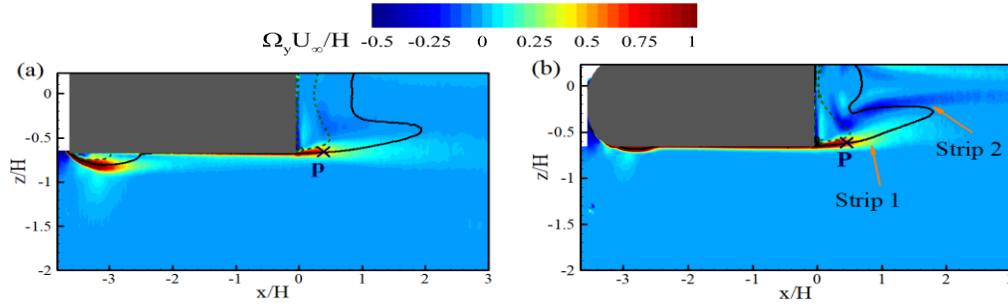


Figure 3.23 Contours of wall-normal mean vorticity for (a) SL and (b) RL body. Solid and dashed lines represent $U^* = 0.5$ and represent $U^* = 0$ respectively

Haffner et al. (2020) reported that a shear layer roll-up emanates from the side surfaces of the Ahmed body due to the Kelvin-Helmholtz (KH) instability and measured the wavelength of the KH vortices (λ_{KH}) as the streamwise distance between two consecutive negative peaks in the distribution of the spatial auto-correlation coefficient based on the spanwise velocity fluctuation. The streamwise distribution of $R_{w'w'}$ with the reference point of $(x^*, z^*) = (0.71, -0.63)$ and $(0.54, -0.58)$ for the SL and RL cases, respectively, is provided in Fig. 3.24. As depicted in this figure, the correlation coefficient in the RL case is weaker than in the SL case. In the RL case, $\lambda_{KH} = 0.4H$ compared to $\lambda_{KH} = 0.5H$ in the SL case. Figure 3.25 presents power spectral density plots of the spanwise fluctuation velocity at the location of $(x^*, z^*) = (0.60, -0.60)$ within the shear layer (indicated by P in Fig. 3.23) emanating from the lateral surface of the body's trailing edge. The figure highlights the peak vortex shedding frequency of $St = 1.04$ and 1.27 in the SL and RL shear layers, respectively. Notably, the peak frequency at $St = 1.27$ is comparable to $St = 1.44$ reported by Haffner et al. (2020) for the shear layer emanating from the lateral side of a square-back Ahmed body. The higher vortex shedding frequency of the shear layer emanating from the lateral surface of the RL body is consistent with the results observed in Fig. 3.17.

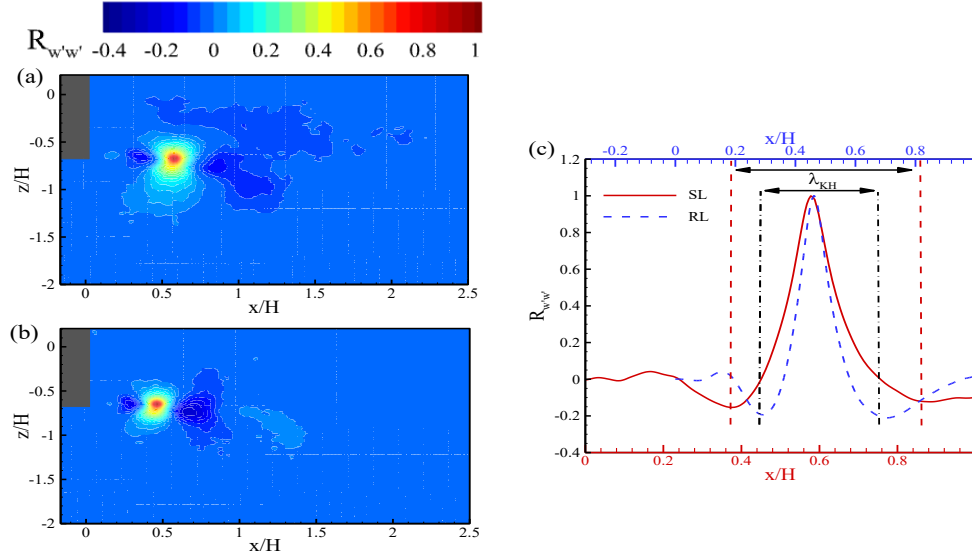


Figure 3.24 Streamwise correlation of spanwise velocity fluctuations for (a) SL case, (b) RL case, (c) comparison of the profile extracted from $(x^*, z^*) = (0.71, -0.63)$ and $(x^*, z^*) = (0.54, -0.58)$ for the SL and RL cases, respectively

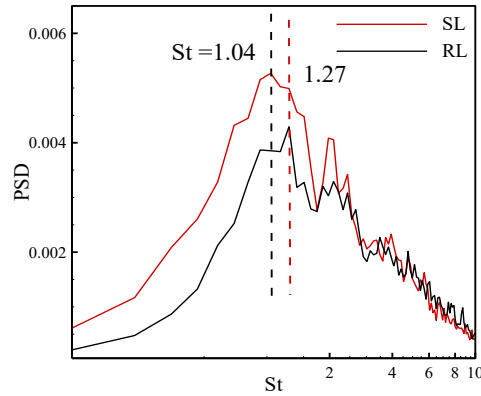


Figure 3.25 PSD of the spanwise fluctuation velocity of the shear layer

3.5.2 POD Analysis

POD analysis was employed to extract dominant flow structures and identify key features crucial for understanding the fluid dynamics in the wake region. The POD was performed in the masked region, $x/H \in [0, 3.55]$ and $z/H \in [-1.70, 0.20]$.

The fractional and cumulative sum TKE energy contributions from the first ten modes are shown in Fig. 3.26. The cumulative energy of the first ten modes is 31% lower when the leading edge is

rounded. The cumulative energy comparison also shows that the energy content in the first two POD modes is 7.4 % and 4.4 % for SL and RL cases, respectively. The higher energy captured by the POD modes of the SL indicates that a vortical structure with higher energy forms behind the SL body compared to the RL case.

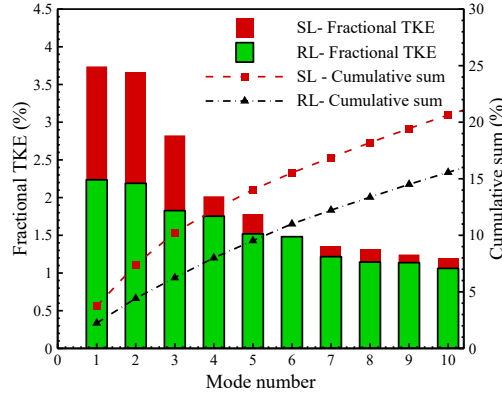


Figure 3.26 Distributions of the fractional and cumulative sum energy contributions of the first ten POD modes in the spanwise planes

The spatial distribution of the first two POD modes by spanwise velocity fluctuations, Ψ_w , is provided in Fig. 3.27 to visualize the vortical structures in the wake region of bodies. Both cases reveal the alternating motion of positive and negative zones, which is evidence of alternate vortex shedding.

To calculate the convective velocity in the wake region, the spatial wavelength of the vortex shedding motion is determined by averaging the distances between several extremum zones of alternating (positive and negative) regions. The local wavelength of the vortices shed from the SL and RL bodies is $\Lambda/2 = 1.38H$ and $0.66H$, respectively. Based on the shedding frequencies of $f = 0.79$ Hz and 2.01 Hz in the wake regions of the SL and RL calculated using the frequency spectra, the convective velocity of the vortices for the SL and RL cases can be estimated as $0.62U_\infty$ and $0.76U_\infty$.

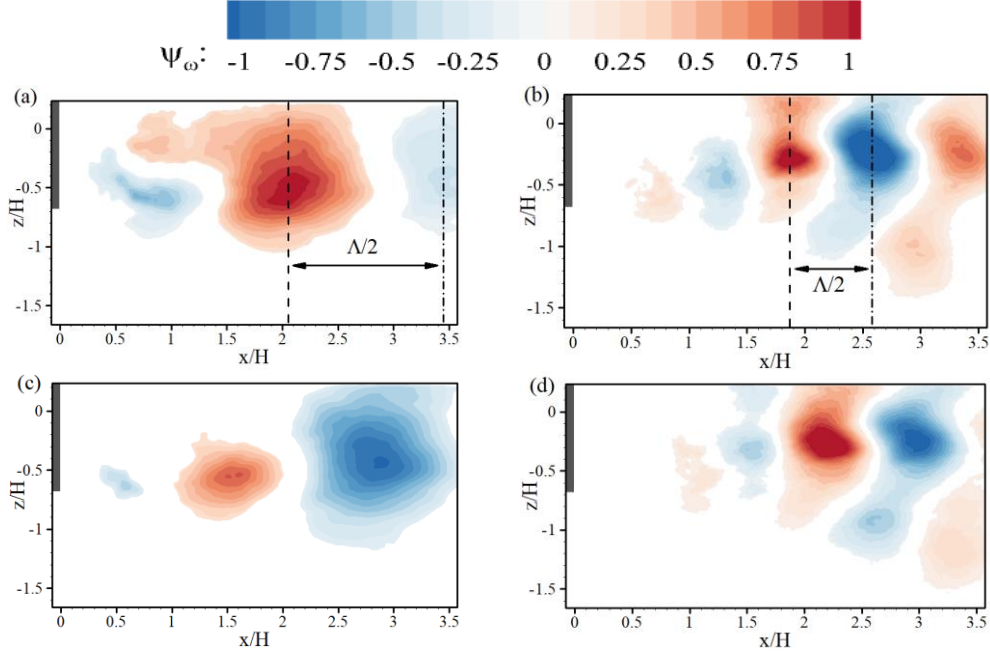


Figure 3.27 Contours of the spanwise components (Ψ_w) of [(a), (b)] first and [(c), (d)] second POD modes in the wake region of [(a), (c)] SL body and [(b), (d)] RL body

3.6 Conclusions

This study provided a comprehensive investigation of the flow characteristics around two distinct Ahmed body shapes: a squared (SL) and a rounded (RL) leading edge, using particle image velocimetry. In the SL case, the presence of a prominent flow separation at the leading edge resulted in increased vorticity flux, which leads to a larger coherent structure with higher energy around the roof compared to the RL case. In the wake region, the focal point of recirculation bubbles shifted toward the vertical base in the RL body, while the recirculation length was nearly independent of the leading-edge shape. Analysis of shedding frequencies and convective velocities using POD coefficients over the body roof revealed a higher shedding frequency and convective velocity over the SL body ($St = 0.36$, and $U_c \approx 0.72U_\infty$) compared with $St = 0.33$ and $U_c \approx 0.47U_\infty$ over the RL roof. In contrast, in the wake region, the RL body exhibited higher values: $St = 0.33$ and $U_c \approx 0.76U_\infty$, compared to the SL body: $St = 0.23$ and $U_c \approx 0.62U_\infty$. Notably, identical vortex

shedding frequency was observed over the roof, slanted surface, and wake region in the RL body, indicating that rounding the leading edge increases the dominance of wake shedding frequency over the roof and slanted surface. Furthermore, POD analysis showed a larger coherent structure around the SL body compared to the RL body. The conditional averaging analysis of the temporal coefficient of the first POD mode reveals distinct vortex dynamics and recirculation behaviours in both leading-edge configurations. The SL case shows a significant bubble-bursting phenomenon due to pressure build-up in the upper recirculation bubble, whereas the RL case maintains a more stable upper recirculation bubble, suggesting different pressure dynamics between the two configurations. Temporal auto and cross-correlation analysis of the reverse flow area near the leading edge and wake regions of bodies has revealed distinct synchronization behaviours, with both cases showing a distinct peak at normalized time $t^* = 3$ and decorrelation at $t^* = 9$ regardless of leading-edge roundedness. The analysis of cross-correlation of fluctuation of reverse flow area showed that for the RL body, instances of expansion or shrinkage of the leading-edge separation bubble, occurring simultaneously with expansion or shrinkage of the wake region separating bubble, are more prevalent than the opposite scenario. However, an opposite scenario was predicted for the SL body. Spatial and temporal characteristics of the shear layer and wake region in the x-z plane have also been investigated, highlighting differences in vorticity concentration, flow reattachment, and shedding frequencies between SL and RL cases. The study of the side shear layer in the wake region showed weaker correlations and higher shedding frequencies compared to the SL body, indicating stronger vortex shedding in the RL case. The presence of two strip structures in the wake region of the RL case is associated with interactions between the C-pillar vorticity and the recirculation bubble from the slanted surface. These structures were also observed in the wake region of the SL case but with lower intensity.

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Chapter 4: Turbulent separations around a slanted-back Ahmed body with square and rounded leading edge

4.1 Abstract

An experimental study was conducted to study the effects of rounded (RL) and squared leading-edge (SL) on the time-averaged and temporal characteristics around a slanted-back Ahmed body. Measurements were conducted at two Reynolds numbers of $Re = 0.17 \times 10^5$ and 0.36×10^5 . The results showed that sharpening the leading-edge induces a larger recirculation bubble near the leading-edge of the body but slightly reduces the recirculation bubble in the wake region. In both the leading and near wake of bodies, the recirculation length for SL cases was independent of Re , but for the RL body, it decreases in the leading edge and increases in the wake region as Re increases. Analysis of turbulent structures showed that the extent of the region of elevated integral time scale around the body is larger in the SL case than in the RL one. Statistical analysis showed that sharpening the leading-edge suppresses downwash flow, which in turn reduces the shear layer interaction behind the body and decreases the dominant shedding frequency. The dominant frequencies obtained using velocity fluctuations, reverse flow area, and the coefficient of the first proper orthogonal decomposition confirmed that the dominant frequency near the leading edge and the wake region of the RL body increases with Re , while it is insensitive to Reynolds number for the SL case. The analysis performed in the spanwise plane also revealed that a region with higher streamwise mean velocity forms in the wake region of the RL body, which originates from the higher flow deviation near the trailing edge of the body.

4.2 Introduction

Many physical phenomena, such as flow separation, reattachments, vortex shedding, and wake formation, can be observed in the flow around bluff bodies (Taylor et al., 2011; Derakhshandeh & Alam, 2019). Flow separation induced by a bluff body leads to a pressure difference between the front-end and after-body, which is the main reason for aerodynamic drag. Vortex shedding can also lead to vibration and noise production (Liu et al., 2019). Bluff bodies have diverse engineering and environmental applications, including heat exchangers, architecture, flow over pipes, and in the transportation industry, where they are used as a simplified model of on-road vehicles. In the transportation industry, for example, aerodynamic drag is responsible for 50 % to 60 % of the fuel consumption of medium-sized cars while driving at around 100 km/h (Sivaraj et al., 2018). This, in turn, causes the release of a significant amount of greenhouse gases that lead to global warming. Concerns about global warming and increasing fuel costs over the past decades have highlighted the need for more aerodynamic and environmentally friendly designs of on-road vehicles. Given the tight connection between the flow structure and aerodynamic drag around on-road vehicles (Joseph et al., 2011), a thorough understanding of flow structures around these bodies is a prelude to optimizing their shapes. Several models, including the Ahmed body (Ahmed et al., 1984; Brackston et al., 2016; Guilmineau, 2018; Venning et al., 2022; and Liu et al., 2021), the Windsor body (Howell, 1993; Pavia et al., 2018; and Haffner et al., 2022), and the Lorry model (Dalla Longa et al., 2019) have been used to study the flow characteristics around on-road vehicles. Although these models are simplified, the wake flow generated around them allows researchers to analyze the fundamental aerodynamic characteristics of an on-road vehicle without the added complexity caused by the detailed body shape. A schematic of the Ahmed body, which is the most widely studied vehicle model, is shown in Fig. 4.1a. The original Ahmed body has dimensions of

$L = 1044$ mm length, $H = 288$ mm height, and $B = 389$ mm width. It also consists of four cylindrical legs with $C = 172$ mm in height, a rounded leading edge, and a slanted trailing edge, with an angle of α . Since the leading edge of the Ahmed body has a round shape, the major flow structure in the wake region is produced by the rear slanted edge (Ahmed et al., 1984).

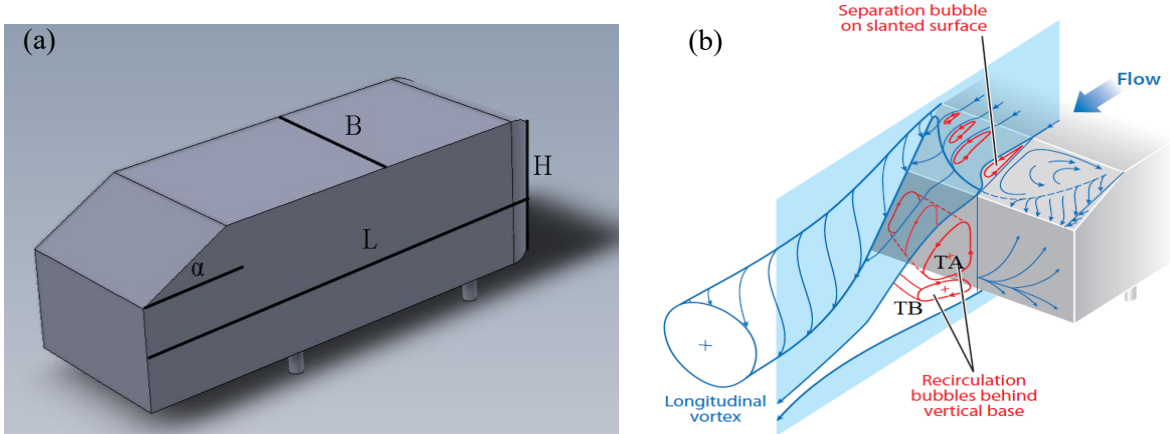


Figure 4.1 (a) Picture of Ahmed body, and (b) Illustration of time-averaged near wake structure on a slanted surface. The figure is redrawn from Choi et al. (2014)

Previous numerical and experimental investigations showed that the wake region consists of a recirculation bubble over the slanted edge; a pair of counter-rotating vortices, named C-pillar vortices that are shed from the side edges of the body, and a recirculation torus behind the vertical base (Krajnović, 2014; Vio et al., 2005; and Choi et al., 2014). The recirculation torus consists of two counter-rotating separation bubbles (bubbles TA and TB) separating from the top and bottom surfaces (Fig. 4.1b). The induced aerodynamic drag is dependent on the interactions of these coherent structures in the wake. For instance, the study of Beaudoin & Aider (2008) demonstrated that installing lateral flaps around the rear slant of the Ahmed body decreased the drag by 17.7 % due to the modification of the C-pillar vortices. Previous studies also showed that these interactions strongly depend on parameters such as rear slant angle, aspect ratio, ground clearance, Reynolds number, turbulence level, and yaw angle (Ahmed et al., 1984; Tunay et al.,

2014; Venning et al., 2022; Grandemange et al., 2013a; Thacker et al., 2010; Aleyasin et al., 2021; and Bello-Millán et al., 2016).

Ahmed et al. (1984) conducted the first comprehensive experiments on an Ahmed body and analyzed the effect of the slanted angle on the wake structure behind the body at a Reynolds number of $Re_L = 4.29 \times 10^6$ (based on the model length). The slant angle was varied from $\alpha = 0^\circ$ to 40° . The results indicated that the minimum and maximum drag coefficients occur at $\alpha = 12.5^\circ$ and 30° , respectively. For $\alpha = 12.5^\circ$, the flow tended to be two-dimensional (except in the regions near C-pillar vortices) as was evident from the parallel isobars of static pressure running across the surface. It was also observed that increasing the slanted edge from $\alpha = 5^\circ$ to 25° reduced the length of the recirculation bubble from $L_r/H = 0.20$ to 0.40 .

More recent studies focused on square-back Ahmed bodies ($\alpha = 0^\circ$) (Plumejeau et al., 2019; Fan et al., 2020; and Chen et al., 2023) and slanted-back bodies, especially with $\alpha = 25^\circ$, which is representative of common fastback cars (Minguez et al., 2008; Evstafyeva et al., 2017; and Chovet et al., 2020). The latter case has received considerable research interest as this configuration presents a complex combination of the flow with a high drag level (Thacker et al., 2013). Researchers have addressed the different flow specifications around these types of Ahmed bodies. A summary of some relevant previous studies on the wake flow characteristics around Ahmed bodies is provided in Table 4.1 and is reviewed in more detail herein. The study by Easanesan et al. (2020) on a square-back Ahmed body showed that two quasi-symmetric separation bubbles form in the wake region of the body. Rodriguez et al. (2017) observed that the length of the recirculation bubble changes from $L_r/H = 1.38$ to 1.45 as Reynolds number increased from $Re = 4.95 \times 10^4$ to 5.30×10^5 . Easanesan et al. (2020) also reported that the wake region was associated with a cluster of peaks in the range of dominant shedding frequency (based on the height of the

model and freestream velocity, $St = fH/U_\infty$) $St = 0.10$ to 0.30 , at $Re = 2.0 \times 10^4$, indicating no regular periodic activity in this region. A similar wake topology was observed in the wake region of the square-back Ahmed body mounted in a thick boundary layer approaching flow (Aleyasin et al., 2021). However, the separation bubble formed due to the underbody flow deflected upward, which is indicative of the higher upwash flow compared to the downwash in the wake region. The wake flow was also characterized by a distinct peak of $St = 0.163$ at $Re = 2.26 \times 10^4$. The wake topology behind Ahmed body is also affected by wall proximity. Grandemange et al. (2013a) examined the flow characteristics for ground clearance of $C_g/B = 0$ to 1.0 . It was observed that for $C_g/B < 0.05$, the flow that passes from the underbody is damped so that only one recirculation bubble is formed near the trailing edge of the body, while two recirculation bubbles are produced in the case of high ground clearance ($C_g/B > 0.09$). Bi-stability of the wake, which leads to one-sided shedding in the lateral or upward and downward directions in the wake region of the square-back Ahmed body, was reported by Grandemange et al. (2012). The laminar simulations of Evstafyeva et al. (2017) also showed that the wake is symmetric at $Re = 340$ but becomes oscillatory at $Re = 410$ to 430 and bifurcates to the lateral direction. It was also found that the sign of this behaviour on the velocity spectra is the presence of a low-frequency domain with a timescale on the order of $10^3 H/U_\infty$ (Grandemange et al., 2013b).

Table 4.1 Summary of previous studies on the wake flow characteristics around the Ahmed body

Researchers	Slant angle	Re	Methodology
Ahmed et al. (1984)	0° to 40°	1.18×10^6	Ten-hole directional Probe, scanivalve, strain gauge balance
Grandemange et al. (2012)	0°	340 and 410	PIV, flow visualization
Grandemange et al. (2013a)	0°	4.50×10^5	Wall pressure measurements, PIV
Grandemange et al. (2013b)	0°	9.20×10^4	Wall pressure measurements, PIV
Rodriguez et al. (2017)	0°	4.95×10^4 to 5.30×10^5	LDV

Evstafyeva et al. (2017)	0°	310, 415 and 435	CFD (LES)
Easanesan et al. (2020)	0°	2×10^4	PIV
Aleyasin et al. (2021)	0°	2.26×10^4 and 2.37×10^4	PIV
Zampogna & Boujo (2022)	0°	150, 250, 350 and 450	CFD (RANS)
Minguez et al. (2008)	25°	8300	CFD (LES)
Thacker et al. (2012)	25°	1.93×10^5 and 1.04×10^6	Hot-wire, PIV
Joseph et al. (2011)	25°	3.86×10^5 and 7.72×10^5	Hot-wire
Thacker et al. (2013)	25°	6.06×10^5	Hot-wire, PIV
Tunay et al. (2014)	25°	1.50×10^4	PIV
Zhang et al. (2015)	25°	3.80×10^4 to 2.05×10^5	Hot-wire, PIV
Wang et al. (2013)	25° and 35°	0.53×10^5	PIV
Liu et al. (2021)	35°	2.57×10^4 to 2.30×10^5	Hot-wire, PIV, flow visualization

Previous research also indicated the formation of different wake topologies and dominant frequencies around the slanted-back compared to the square-back Ahmed bodies. Thacker et al. (2012) investigated the behaviour of the separation region over the rear slanted surface of the Ahmed body with $\alpha = 25^\circ$. The results showed that the Strouhal number (based on the frontal surface area, St_A) increased from $St_A = 0.22$ to 0.25 as the Reynolds number increased from $Re_L = 1.40 \times 10^6$ to 2.80×10^6 . This increase in dominant frequency with Reynolds number was confirmed by Joseph et al. (2011), who also noted that, over the slant surface, the dominant Strouhal number increases from $St_L = 0.1$ to 0.14 when the Reynolds number increases from $Re_L = 1.48 \times 10^6$ to 2.70×10^6 . This frequency was ascribed to the flapping motion of the shear layer emanating from the upper surface of the slanted surface. Recently, Liu et al. (2021) carried out an experimental study of the unsteady coherent structures on a low-drag Ahmed body with $\alpha = 35^\circ$ for $Re_A = 0.30 \times 10^5$ to 2.70×10^5 . The dominant frequency in the wake region was $St = 0.30$, and nearly independent of the Reynolds number. On the contrary, the dominant frequency on the roof and the side surface of Ahmed body increased from $St = 0.20$ to 0.32 as Re_A increased from 0.30×10^5 to 2.70×10^5 . The Reynolds number independence of the Strouhal number in the wake region is, however, at variance with Zhang et al. (2015), who investigated the flow structure behind the

high-drag Ahmed body with $\alpha = 25^\circ$ and concluded that the dominant vortex shedding frequency in the wake region increased from $St_A = 0.40$ to 0.54 as Reynolds number increased from $Re_A = 0.45 \times 10^5$ to 2.40×10^5 . Thus, it can be concluded that there is a difference in the impact of the Reynolds number on the temporal flow features for the low and high-drag regimes. Furthermore, while unsteady flow structures were observed above the roof for $Re_A = 0.62 \times 10^5$ ($St_A = 0.14$), no dominant frequency was observed near the leading edge of the body over the roof and side surfaces for $Re_A > 1.0 \times 10^5$ due to the disappearance of the pulsation of the separation bubble near the lateral surfaces of the leading edge. It was also reported that the length of the recirculation bubble behind Ahmed body varied between $L_r/H = 0.54$ to 0.67 for $Re = 1.48 \times 10^4$ to 5.3×10^4 (Wang et al., 2013; Tunay et al., 2014; and Rodriguez et al., 2017).

There is only a handful of research regarding the effect of leading-edge geometry on flow structures around the Ahmed body. Easanesan et al. (2020) conducted a particle image velocimetry (PIV) experiment to study the effects of leading-edge geometry on flow characteristics behind a square-back Ahmed body. To this end, rounded and elliptical noses with a 3:1 length ratio were examined at $Re = 2 \times 10^4$. Behind the body with the elliptical leading edge, a symmetrical wake with two recirculation bubbles of comparable size was observed. However, the wake region behind the rounded edge of the Ahmed body showed a degree of asymmetry, and the wake was dominated by the upper shear layer. Analysis of the time-dependent flow also showed evidence of a dominant Strouhal number, $St = 0.25$ for the elliptical-nosed body, while there was a cluster of smaller peaks in the range of $St = 0.1$ to 0.3 , with the highest peak occurring at $St = 0.22$ for the rounded-edge body. The effect of the leading-edge geometry on flow characteristics around a square-back Ahmed body and a cuboid at $Re = 2.26 \times 10^4$ was also investigated by Aleyasin et al. (2021). It was shown that while a large recirculation bubble appeared in the vicinity of the cuboid leading-

edge, no distinct recirculation bubble was observed over the Ahmed body. In addition, the wake structures behind these two bodies were quite different. For instance, two recirculation bubbles of roughly the same size were observed in the wake region of Ahmed body, but one recirculation bubble formed on the lower side of the trailing edge and another one formed farther from the cuboid. This change was attributed to the lower flow momentum under the surface of the cuboid. It was also observed that behind the Ahmed body, a dominant frequency of $St = 0.163$ was observed, while three dominant frequencies of $St = 0.217$, 0.271 , and 0.325 were reported behind the cuboid case. This was attributed to the significant interaction of shear layers behind the cuboid compared to the Ahmed body, which changed the regular vortex shedding behaviour. Recently, Zampogna & Boujo (2022) numerically studied the effect of leading-edge shape and body length on the flow characteristics in the wake region of the square-back Ahmed body. The main finding of this study was that rounding the leading-edge suppressed the side recirculation bubble that forms in the vicinity of the body. It was also reported that shorter bodies are more affected by changing the leading-edge shape, and the wake flow behind the rounded leading-edge body is shorter and narrower compared to the sharp leading-edge body. To the best of our knowledge, there has been no systematic study on the effects of the leading edge on the flow structure around the slanted-back Ahmed body. As such, several questions remain unanswered. For instance, how does the dominant shedding frequency shift from the leading-edge to the downstream region of the body? Also, the role of the leading-edge shape in this behaviour is unclear at this moment. What is the effect of the shear layer arising from the leading-edge on the flow dynamics in the wake region? Thus, the objectives of the present study are to investigate the effects of the leading edge on the spatiotemporal characteristics of vortical structures originating from the leading and trailing edges of the Ahmed body. The study was performed using a PIV system. Two different configurations,

rounded and square leading edges, were implemented to examine the effects of leading-edge shape on the flow behaviour around the body, and the measurements were carried out at two Reynolds numbers of $Re = 0.17 \times 10^5$ and 0.36×10^5 . This Chapter is organized as follows: The experimental setup is described in Section 4.3. Section 4.4 presents the experimental results regarding the effect of leading-edge shapes. The conclusions are also made in section 4.5.

4.3 Experimental Procedure

4.3.1 Test Conditions

The experiments were carried out in an open recirculating water channel in the Turbulence and Hydraulic Engineering Laboratory (THEL) at the University of Manitoba. The schematic of the experimental setup is shown in Fig. 4.2. The length, width, and height of the test section are 6000 mm, 600 mm, and 450 mm, respectively. The test section was fabricated from 31.8 mm thick Super Abrasion Resistant (SAR) transparent acrylic plates to facilitate optical access. Water was circulated by an impeller pump, and the flow rate was controlled by a 30 kW variable speed motor. The water channel is equipped with a settling chamber fitted with perforated steel plates, a honeycomb arrangement, mesh screens, and a 4.88:1 converging section to break down the large-scale turbulence before entering the test section of the channel.

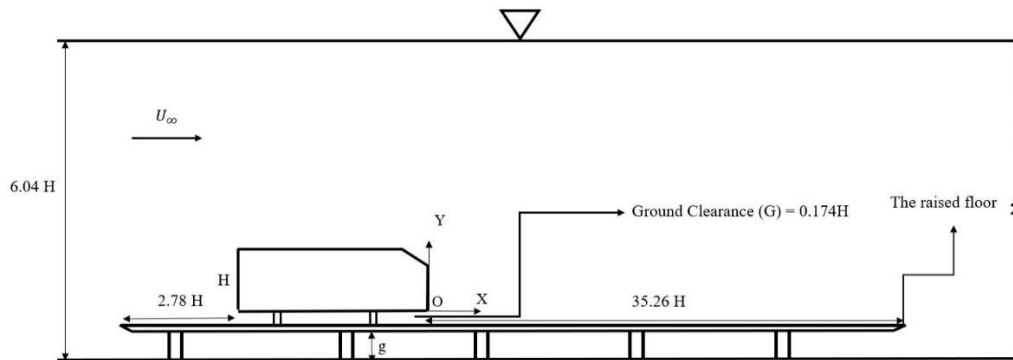


Figure 4.2 Schematic of the experimental setup

The Ahmed body model is a quarter of the original Ahmed body studied by Ahmed et al. (1984). As shown in Fig. 4.3, the bodies have an overall length of $L = 261$ mm, a width of $B = 97.25$ mm, and a height of $H = 72$ mm, supported by four cylindrical struts of $C = 12.5$ mm in height and $d = 7.5$ mm in diameter.

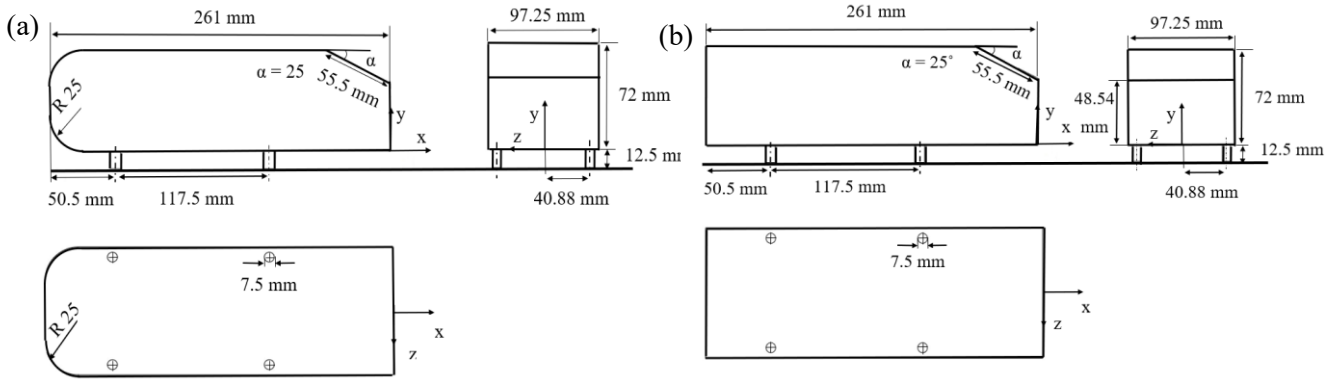


Figure 4.3 Bluff body geometry: (a) Round nose leading edge, and (b) Square edge leading edge

The bodies were placed on a raised plate of $3000 \text{ mm} \times 590 \text{ mm} \times 9 \text{ mm}$ (length $\times$ width $\times$ thickness), which was installed horizontally and 50 mm above the floor of the test section. Following Grandemange et al. (2013a), the leading and trailing edges of this plate have a sharp-edge shape with an angle of 45° to avoid flow separation. The front end of the bluff bodies was placed 200 mm downstream of the leading edge of the plate. The x-coordinate is in the streamwise direction, while the y-coordinate is aligned with the wall-normal direction, and the z-axis shows the spanwise direction (Fig. 4.3). Measurements were carried out at $Re = 0.17 \times 10^5$ and 0.36×10^5 by setting the freestream velocity to $U_\infty = 0.24$ (m/s) and 0.50 (m/s), respectively. The water height was adjusted to 435 mm, which led to the blockage ratio (the ratio between the frontal area and the rectangular cross-stream area of the water column) of 3%. This is less than the suggested limit of 5%, beyond which the blockage effect cannot be neglected (Farell et al., 1977). The

maximum value of the Froude number, $Fr = (U_{\infty} / \sqrt{gD})$, is 0.25 and indicates that the effects of surface waves on the flow around the bodies are negligible (Munson et al., 2013).

4.3.2 PIV Measurement Procedure

Both double-frame and time-resolved PIV techniques were implemented to characterize the flow field. The flow was seeded with 10 μm silver-coated hollow glass spheres with a specific gravity of $\rho_p = 1.4$. The Stokes numbers were estimated as $S_k = 0.73 \times 10^{-5}$ and 1.55×10^{-5} for $Re = 0.17 \times 10^5$ and 0.36×10^5 , respectively, which are less than the recommended value of $S_k = 0.05$ proposed by Samimy & Lele (1991) for the particles to reliably follow the flow motion. The flow field was illuminated by a Photonics DM30 - 527DH dual-cavity dual-head high-speed Neodymium-doped yttrium lithium fluoride (Nd: YLF) laser that emits green light of wavelength 527 nm at a maximum energy output of 30 mJ/pulse for each laser at a frequency of 10000 Hz. Measurements in the x-y plane were performed at the mid-span of the bodies, namely, the laser was positioned above the water channel, and measurements were performed at $z/H = 0$ (symmetry plane). For the x-z plane measurements, the laser was shot through the sidewall of the channel, and measurements were performed at mid-height, $y/H = 0.59$, of the models. The laser was used to illuminate the seeding particles, and 12-bit complementary metal-oxide semiconductors (CMOS) cameras captured the particle images. The cameras were operated at their full resolution, 2560 pixels $\times$ 1600 pixels. In the x-y plane, two cameras, each with a field of view (FOV) of 288 mm $\times$ 180 mm (4 H $\times$ 2.50 H) with an overlap of 10 mm, were used. They were positioned side-by-side on a traverse system to measure the flow field upstream and downstream of the bluff bodies. For the x-z plane measurements, the measurements were performed using two cameras, each with a FOV of 277 mm $\times$ 173 mm (3.84 H $\times$ 2.40 H). For the double-frame data collection,

a total of 12000 image pairs were captured for each FOV, while for the time-resolved measurement, the sampling frequency was $f_{sp} = 806$ Hz, and a total of 60000 images were captured in each FOV. The data acquisition was controlled using commercial software (DaVis version 10.0.5) supplied by LaVision Inc. The velocity vectors were calculated using a GPU-accelerated multi-pass cross-correlation algorithm with an initial interrogation window of $128 \text{ pixels} \times 128 \text{ pixels}$ with 50% overlap and a final interrogation window of $24 \text{ pixels} \times 24 \text{ pixels}$ with 75 % overlap using four passes, leading to vector spacing of $0.009 H$ in each direction. Analysis and post-processing of raw data were performed using an in-house MATLAB code. The instantaneous velocity component is decomposed into mean and fluctuating components according to the Reynolds decomposition: $u = U + u'$, where U and u' indicate the time average and fluctuation velocity, respectively. An asterisk is used to denote the normalization of velocities with freestream velocity, U_∞ , and of lengths with Ahmed body height, H e.g., $x^* = x/H$, $y^* = y/H$, and $z^* = z/H$. Hereafter, the square-leading-edge and rounded leading-edge bodies will be denoted by SL and RL cases, respectively.

4.3.3 Uncertainty Estimation

Measurement uncertainties at a 95% confidence level for the mean velocity and Reynolds stresses at their respective peak locations were calculated following the procedure outlined in Sciacchitano & Wieneke (2016) and Bendat & Piersol (2011). In this study, time-averaged data collected using double-frame measurement were used for presenting mean velocity, Reynolds normal, and shear stress plots. The estimated uncertainties for the mean velocity, Reynolds normal, and shear stresses for double-frame measurements are less than $\pm 1.5 \%$, 2.5% , and 2% of their peak values, respectively.

4.4 Results and Discussion

4.4.1 Characteristics of Approach Flow

The boundary layer approaching the body plays an important role in the flow structure around finite-height bluff bodies like Ahmed body (Wang et al., 2006; Kang et al., 2021). Following Joseph et al. (2011), the incoming boundary layer profile was measured 0.2 m downstream from the raised floor's leading edge, in the absence of the bodies. The boundary layer thickness based on 99% of the freestream velocity at the location of the front of the body is $\delta/H = 0.63$ and 0.54 for $Re = 0.17 \times 10^5$ and 0.36×10^5 , respectively. Therefore, the model height is located outside of the TBL thickness. Figures 4.4a-d show profiles of the mean streamwise velocity, Reynolds stresses, and turbulence intensities for the approach boundary layer.

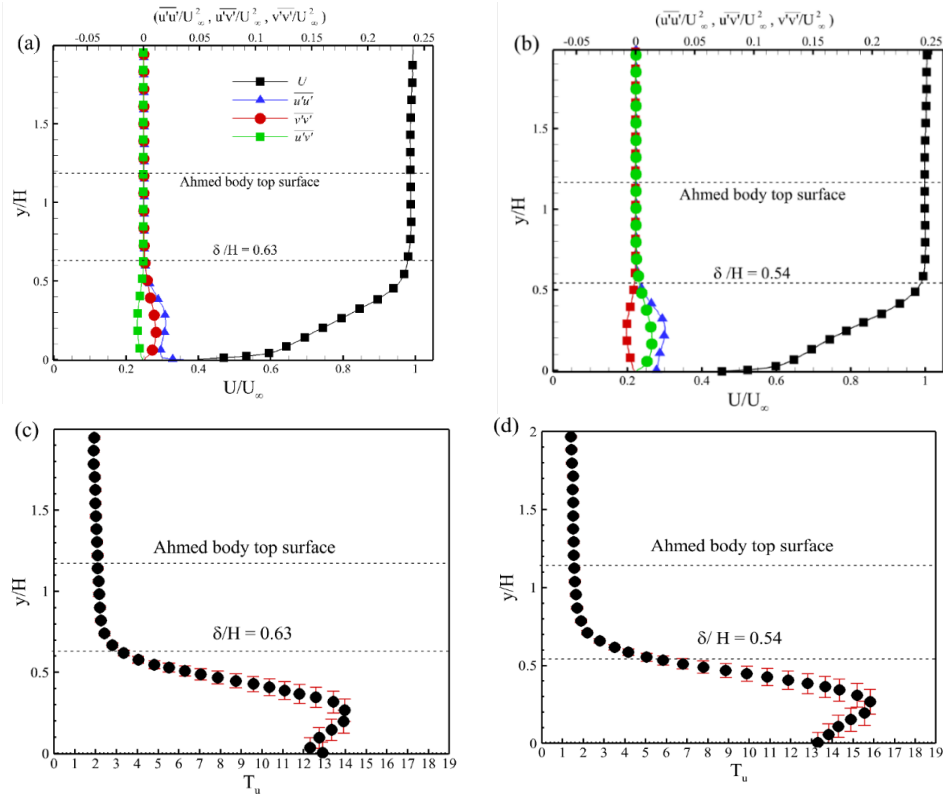


Figure 4.4 Vertical profiles of approach boundary layer (a) time-averaged streamwise velocity and (b) Reynolds stresses and (c) and (d) Turbulence intensity for a, c) $Re = 0.17 \times 10^5$, b, d) $Re = 0.36 \times 10^5$.

The vertical lines in figures (c) and (d) represent the uncertainty

4.4.2 Flow Characteristics in the x-y Plane

4.4.2.1 Mean Velocity and Shear Layer

In this section, the mean flow characteristics in the x-y plane at $z^* = 0$ of the bodies are presented. Figure 4.5 shows the normalized mean streamwise velocity (U^*) superimposed by the mean streamlines (solid lines). In all cases, three distinct recirculation bubbles are formed and labeled with the letters LE, TA, and TB. The recirculation bubble LE forms due to the flow deflection near the leading edge of the bodies, while bubbles TA and TB are formed because of the interaction of the shear layers emanating from the top of the slanted edge and under the surface of the body (Ahmed et al., 1984). While flow separation is fixed at the leading edge ($x^* \approx -3.64$) on the square leading body, flow detachment occurs at the end of the nose of the rounded leading edge, specifically, at $x^* \approx -3.27$ and $x^* \approx -3.31$ for $Re = 0.17 \times 10^5$ and 0.36×10^5 , which is within the range of $-3.5 < x^* < -3.0$ reported by Grandemange et al. (2013a) for $Re = 9.20 \times 10^4$. Reattachment on the surface, which is associated with pressure recovery, occurs at $x^* \approx -2.42$ and -2.52 on the top face of the RL body at $Re = 0.17 \times 10^5$ and 0.36×10^5 , respectively. These values are comparable to $x^* = -2.60$ reported by Minguez et al. (2008). It is noted that the length of bubble LE near the top face of the RL body is $0.87H$ and $0.79H$ for $Re = 0.17 \times 10^5$ and 0.36×10^5 , respectively, the latter being in good agreement with a value of $0.7H$ measured by Minguez et al. (2008) at $Re = 7.68 \times 10^5$. Meanwhile, the reattachment points for the SL case occur at $x^* = -1.74$, for both Reynolds numbers. In the SL case, two recirculation bubbles formed near the leading edge: a primary recirculation bubble with a normalized core height of 0.3 and a secondary recirculation bubble that formed at the very beginning of the leading edge (insert in Figs. 5a and 5b). The streamwise position and height of the primary recirculation bubble are the same for both Reynolds numbers. In contrast, for the RL body, the foci point shifts toward the leading edge (from $x^* = -2.80$ to -2.95 and closer to the wall as the Reynolds number increases from 0.17×10^5 to

0.36×10^5 . This shows that increasing the Reynolds number in the RL case suppressed the bubbles and led to the shrinkage of the recirculating bubble. Thus, the characteristics of bubble LE depend on both the Reynolds number and curvature of the leading edge. The reason for the presence (absence) of the secondary recirculation bubble in the vicinity of the SL (RL) case can be related to the presence (absence) of the strong adverse pressure gradient near the leading edge of sharp (round) edge bodies.

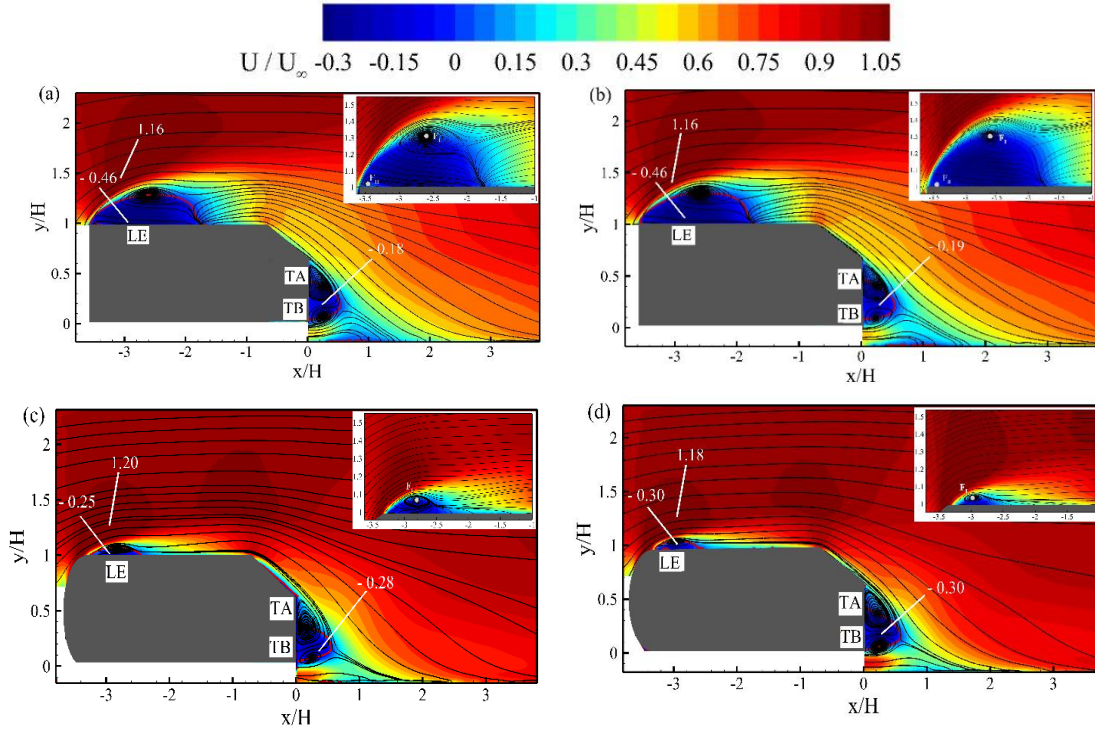


Figure 4.5 Contours of normalized streamwise mean velocity superimposed by time-averaged streamlines for SL body at (a) $Re = 0.17 \times 10^5$ and (b) $Re = 0.36 \times 10^5$ and RL body at (c) $Re = 0.17 \times 10^5$ and (d) $Re = 0.36 \times 10^5$. Solid red lines show the recirculation bubble

The presence of such a small recirculation bubble was also observed by Minguez et al. (2008) and Franck et al. (2009), but not in Aleyasin et al. (2021), due to the higher freestream turbulence intensity ($T_u = 7\%$) of the approaching flow. Indeed, previous studies showed that high turbulence intensity tends to suppress flow separation near the leading edge of the body (Conan et al., 2011; Zhang et al., 2015).

One of the key important parameters that modifies the aerodynamics around the Ahmed body is the reverse flow region behind the bodies (Wang et al., 2013). The reverse flow area can be identified by the area enclosed by the isopleth $U^* = 0$. In the near wake of bodies, the recirculation length (L_r^*), which is defined as the maximum longitudinal length of $U^* = 0$, is $L_r^* = 0.53$ for the SL cases, and independent of Reynolds number. For RL cases, the recirculation lengths are $L_r^* = 0.55$ and 0.58 for $Re = 0.17 \times 10^5$ and 0.36×10^5 , respectively. The value of the recirculation bubble for $Re = 0.17 \times 10^5$ is in good agreement with previous experimental results (Table 4.2).

Table 4.2 Comparison of the recirculation length with previous studies

Authors	Re	L_r^*
Present study (SL)	1.70×10^4	0.55
Present study (RL)	1.70×10^4	0.58
Tunay et al. (2014)	1.48×10^4	0.54
Rodriguez et al. (2017)	4.95×10^4	0.57
Wang et al. (2013)	5.30×10^4	0.67
Liu et al. (2021)	14.60×10^4	0.55

This difference in recirculation length in RL and SL cases mostly comes from the larger bubble TA in the RL case than in the SL case. A second reverse flow area is also observed in the streamwise location of $0.3 < x^* < 1.5$ in the vicinity of the wall behind the SL case, which is less conspicuous in the RL cases. The presence of this wake region is consistent with the observation made by Grandemange et al. (2013a), Lucas et al. (2017), and Zhang et al. (2022), who related its presence to the momentum of the underflow body. Since the velocity of underbody flow in the RL case is higher than in the SL case, it can suppress boundary layer separation that forms due to the adverse pressure gradient on the floor, leading to a smaller reverse flow area near the wall. To study the effect of the leading-edge shape on the C-pillar vortices and downwash flow in the wake

region of the body, a comparison of downwash strength, S_D , between the SL and RL cases is provided in Fig. 4.6. Following Li et al. (2022), the difference between downwash and upwash strength is defined as the integral of wall-normal momentum as follows:

$$S_D(y^*) = \int_{x_{start}}^{+\infty} [V^*(x^*, y^*)]^2 dx^* \quad (4.1)$$

The integration covers the wake region and starts from $x^* = 0$ to 3. As shown in Fig. 4.6, the values of S_D collapse reasonably well for $y^* > 0.7$, and the maximum value of $S_D = 0.33$ appears at $y^* = 0.23$ for the RL body at $Re = 0.17 \times 10^5$. It can also be inferred that increasing the Reynolds number decreases the S_D , irrespective of leading-edge shape. For instance, the value of S_D in the RL case $Re = 0.36 \times 10^5$ is $S_D = 0.31$, which is 9.67 % lower than the corresponding value for the lower Reynolds number. The maximum S_D in this case, it occurs at a higher wall-normal location than at the lower Reynolds number, i.e., $y^* = 0.29$. However, the maximum downwash and upwash strength difference for the SL case occurs at a higher elevation, $y^* = 0.40$. The figure also shows that the maximum S_D decreases by roughly 50% as the leading-edge shape changes from round to square. According to Venning et al. (2015), higher downwash flow increases the possibility of flow reattachment over the slant of the body and increases C-pillar vorticity strength.

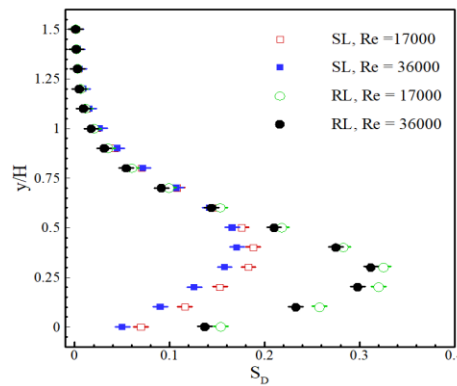


Figure 4.6 Comparison of the difference between downwash and upwash strength (S_D) in the wake region. The horizontal line represents error bars.

Following Kang et al. (2021) and Veerasamy et al. (2022), the vorticity thickness, which is formulated in equation 4.2, is used to characterize the effects of leading-edge shape on the separated shear layers from the leading edge.

$$\delta_\omega = (U_{\max} - U_{\min}) / \left(\frac{\partial U}{\partial y} \right)_{\max} \quad (4.2)$$

In equation 4.2, $U_{\max}$ and $U_{\min}$ are, respectively, the local maximum and minimum mean streamwise velocities in the shear layer at a given streamwise location. Figure 4.7a examines the streamwise evolution of velocity deficit $\Delta U_{\max} = U_{\max} - U_{\min}$ along the separated shear layer. For SL cases, the value of the velocity difference is independent of Reynolds number. The maximum value of the velocity difference for these cases occurs at $x^* = -2.75$, which corresponds to the location of the focal point of the main recirculation bubble. A similar observation was made by Nematollahi & Tachie (2018), who studied turbulent flow over the forward-facing step (FFS).

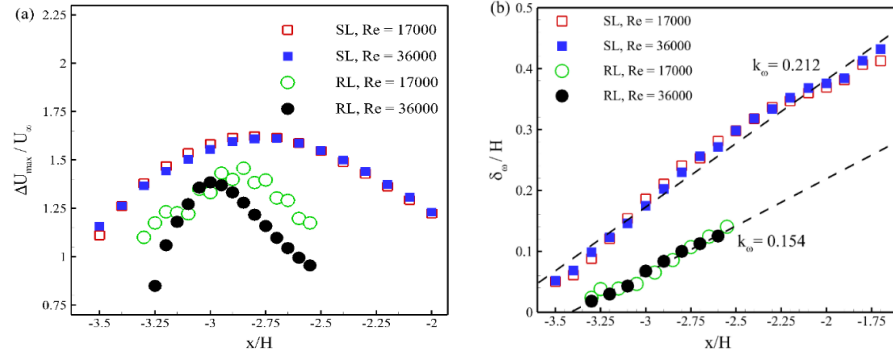


Figure 4.7 Streamwise development of (a) the velocity deficit, and (b) vorticity thickness

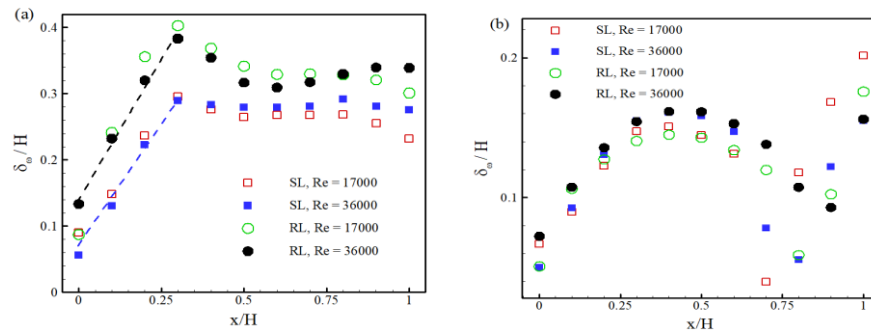


Figure 4.8 Streamwise development of vorticity thickness for upper shear layer (a) and lower shear layer (b) in the wake region

The streamwise evolution of vorticity thickness for SL and RL for both Reynolds numbers is plotted in Fig. 4.7b. These plots show that the vorticity thickness ($\delta_\omega^* = \delta_\omega/H$) along the recirculation bubble is Re-independent. It is also linear with respect to streamwise distance, which is consistent with the observation made for the 2D mixing layer by Bonnet et al. (1998) as well as wall-mounted bluff bodies (Nematollahi & Tachie, 2018). Based on the figure, a thicker shear layer emanated from the leading edge of the SL bodies compared to the RL cases. The linear growth rate of the vorticity thickness, $k_\omega = d\delta_\omega/dx$ is estimated to be 0.212 and 0.154 for SL and RL cases, respectively, indicating a 37% increase in the growth rate for the SL case compared to the RL case, and this can be attributed to the higher value of $\Delta U_{\max}$ in SL cases. Nonetheless, the growth rates for RL and SL cases are within the range of $k_\omega = 0.14$ to 0.22 reported for a plane mixing layer by Brown & Roshko (1974), 0.15 to 0.30 for wall-mounted bluff bodies (Agelinchaab & Tachie, 2008; and Fang & Tachie, 2019), and for the RL case within the values of 0.11 to 0.18 reported by Rahman et al. (2018) and Essel et al. (2021) for free shear flow.

The streamwise evolution of the vorticity thickness of the shear layer emanating from the slanted surface and the base (referred to as the upper shear layer and lower shear layer, respectively) is provided in Fig. 4.8. Figure 4.8a clearly shows that a shear layer with higher vorticity thickness is induced from the slanted surface of the RL case than that of the SL body. This higher vorticity thickness can be attributed to the higher downwash strength behind the RL case. However, in both cases, the increase in vorticity thickness is persistent till $x/H = 0.3$, where, after this location, the vorticity thickness experiences a plateau. In terms of the Reynolds number effect, while there is a small increase in vorticity thickness with the Reynolds number in the SL case, the RL case does not follow a regular trend. Figure 4.8b shows that the lower shear layer thickness keeps increasing till $x/H = 0.5$, and the higher thickness is related to the RL case with $Re = 0.36 \times 10^5$. This higher

vorticity thickness value for the RL case is likely due to the high gap flow momentum, which induces higher vorticity thickness compared to the other cases.

4.4.2.2 Reynolds Stresses

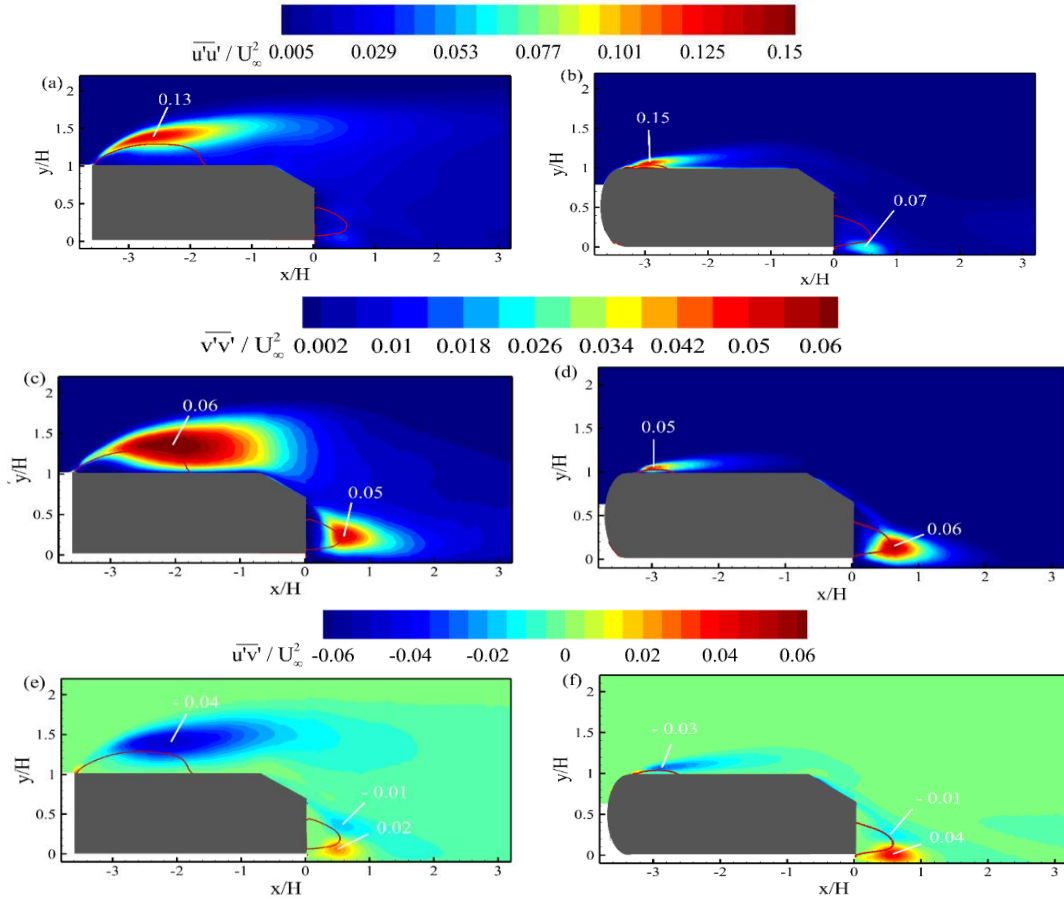
Figures 4.9a and 4.9b show the contours of the normalized streamwise Reynolds normal stress, $\overline{u'u'}^*$ for both RL and SL cases at $Re = 0.36 \times 10^5$. The red solid lines in these figures encompass the recirculation bubbles. The values of maximum stress for the shear layer emanating from the leading edge are 0.13 and 0.15 for SL and RL, respectively. Furthermore, the position of maximum occurs at $(x^*, y^*) = (-2.61, 1.38)$ and $(x^*, y^*) = (-2.93, 1.06)$ for SL and RL cases, respectively. This shows that rounding the leading edge can shift the position of the shear layer closer to the leading edge and closer to the body roof. The value of streamwise normal stress in the wake region of the RL case is higher than that of the SL case, as the momentum of underbody flow and downwash flow is higher for the RL case, which leads to higher flow interaction in the wake region. The contours of wall-normal Reynolds normal stress, $\overline{v'v'}^*$, for SL and RL cases, are provided in Figs. 4.9c and 4.9d, respectively. A thicker cluster of wall-normal Reynolds stress with a maximum value of $\overline{v'v'}^* = 0.06$ is formed over the SL case, compared to the RL case, which signifies the effect of leading-edge sharpness on the vertical component of Reynolds stresses. While the maximum value of $\overline{v'v'}^*$ in the SL case, the value is lower than that of the RL case ($\overline{v'v'}^* = 0.05$ and 0.06 , respectively), the former encompasses a larger area behind the body. Figures 4.9e and 4.9f show the contours of the normalized Reynolds shear stress $\overline{u'v'}^*$ around the two bluff bodies. Near the leading edge of the body, the maximum value of shear stress in the RL case is less than in the SL case. However, the opposite occurs downstream of the body. It is noted that the distribution and maximum value of shear stress are identical for both SL cases. The maximum

value of shear stress behind the body occurs near the bubble TB, and it is related to the periodic motions of the upper and lower bubbles (Liu et al., 2021). The maximum value of shear stress in the near wake region of the RL body is $\overline{u'v'}^* = 0.02$, at $Re = 0.36 \times 10^4$. This value is consistent with the value of shear stress observed by Siddiqui & Agelin-Chaab (2022), who reported $\overline{u'v'}^* = 0.03$ at $Re = 4.30 \times 10^4$.

Figures 4.9g and 4.9f also represent the contours of turbulent kinetic energy (TKE) around the bodies, which is estimated as:

$$TKE = \frac{1}{2} (\overline{u'u'}^* + \overline{v'v'}^*) \quad (4.3)$$

Near the leading edge and in the wake region, the value of maximum turbulent kinetic energy is higher in the RL than in the SL cases.



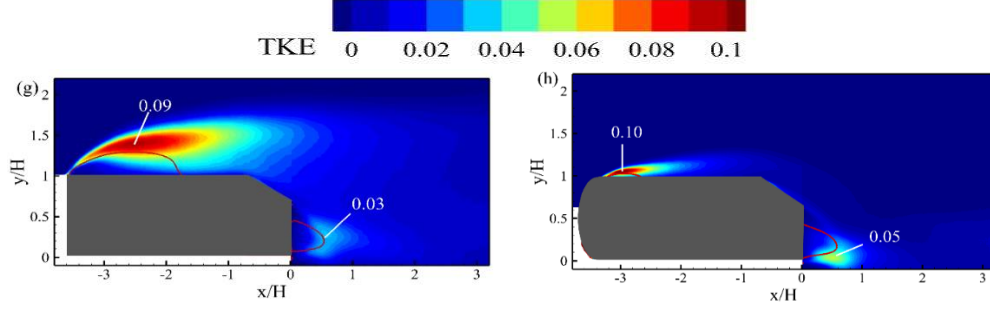


Figure 4.9 Contours of streamwise Reynolds normal stress [(a) and (b)], wall-normal Reynolds normal stress [(c) and (d)], Reynolds shear stress [(e) and (f)], and turbulent kinetic energy [(g) and (h)] at $Re = 0.36 \times 10^5$. Solid red lines show the recirculation bubble

The main reason for the higher turbulent energy downstream of the RL case can be attributed to the stronger downwash flow and the fact that rounding the bottom leading edge induces a significant increase in the flow between the raised floor and the Ahmed body, as shown by Figs. 4.5 and 4.6 in this case.

4.4.2.3 Turbulent Structures

To assess the large-scale structures around the bodies, an analysis of the two-point autocorrelation coefficient of the streamwise fluctuating velocity (R_{uu}), which provides a measure of spatial correlation of the turbulence structures (Volino et al., 2007), was performed. Figure 4.10 shows the isopleth of R_{uu} for SL and RL cases at $Re = 0.36 \times 10^5$ at six different locations, including four streamwise locations corresponding to maximum turbulent kinetic energy over the body, as well as $(x^*, y^*) = (0.40, 0.03)$ and $(0.46, 0.37)$ corresponding to the maximum turbulent kinetic energy behind the body. A very small structure is formed in the vicinity of the leading edge of both SL and RL cases. For the SL case, the structure at $x^* = -3$ is inclined $\beta = 26^\circ$ with the horizontal. As the flow evolves downstream, its spatial coherence increases, and the flow inclination angle reaches $\beta = 30^\circ$ at $x^* = -2.5$, and $\beta = 35^\circ$ at $x^* = -1.5$. The inclination angle remains unchanged as the flow passes onto the slanted surface. On the other hand, a smaller structure is formed in the vicinity of the leading edge ($x^* = -3.5$) of the RL body. Further downstream, the coherent structure

stretches over the body in the horizontal direction, and from $x^* = -2$ onward, its size remains constant as the flow passes over the slanted-back. Since the shear layer emanating from the leading edge of the RL body travels downstream closer to the body, wall confinement decreases the coherence of energetic scales, as can also be seen in Fig. 4.10c. Hence, as the contours of R_{uu} over the SL case are larger, they are associated with a larger integral time scale. In addition, the coherent structures emanating from the leading edge of the SL body have larger scales and possess higher time scales, which creates larger-scale vortices as they travel downstream.

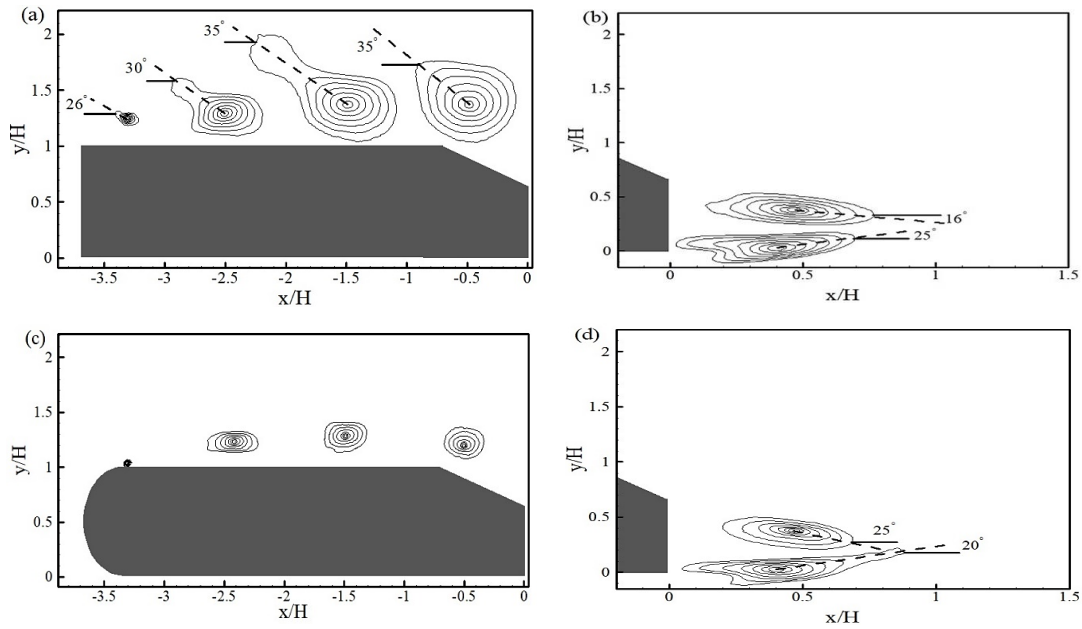


Figure 4.10 Contours of the R_{uu} over bodies along the shear layer for (a) SL, (c) RL and at $(x/H, y/H) = (0.40, 0.03)$ and $(x/H, y/H) = (0.46, 0.37)$ in wake of (b) SL, and (d) RL body. Contour levels at intervals of 0.1 are from 0.3 to 0.9

This can explain the higher growth rate of vorticity for the SL case than the RL one (Fig. 4.7b). The distribution of isopleths of R_{uu} in the wake region (Figs. 4.10b and 4.10d) shows that R_{uu} distribution for SL and RL body in the lower shear layer is inclined at 25° and 20° , respectively, while the inclination in the upper shear layer is 16° and 25° , respectively. The inclination angle of the upper shear layer for the RL body is in good agreement with $\beta = 26^\circ$ reported by Siddiqui & Agelin-Chaab (2022). It is also noteworthy that the distribution of R_{uu} in the vicinity of the leading

edge of the RL body is different from that observed by Aleyasin et al. (2021). In contrast to the present results, comparatively larger structures with an inclination of $\beta = 13^\circ$ and $\beta = 10^\circ$ were formed near the nose of the body in freestream turbulence intensity of $T_u = 4\%$ and 7% studied by Aleyasin et al. (2021), respectively. However, the spatial distribution of R_{uu} near the leading edge for the SL case is similar to that observed around the cuboid case studied by Aleyasin et al. (2021). These results suggest that upstream turbulence can strongly alter the spatial distributions of coherent structures near the leading edge of a rounded body, but not structures formed in the vicinity of the leading edge of the SL body. The R_{uu} distributions around the bodies at the lower Reynolds number are similar to their higher Reynolds number counterparts. Contours of the integral time scale near the leading edge and wake region of the bodies at $Re = 0.36 \times 10^5$ are presented in Fig. 4.11. The streamline emanating from the leading edge of the body is also superimposed (dashed line). The integral time scale (τ) at a reference location (x_{ref}, y_{ref}) is calculated by integrating the temporal autocorrelation of streamwise velocity fluctuations (u') from the time displacement (T) of zero to the point associated with the first zero correlation (T^*), as follows: (Tennekes & Lumley, 1972)

$$R(x_{ref}, y_{ref}, T) = \frac{\overline{u'(x_{ref}, y_{ref}, t)u'(x_{ref}, y_{ref}, t + T)}}{u_{rms}^2(x_{ref}, y_{ref})} \quad (4.4)$$

$$\tau = \int_0^{T^*} R(x_{ref}, y_{ref}, T) dT \quad (4.5)$$

The formation of maximum clusters of integral time scales coincides with the locations where streamwise Reynolds normal stress and turbulent kinetic energy are maximum. This behaviour is consistent with the observations made by Fang et al. (2022), who studied the shear layer characteristics beneath semi-submerged bluff bodies. In both cases, the integral time scale of bubble TB is larger than bubble TA ($\tau = 0.63$ versus $\tau = 0.59$ for SL, and $\tau = 0.87$ versus $\tau = 0.68$

for RL). The integral time scale formed near the leading edge of the body is higher in the SL case than in the RL one. For example, the maximum value of the integral time scale near the leading edge of the SL body is $\tau = 0.68$, and its location coincides with the location of the foci points within the main recirculation bubble over the body, while the maximum value for the RL case is $\tau = 0.39$, and it is located along the recirculation bubble line. Beyond the reattachment point, there is a decrease in integral time scales with increasing distance downstream, where the streamwise Reynolds normal stress also decreases. The same behaviour was observed by Castro & Haque (1987) for flow over a long splitter plate. Since the reattachment point occurs closer to the leading edge in RL compared to SL, the clusters with elevated integral time scale only persist for a short distance in the former. The extent of the region of elevated integral time scale behind the body in the wake region is also larger in the SL case than in the RL one.

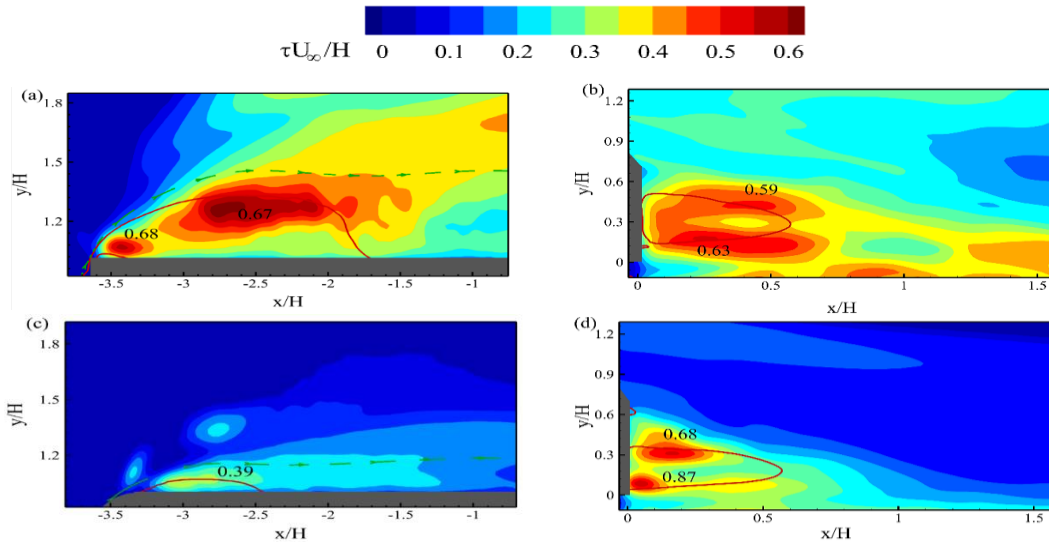
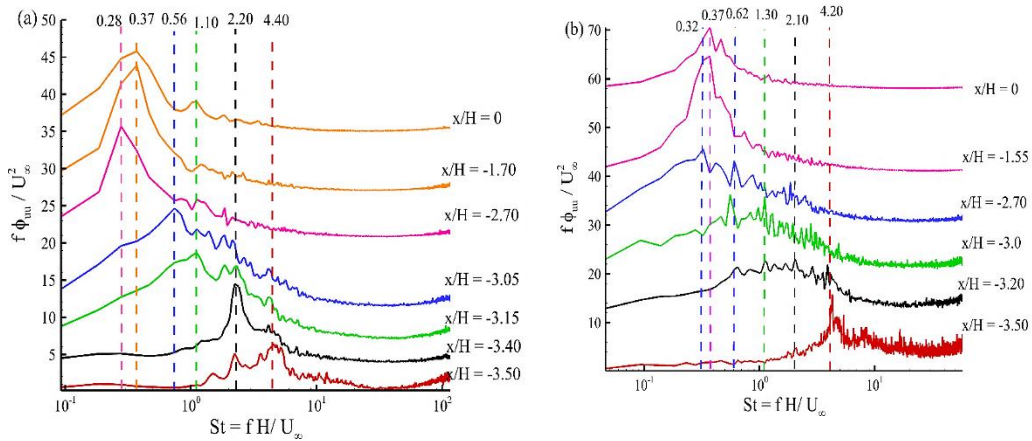


Figure 4.11 Contours of the integral time scale at $Re = 0.36 \times 10^5$ for SL body at (a) leading edge, (b) wake region, and RL body at (c) leading edge, (d) wake region. Dashed lines show the streamlines emanating from the leading edge. Solid lines show the recirculation bubbles.

4.4.2.4 Frequency Spectra

The spatiotemporal dynamics of the shear layer around the bodies are evaluated using frequency spectra of the velocity fluctuations. Figure 4.12 presents the streamwise evolution of the pre-

multiplied frequency of the streamwise fluctuating velocity (ϕ_{uu}) along the mean shear layer at the locations of maximum TKE (Moore et al., 2019; Aleyasin et al., 2021 and Fang et al., 2022). As can be seen in Fig. 4.12a for the SL body at $Re = 0.17 \times 10^5$, the first frequency of $St = 4.40$ is detected at $x^* = -3.50$, which can be attributed to Kelvin–Helmholtz (KH) instability. As the flow separates from the separation point, the velocity fluctuations are amplified along the shear layer, leading to shear layer roll-up and vortex shedding phenomenon by KH instability (Lang et al., 2004). Slightly downstream, at $x^* = -3.40$, a subdominant frequency ($St = 2.20$), which corresponds to the first sub-harmonic of the KH instability, emerges and persists until $x^* = -3.15$. Hereafter, the dominant frequency decreases further to a broad peak with a Strouhal number of $St_H = 1.10$, while its energy content decreases compared to the dominant frequencies, detected closer to the leading edge. This frequency is the second subharmonic of KH instability. The third ($St = 0.56$) and fourth ($St = 0.28$) sub-harmonics of the fundamental KH frequency are observed at $x^* = -3.05$ and -2.70 , respectively.



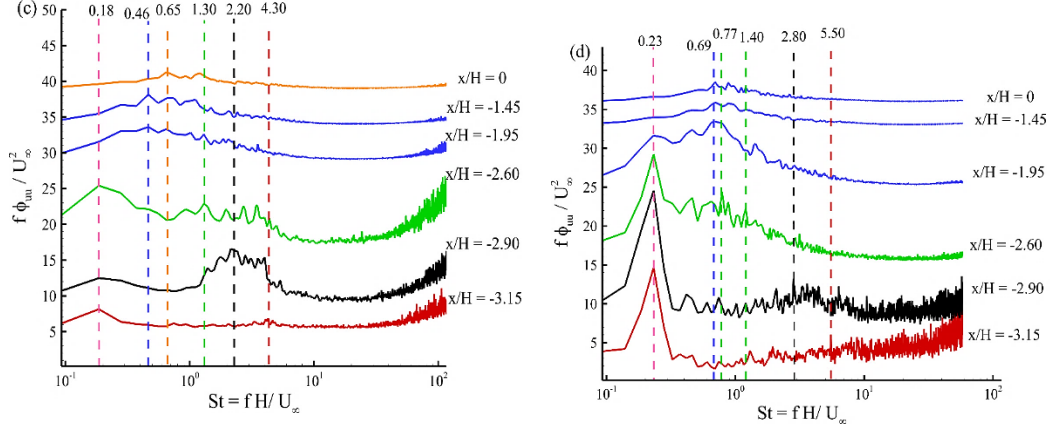


Figure 4.12 Pre-multiplied frequency spectrum of the streamwise velocity at the streamwise locations along the peak locations of TKE for the SL body [(a), (b)] and RL body [(c), (d)] at $Re = 0.17 \times 10^5$ (left) and 0.36×10^5 (right). To facilitate visualization, the spectra are vertically offset by the values indicated on the right-hand side. Vertical dash-dotted lines mark characteristic St

The frequency of $St = 0.28$ persists until $x^* = -1.70$, and hereafter, the dominant Strouhal number increases to $St = 0.37$, which persists until the trailing edge of the Ahmed body. The emergence of higher-rank sub-harmonics has also been observed by Fang et al. (2022), who studied the frequency migration along the shear layer beneath semi-submerged bluff bodies with smooth and rough undersurfaces. As remarked by Winant & Browand, (1974), Fang et al. (2022), and Moore et al. (2019), this pattern of frequency migration is due to vortex pairing that occurs repeatedly, that is, after initiation of the small-scale vortices due to the KH instability, two adjacent vortices roll up, mix, and create another vortex with the size twice the previous one and with a lower (half of) frequency. Furthermore, the value of the dominant frequency at $x^* = -2.70$ is in good agreement with $St = 0.27$ reported by (Aleyasin et al., 2021) for the flow around a cuboid at $Re = 2.26 \times 10^4$. However, the dominant shedding frequency in their study was constant until $x^* = -2$, without frequency migration, which means that the trailing edge shape has an impact on frequency migration near the leading edge. The KH instability for $Re = 0.36 \times 10^5$ also appears at $x^* = -3.50$. However, the dominant frequency associated with this KH frequency is $St = 4.20$, which is lower

compared to $Re = 0.17 \times 10^5$. Similar to the lower Reynolds number, as the flow evolves downstream, the second, third, and fourth harmonic frequencies appear, and the dominant frequency reduces to $St = 0.37$ at $x^* = -1.55$. From this point to the trailing edge of the body, the dominant frequency remains constant to $St = 0.37$, which is the same dominant frequency for the same geometry at a lower Reynolds number (Fig. 4.12a). Figure 4.12c shows that in the RL case at $Re = 0.17 \times 10^5$, the first location of the KH instability frequency is at $x^* = -3.15$. The vortex pairing phenomenon triggers hereafter, and by $x^* = -2.90$, a broad peak with $St = 2.20$ can be seen, which is close to the value of at $St = 2.25$ reported by Spohn & Gillieron (2002).

At $x^* = -2.60$, multiple peaks are evident and the subharmonic peak of $St = 1.30$ is observable. At this streamwise location, another low-frequency peak strength at $St = 0.18$. Further downstream, the dominant frequency changes to $St = 0.46$, and at $x^* = 0$, a frequency of $St = 0.65$ is observed. Figure 4.12d shows the frequency migration for the RL body at $Re = 0.36 \times 10^5$. In this case, a shedding frequency of $St = 0.23$ is dominant, and its energy is considerable compared to the subharmonic of KH instability frequencies. The value of this frequency at this streamwise location is higher than the corresponding value for the same geometry at a lower Reynolds number (Fig. 4.12c) but consistent with what was reported by Minguez et al. (2008).

4.4.2.5 Proper Orthogonal Decomposition

In order to further identify coherent structures of flows, the proper orthogonal decomposition (POD) was applied to the streamwise and wall-normal fluctuating velocity field measured by the high-speed PIV system. POD was introduced by Lumley (1967) and has since been used to analyze different turbulent shear flows, including flow around Ahmed bodies (Podvin et al., 2020; Aleyasin et al., 2021; Siddiqui & Agelin-Chaab, 2022). The POD algorithm was implemented according to the snapshot method proposed by Sirovich (1987), and the detailed formulation and

implementation have been provided by Meyer et al. (2007) and Fang & Tachie (2019). The spatiotemporal fluctuating velocity of a velocity field is decomposed into a set of spatial eigenfunctions (or modes) ($\Psi^{(j)}$) multiplied by the associated mode coefficient ($a^{(j)}(t)$) as follows:

$$u(x, t) = U(x) + \sum_{j=1}^N a^{(j)}(t) \Psi^{(j)}(x) \quad (4.6)$$

where $\Psi^{(j)}$ and $a^{(j)}$ represent the j -th mode and the associated mode coefficient, respectively, and N is the POD mode number. Therefore, the goal of POD analysis is to sort out the fluctuating velocity field u' as the linear sum of time coefficients and spatial functions.

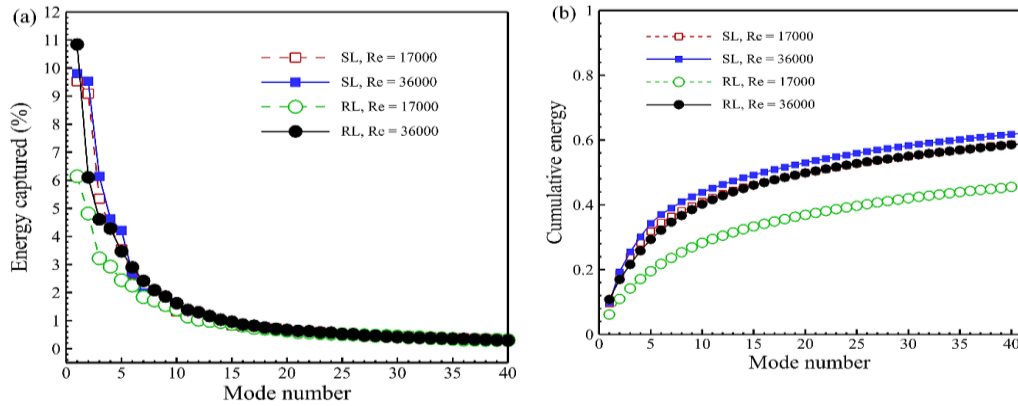


Figure 4.13 (a) Relative and (b) cumulative POD eigenvalues extracted in the wake region

The POD analysis was performed over $x^* \in [-3.89, 0]$ and $y^* \in [1, 2.22]$ over the body and $x^* \in [0, 2.24]$ and $y^* \in [-0.17, 1.05]$ in the wake region of the body. The relative and cumulative modal energies for the first forty spatial modes for SL and RL bodies are shown in Figs. 4.13a and 4.13b, respectively. Figure 4.13b also shows that a higher number of decomposed modes is required to describe the velocity fluctuations in the RL case than in the SL case. However, the difference in energy between the energy levels in the first and second modes is higher in the RL case compared to the SL ones. For RL and SL cases, the energy of the most energetic mode (mode 1) changes slightly from 8% to 9% and from 6% to 11% for $Re = 0.17 \times 10^5$ and 0.36×10^5 , respectively. This shows that increasing the Reynolds number does not significantly affect the energy content

of the energetic modes in the SL body; however, it dramatically increases the energy content of RL cases. In the SL case, the first two modes have similar levels. Figure 4.13b also shows that a higher number of decomposed modes is required to describe the velocity fluctuations in the RL case than the SL one, indicating higher spatial coherence of shear layers of SL cases compared to the RL case (Istvan & Yarusevych, 2016).

To show a typical pattern associated with vortex shedding near both leading-edge and wake regions, Fig. 4.14 presents the first two POD modes and their corresponding vectors at $Re = 0.36 \times 10^5$. Figure 4.15 provides the corresponding pre-multiplied frequency spectra of the time coefficients of the first two POD modes at $Re = 0.36 \times 10^5$ over the body and in the wake region. Figures 4.14a and 4.14c show the alternate shedding motion of vortices from the leading edge of the SL case. Both figures show a similar flow structure with a phase shift, which is evidence of mode pairing. However, Fig. 4.14e is associated with fluctuations of the streamwise velocity, which encompasses the entire recirculated zone of the RL case. This demonstrates that the first mode is indicative of the flapping motion of the recirculated zone. The second mode (Fig. 4.14g), however, is associated with the alternate shedding of positive and negative velocity clusters. Figures 4.14b and 4.14d show that the first two modes of the SL body are dominated by two counter-rotating vortical structures that formed due to the interaction of the shear layers from the top and undersurface of the body. The first mode represents the formation of a single vortical structure near the base, which sweeps fluid from one side of the wake to the other, while the second vortical structure is related to the interaction of the lower shear layer and ground. Comparing Figs. 4.14b and 4.14f provide a reasonable explanation for why the dominant frequency shedding in the wake region of the RL case is higher than in SL (Figs. 4.15b and 4.15d). In the SL case (Fig. 4.14b), due to the comparatively lower downwash and upwash flow, the recirculation bubble that

is formed due to the interaction of shear layers from the slanted edge and the undersurface of the body is not strong enough. Meanwhile, compared to the SL body, the more intense downwash and upwash beneath the RL body (Fig. 4.14f) have shifted the two bubbles closer together, which enhances the interaction between the shear layers in the wake region. The frequency of the first two modes near the leading edge of the SL body (Fig. 4.15a) is $St = 0.37$. This frequency, which is associated with vortex shedding frequency based on Figure 12b, coincides with the dominant frequency of streamwise fluctuating velocity at $x^* = -1.55$ until $x^* = 0$. The spatial distributions of energy for these two modes (Figs. 4.14b and 4.14c) also show that the energy is concentrated in the middle of the SL body onwards, which justifies the reason for the same dominant frequency between the first two modes and the dominant frequency spectra after $x^* = -1.55$. The energy content of modes 3, 4, and 5 is lower than that of the first two modes, and the spatial distribution of these modes is concentrated near the leading edge of the body (not shown). According to Fig. 4.15b, the dominant frequency of the first two modes in the wake region is $St = 0.20$, while it increases to 0.33 for modes 3 to 5. The frequency spectra of the temporal coefficients for the RL case also show that the dominant Strouhal number of these modes is $St = 0.23$, which is the same as the dominant Strouhal number from $x^* = -3.15$ until $x^* = -2.60$, as shown in Fig. 4.12d. This suggests that the energy contained in these modes is associated with the development of shear layer rollers. Comparing the spectra of the temporal coefficients for the RL and SL cases at the same Reynolds number reveals that the dominant frequency of the most energetic modes for the RL case ($St = 0.23$) is lower than for SL cases ($St = 0.37$).

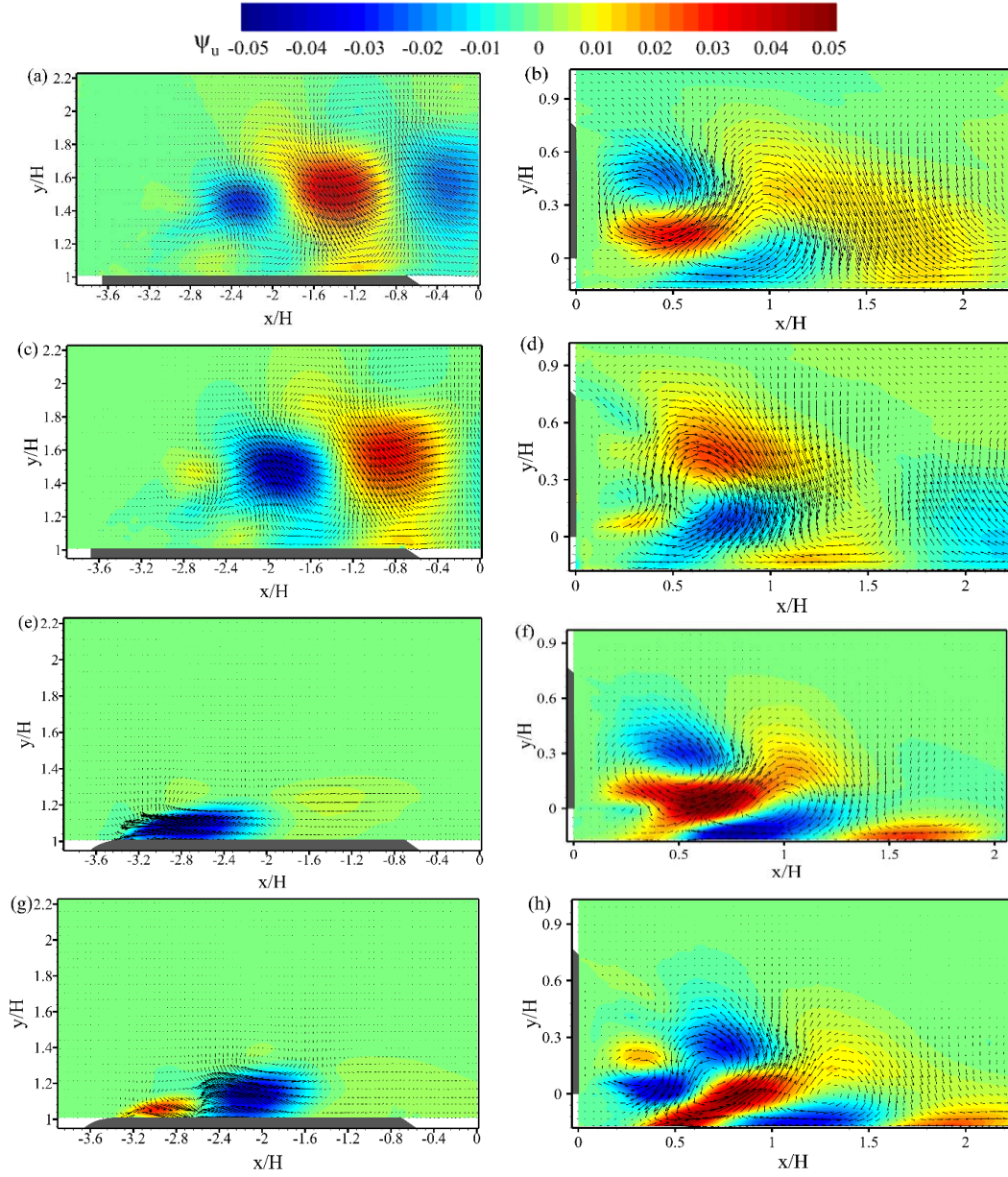


Figure 4.14 Contours of the streamwise components of first [(a), (b), (e), (f)] and second [(c), (d), (g) and (h)] POD modes superimposed by corresponding vector field over the body (left) and wake region (right) of SL body [(a)-(d)] and RL [(e)-(h)] at $Re = 0.36 \times 10^5$

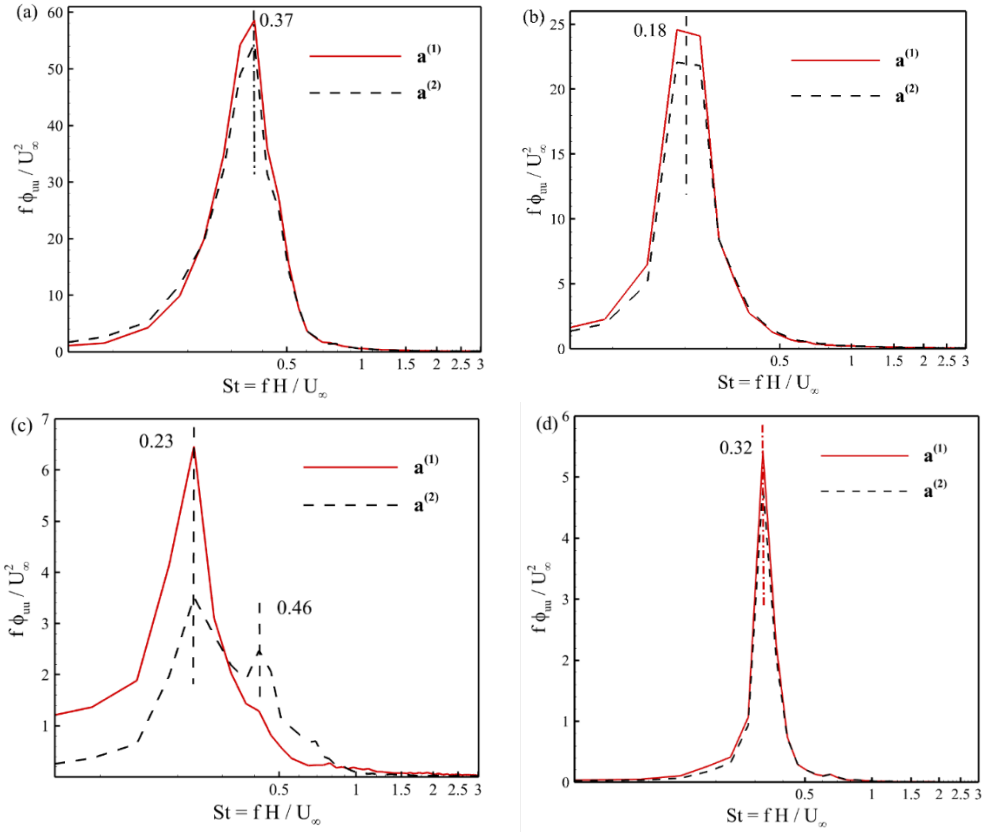


Figure 4.15 Frequency spectra of the time coefficients for the first two POD modes at $Re = 0.36 \times 10^5$ for SL body (a) over the body (b) wake region and for RL body (c) over the body (d) wake region

Figure 4.15d also shows that the dominant Strouhal number for the most energetic modes in the wake region of the RL body is equal to $St = 0.32$. The value of this dominant Strouhal number is comparable to $St = 0.31$ reported by Siddiqui & Agelin-Chaab (2022) and Tunay et al. (2014), at $Re = 4.3 \times 10^4$ and 1.5×10^4 , respectively.

4.4.2.6 Unsteady Characteristics of Reverse Flow Area

Statistical analysis was performed to assess the effect of the leading edge on the spatiotemporal variation of the reverse flow area in the wake region. The instantaneous reverse flow area is evaluated by summing up the areas of $u < 0$ within a region of interest (S) as follows (Pearson et al., 2013):

$$A(t) = \int_S J(u(x, y, t)) dx dy \quad (4.7)$$

where $u(x, y, t)$ is the streamwise instantaneous velocity and dx and dy are the vector spacing in the x and y directions, respectively, and the J function is a detector function based on the event. In this equation, if $u(x, y, t) \geq 0$, the value of $J(u(x, y, t))$ would be 0; otherwise, it is 1. The analysis was performed over $x^* \in [0, 2.24]$ and $y^* \in [-0.17, 1.05]$ in the wake region of the body. Figure 4.16 shows the probability density function of the normalized reverse flow area in the wake region of bodies. Reynolds number has an insignificant effect on the size of extremely large reverse flow areas (epitomized by the right tail of the pdf), and it is similar for the SL cases. However, Reynolds number dramatically affects the large reverse flow areas in the RL case, and the probability of extremely large reverse flow areas is lower at $Re = 0.17 \times 10^5$. On the other hand, instances of smaller instantaneous reverse flow in the RL case at $Re = 0.17 \times 10^5$ is most likely. At $Re = 0.17 \times 10^5$, the value of the normalized mean reverse flow area in the wake region for the SL and RL cases is $A_{\text{mean}} = 0.22$ and 0.17 , respectively, indicative of a 22.7% reduction. However, as the Reynolds number increases to $Re = 0.36 \times 10^5$, the plot of the pdf curves gets similar, and at this Reynolds number, the corresponding value for SL and RL cases lies at $A_{\text{mean}} = 0.20$ and 0.19 , accounting for only a 5% difference. Hence, the results clearly show the effect of Reynolds number variation on reverse flow areas behind the bodies.

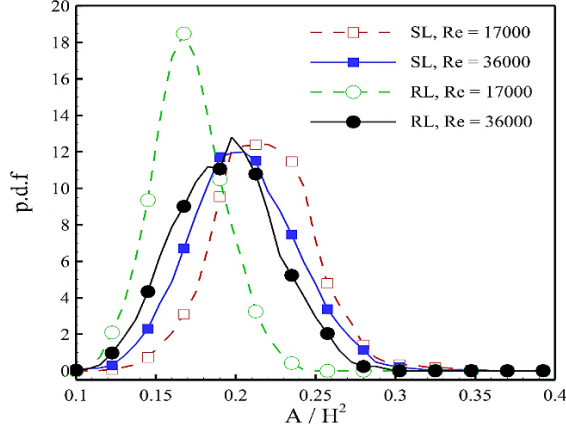


Figure 4.16 Probability density function of reverse flow in the wake region

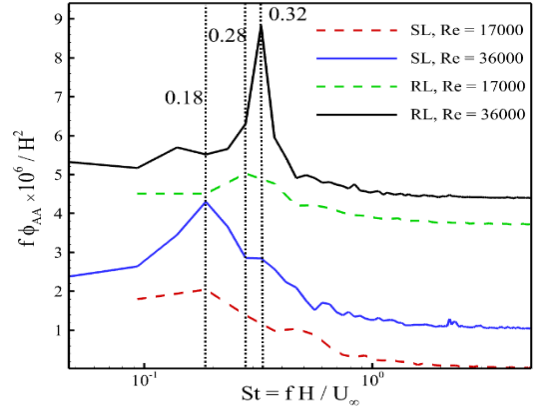


Figure 4.17 Pre-multiplied frequency spectra of reverse flow area ($f\Phi_{AA}$) in the wake region

The pre-multiplied spectra of the reverse flow area are provided in Fig. 4.17. In SL cases, $f\phi_{AA}$ possess a peak at $St = 0.18$, and this frequency does not change with Reynolds number. However, the peak is more dominant at $Re = 0.36 \times 10^5$ than at $Re = 0.17 \times 10^5$. The dominant frequency of the reverse flow area behind the RL body increases from $St = 0.28$ to 0.32 as Reynolds number increased from $Re = 0.17 \times 10^5$ to $Re = 0.36 \times 10^5$. The peak value of the normalized vortex shedding frequency obtained using the reverse flow area at $Re = 0.36 \times 10^5$ is consistent with the values obtained from the POD modes, as shown in Figs. 4.15b and 4.15d.

4.4.3 Flow Characteristics in the Spanwise Plane

4.4.3.1 Mean Flow Pattern

Figure 18 shows the contours of the normalized mean streamwise (U^*) and spanwise velocity (W^*) around the SL and RL bodies at $Re = 0.36 \times 10^5$. Figures 18a and 18c show that a small recirculation bubble is formed near the leading edge of the SL case, which persists until $x^* = -2.90$, but no distinct recirculation bubble is formed in the RL case. The maximum and minimum streamwise mean velocity in the SL case are $U^* = 1.3$ and -0.13 , respectively, and the maximum

velocity for the RL case is $U^*=1.21$, as indicated in the plot. Some differences in the wake region behind the bodies are noticeable. The maximum backflow is $U^* = -0.11$ and -0.15 for SL and RL bodies, respectively. However, in regions remote from the recirculation bubble, the value of streamwise velocity behind the RL case is higher than that of the SL case. As evident from the streamline's trajectories near the trailing edge of the bodies, for the RL case, the flow is mostly deflected towards the wake and feeds the wake region, which in turn increases the flow velocity behind the Ahmed body. The reverse flow area, which is the region encompassed by the line $U^* = 0$, is also smaller in the RL case than the SL one. This is attributed to the increase of downwash flow in the RL case (Fig. 4.6), which brings the core of vortices towards the base of the body (Li et al. 2022). From the plots of spanwise mean velocity for the SL case, two regions of elevated velocity are observed: the first area is located downstream of the leading recirculation bubble, and the other is near the trailing edge. For the RL case, this region with higher velocity is formed near the trailing edge of the body, which is a sign of deflection of the flow towards the wake region.

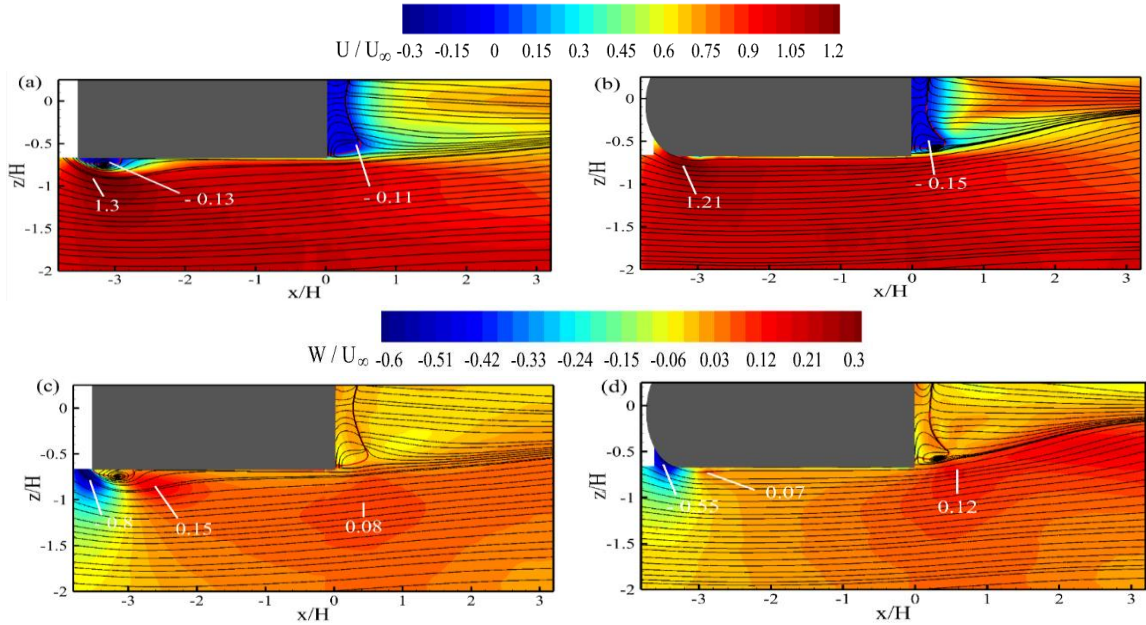


Figure 4.18 Contours of streamwise mean velocity [(a) and (b)] and spanwise mean velocity [(c) and (d)] for [(a) and (c)] SL body and [(b) and (d)] RL body at $Re = 0.36 \times 10^5$. Solid lines show the recirculation bubble

4.4.3.2 Reynolds Stresses

Contours of Reynolds stresses and TKE at $Re = 0.36 \times 10^5$ are provided in Fig. 4.19. The maximum local peaks in the vicinity of both the leading and trailing edges of the body are also labelled on the plot. The figure demonstrates that in the vicinity of the trailing edge, where the shear layers are relatively thin and the mean shear is high, Reynolds normal, shear stresses and TKE are maximum. The level of maximum streamwise Reynolds stress and the energy of fluctuating velocities in the near wake region are higher in the SL case than in the RL case. This results from higher interaction of shear layers separated from the leading edge with those emanating from the trailing edge. However, the maximum value of wall-normal and shear stresses in the vicinity of the trailing edge is the same. In the SL body, the shear layer emanating from the leading edge is advected across the side surface and fades as it evolves downstream. In contrast, the shear layers deflect towards the wake region in the RL body.

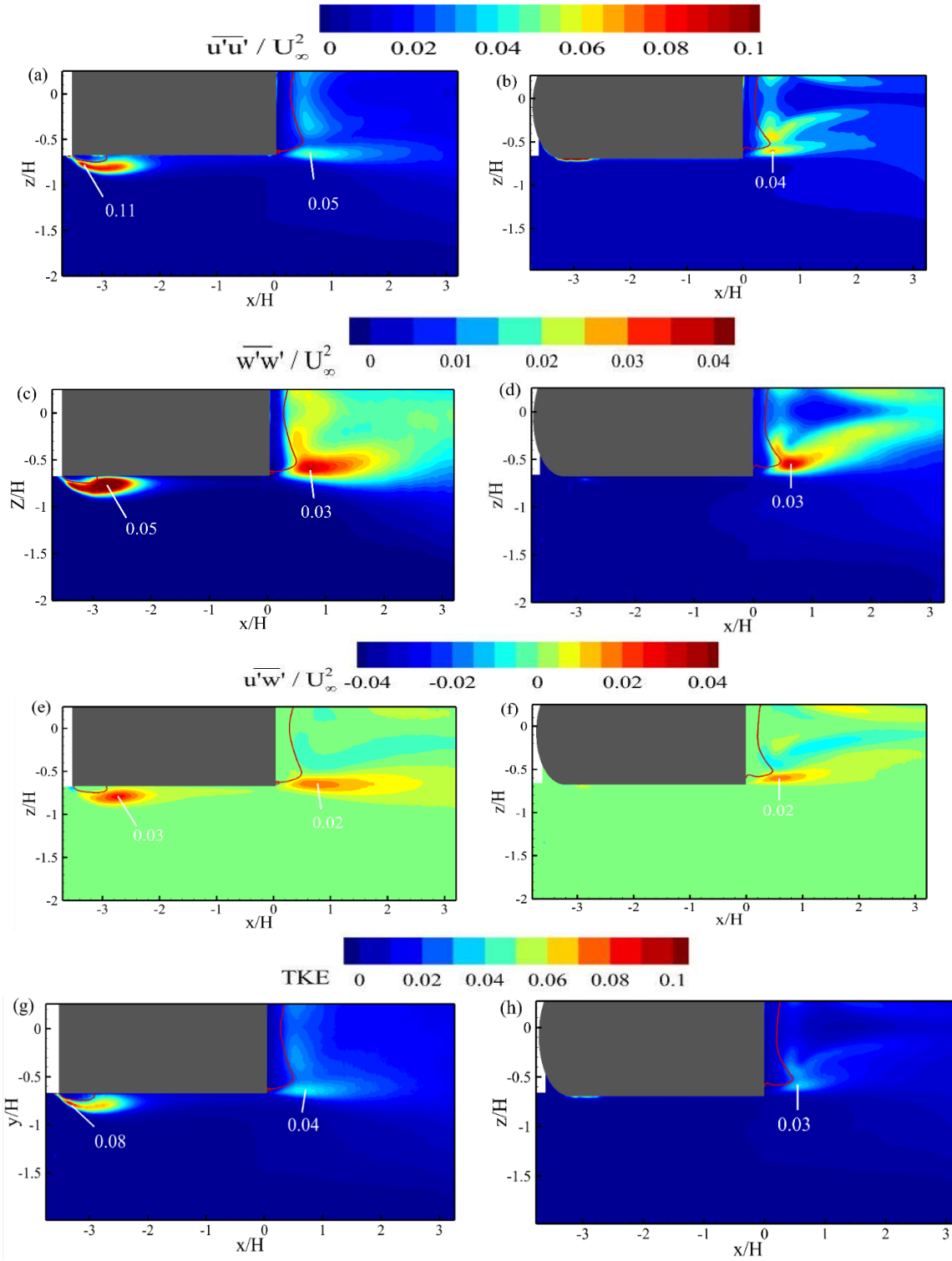


Figure 4.19 Contours of streamwise Reynolds normal stress [(a) and (b)], Spanwise Reynolds normal stress [(c) and (d)], Reynolds shear stress [(e) and (f)], and turbulent kinetic energy [(g) and (h)] at $Re = 0.36 \times 10^5$. Solid red lines show the recirculation bubble

4.4.3.3 POD Analysis

A POD analysis was also performed to explore the dynamic roles of coherent structures in the wake region of bodies. Figure 4.20 shows the energy percentage of the first 1000 POD modes in all cases. The energy percentage of the most dominant mode is about 3.8% and 2.6% for SL and RL cases, respectively. Meanwhile, the corresponding values for the second mode are 3.7% and 2.3%, respectively. As can be seen, there is a significant difference in the energy percentage of SL and RL cases in the first eight modes. The difference disappears from the eighth mode onwards. In both Reynolds numbers, the energy content of the first POD mode differs, while the difference diminishes as the mode increases.

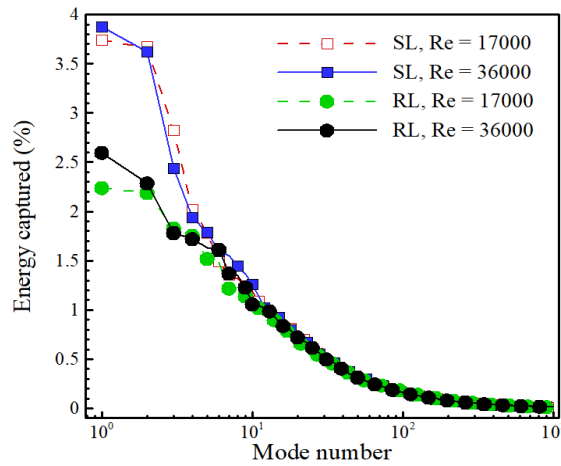


Figure 4.20 Distributions of the fractional energy contributions of the first 1000 modes in the spanwise planes. The results are related to the wake region

The spatial distribution of POD modes is shown in Fig. 4.20. The figure shows evidence of von Kármán vortex shedding in the wake region. Based on Fig. 4.21a, there are a pair of counter-rotating large vortical structures behind the SL case, while two pairs of smaller structures formed in the wake region of the RL case. It can also be seen that spatially larger structures are formed near the wake in the SL case than in that of the RL case (Fig. 4.21c), which can be attributed to the weaker influence of the downwash in the SL case (Essel et al., 2023). Furthermore, Figures

4.21a and b show the motion of structures downstream in the center. On the other hand, in Figs. 4.21c and 4.21d, the spatial structures are deviated to a spanwise direction, indicating a stronger flapping motion of shear layers emanating from the lateral side of the RL body. These results suggest that rounding the leading edge significantly modifies the vortical structures downstream of the body.

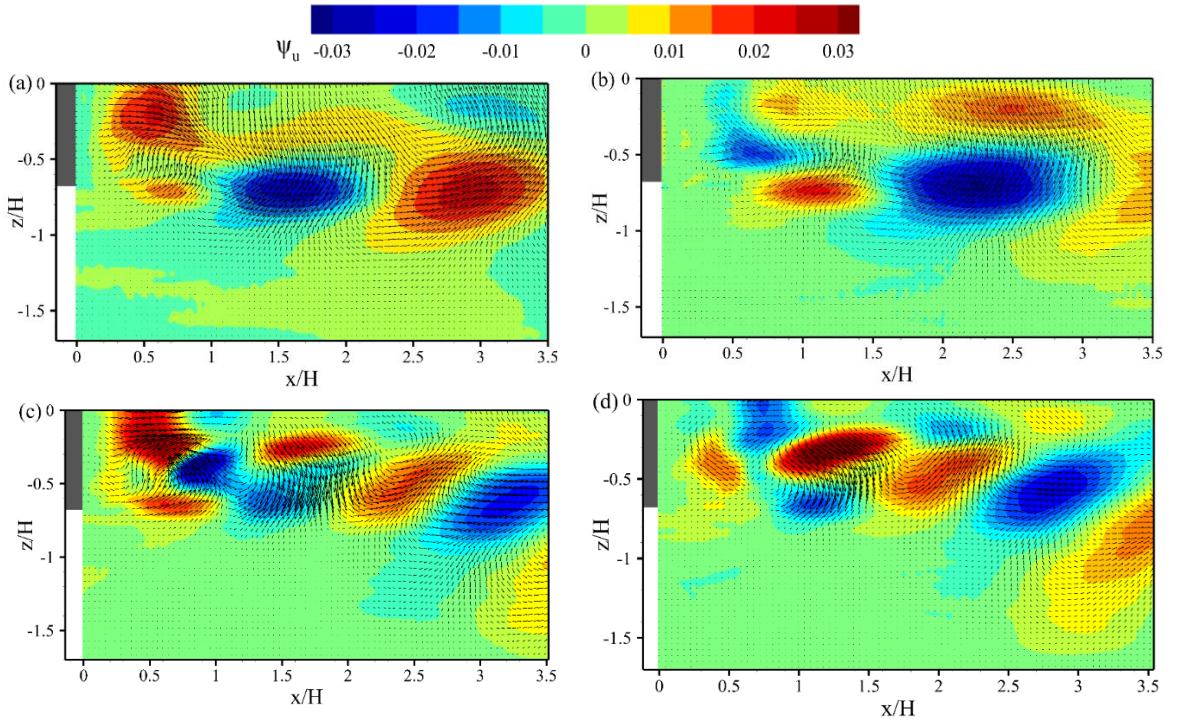


Figure 4.21 Contours of the streamwise components of [(a), (c)] first and [(b), (d)] second POD modes superimposed by the corresponding vector field in the wake region of [(a), (b)] SL body and [(c), (d)] RL body at $Re = 0.36 \times 10^5$

The pre-multiplied frequency of the first POD modes is plotted in Fig. 4.22 (the frequency spectra of the second POD temporal coefficients are similar to the first mode, therefore, not shown here). This figure shows that the dominant St for the SL case is lower than the RL case, indicating longer-time dynamics evolution in the wake region of the SL case. It is worth noting that the peak frequencies also correspond to the dominant frequency of the reverse flow area in the wake region,

as shown in Fig. 4.17. This interesting observation indicates that the dynamic structures of the recirculation bubbles in the x-y and x-z planes are correlated.

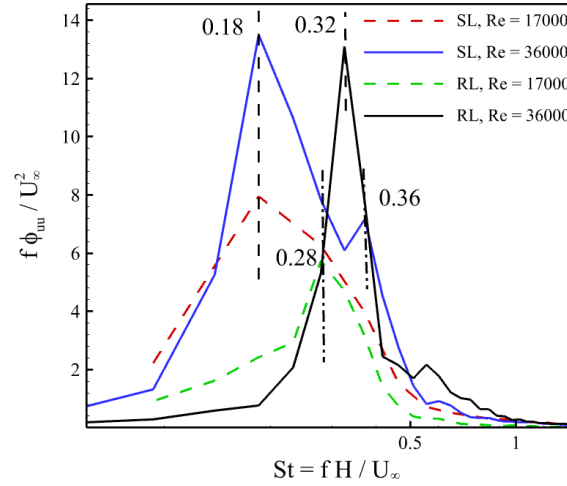


Figure 4.22 Pre-multiplied frequency of the first POD modes

4.5 Conclusions

A comparison of two slanted-backed bodies with differing flow properties induced by different leading-edge shapes; squared leading-edge and rounded leading-edge bodies have been presented. The spatiotemporal characteristics of flow separations around the bodies were investigated using double-frame particle and time-resolved image velocimetry systems. The Ahmed body used in this study has a $\frac{1}{4}$ scale of the original model introduced by Ahmed et al. (1984) with a slant angle of 25° . Comprehensive measurements were performed for two Reynolds numbers of $Re = 0.17 \times 10^5$ and $Re = 0.36 \times 10^5$ at x-y and x-z measurement planes.

The mean velocity contours revealed that three distinct bubbles are formed around the bodies. While the results showed a degree of Reynolds independence in the SL body, the length of the recirculation bubble over the body is smaller in the RL body, and its extension becomes smaller as the Reynolds number increases. The appearance of the recirculation bubble over the RL body was in sharp contrast with that of the Aleyasin et al. (2021) observation, and the difference was

attributed to the turbulence intensity differentiation of the approach flow between the cases. A higher downwash flow was observed behind the RL body than that of the SL body, and increasing the Reynolds number decreased the downwash strength for both bodies. A thicker separated shear layer was emanating from the leading edge of the SL body than in the RL case. However, the thickness of this shear layer was insensitive to the Reynolds number for both bodies. It was also observed that the shear layer with higher vorticity thickness is induced in the slanted surface of the RL case than that of the SL body. A higher level of Reynolds normal and shear stresses was observed behind the RL case compared with the SL one, which indicated that the interactions between the lower and upper shear layers of the RL body are more intense compared to the SL one. However, the contours of TKE in the x-z plane showed that the energy of fluctuating velocity in the near wake region of the SL body is higher than that of the RL case. This observation was supported by the study of turbulent structure characteristics and frequency spectra. Near the leading edge, the Kelvin–Helmholtz instability observed over the bodies at $St = 4.4$ and 4.2 for SL, and $St = 4.3$ and 5.5 for RL bodies at $Re = 0.17 \times 10^5$ and $Re = 0.36 \times 10^5$ respectively. It was also observed that the frequency of the separated shear layer migrates from high to low values through the vortex pairing mechanism. The frequency spectra of the fluctuating streamwise velocity, reverse flow area, and the coefficient of the first POD mode showed a dominant frequency of $St = 0.18$, and 0.23 over the RL body for $Re = 0.17 \times 10^5$ and $Re = 0.36 \times 10^5$, respectively, while it was fixed at $St = 0.37$ for both Reynolds numbers in the SL case. In the wake region of the body, the dominant frequency of SL cases was $St = 0.18$, while the peak frequency of $St = 0.28$ and 0.32 were observed in the wake region of the RL case at $Re = 0.17 \times 10^5$ and $Re = 0.36 \times 10^5$ respectively. The frequencies are in good agreement with those reported in previous studies on RL bodies in uniform flows. The dependency of the Strouhal number on the Reynolds

number in RL cases is also in agreement with that reported by Zhang et al. (2015); however, this observation does not apply to the SL cases. The energy distribution of different POD modes also showed a higher spatial coherence of shear layers of SL cases compared to the RL case. The POD analysis in the x-y plane also revealed that the higher upwash and downwash flow behind the RL case led to a higher interaction of shear layers. This observation was supported by the contours of mean velocities in the x-z plane. The frequency spectra of the first POD modes in this plane were identical to those of the x-y plane, and were higher in the RL than in the SL case, which was justified by the larger coherent structures of the SL case than those in the RL case.

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Chapter 5: Effects of Freestream Turbulence Intensity on Flow Dynamics and Vortical Structures Around a High-drag Ahmed Body

5.1 Abstract

This study investigates the effects of freestream turbulence (FST) on the spatiotemporal flow dynamics around an Ahmed body with a slanted angle of $\alpha = 25^\circ$ using time-resolved particle image velocimetry (TR-PIV). Three FST intensities ($T_u = 5.0\%$, 10.0% , and 15.0%) were generated using regular and fractal grids, and the results were compared with those obtained at a baseline turbulence level of $T_u = 1.5\%$ achieved in the absence of the grids. The size of the roof recirculation bubble decreased monotonically with increasing FST; however, the wake bubble size is independent of FST. Over the slanted surface, the bubble size increased with FST for $T_u \leq 10.0\%$ and remained constant at $T_u = 15.0\%$. The increase in the bubble size was attributed to a stronger spatial and temporal correlation between the C-pillar vortex and the separated shear layer from the slanted surface. FST also promotes turbulence transition by generating elongated streaks characterized by higher streamwise than wall-normal velocity fluctuations. The results also show that FST suppresses the magnitudes of Reynolds stresses over the roof and in the wake region and has no significant effects on the turbulence levels over the slanted surface. The spatiotemporal features were analyzed using velocity spectra and two-point spatial and space-time correlation coefficients, while Spectral Proper Orthogonal Decomposition (SPOD) was used to study vortical structures linked to dynamically important frequencies. FST suppressed the dynamically important frequencies of the vortical structure, including roof bubble pulsation, disrupted the flapping motion of recirculation bubbles in the wake, and reduced their spectral coherence.

5.2 Introduction

The Ahmed body, introduced by Ahmed et al. (1984), is one of the simplest yet most widely adopted bluff bodies for studying the salient dynamics of flow around on-road vehicles. As shown in Fig. 5.1, the Ahmed body has a rounded frontal area, an extended mid-section, and a rear slanted surface with an adjustable angle (α) to mimic various configurations of on-road vehicles. The flow around the Ahmed body is three-dimensional and exhibits intricate features such as flow separation and reattachment over the roof and side surfaces, followed by the development of a boundary layer. The wake region consists of a recirculation zone over the slanted edge, a pair of counter-rotating vortices known as C-pillar vortices, and a counter-rotating recirculation torus behind the vertical base. The recirculation torus forms due to the flow separation from the slanted and bottom surface (Spohn & Gillieron, 2002; Krajnović & Davidson, 2005; Wang et al., 2013; Zhang et al., 2015; Sellappan et al., 2018; Liu et al., 2021; Sagharichi & Tachie, 2024).

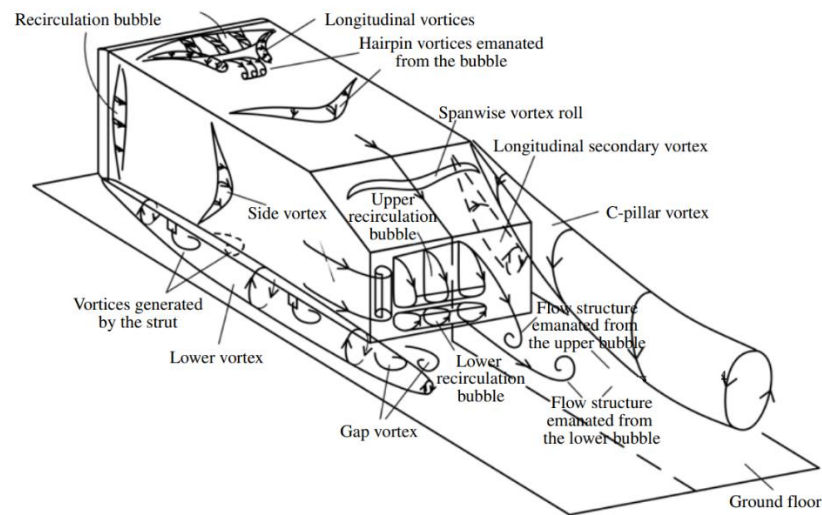


Figure 5.1 Mean flow structure around the Ahmed body with $\alpha = 25^\circ$ (Zhang et al., 2015)

Ahmed et al. (1984) experimentally investigated the flow around the slanted-back Ahmed body and identified two distinct flow regimes delineated by $\alpha = 30^\circ$: high-drag ($0^\circ < \alpha < 30^\circ$) and low-

drag ($\alpha > 30^\circ$). Subsequent numerical and experimental studies have evaluated the effects of Reynolds number (Vino et al., 2005; Thacker et al., 2010; Zhang et al., 2015), aspect ratio (Venning et al., 2015; Corallo et al., 2015; Venning et al., 2022), ground clearance (Wang et al., 2013; Plumejeau et al., 2020) and leading-edge configuration (Sagharichi et al., 2023; Sagharichi & Tachie, 2024) on the dynamics of flow around the slanted-back Ahmed body.

Thacker et al. (2010) examined turbulent flow induced by a $\alpha = 25^\circ$ slanted Ahmed body and reported that the Strouhal number ($St = fH/U_\infty$; where f is vortex-shedding frequency, H is body height, and U_∞ is freestream velocity) over the slanted surface increased from $St = 0.18$ to 0.21 as the Reynolds number (based on freestream velocity and body height) rose from $Re = 1.93 \times 10^5$ to 1.04×10^6 . Joseph et al. (2012) investigated the wake flow of an Ahmed body with a $\beta = 25^\circ$ and demonstrated that the separation region over the slanted surface underwent a longitudinal contraction as the Reynolds number increased from $Re = 3.86 \times 10^5$ to 7.72×10^5 . Sagharichi et al. (2023) also observed a reduction from $0.85H$ to $0.79H$ in the recirculation length (defined as the maximum longitudinal extent of $U/U_\infty \leq 0$) over the roof as Reynolds number increased from $Re = 0.17 \times 10^5$ to 0.36×10^5 . Liu et al. (2021) studied a $\alpha = 35^\circ$ Ahmed body at Reynolds numbers of $Re = 2.57 \times 10^4$ to 2.31×10^5 and found that the Strouhal number ($St = 0.27$) in the wake region is independent of the Reynolds number. However, Zhang et al. (2015) observed shear layer frequency in the wake of a $\alpha = 25^\circ$ Ahmed body increased from $St = 0.37$ to 0.46 as the Reynolds number climbed from $Re = 3.80 \times 10^4$ to 2.05×10^5 .

The wake characteristics of the Ahmed body are also influenced by the ground clearance ratio (C_g , clearance ratio between the model underside and the ground surface to body height). Wang et al. (2013) studied slanted-back Ahmed bodies ($\alpha = 25^\circ, 35^\circ$) at $Re = 5.30 \times 10^4$ at $C_g = 0$ and 0.174 .

For $C_g = 0.174$, recirculation torus and C-pillar vortices emerged, while $C_g = 0$ eliminated the recirculation torus and increased C-pillar vorticity strength by 50% for both slanted angles. The absence of ground clearance also extended wake recirculation length from $0.67H$ to $0.86H$ for $\beta = 25^\circ$, and from $1.03H$ to $1.43H$ for $\alpha = 35^\circ$.

Krajnović & Davidson (2005), Minguez et al. (2008), and Liu et al. (2021) reported that small-scale Kelvin-Helmholtz (KH) vortices at the Ahmed body's leading edge evolve into hairpin structures downstream. This suggests that altering the leading-edge geometry modifies shear layer dynamics and interactions with 3D vortical structures. Sagharichi et al. (2023) experimentally investigated turbulent flow around a slanted-back Ahmed body with squared and rounded leading edges at $Re = 0.17 \times 10^5$ and 0.36×10^5 . The study revealed that the square leading edge generates a larger recirculation bubble over the roof (measuring $1.91H$, compared to $0.85H$ and $0.79H$ for the rounded leading edge body at $Re = 0.17 \times 10^5$ and 0.36×10^5 , respectively), thicker shear layers with higher energy content, and reduced downwash flow ($V < 0$, where V is the mean wall-normal velocity) in the wake region compared to the rounded edge. While the dominant vortex shedding frequency in the wake region of the square leading-edge body remains constant ($St = 0.18$) across Reynolds numbers, for the rounded leading-edge body it increases from $St = 0.28$ to 0.32 .

The square-back Ahmed body ($\alpha = 0^\circ$) has also received significant research attention. One of the key distinctions between the square-back and slanted-back Ahmed bodies lies in the near-wake topology. While the wake behind a slanted-back Ahmed body features multiple interacting vortices, the wake of a square-back Ahmed body forms a large recirculation bubble shaped like a toroidal structure (Aleyasin et al., 2021; Chen et al., 2023a; Chen et al., 2024). Additionally, the wake region of the square-back Ahmed body is characterized by a bistability phenomenon in which the wake structure switches between two asymmetric steady-state modes (Cogotti, 1986; Volpe et

al., 2015) even though the flow is statistically symmetric in the long-time average (Grandemange et al., 2013).

Most of the previous research on the Ahmed body was conducted at freestream turbulence (FST)

intensities ($T_u = u'_{rms}/U_\infty$, where $u'_{rms} = \sqrt{\overline{u'^2}}$ is root-mean-square of the streamwise fluctuation velocity u' , and $(\cdot)$ denotes time averaging) of less than $T_u = 2.0\%$ (Tunay et al., 2014; Venning et al., 2015; Zhang et al., 2018; Siddiqui & Agelin-Chaab, 2022; Venning et al., 2022). Meanwhile, FST intensity in open-road and wind gust conditions can vary from $T_u = 2.0\%$ and 16.0% (Saunders & Mansour, 2000; Passaggia et al., 2021; Burton et al., 2021). Additionally, the streamwise integral length scale (L_u , which represents the size of energy-containing eddies in the approaching flow) varies with the driving environment and may range from $L_u = 0.3H$ when in traffic to $L_u = 3.5H$ on open roads (Saunders & Mansour, 2000; Passaggia et al., 2021).

Table 5.1 Summary of previous studies on the effects of FST level on the turbulent flow characteristics around Ahmed body

Researchers	α	Re^1	T_u (%)	L_u/H	Techniques	Measurements
Zhang et al. (2015)	25°	5.30×10^4	0.3 and 7.8	-	Hot-wire	Frequency analysis
Cadot et al. (2020)	0°	8.0×10^4	1.8 and 5.6	-	Pressure taps	Bistability, Pressure distribution
Wang et al. (2020)	0°	2.74×10^5	2.0 to 16.0	-	4-hole pressure probes, base-pressure measurement	Bistability, Pressure distribution
Aleyasin et al. (2021)	0°	2.26×10^4 and 2.37×10^4	4.0 and 7.0	0.68 and 0.91	PIV ²	Frequency analysis, Mean velocities, Reynolds stresses, Vorticity
Burton et al. (2021)	0°	2.74×10^5	1.0 to 16.0	0.27 to 1.70	4-hole pressure probes, Base-pressure measurement	Bistability, Pressure distribution
Passaggia et al. (2021)	0°	4.80×10^5	0.5 to 12.9	0.22 to 0.63	Hot-wire, PIV	Drag, Pressure distribution, Mean velocities

Chen et al. (2023a)	0°	9.60×10^4	3.4, 6.9 and 11.4	0.24, 0.22 and 0.21	IDDES ³	Mean velocities, Bistability, Pressure distribution, Frequency analysis
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1) Reynolds number based on freestream velocity and body height
2) Particle image velocimetry
3) Delayed detached eddy simulation

Table 5.1, which summarises previous research on the effects of FST on the flow around the Ahmed body, shows that, except for Zhang et al. (2015), these investigations have focused exclusively on the square-back Ahmed body.

The effects of FST on the flow dynamics around a full-scale square-back Ahmed body were investigated by Passaggia et al. (2021). Nine different FST levels (T_u (%) $\in$ 0.5 to 12.9 and $L_u/H \in$ 0.22 to 0.63) were examined. Under low FST conditions ($T_u = 0.5\%$, $L_u = 0.3H$), the growth of the roof shear layer is suppressed, leading to a reduction in base pressure and a 16% increase in drag. Conversely, higher FST levels enhanced shear-layer growth in the wake region, which disrupted the formation of strong coherent structures and reduced drag by up to 17%. Chen et al. (2023a) reported that the recirculation length in the wake region decreases under FST; however, the frequency of the pumping motion (a motion associated with the low-frequency periodic extension and contraction of the separation bubble) in the wake region increases with the FST. Nonetheless, the normalized von Kármán vortex shedding frequency of $St = 0.15$ is unaffected by FST changes. Aleyasin et al. (2021) investigated the effect of turbulence intensity on the wake around a square-back Ahmed body using PIV, achieving turbulence levels of $T_u = 4.0\%$ and $T_u = 7.0\%$ by exposing the body to an approaching turbulent boundary layer over smooth and rough walls, respectively. Increasing the turbulence intensity resulted in an increase of 25% and 70%,

respectively, in the reverse flow area and peak value of streamwise Reynolds normal stress ($\overline{u'u'}$) over the roof.

To date, knowledge of FST effects on the slanted-back Ahmed body is limited to Zhang et al. (2015), who studied the flow around a high-drag Ahmed body at $T_u = 0.3\%$ and 7.8% . Their results indicated suppression of both the recirculation bubble and spectral peaks, particularly near the leading edge of the roof and side surfaces, at higher FST. For instance, the dominant frequency of $St = 0.17$, which is linked to vortex generation and bubble pulsation, was observed at $T_u = 0.3\%$ but was absent at $T_u = 7.8\%$. Even though no significant change was observed in von Kármán vortex shedding frequency in the wake region, the spectral peak over the slanted surface was broader at $T_u = 7.8\%$ compared to $T_u = 0.3\%$, indicative of reduced periodicity spanwise vortices at higher FST (Hearst et al., 2016; Mannini et al., 2017). Despite the insights gained from these findings, significant gaps exist in our understanding of how FST affects the spatiotemporal flow dynamics, particularly in real-world FST conditions. This study addresses this gap by investigating a broader FST range ($T_u = 1.5\%$ to 15%) and employing advanced spatiotemporal analysis tools such as spatial two-point correlation, space-time correlation, spectral coherence, and spectral proper orthogonal decomposition (SPOD) to provide new insights into flow dynamics under realistic turbulence levels.

The objective of this study is to experimentally evaluate the effects of FST intensity on the spatiotemporal flow dynamics around a high-drag Ahmed body with a slanted angle of $\alpha = 25^\circ$. Three different passive grids (a regular grid and two fractal grids) were installed at the inlet section of a water channel to generate turbulence intensity levels of $T_u = 5.0\%$, $T_u = 10.0\%$ and $T_u = 15.0\%$, with corresponding integral length scales of $L_u = 0.68H$, $1.07H$, and $1.0H$, respectively. The experimental results from these configurations were compared against a baseline condition

characterized by a background turbulence intensity of $T_u = 1.5\%$ (without grid installation). The experiments were performed using time-resolved particle image velocimetry (TR-PIV), and the results were used to investigate the influence of varying FST intensities on key flow characteristics, including recirculation bubbles, Reynolds stresses, space-time correlation, frequency spectrum, and spectral coherence. SPOD is also used to analyze how FST intensity affects the spatiotemporal evolution and modal dynamics of dominant coherent structures in the flow field.

The remainder of this Chapter is organized as follows. Section 5.3 describes the experimental setup and details the test cases, including the Ahmed body, turbulence-generating grids, and the measurement procedure. In Section 5.4, a comparison between the test cases subjected to varying FST intensities is discussed. Section 5.5 contains concluding remarks.

5.3 Experimental Method

5.3.1 Test Facility

The experiments were performed in an open recirculating water channel at the University of Manitoba. The test section has dimensions of 6000 mm in length, 600 mm in width, and 450 mm in height. Its walls are constructed using 31.8 mm thick Super Abrasion Resistant transparent acrylic plates for optical accessibility. An impeller pump with a 30 kW variable speed motor was used to regulate the flow rate. The water channel features a settling chamber containing perforated steel plates, a honeycomb, mesh screens, and a 4.88:1 converging section upstream of the test section to reduce large-scale turbulence. An indoor picture and schematic of the experimental setup is shown in Fig. 5.2.

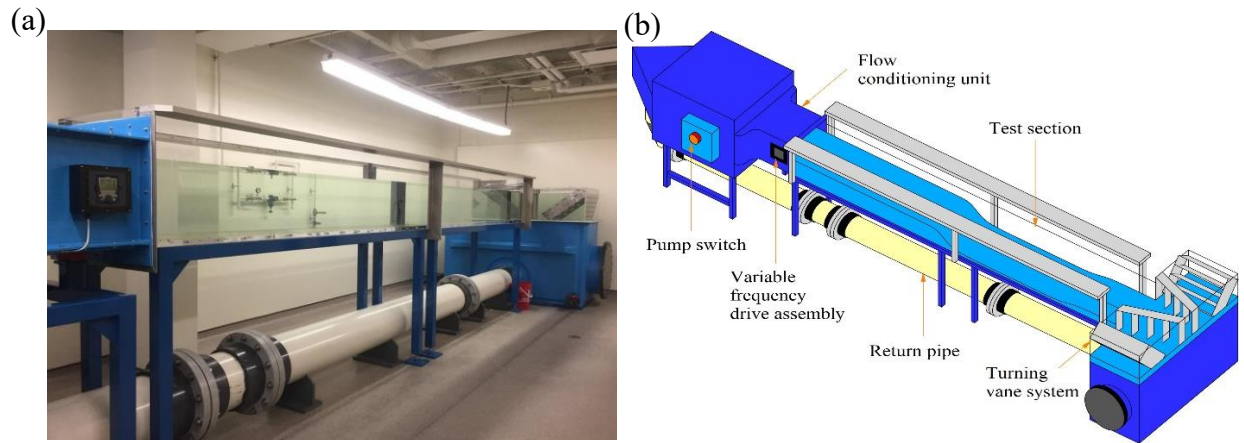


Figure 5.2 A picture (a) and schematic (b) of the open recirculating water channel in the Turbulence and Hydraulics Engineering Laboratory. Picture (b) is redrawn from the Shirinzad et al. (2023)

The Ahmed body model is a quarter-scale version of the original body studied by Ahmed et al. (1984). As illustrated in Fig. 5.3, the model has a total length of $L = 261$ mm, a width of $B = 97.25$ mm, and a height of $H = 72$ mm, supported by four cylindrical struts, each measuring 12.50 mm in height and 7.50 mm in diameter. To minimize the incoming boundary layer thickness, the body was installed on a raised plate that measures 3000 mm in length, 590 mm in width, and 9 mm in thickness. This plate was positioned horizontally in the test section and mounted 50 mm above the floor. Following the method described by Grandemange et al. (2013a) and Kim et al. (2020), the leading and trailing edges of the plate feature a sharp-edge profile with a 45° angle to minimize flow separation. As shown in Figure 5.3, the origin of the coordinate system is located at the bottom of the rear base in the symmetry plane, and x -, y -, and z -coordinates represent the streamwise, wall-normal, and spanwise directions, respectively.

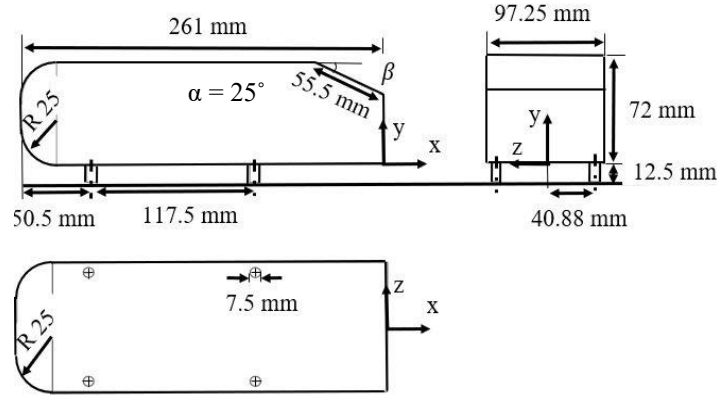


Figure 5.3 Detailed drawings of Ahmed body

5.3.2 Turbulence Generation

Various levels of FST were generated using turbulence-generating grids positioned at the inlet of the test section. A square regular grid (denoted as RG) with a solidity of $\sigma = 48\%$ and two square fractal grids (denoted as FG) with a solidity of $\sigma = 32\%$ (FG32) and 41% (FG41) were fabricated from stainless steel and installed at the inlet of the test section. The grids have a streamwise thickness of 6.35 mm. The grids' specifications are presented in Table 5.2. The fractal grid design follows a square shape and incorporates $N_f = 3$ iterations of fractal patterns, space-filling with a fractal dimension $D_f = 2$ (Hurst & Vassilicos, 2007; Seoud & Vassilicos, 2007). Unlike regular grids, which feature uniform bar thicknesses and generate turbulence through wakes of a single characteristic scale, fractal grids employ a multi-scale design with repeated bar patterns of varying thicknesses. This geometry produces a hierarchy of wake interactions: smaller wakes, shed from the thinnest bars, merge and decay near the grid, while larger wakes, generated by thicker bars, persist and interact at greater downstream distances. This multi-scale wake interaction sustains higher FST intensities and prolongs the turbulence decay region compared to regular grids, where wakes of identical size dissipate more rapidly near the grid (Hurst & Vassilicos, 2007). The production and decay of turbulence downstream of the grids were characterized before installing the Ahmed body. These results are documented in Sagharichi & Tachie (2025).

Table 5.2 Regular and fractal grids' specifications. L_0 to L_2 and t_0 to t_2 represent the bars' length and thickness for each pattern in descending order

Parameters	RG	FG32	FG41
N_f	-	3.0	3.0
L_0 (mm)	62.85	238.0	238.0
L_1 (mm)	-	119.0	119.0
L_2 (mm)	-	59.50	59.50
t_0 (mm)	15.75	28.50	51.0
t_1 (mm)	-	9.25	12.37
t_2 (mm)	-	3.0	3.0
t_0/L_0	0.25	0.12	0.21
σ %	48.0	32.0	41.0

The distance from the leading edge of the raised plate to the leading edge of Ahmed body is $x_{LL} = 2.77H$ for all test cases. Additionally, the distance from each lateral surface of the Ahmed body to the corresponding edge of the plate was set to $3.42H$.

It is noted that the distance from the grid to the leading edge of the Ahmed body is $x_{GL} = 21.94H$, $20.69H$ and $19.30H$ for RG, FG32, and FG41, respectively. Based on flow characterization reported by Sagharichi & Tachie (2025), these distances guarantee that the leading edge of the Ahmed body was positioned in the decay region, where the turbulence is homogeneous and isotropic (Hurst & Vassilicos, 2007). The FST intensity at the location of the leading edge increased from the baseline turbulence intensity of $T_u = 1.5\%$ to 5.0% , 10.0% and 15.0% for RG, FG32 and FG41, respectively. The integral length scales at the Ahmed body's leading edge were measured as $L_u = 0.68H$, $1.07H$, and $1.0H$ for the RG, FG32, and FG41 grids, respectively. These values are of the same order of magnitude ($\sim 1H$) and comparable to the body height. Bearman & Morel (1983) indicated that for flow around road vehicles, FST intensity primarily governs separation and wake dynamics when L_u is smaller than the body scale, as it will tend to decay rapidly over the length of the body. Similarly, Li & Melbourne (1995) reported that for $0.4 < L_u/H$

< 3.8 , the integral length scale did not make any significant difference to the mean pressure distribution of a rectangular plate. Since L_u/H values in this study fall well within this range ($0.4H$ – $3.8H$); the differences in integral length scales across the grids are not expected to impact the flow dynamics. Therefore, any observed differences in the flow dynamics are primarily attributable to variations in FST intensity rather than the integral length scale.

5.3.3 Measurement Procedure

The water level was adjusted to $D = 435$ mm, resulting in a blockage ratio (the proportion of the body frontal area to the test section's area above the raised plate) of 3%, which is smaller than the maximum permissible value of 7.5% to minimize disturbances from the test section walls (Barlow et al., 1999; Deng et al., 2024). The freestream velocity was adjusted to $U_\infty = 0.24$ m/s resulting in $Re = 0.17 \times 10^5$ and Froude number ($F_r = U_\infty / \sqrt{gD}$) = 0.12, sufficiently low to eliminate free surface effects on the flow around the Ahmed body (Tunay et al., 2014; Sagharichi et al., 2023). The boundary layer thickness (in the absence of the body) at $x_{LL} = 2.77H$ was measured as $\delta = 0.68H, 0.79H, 0.86H$, and $0.87H$ for FST intensities of $T_u = 1.5\%, 5.0\%, 10.0\%$, and 15.0% , respectively. This thin boundary layer ensures that the flow impinging on the Ahmed body is dominated by freestream conditions rather than a thick boundary layer (Joseph et al., 2012; Tunay et al., 2013; Sagharichi et al., 2023). A schematic of the experimental setup is shown in Fig. 5.4.

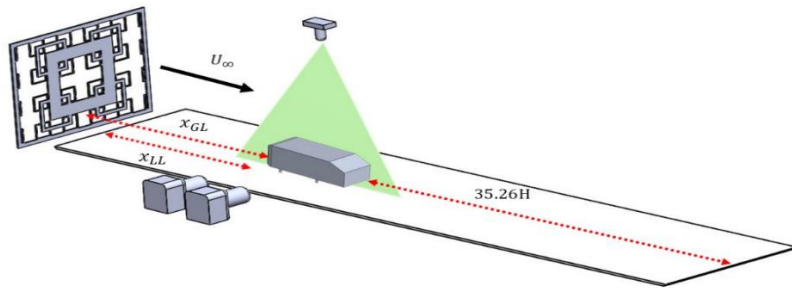


Figure 5.4 Schematic of the experimental setup with FG41 installed at the inlet

The measurements were conducted in the x - y and x - z planes using a planar (2D-2C) PIV technique. The flow was seeded with 10 μm silver-coated hollow glass spheres with a specific gravity of 1.4. The Stokes number was estimated as $S_k = 0.73 \times 10^{-5}$, significantly lower than the threshold of $S_k = 0.05$ proposed by Samimy & Lele (1991) for the particles to follow the flow motion reliably. Illumination was provided by a Photonics DM30-527DH dual-cavity, dual-head, high-speed neodymium-doped yttrium lithium fluoride (Nd:YLF) laser, emitting green light with a wavelength of 527 nm. Each laser has a maximum energy output of 30 mJ/pulse. Two high-speed, 12-bit Phantom VEO340L complementary metal-oxide semiconductor (CMOS) cameras, each with a full resolution of 2560×1600 pixels, were used to capture the images. Measurements in the x - y plane were performed at $z/H = 0$ (symmetry plane), with the laser positioned above the water channel. To reduce laser distortion caused by free-surface bubbles, a 9-mm thick acrylic surface plate (585 mm long and spanning the entire section width) was partially submerged 2 mm beneath the laser sheet (Aleyasin et al., 2021; Sagharichi & Tachie, 2024). To capture the C-pillar vortex in the x - z plane, following Liu et al. (2021), the laser was directed through the sidewall of the test section, with measurements taken in the spanwise plane at $y/H = 0.89$. In the x - y plane, camera 1 and camera 2 had a field of view (FOV_1 and FOV_2) of $288 \text{ mm} \times 180 \text{ mm}$ ($4.0H \times 2.50H$) with an overlap of 10 mm. In the x - z plane, one camera with a field of view of $278 \text{ mm} \times 174 \text{ mm}$ ($3.86H \times 2.41H$) was used. The digital resolution of each FOV was $112.5 \mu\text{m}$ per pixel in the x - y plane and $108.2 \mu\text{m}/\text{pixel}$ in the x - z plane. 60,000 images were captured in time-resolved mode at a sampling frequency of $f_{\text{sp}} = 803 \text{ Hz}$ to resolve all dynamically important vortical structures. Data acquisition was controlled using commercial software (DaVis version 10.2.1) supplied by LaVision Inc. Velocity vectors were computed using a GPU-accelerated, multi-pass cross-correlation algorithm with an initial interrogation window of 128×128 pixels with 50% overlap,

followed by four passes with a final window size of 24×24 pixels and 75% overlap. This iterative process results in a velocity vector spacing of $0.009H$, which is deemed sufficient to resolve small-scale flow structures and consistent with prior PIV studies of Ahmed body flows (Wang et al., 2013; Tunay et al., 2014; Zhang et al., 2015; Venning et al., 2022; Gericke et al., 2023).

The instantaneous velocity component was decomposed into mean and fluctuating components following Reynolds decomposition, $u = U + u'$, where U and u' indicate the mean and fluctuating velocity, respectively. In this study, dimensions and velocities were normalized by the model height (H) and the freestream velocity (U_∞), respectively. Following Sciacchitano and Wieneke (2016) and Essel et al. (2021), the uncertainties in the mean velocities, Reynolds normal stresses, and shear stresses at the 95% confidence level were measured to be $\pm 5.0\%$, $\pm 9.0\%$, and $\pm 6.0\%$, respectively, at the location of maximum turbulence kinetic energy over the roof.

5.4 Results and Discussions

5.4.1 Mean Flow Characteristics

Figure 5.5 shows the streamwise mean velocity contours superimposed with mean streamlines around the body. As the flow approaches the body's leading edge, the shear layer separates at the end of the rounded front part of the body and subsequently reattaches over the roof (see Figs. 5.5a, 5.5c, and 5.5e and 5.5g). This leads to a recirculation bubble known as the roof bubble. Within the roof bubble, there is a small recirculation bubble that counter-rotates with respect to the roof bubble at $T_u = 1.5\%$ but is suppressed at higher FST intensities. This bubble, which is often referred to as a secondary bubble, was also observed in wall-mounted bluff bodies (Rastan et al., 2021; Goswami & Hemmati, 2024) and rectangular prisms in uniform flow (Ricci et al., 2017; Kumahor & Tachie, 2021; Zhang et al., 2023; Abdul-Salam et al., 2024), and is attributed to the adverse pressure

gradient caused by the decelerating reverse flow near the leading edge. Figures 5.5b, 5.5d, 5.5f, and 5h show contours of streamwise mean velocity over the slanted surface and in the wake region. As the flow reattaches over the roof, a new boundary layer develops and detaches from the leading edge of the slanted surface. It then attaches further downstream, forming a slanted bubble (Ahmed et al., 1984; Zhang et al., 2015; Sagharichi & Tachie, 2024). After reattachment on the slanted surface, the flow separates at the trailing edge of the slanted surface, creating a wake region. The wake region is characterized by two counter-rotating horseshoe vortices: one originating from the slanted surface (upper bubble) and the other from the undersurface of the body (lower bubble). Previous numerical and experimental results show a similar arrangement of vortices in the wake region (Tunay et al., 2014; Ashton & Revell, 2015; Delassaux et al., 2021; Li et al., 2022).

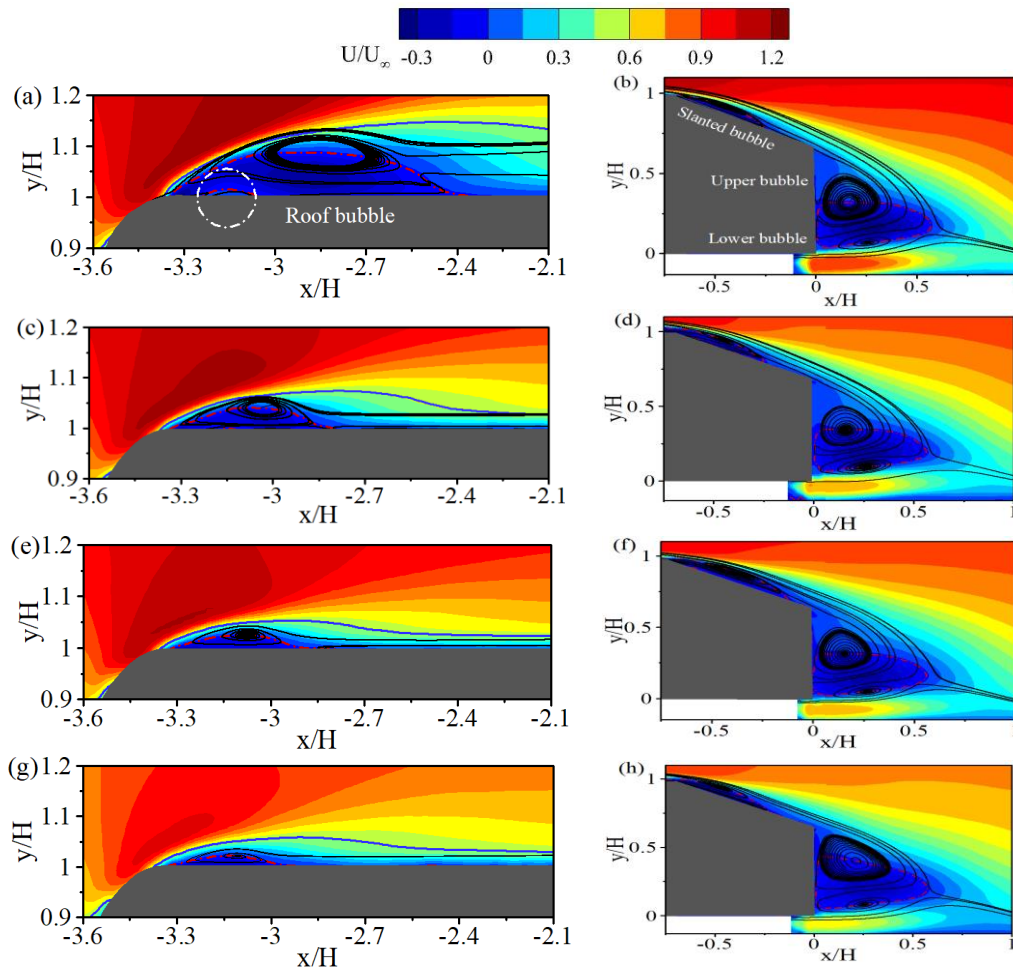


Figure 5.5 Contours of normalized streamwise mean velocity superimposed with mean streamlines [(a), (c), (e) and (g)] over the roof and [(b), (d), (f) and (h)] the slanted surface and wake region for [(a) and (b)] $T_u = 1.5\%$; [(c) and (d)] $T_u = 5.0\%$; [(e) and (f)] $T_u = 10.0\%$ and [(g) and (h)] $T_u = 15.0\%$. The dashed-dot line shows the recirculation bubble.

Figure 5.6 shows the variations of recirculation length over the roof, slanted surface, and wake region with FST. Over the roof, both the recirculation length and bubble height (h_r) decreases monotonically from $L_{e,r}/H = 0.90$ to 0.32 and $h_r/H = 0.08$ to 0.01 , respectively, as FST intensity increases from $T_u = 1.5\%$ to 15.0% . As shown by the slopes of the linear fits, the rate of reduction in recirculation length and bubble height is steeper from $T_u = 1.5\%$ to $T_u = 5.0\%$ compared to $T_u = 5.0\%$ to $T_u = 15.0\%$. This reduction in recirculation length and height with FST intensity is consistent with that observed over blunt flat plates (Kiya & Sasaki, 1983) and airfoils with constant thickness (Samson & Sarkar, 2016). Over the slanted surface, the recirculation length of the slanted bubble increases slightly from $L_{s,r}/H = 0.35$ to 0.41 as the FST level increases from $T_u = 1.5\%$ to 10.0% and remains unchanged from $T_u = 10.0\%$ to $T_u = 15.0\%$. In the wake region, the recirculation length is independent of the FST level ($L_{w,r}/H \approx 0.56$), which is within the range of $L_{w,r}/H \in [0.54 - 0.67]$ reported in previous studies (Wang et al., 2013; Tunay et al., 2014; Zhang et al., 2015; McNally et al., 2019). This trend can be attributed to the rapid dissipation of FST over the body's surface and shielding of the wake by the Ahmed body's geometry, which limits FST's influence on the large-scale recirculation structure (Chen et al., 2022). The relative independence of wake recirculation length with changing FST intensity agrees with previous studies on a wall-mounted square (Hearst et al., 2016) and a rectangular cylinder in freestream flow (Zhu et al., 2020) under elevated FST conditions.

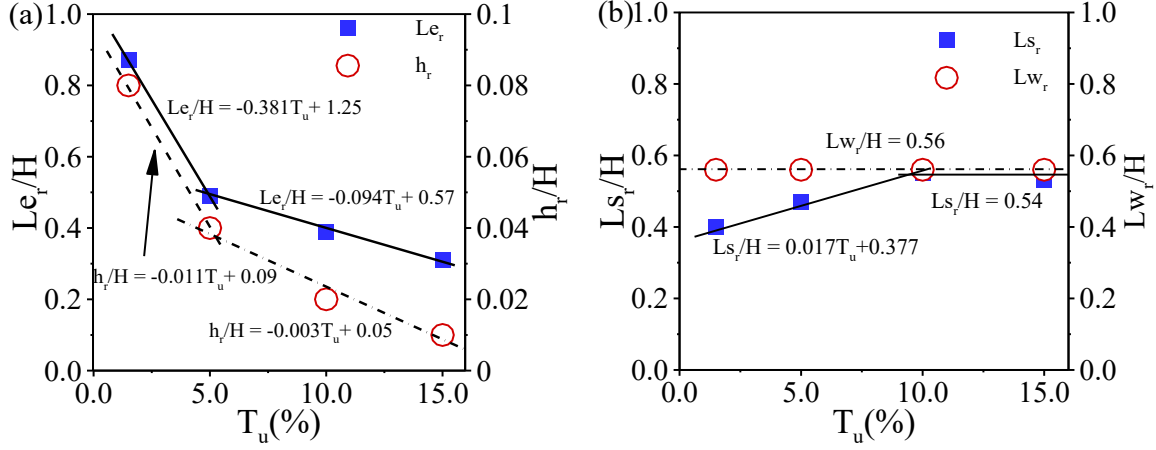


Figure 5.6 Recirculation length and bubble height variation with FST intensity (a) over the roof and (b) over the slanted and wake region

As shown in Figs. 5.5 and 5.6, FST intensity primarily influences the mean characteristics of the roof bubble. This finding indicates that the shear layer originating from the leading edge exhibits higher receptivity to FST intensity, aligning with Zhu et al. (2020) and Zhang et al. (2023) measurements. To further investigate the roof bubble dynamics, Figure 5.7 illustrates the probability distribution (P_x) of the reattachment point on the roof. In this analysis, the flow field over the roof was calculated by the probability of points where $U < 0$ occurred for the first time. The vertical dashed line in the plots represents the mean reattachment point of the roof bubble (x_r). Figures 5.7a and 5.7b demonstrate that at $T_u = 1.5\%$, the probability distribution of the reattachment point is distinctly bimodal. The location of the upstream peak corresponds to the reattachment point of the secondary recirculation bubble observed in Fig. 5.5, while the downstream peak aligns closely with the mean reattachment point of the roof bubble. For the higher FST intensities, the probability distribution becomes unimodal, with the peak coinciding with the location of the reattachment point. A comparison of the figures also reveals that the flow tends to attach to the roof surface at downstream locations more frequently for $T_u = 1.5\%$. This behaviour reflects the presence of a larger, less stable recirculation bubble at the lower FST

intensities, while increasing FST reduces flow reattachment intermittency on the roof surface. This observation is consistent with previous findings on separation and attachment dynamics, such as those reported for a thick flat plate subjected to FST intensity (Saathoff & Melbourne, 1997) and a wall-mounted cube immersed in a turbulent boundary layer (Hearst et al., 2016).

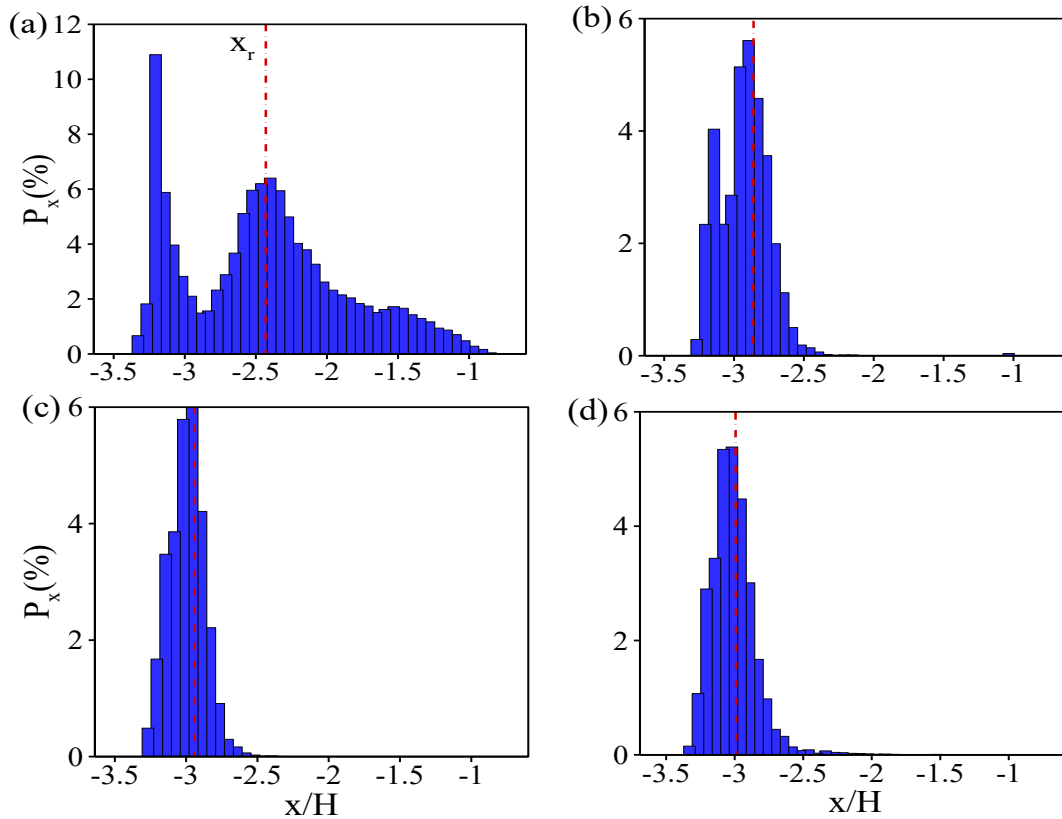


Figure 5.7 Probability distribution (P_x) of the first reattachment point on the roof for (a) $T_u = 1.5\%$, (b) $T_u = 5.0\%$; (c) $T_u = 10.0\%$ and (d) $T_u = 15.0\%$. x_r indicates the roof bubble reattachment point

Figure 5.8a shows the streamwise variation of maximum velocity deficit $\Delta U = U_{\max} - U_{\min}$. In this analysis, $U_{\max}$ and $U_{\min}$ are the local maximum and minimum streamwise mean velocities, respectively. The profiles rise steeply, reaching a peak at the point of maximum backflow velocity. Similar to the power-law trend observed in the wake region of permeable disks subjected to the various FST intensities (Li et al., 2024a), the profile for $T_u > 1.5\%$ experiences an approximately power-law decline, followed by a plateau. However, for $T_u = 1.5\%$, a small recirculation bubble in the roof bubble alters the trend. Specifically, after reaching its peak, the profile first declines,

then plateaus, followed by another decrease before stabilizing again. Increasing FST intensity shifts the starting point of recovery upstream, reduces the magnitude of velocity deficit, and increases the recovery rate.

Figure 5.8b shows the distributions of the mean pressure coefficient $C_p (= 1 - (U_e^2 + V_e^2 / U_\infty^2))$ over the roof. Here U_e and V_e are streamwise and wall-normal edge velocities of the shear layer, defined as the maximum velocity in the freestream side of a separated shear layer (Mohamed Aniffa et al., 2023). As shown in the figure, the distribution of the mean pressure coefficient at $T_u = 1.5\%$ closely aligns with the literature (Ladwig et al., 2023). The C_p profile exhibits a low-pressure region near the leading edge, consistent with the shear layer detachment and the formation of the roof bubble. For $T_u = 1.5\%$, the C_p profile suggests a more extended low-pressure region, consistent with a larger recirculation bubble and delayed reattachment (Fig. 5.5). At $T_u \geq 5.0\%$, the pressure recovery grows monotonically, aligning with the earlier flow reattachment with FST intensity observed in Fig. 5.5. The negative peak in the mean pressure coefficient decreases while the location of the minimum mean pressure coefficient shifts further upstream as freestream turbulence intensity increases.

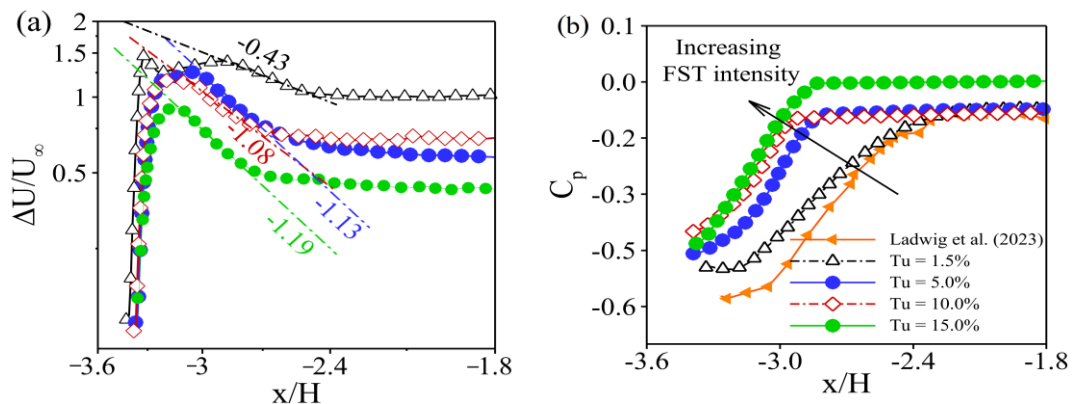


Figure 5.8 Streamwise development of velocity deficit (a) and mean pressure coefficient over the roof (b)

5.4.2 Reynolds Stresses and Flow Reattachment Over the Roof

Figure 5.9 illustrates the streamwise evolution of the maximum Reynolds normal stresses ($\overline{u'u'}$ and $\overline{v'v'}$), shear stress ($\overline{u'v'}$) and turbulent kinetic energy ($\text{TKE} = 0.5 (\overline{u'u'} + \overline{v'v'})$) over the roof. The plots exhibit a characteristic growth–peak–decay behaviour, consistent with the observations of Stevenson et al. (2016) for separated flow from the leading edge of a round-nosed plate. Regardless of FST intensity, the peak magnitude of $\overline{u'u'}$ remains higher than that of other Reynolds stresses, consistent with the observations of Grandemange et al. (2013a) for a square-back Ahmed body. The peak magnitudes of each Reynolds stress over the roof decrease with increasing FST intensity, while the peak location shifts closer to the leading edge, indicative of an earlier shear layer roll-up under higher FST conditions. Notably, the decay rates of TKE for $T_u \geq 5.0\%$ become remarkably similar as the flow evolves downstream. This similarity may suggest the presence of a shear sheltering effect, as explained by Hunt & Durbin (1999) and Kalter & Fernholz (2001). According to this mechanism, the efflux from the recirculation bubble acts as a protective layer, reducing the influence of external turbulence on the reattaching boundary layer in downstream regions. Additionally, a second peak in the $\overline{u'u'}$, $\overline{v'v'}$ and TKE plots are evident close to the leading edge for $T_u = 1.5\%$. The location of this peak corresponds to the secondary recirculation bubble identified in Fig. 5.5. However, this secondary peak vanishes as the FST, aligning with the disappearance of the secondary recirculation bubble from the mean flow dynamics.

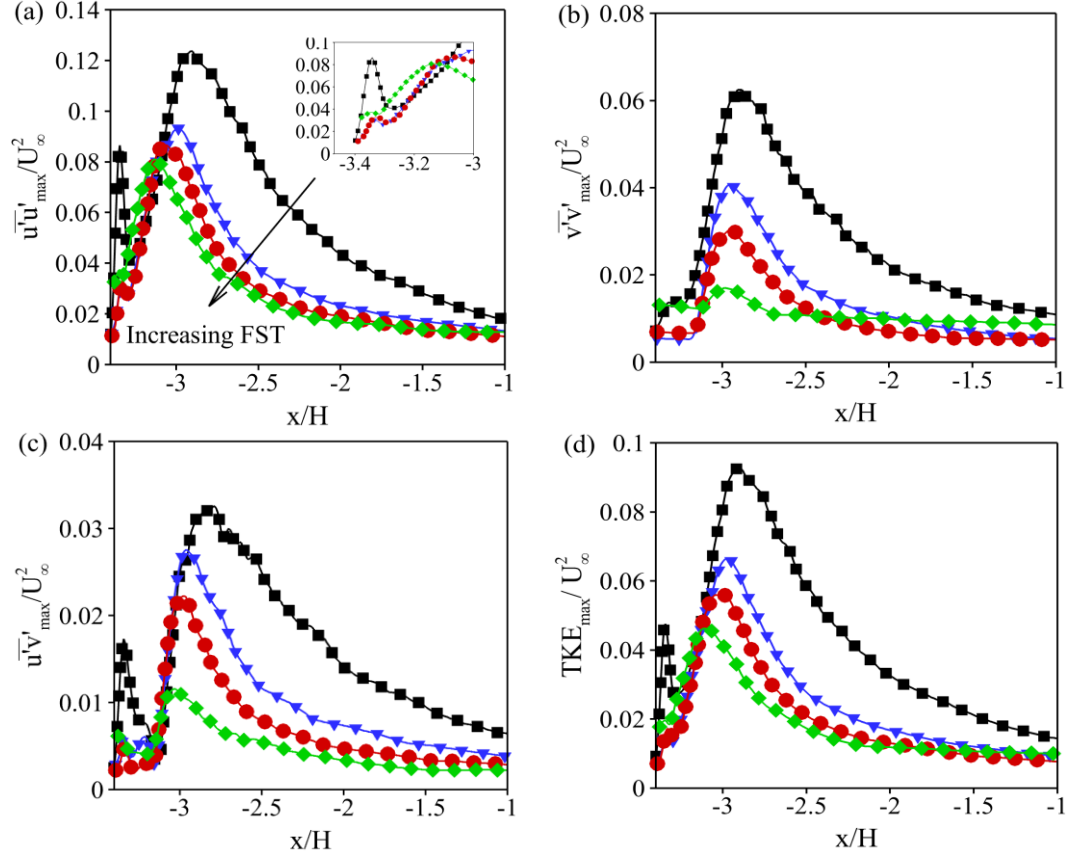
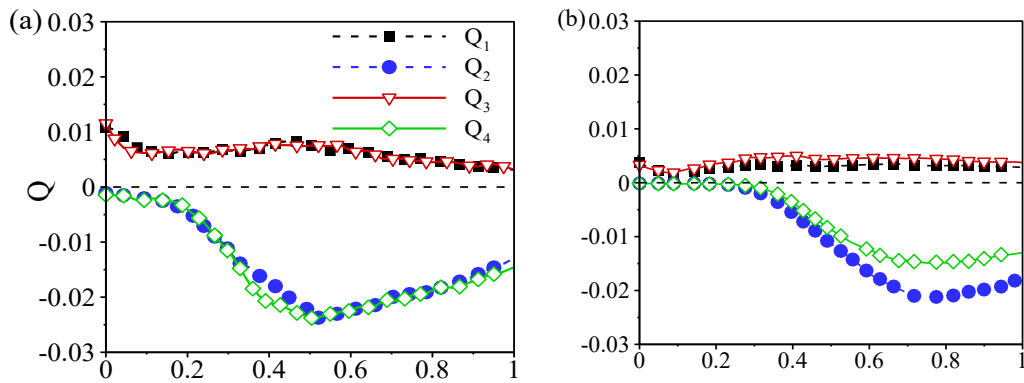


Figure 5.9 Streamwise evolution of maximum (a) $\overline{u'u'}$ (b) $\overline{v'v'}$ (c) $\overline{u'v'}$ and (d) TKE over roof

The quadrant analysis (Nolan et al., 2010; Wallace et al., 2016) is used to provide insights into the turbulent transport mechanisms governing the shear layer along the roof bubble under varying FST intensities. This approach decomposes the contributions of the turbulent fluctuations to Reynolds shear stress into four quadrant events, which are defined as outward interactions in quadrant 1 (Q_1 : $u' > 0$ and $v' > 0$), ejections in quadrant 2 (Q_2 : $u' < 0$ and $v' > 0$), inward interactions in quadrant 3 (Q_3 : $u' < 0$ and $v' < 0$), and sweeps in quadrant 4 (Q_4 : $u' > 0$ and $v' < 0$). Shear layer evolution is driven by either the transport of high-momentum fluid into the wall ($u' > 0$ and $v' < 0$) or the transport of low-momentum fluid away from the wall into the shear layer ($u' < 0$ and $v' > 0$) (Gambuzza & Ganapathisubramani, 2023). Figure 5.10 shows the quadrant events over the roof shear layer for different FST intensities. The figure shows that for all FST intensities, the roof

shear layer is dominated by Q_2 and Q_4 events. Consistent with the reduction of $\overline{u'v'}$ with FST intensity (see Fig. 5.9), increasing FST intensity diminishes Q_2 and Q_4 events, while Q_1 and Q_3 events remain unchanged. The reduction in Q_2 and Q_4 events are consistent with the observation made by Li et al. (2024a) for high FST intensity around permeable disks. This reduction indicates that the primary mechanisms driving shear layer evolution (Q_2 and Q_4 events) are progressively suppressed as FST intensity increases. Consequently, the roof shear layer exhibits greater stability (Gambuzza & Ganapathisubramani, 2023). While sweep and ejection events provide similar contributions to $\overline{u'v'}$ at $T_u = 1.5\%$, increasing FST intensity suppresses sweep events more than ejections. Specifically, Q_4 decreases by 18.2%, 31.8%, and 40.9% for $T_u = 5.0\%$, 10.0%, and 15.0%, respectively, while Q_2 decreases by 9.1%, 22.7%, and 27.3%, indicating that sweep events are more sensitive to increasing FST. This shift in balance between Q_2 and Q_4 events emphasize the ejections' more important dynamic role in driving momentum within the roof bubble under elevated FST conditions. The imbalance creates a net upward transport of momentum away from the separation bubble due to ejections. This enhances flow acceleration downstream of the bubble and promotes a faster flow reattachment.



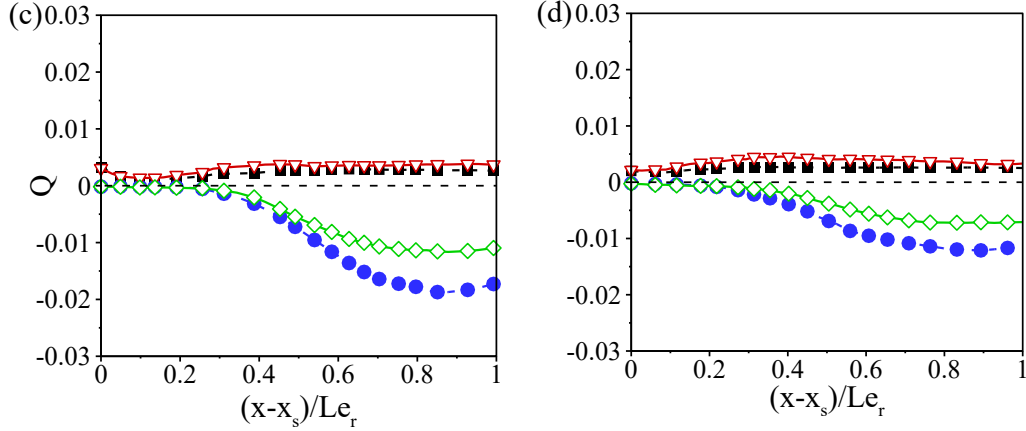


Figure 5.10 Quadrant analysis along the roof shear layer. (a) $T_u = 1.5\%$, (b) $T_u = 5.0\%$; (c) $T_u = 10.0\%$ and (d) $T_u = 15.0\%$. x_s denotes the roof bubble separation point

5.4.3 Development of Turbulent Structures Over the Roof

This section analyses how FST intensity affects boundary layer and vortical structure development after flow reattachment on the roof. Beyond the reattachment point, the interaction of elevated Reynolds stresses with coherent turbulent structures leads to the development of transitional features in the boundary layer (Li et al., 2024). The shape factor (H^*), defined as the ratio of displacement thickness to momentum thickness, is employed as a quantitative measure to diagnose laminar-to-turbulent transition and is calculated using the following expression:

$$H^* = \frac{\delta^*}{\theta} \quad (5.1)$$

where δ^* and θ represent the displacement and momentum thickness, respectively, and are calculated using equations (5.2) and (5.3), respectively.

$$\delta^* = \int_0^\delta \left(1 - \frac{U}{U_\infty}\right) dy \quad (5.2)$$

$$\theta = \int_0^\delta \frac{U}{U_\infty} \left(1 - \frac{U}{U_\infty}\right) dy \quad (5.3)$$

Here, δ represents the boundary layer thickness, determined as $U_\delta = 0.99 U_\infty$.

The boundary layer can be classified as the laminar regime ($H^* \geq 2.59$), laminar-to-turbulent transition regime ($1.40 < H^* < 2.59$) and fully turbulent ($H^* \leq 1.40$) (Hoffmann, 1981; Li et al., 2024). Figure 5.11 shows the streamwise distribution of the shape factor from the reattachment point up to the leading edge of the slanted surface. Regardless of FST intensity, the shape factor decreases as the boundary layer develops over the roof and reaches a plateau. This observation aligns with the boundary layer characteristics observed downstream of the reattachment point of the recirculation bubble induced by the adverse pressure gradient (Kalter & Fernholz, 2001; Stevenson et al., 2014) and induced over an airfoil (Samson & Sarkar 2016) and rectangular prism (Li et al., 2024). The evolution of H^* reveals that at $T_u = 10.0\%$ and 15.0% , the boundary layer remains in the laminar-to-turbulent transition regime over a longer region compared to $T_u = 5.0\%$ and 1.5% . The laminar-to-turbulent transition regime starts at $x/H = -2.79$ and -2.14 for $T_u = 5.0\%$ and 1.5% , respectively. Similarly, the fully turbulent regime occurs at $x/H = -2.0$ and -2.14 for $T_u = 10.0\%$ and $T_u = 15.0\%$, while this occurs further downstream at $x/H = -1.60$ and $x/H = -0.77$ for $T_u = 5.0\%$ and 1.5% , respectively.

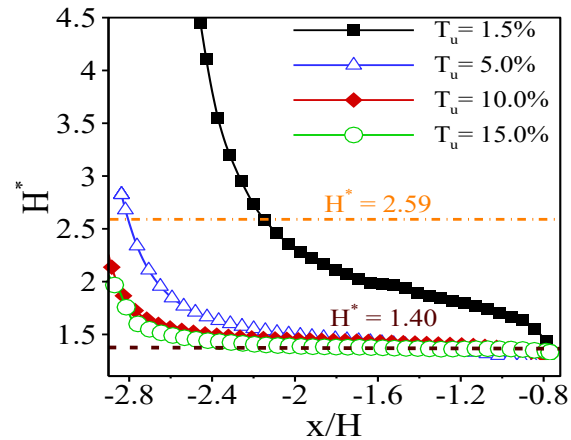


Figure 5.11 Streamwise evolution of shape factors after reattachment point for different FST intensities

The root mean square of the streamwise velocity fluctuation profiles in Fig. 5.12 examines how FST intensity influences boundary layer transition and the onset of turbulence. The analysis is conducted at three streamwise locations ($x/H = -2.0, -1.5, \text{ and } -1.0$) downstream of the reattachment point to track turbulent energy growth and boundary layer development. Figure 5.12a illustrates that the u'_{rms} profile exhibits a sharp peak that moves away from the roof as the flow progresses downstream. This observation is consistent with the results related to the shape factor, suggesting that the boundary layer is not in a fully turbulent regime at this specific FST intensity. At $T_u = 5.0\%$ and 10.0% a second u'_{rms} peak gradually appears inside the boundary layer, while at $T_u = 15.0\%$ the u'_{rms} profile becomes fuller, reflecting the development of a more energetic and spatially distributed turbulent boundary layer (Li et al., 2024). The emergence of the second peak enhances momentum transport within the boundary layer. The second peak at $T_u = 5.0\%$ and 10.0% give rise to an inflection point between the two peaks due to the sheltering effect near the wall caused by the strong mean shear (Hunt & Durbin, 1999; Jacobs & Durbin, 2001). This sheltering region filters low-frequency disturbances to penetrate near the wall region and generate streaks (Zaki & Saha, 2009; Wang et al., 2019). A key observation is that at $T_u = 15.0\%$, turbulence energy is more evenly distributed across the boundary layer, suggesting greater mixing and a sustained transition region. This aligns with Fig. 5.11, which shows that at higher FST, the shape factor decreases more gradually, indicating a prolonged transition phase before reaching a fully turbulent regime. This observation is consistent with findings by Li et al. (2024) and Samson & Sarkar (2016).

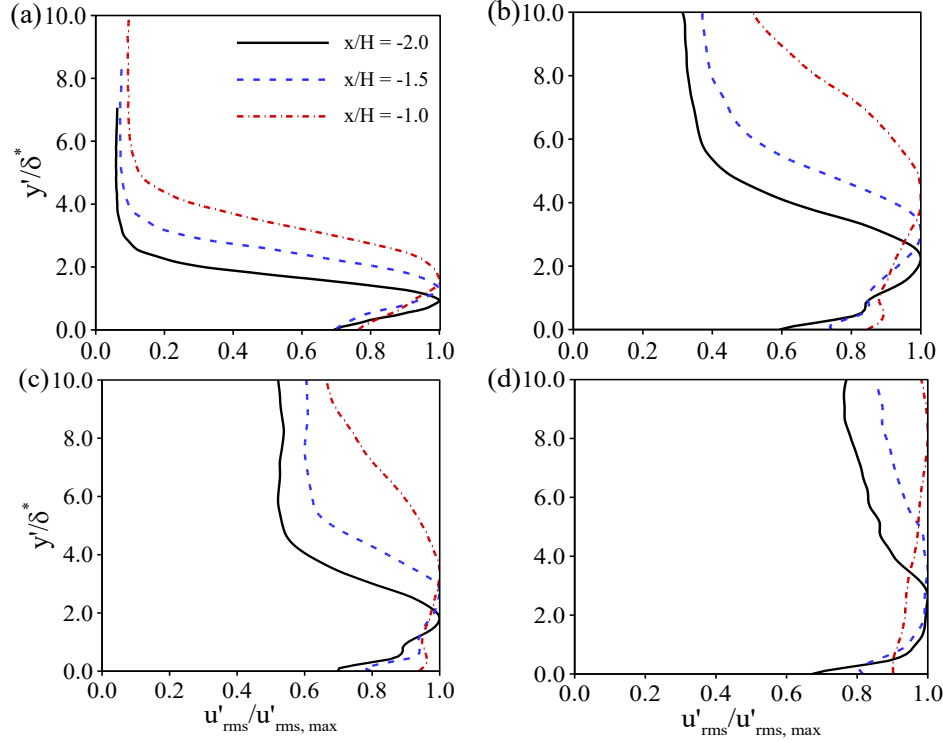


Figure 5.12 Profiles of the streamwise velocity fluctuation intensity for streamwise locations of $x/H = -2.0, -1.5$ and -1.0 . (a) $T_u = 1.5\%$, (b) $T_u = 5.0\%$; (c) $T_u = 10.0\%$ and (d) $T_u = 15.0\%$

The interaction between streamwise and wall-normal velocity fluctuations is examined through Joint Probability Density Functions (JPDF) to analyze the mechanisms governing the transition to turbulence and the evolution of turbulent structures within the shear layer. Figure 5.13 shows the JPDF of streamwise and wall-normal fluctuation velocities at the location of maximum TKE at $x/H = -1.5$. The inclination angle of the JPDF structure is also indicated for each FST intensity. For $T_u = 1.5\%$ (laminar-to-turbulent transition regime), the JPDF contours are skewed toward the second and fourth quadrants, indicating the dominance of sweep (Q_2) and ejection (Q_4) events consistent with localized turbulence development near the wall (Fig. 5.13a). As T_u increases to 15.0% (fully turbulent boundary layer), the JPDF rotates counterclockwise and stretches along the streamwise axis. In this regime, wall-normal fluctuations diminish, with a higher probability density concentrated near the positive or negative streamwise fluctuation velocity. This

observation aligns with turbulent flow behavior in the boundary layer over the flat plate subjected to high FST intensity (Nolan et al., 2010).

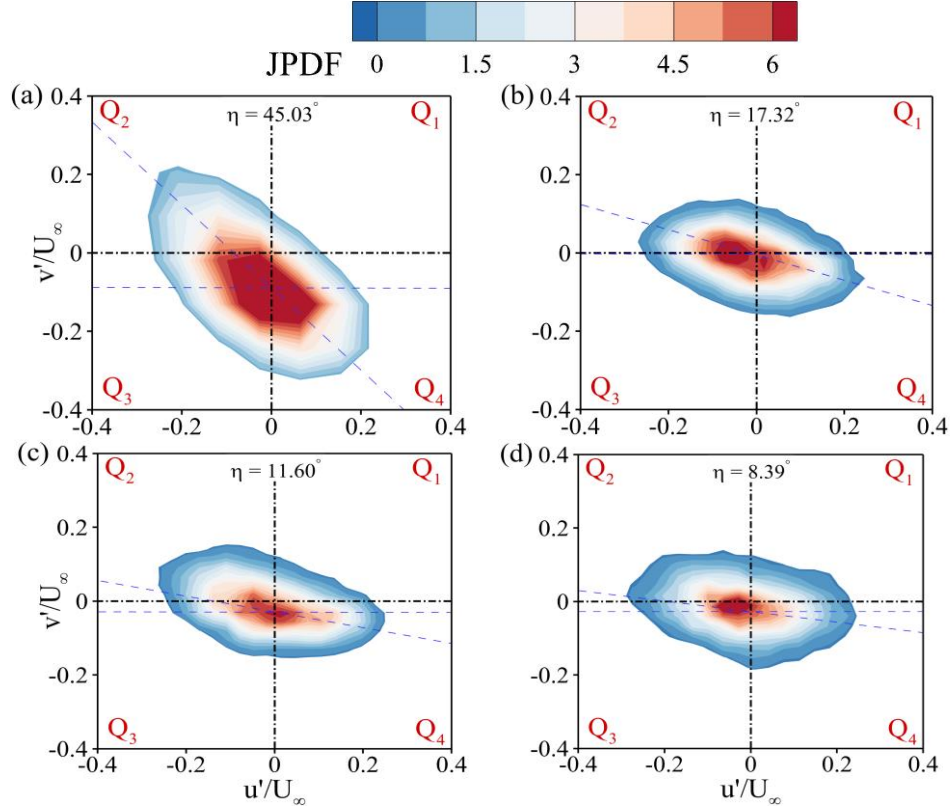


Figure 5.13 JPDF of u' and v' at $x/H = -1.5$ for (a) $T_u = 1.5\%$, (b) $T_u = 5.0\%$; (c) $T_u = 10.0\%$ and (d) $T_u = 15.0\%$. The inclination angle of each JPDF structure is indicated as η

Figure 5.14 illustrates velocity fluctuation for $T_u = 1.5\%$ and $T_u = 15.0\%$ at two instances corresponding to the extreme ends of the joint JPDFs shown in Fig. 5.13. For $T_u = 1.5\%$ (Fig. 5.14a) the laminar to turbulence regime ($x/H > -2.14$) is marked by localized positive and negative streamwise velocity fluctuations, which evolve downstream. In contrast, under high FST intensity ($T_u = 15.0\%$), the roof flow is characterized by elongated streaks (Fig. 5.14b). These structures dominate the boundary layer and drive the flow into a fully turbulent regime. This observation aligns with the findings of Hosseini-verdi & Fasel (2019), who identified the formation of streaks downstream laminar separation bubbles (LSBs) as a critical mechanism in accelerating

the transition process under moderate ($T_u = 0.5\% - 1.0\%$) to high ($T_u = 2.0\% - 3.0\%$) FST intensities.

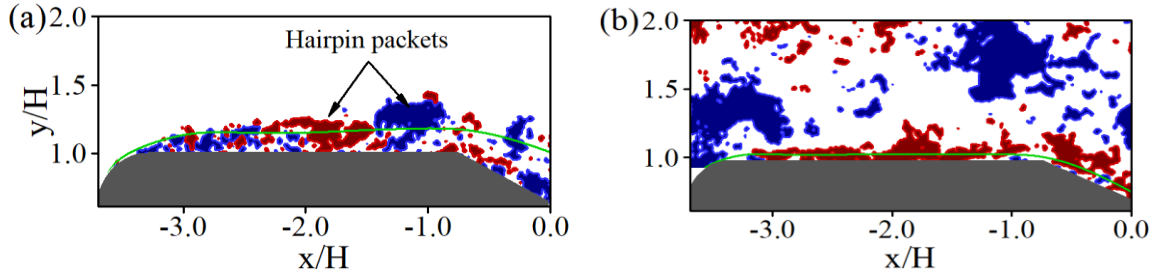


Figure 5.14 Instantaneous iso contours of $|u'/U_\infty| = 0.12$, represented by blue (negative u') and red (positive u'). (a) $T_u = 1.5\%$, (b) $T_u = 15.0\%$. The mean streamline emanating from the leading edge is superimposed on the figure (Multimedia available online)

The influence of FST intensity on the spatial characteristics of the hairpin vortex packets and longitudinal streaks over the roof is evaluated using the spatial two-point autocorrelation of the streamwise fluctuation velocities. The spatial two-point autocorrelation is defined as:

$$R_{u'u'}(x_{\text{ref}}, y_{\text{ref}}, r_x) = \frac{\overline{u'(x_{\text{ref}}, y_{\text{ref}})u'(x_{\text{ref}} + r_x, y_{\text{ref}})}}{\sqrt{\overline{u'(x_{\text{ref}}, y_{\text{ref}})^2}} \sqrt{\overline{u'(x_{\text{ref}} + r_x, y_{\text{ref}})^2}}} \quad (5.4)$$

where $(x_{\text{ref}}, y_{\text{ref}})$ is the reference point, r_x represents the relative spatial streamwise displacement.

The reference points are chosen at the following four locations: $(x/H, y/H) = (-3.30, \delta)$, $(-2.0, 0.15\delta)$, $(-1.5, 0.15\delta)$ and $(-1.0, 0.15\delta)$, where δ is the local boundary layer thickness. The results, shown in Fig. 5.15, include the inclination angle α of the hairpin vortex structures. For $T_u = 1.5\%$, the size of hairpin structures remains unchanged as they evolve downstream. In contrast, at higher FST intensities, the autocorrelation results show increased vortex stretching and growth, suggesting that newly generated vortices accumulate and merge, contributing to a more sustained turbulent regime. The structures' spatial extent and inclination angle increase with higher FST intensity. For all FST intensities, the inclination angle decreases along the streamwise direction

and varies from $\alpha = 10.5^\circ$ to 4.3° for $T_u = 1.5\%$, and 17.3° to 12.1° for $T_u = 15.0\%$. The inclination angle falls within the range $3.0^\circ \leq \alpha \leq 35.0^\circ$ measured using the inclination of hairpin packets in the x-y plane obtained from PIV data over a flat plate, as reported by Adrian et al. (2000). A Higher inclination angle of turbulent structures with FST intensity suggests a significant lift-up of the hairpin vortex structures as FST intensity increases.

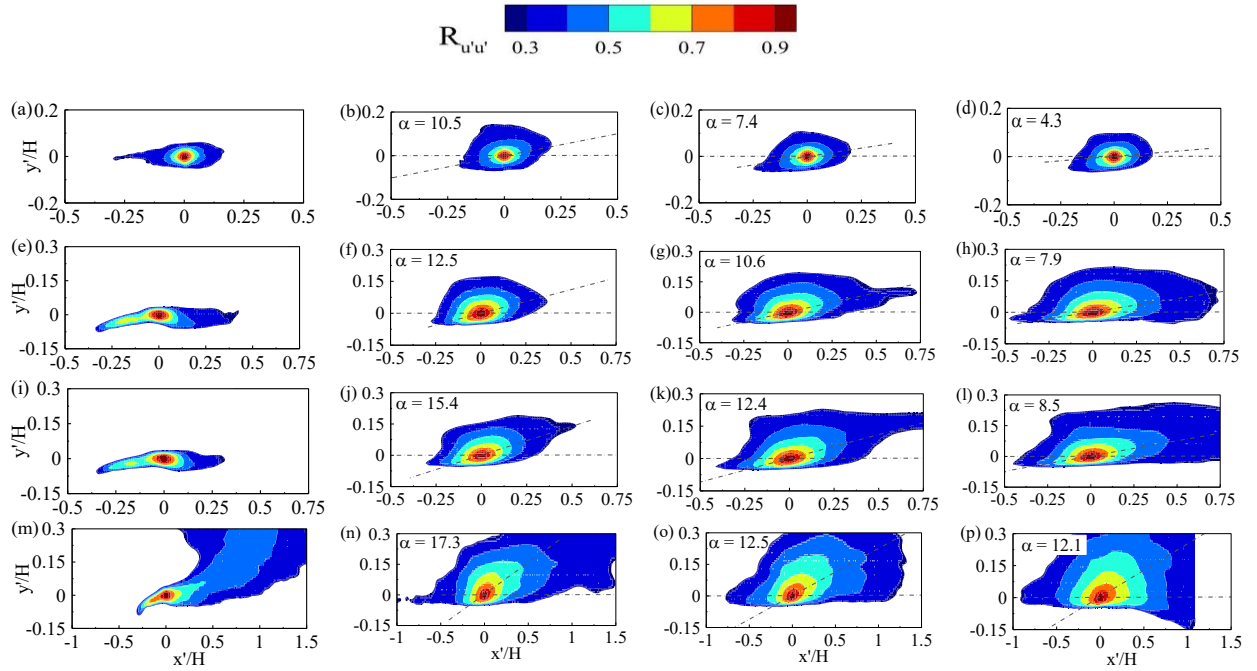


Figure 5.15 Two-point correlations of the streamwise fluctuation velocity for [(a-d)] $T_u = 1.5\%$, [(e-h)] $T_u = 5.0\%$, [(i-l)] $T_u = 10.0\%$ and [(m-p)] $T_u = 15.0\%$. The reference points are $(x'/H, y'/H) = (-3.30, \delta)$, [(a), (e), (i), (m)]; $(-2.0, 0.15\delta)$ [(b), (f), (j) and (n)]; $(-1.5, 0.15\delta)$ [(c), (g), (k) and (o)] and $(-1.0, 0.15\delta)$ [(d), (h), (l) and (p)]

Figure 5.15 shows that as FST intensity increases, a stronger correlation exists between the reference point and the structures emanating from the leading edge. To investigate the mechanism underlying this behaviour, the JPDP of streamwise and wall-normal velocity fluctuations at $(x'/H, y'/H) = (-3.30, \delta)$ at the mean separation point is analyzed and shown in Figure 16. For $T_u = 1.5\%$, the JPDP exhibits an independent trend between u' and v' near the leading edge. However,

as FST intensity increases, the JPDF transforms into an elliptical shape, increasingly stretching toward Q_1 and Q_3 . Similar JPDF structures have been observed in boundary layers on flat plates exposed to elevated freestream turbulence (Nolan et al., 2010; Nolan et al., 2012) and are attributed to the presence of Klebanoff structures, which are elongated, narrow streamwise features formed by the penetration of freestream turbulence into the boundary layer, manifesting as positive (high-speed) and negative (low-speed) streaks that amplify local instabilities and accelerate the laminar-to-turbulent transition. The formation of Klebanoff structures accelerates the transition to turbulence by amplifying local instabilities, leading to the earlier breakdown of laminar flow.

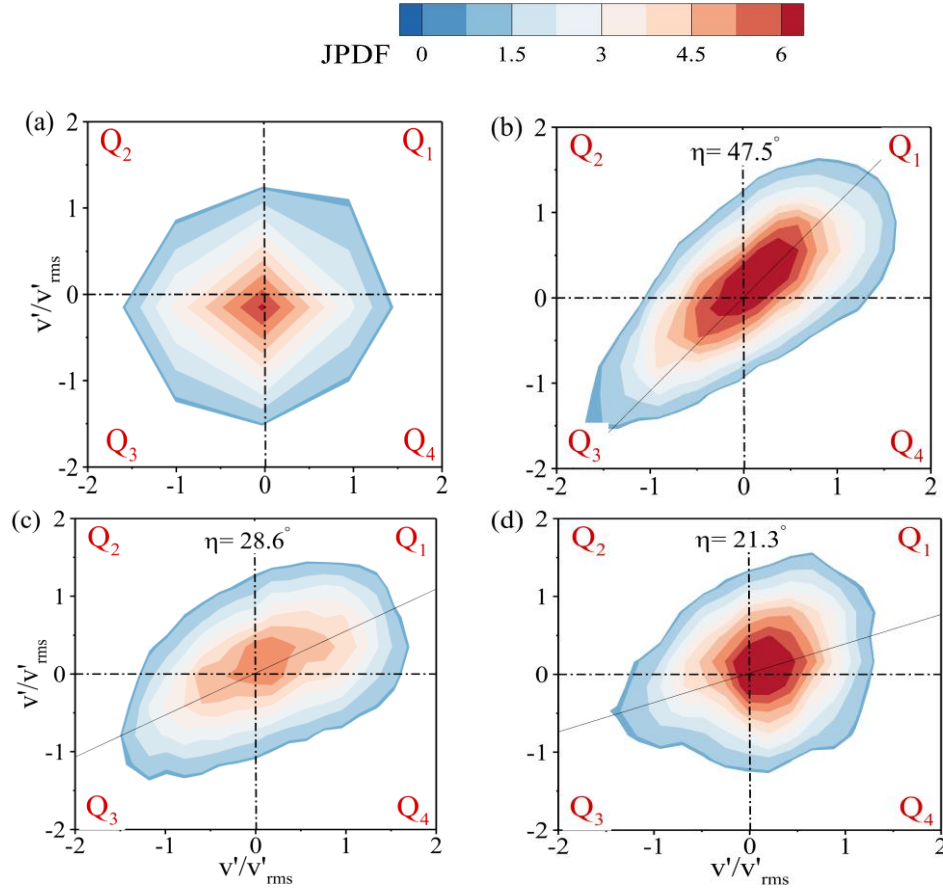


Figure 5.16 JPDF of u' and v' ($x/H, y/H$) = $(-3.30, \delta)$ for (a) $T_u = 1.5\%$, (b) $T_u = 5.0\%$; (c) $T_u = 10.0\%$ and (d) $T_u = 15.0\%$. The inclination angle of each JPDF structure is indicated as η

5.4.4 Reynolds Stresses Over the Slanted Surface and Wake Regions

The plots of Reynolds stresses and TKE over the slanted and wake regions are shown in Fig. 5.17 to assess the effects of FST intensity on turbulent dynamics in these regions. The contours reveal two distinct peaks: over the slanted surface (along the line of $U/U_\infty = 0.5$), associated with the separated shear layer from the upper edge of the slanted surface and downstream of the lower edge of the base in the wake region. The latter peak is linked to the periodic motion of the upper and lower bubbles, as previously observed by Tunay et al. (2014), Zhang et al. (2015), and Sagharichi et al. (2023). Notably, the elevated region in the wake occurs closer to the lower edge, driven by the dominance of downwash flow over upwash flow. For the shear layer over the slanted surface, the peak magnitudes of $\overline{u'u'}$ and $\overline{u'v'}$ remain constant at 0.03 and -0.02 , regardless of FST intensity. However, the maximum values of $\overline{v'v'}$ and TKE increases from 0.02 to 0.03 as FST intensity increases from $T_u = 1.5\%$ to $T_u \geq 5.0\%$. In the wake region, increasing FST levels from $T_u = 1.5\%$ to $T_u = 5.0\%$ leads to a reduction in the peak values of Reynolds stresses and TKE: $\overline{u'u'}$ decreases by 33.3%, $\overline{v'v'}$ by 25.0%, $\overline{u'v'}$ by 33.3% and TKE by 20%. Further increasing the FST level to $T_u = 10.0\%$ does not alter these peak magnitudes. However, at $T_u = 15.0\%$, a significant suppression is observed: $\overline{v'v'}$, $\overline{u'v'}$ and TKE decrease by 33.3%, 25.0%, and 50.0%, respectively, while $\overline{u'u'}$ remains unaffected.

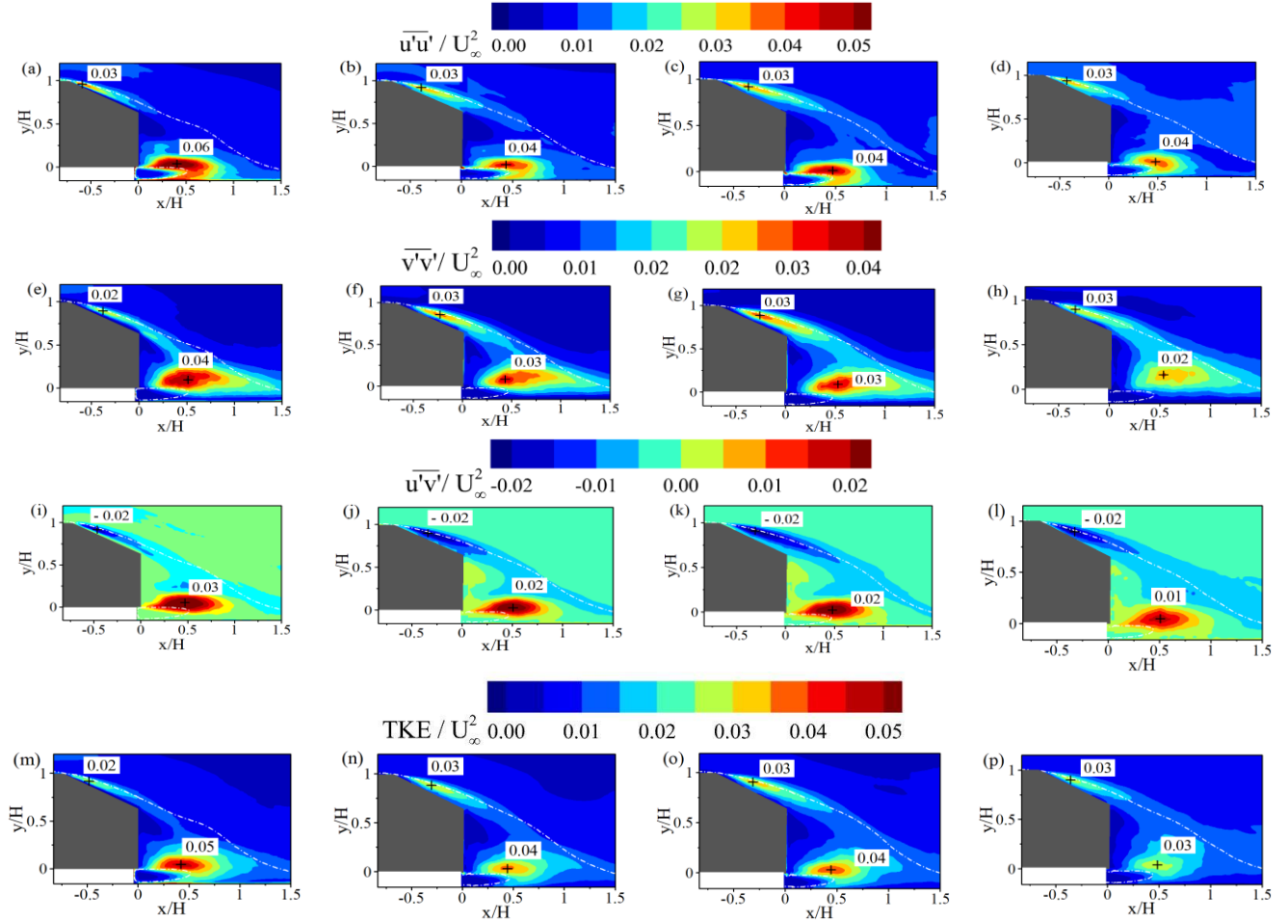


Figure 5.17 Contours of [(a-d)] normalized streamwise Reynolds normal stress ($\overline{u'u'}$) [(e-h)] wall-normal Reynolds normal stress ($\overline{v'v'}$), [(i-l)] Reynolds shear stress ($\overline{u'v'}$) and [(m-p)] turbulent kinetic energy for $T_u = 1.5\%$ [(a), (e), (i) and (m)]; $T_u = 5.0\%$ [(b), (f), (j) and (n)]; $T_u = 10.0\%$ [(c), (g), (k) and (o)]; and $T_u = 15.0\%$ [(d), (h), (l) and (p)]. The dashed-dot line represents $U/U_\infty = 0.5$

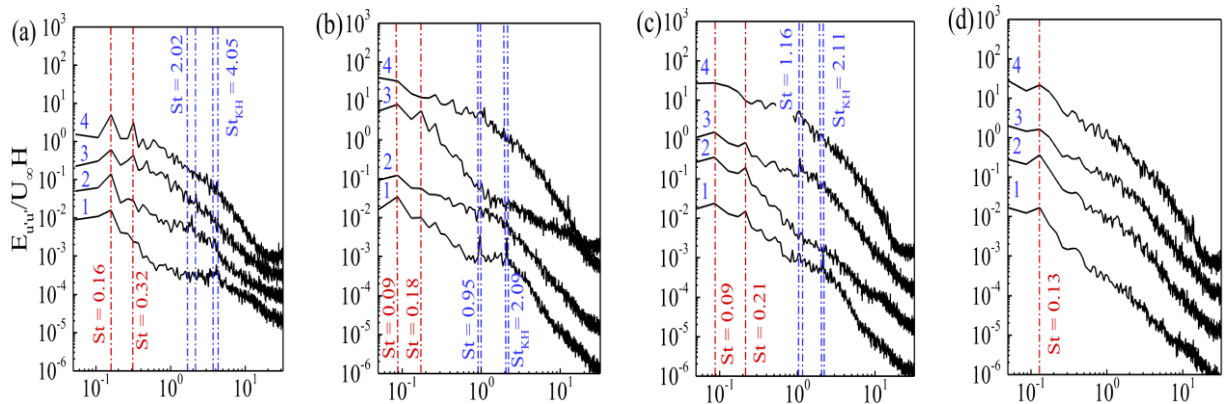
5.4.5 Temporal Characteristics and Frequency Analysis

Spectral analysis of the streamwise velocity fluctuations is performed at seven strategically chosen reference points around the body. These points include near the leading edge ($x/H, y/H$) = (-3.30, δ) (Point 1), at the focal point of the roof bubble (Point 2), local $(\overline{u'u'})_{\max}$ at reattachment point (Point 3), local $(\overline{u'u'})_{\max}$ at $x/H = -1$ (Point 4), local $(\overline{u'u'})_{\max}$ over the slanted surface (Point 5), the focal point of the upper (Point 6), and the lower recirculation bubble (Point 7) in the wake region.

Figure 5.18 presents the Premultiplied Spectral Density (PSD) of streamwise velocity fluctuation

under varying FST intensities. Figure 18a shows that at $T_u = 1.5\%$ (Point 1), the spectral frequency exhibits two distinct peaks: $St = 0.16$ and $St = 4.05$, corresponding to roof bubble pulsation and Kelvin–Helmholtz (KH) vortices, respectively. The former frequency closely aligns with $St = 0.17$ and 0.15 observed by Zhang et al. (2015) and Mínguez et al. (2008) at $Re = 5.0 \times 10^4$ and 7.6×10^5 , respectively. At point 2, in addition to $St = 0.16$, a distinct frequency of $St = 2.02$ (subharmonic of $St = 4.05$) is observed and is attributed to KH vortices induced by shear layer instability. Spohn & Gillieron (2002) also reported similar subharmonic frequency (at $Re = 3.0 \times 10^4$) and Mínguez et al. (2008) at $St = 2.26$ and 2.03 , respectively. In contrast, Zhang et al. (2015) did not observe the KH frequency and its harmonics, due to their exclusion of frequency activity near the leading edge ($X/H = -2.33$). Further downstream, at the reattachment point and $X/H = -1$, the leading-edge vortex shedding frequency persists, indicating the sustained influence of upstream-generated vortices on the reattached flow dynamics. Additionally, a harmonic frequency ($St = 0.32$) emerges. Notably, $St = 0.16$ and 0.32 also appear over the slanted surface (Fig. 5.18e), and the former frequency can be attributed to shear layer roll-up behind the slanted bubble (Wang et al., 2013). The frequency of $St = 0.32$ is also present within the upper and lower bubbles in the wake region (Fig. 5.18e). This frequency is consistent with prior observations of $St = 0.31$, 0.36 , and 0.37 by Joseph et al. (2012) at $Re = 4.5 \times 10^5$ and Kourta and Leclerc (2013) at $Re = 3.9 \times 10^5$ and Zhang et al. (2015) at $Re = 0.5 \times 10^5$, respectively. The dominance of $St = 0.32$ around the body shows that there is a link between the recirculation dynamics of the roof bubble, slanted surface, and alternating vortex-shedding motion in the wake region at $T_u = 1.5\%$, and a possible global instability mode that governs flow reattachment and wake vortical structures. When FST intensity increased to $T_u = 5.0\%$ and 10.0% (Figs. 5.18b, 5.18f, 5.18c, and 5.18g), the KH frequency was reduced to half the corresponding value for $T_u = 1.5\%$ ($St = 2.09$ and 2.11 , respectively), and the

roof bubble frequency to $St = 0.09$. The shedding frequency of the slanted surface bubble peaks at $St = 0.17$ and 0.30 . For these FST intensities, the upper bubble frequency changes to $St = 0.21$ and 0.17 for $T_u = 5.0\%$ and 10.0% , respectively, while the dominant lower bubble frequency is $St = 0.30$. Thus, the upper bubble in the wake no longer flaps with a unique frequency. At $T_u = 15.0\%$, the roof bubble vortices are shed at a dominant frequency of $St = 0.13$, with no evidence of the KH frequency over the roof (Fig. 5.18d). This suggests that higher freestream turbulence disrupts shear layer instabilities, leading to a field of flow dominated by low-frequency fluctuations. This change is particularly relevant when considering the findings from Fig. 5.15, which showed increased spatial correlation at high FST intensity, reinforcing the notion that these lower-frequency fluctuations are associated with large-scale structures spanning the roof bubble. The absence of the KH instability mechanism at $T_u = 15.0\%$ is consistent with observations by Chen et al. (2023), who noted a similar suppression of KH instabilities for wall-mounted cylinders exposed to elevated FST levels. At $T_u = 15.0\%$ (Fig. 5.18h), frequencies of the upper and lower bubbles are $St = 0.27$ and 0.18 , respectively, which are lower than $St = 0.32$ observed in the wake region of the case $T_u = 1.5\%$.



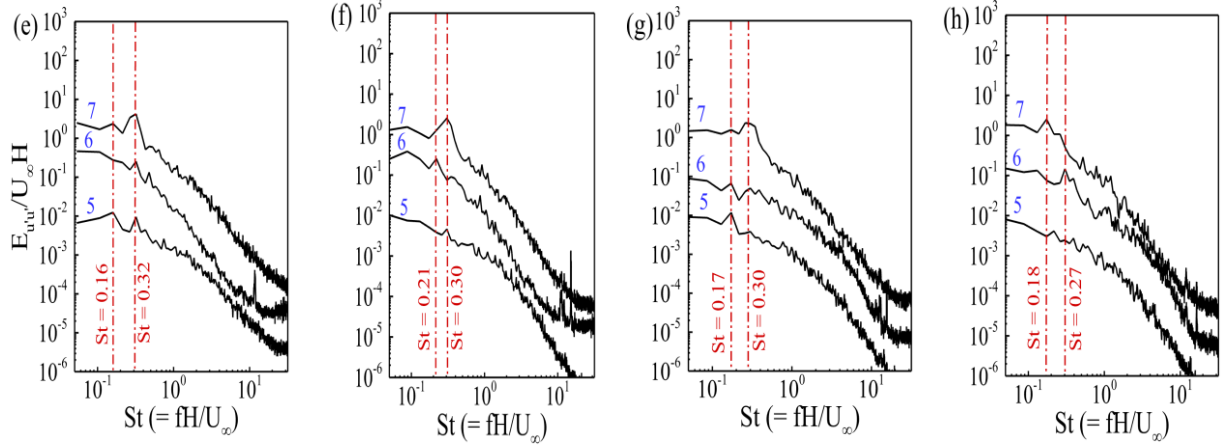


Figure 5.18 Premultiplied frequency spectra of streamwise fluctuation velocity ($x/H, y/H$) = $(-3.30, \delta)$ (Point 1), at the focal point of the roof bubble (point 2), at $(\overline{u'u'})_{\max}$ in reattachment point (Point 3), at $(\overline{u'u'})_{\max}$ $x/H = -1$ (Point 4), at $(\overline{u'u'})_{\max}$ over the slanted surface (Point 5), at the focal point of the upper (Point 6) and lower recirculation bubble (Point 7) in the wake region. $T_u = 1.5\%$ [(a, e)]; $T_u = 5.0\%$ [(b, f)]; $T_u = 10.0\%$ [(c, g)]; $T_u = 15.0\%$ [(d, h)]

The spectral analysis of streamwise fluctuation velocity at reference points around the Ahmed body reveals temporal coherence in the flow dynamics for $T_u = 1.5\%$, and $T_u = 15.0\%$ with recurring dominant frequencies as $St = 0.32$ and 0.13 , respectively. However, for intermediate FST intensities ($T_u = 5.0\%$, and $T_u = 10.0\%$), the coherence diminishes. Thus, spectral coherence analysis is employed to investigate the spatiotemporal evolution of these interactions under varying FST intensities. Following Antonia et al. (1993), the linear coherence magnitude between two synchronized signals, i and j , is determined using:

$$\Lambda_{ij}(f) = \frac{|P_{ij}(f)|^2}{P_{ii}(f) \times P_{jj}(f)} \quad (5.5)$$

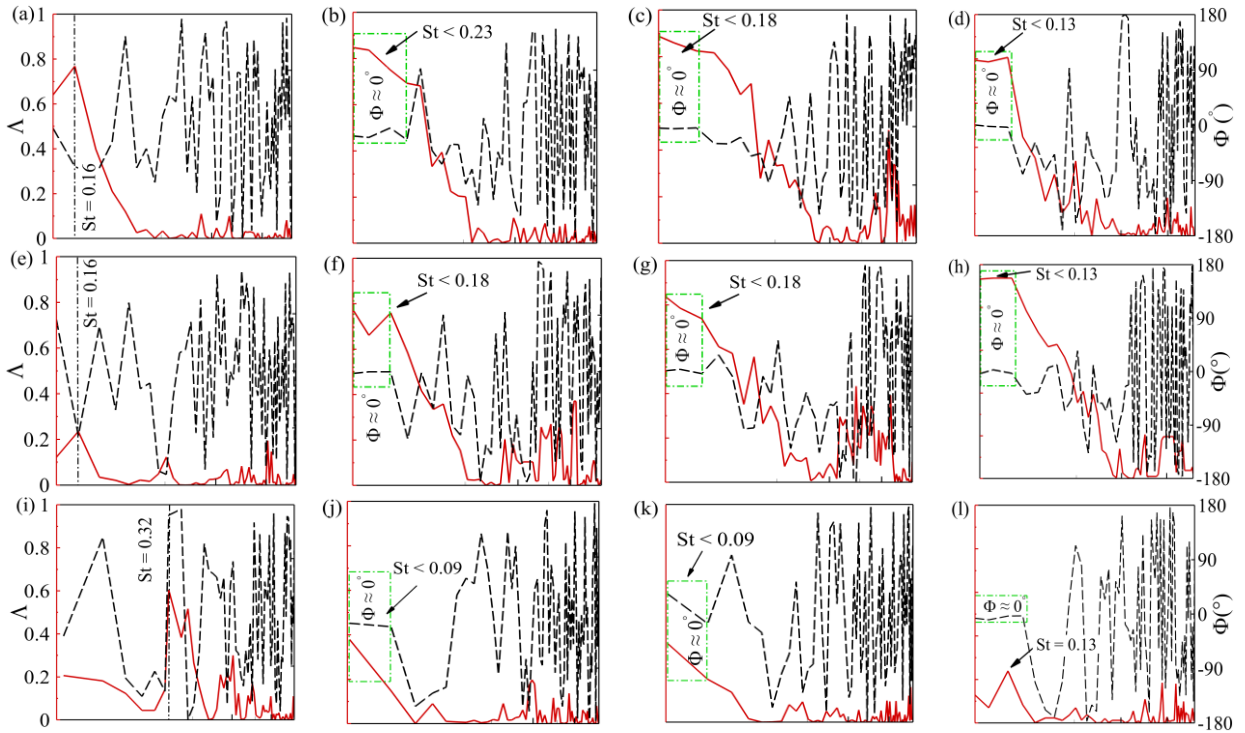
where $P_{ij}(f)$ is the cross-spectrum and P_{ii} and P_{jj} are the auto-spectra of signals i and j . The spectral coherence, ranging from 0 to 1, identifies the frequencies where signals are most correlated (Thacker et al., 2013). The phase relationship between signals is calculated as follows:

$$\phi_{ij}(f) = \arctan\left(\frac{\text{Im}(P_{ij}(f))}{\text{Re}(P_{ij}(f))}\right) \quad (5.6)$$

where $\text{Im}(P_{ij}(f))$ and $\text{Re}(P_{ij}(f))$ are the imaginary and real parts of the cross-spectrum, respectively. The co-spectrum, derived from the Fourier transform of the temporal correlation of signals i and j , is calculated for streamwise velocity fluctuations at the reference points in Figure 18.

Figure 5.19 presents spectral coherence and associated phase angles at various reference points around the Ahmed body for all test cases. At $T_u = 1.5\%$, a dominant peak at $St = 0.16$ is observed between points 1 to 3, reflecting a strong coherence in the roof recirculation bubble, while the spectral coherence drops from $\Lambda_{1-2} = 0.78$ to $\Lambda_{2-3} = 0.23$ (Figs. 5.19a and 5.19e). Beyond point 3, a secondary peak at $St = 0.32$ emerges, with the highest coherence between points 6 and 7 in the wake region (Fig. 5.19m). It is noted that the phase relationship at $St = 0.32$ shows a $\phi = 180^\circ$ shift between the upper and lower shear layers, confirming anti-phase vortex shedding consistent with von Kármán vortex shedding. This agrees with previous findings in the literature (Zhang et al., 2015; Pavia et al., 2018; Cicolin et al., 2024). At $T_u = 5.0\%$, the spectral coherence around the recirculation bubble (Fig. 5.19b) broadens to the frequency range of $St \leq 0.23$, characterized by significant coherence ($0.70 \leq \Lambda \leq 0.84$). The increase in strength of low-frequency motions at higher FST intensity was also observed by Hearst et al. (2016) and Mannini et al. (2017) for wall-mounted square cylinders and rectangular cylinders in uniform flow, respectively. The phase function within this range plateaus at $\phi = 0^\circ$, indicating in-phase oscillations between the separation and reattachment zones. Over the slanted surface and upper recirculation bubble (Fig. 5.19n), the peak coherence at $St = 0.21$ aligns with previously reported C-pillar vortex frequencies of $St = 0.23$ and $St = 0.26$ (Heft et al., 2011; Zhang et al., 2015), indicative of interactions driven

by the C-pillar vortex. In the wake region, at $St = 0.30$, the phase angle $\phi = -90^\circ$ shows a lack of synchronization between the upper and lower shear layers, reflecting disrupted vortex shedding and reduced TKE (Fig. 5.17). Similarly, at $T_u = 10.0\%$ and 15.0% , strong coherence near the roof bubble is confined to low-frequency ranges of $St < 0.18$ and $St < 0.13$, respectively. At $T_u = 15.0\%$, the coherence of $St = 0.13$ remains dominant until point 5 (over slanted surface). However, points 4 to 6 in $T_u = 10.0\%$ are driven by the characteristic frequency of $St = 0.30$ (Fig. 5.19o). The coherence in the wake region diminishes and shifts to lower frequencies ($St = 0.18$ and 0.27), while their coherence diminishes compared with $T_u = 1.5\%$. This suggests that wake structures lose synchronization due to enhanced turbulence, and the dominant flow behaviour shifts toward a more spatially extensive, low-frequency coherent structure.



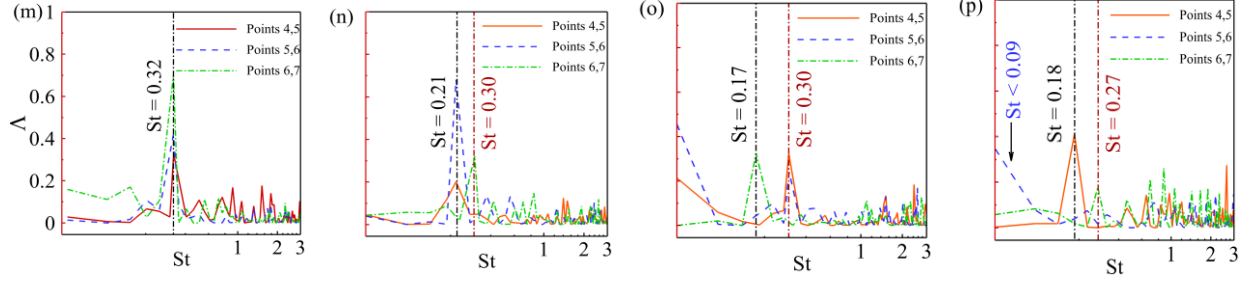


Figure 5.19 Spectral coherence of streamwise fluctuation velocity for points 1, 2 [(a)-(d)]; 2, 3 [(e)-(h)]; 3, 4 [(i)-(l)]; 4,5; 5,6; 6,7 [(m)-(p)] at $T_u = 1.5\%$ [(a),(e), (i) and (m)]; $T_u = 5.0\%$ [(b),(f), (j) and (n)]; $T_u = 10.0\%$ [(c),(g), (k) and (o)] and $T_u = 15.0\%$ [(d),(h), (l) and (p)]. The phase function related to points 1 to 4 is also included in figures [(a)-(l)]

To further investigate the temporal characteristics of the flow structures encompassing the roof bubble, the space-time-correlation of streamwise velocity fluctuations between points 1 and 2 (R_{12}), 1 and 3 (R_{13}), and 1 and 4 (R_{14}) is calculated using the equation (5.7):

$$R_{1j}(r_{xj}, \Delta\tau) = \frac{\overline{u'(X_1, t) u'(X_j, t + \Delta\tau)}}{\sqrt{\overline{u'(X_1, t)^2}} \sqrt{\overline{u'(X_j, t + \Delta\tau)^2}}} \quad j=2, 3, 4 \quad (5.7)$$

where $r_{xj} = X_j - X_1$ is the streamwise spatial separation between point 1 and point j , and $\Delta\tau$ represents the time lag. The results of space-time-correlation are shown in Fig. 5.20. At $T_u = 1.5\%$ space-time-correlation between -0.1 and 0.1 across all point pairs. These fluctuations suggest intermittent vortex shedding with no strong synchronization and support the findings from Figure 19, where coherence was localized around $St = 0.16$. At $T_u = 5.0\%$, and 10.0% the correlation profiles of R_{12} and R_{13} coincides, indicating that the flow structures influencing these points are coherent and move synchronously within the separation region of the roof bubble. However, R_{14} lags R_{12} and R_{13} , which suggests a propagation delay where separation structures take time to reach $x/H = -1$. For $T_u = 15.0\%$, the space-time-correlation coefficients across all point pairs coincide, with a significant correlation between -0.3 and 0.2 . Considering the large spatial autocorrelation in Fig. 5.15, it can be concluded that for $T_u = 15.0\%$, the points are influenced by a large, coherent structure spanning the roof bubble. These points exhibit the same temporal

behaviour, suggesting that the flow structures at these locations are part of a unified, large-scale motion.

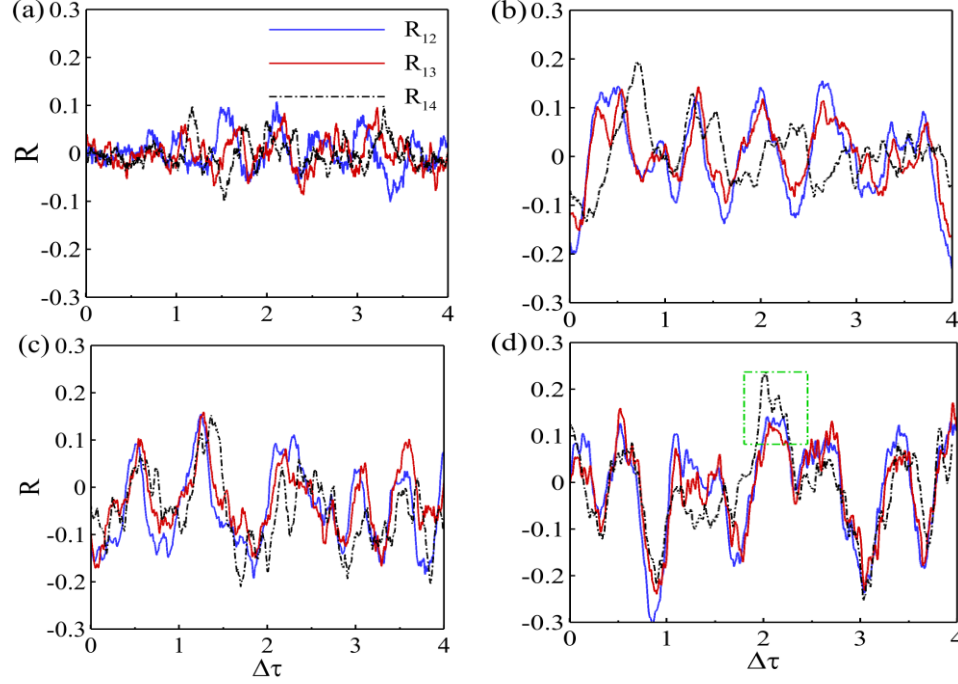


Figure 5.20 space-time-correlation of streamwise fluctuation velocity between points 1 and 2 (R_{12}); 1 and 3 (R_{13}); 1 and 4 (R_{14}) for $T_u = 1.5\%$ (a); $T_u = 5.0\%$ (b); $T_u = 10.0\%$ (c) and $T_u = 15.0\%$ (d)

5.4.6 Spectral Proper Orthogonal Decomposition (SPOD)

Thus far, it has been demonstrated that increasing FST significantly affects the temporal characteristics and dominant frequencies of flow structures around the Ahmed body. Here, Spectral Proper Orthogonal Decomposition (SPOD) is employed to investigate the dynamics of the vortical structures associated with the dominant frequencies. The SPOD methodology outlined in detail by Towne et al. (2018) was adopted in this study. In this method, the fluctuating velocity field, $u'(x, y, t)$ is decomposed as:

$$u'(x, y, t) = \sum_{j=1}^{\infty} \sum_{m=1}^{\infty} \phi_j^m(x, y) a_j^m e^{-i\omega_j t} + c. c., \quad (5.8)$$

where the indices j and m denote the frequency and mode number, respectively. The term ϕ_j^m refers to the orthogonal spatial eigenfunctions (modes) and a_j^m denotes their corresponding coefficients. The wavenumber is given by $\omega_j = 2\pi f_j$, where $i = \sqrt{-1}$ and c.c. denotes the complex conjugate. For this analysis, the sample size of 60,000 was divided into ten blocks of 6,000 images. A fast Fourier Transform (FFT) was applied to each block using Welch's overlapped window technique (Welch, 1967). FFT window size N_w was 4500, yielding a frequency resolution of $\Delta f (f_s/N_w) = 0.17$ Hz. Subsequently, for each selected dominant frequency, the snapshot POD method (Sirovich, 1987) was applied to the FFT data using Singular Value Decomposition (SVD) (Meyer et al., 2007; Fang & Tachie, 2019). SVD calculates modes and eigenvalues (λ), which represent the energy of each mode, and sorts them in descending order, with the first modes corresponding to more energetic structures.

Figure 5.21 shows the energy contribution of the first hundred SPOD modes for the various FST intensities over the roof and wake regions. Over the roof, the first mode captures 29.8% of the total TKE for FST intensities of $T_u = 1.5\%$, 5.0% , and 10.0% , with a comparable percentage of energy distributed across higher modes. However, at $T_u = 15.0\%$, the energy captured by the first mode increases significantly to 52%, indicating a stronger dominance of the most energetic coherent structure at higher FST levels. This concentration of energy in the first SPOD mode at higher FST aligns with findings by Chen et al. (2023a), who applied SPOD to the wake of a square-back Ahmed body under varying FST intensities ($T_u = 0$ to 11.4%) at $Re = 9.6 \times 10^4$. They observed that the first SPOD mode increasingly dominated the energy spectrum as FST intensified. In the wake region, the energy distribution is less sensitive to FST intensity changes: the first mode captures 26% of the total TKE at $T_u = 1.5\%$ and 10.0% , and 32% at $T_u = 5.0\%$ and 15.0% .

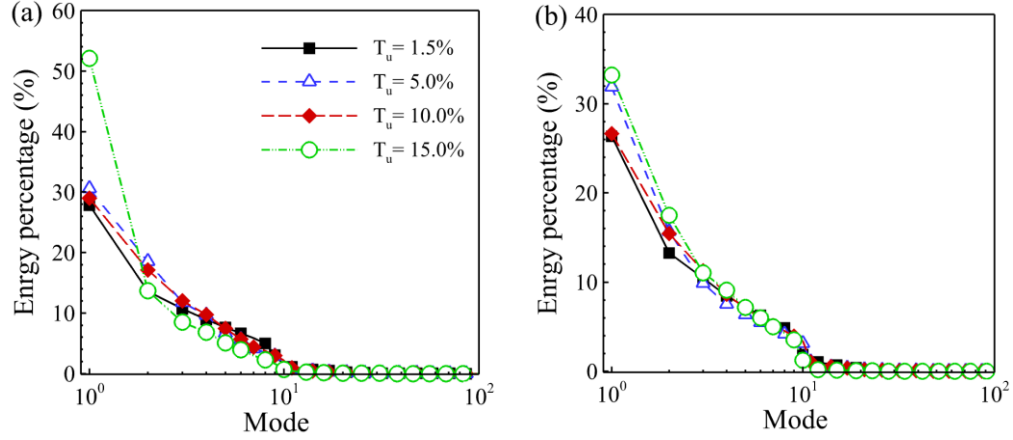


Figure 5.21 Energy contribution of SPOD modes. Over the roof (a) and wake region (b)

Figure 5.22 presents the spectra of the first SPOD mode around the body for the various FST intensities. The distinct peaks observed in the SPOD modes align well with those identified in the spectra of streamwise velocity fluctuations (Fig. 5.18). However, the SPOD analysis also uncovers additional peaks that warrant further investigation into their underlying dynamics and significance.

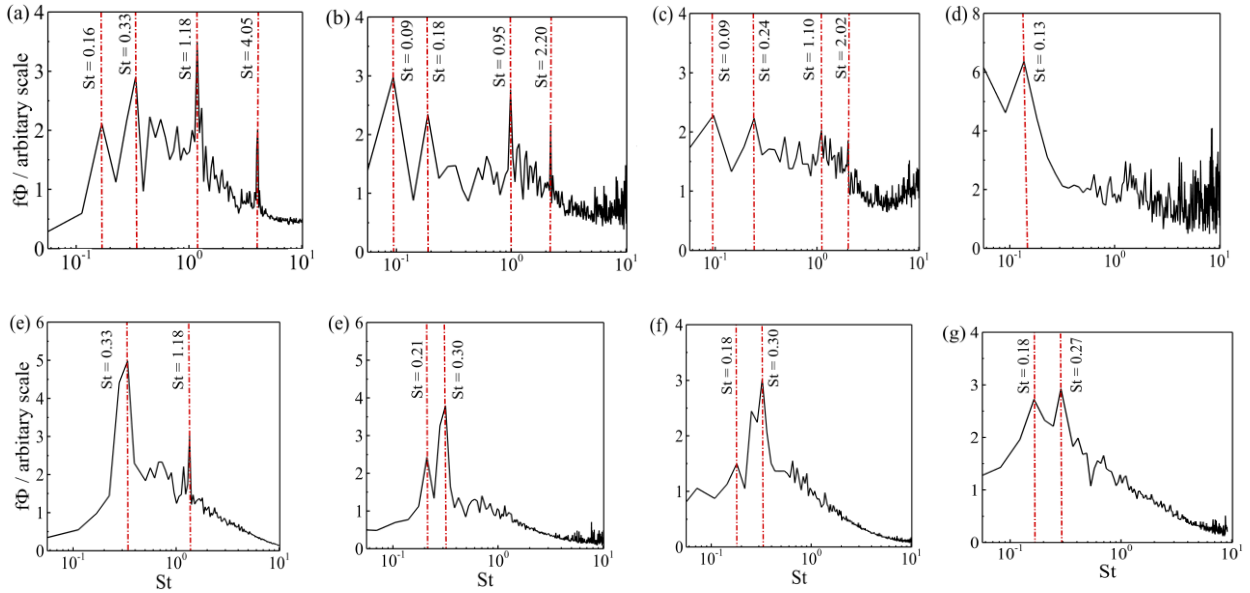


Figure 5.22 Premultiplied frequency spectra of the first SPOD mode. Over the roof [(a)-(d)] and wake region [(e) - (g)] at $T_u = 1.5\%$ [(a), (e)]; $T_u = 5.0\%$ [(b), (e)]; $T_u = 10.0\%$ [(c), (f)]; $T_u = 15.0\%$ [(d), (g)]

Figure 5.23 compares the vortical structures over the roof using the streamwise (ϕ_u) component of the first SPOD mode at the distinct frequencies identified in Fig. 5.22. These vortical structures

can be classified into four distinct categories. The first one corresponds to the highest frequencies ($St = 4.05, 2.20, \text{ and } 2.02$ for $T_u = 1.5\%, 5.0\% \text{ and } 10.0\%$, respectively). These structures are characterized by small-scale, alternating-sign vortices that originate near the leading edge and are advected downstream along the shear layers, indicating high-frequency dynamics primarily driven by shear layer instability. A comparison of the figures reveals that these small-scale structures gradually diminish as FST intensity increases and are absent at $T_u = 15.0\%$. To investigate the origin of these structures, their Strouhal number is evaluated using the local shear layer thickness at the location of intense vorticity near the leading edge. At $x/H = -3.0$, the shear layer thickness is measured as $\delta_\omega = 0.05H, 0.08H, \text{ and } 0.09H$ for $T_u = 1.5\%, 5.0\% \text{ and } 10.0\%$, respectively. The calculated Strouhal numbers are $St_\omega (= f\delta_\omega/U_\infty) = 0.20, 0.17, \text{ and } 0.18$, which align closely with $St_\omega = 0.20$ predicted by linear stability theory for KH instabilities (Monkewitz & Huerre, 1982; Chen et al., 2024). The second category is characterized by alternating positive and negative spatially larger structures (vortex pairing) with characteristic frequencies that correspond to subharmonic frequencies of the KH instabilities in the roof region of the body, subjected to $T_u = 1.5\%, 5.0\%, \text{ and } 10.0\%$ are (Figs. 5.23b, 5.23f, and 5.23j). The third category corresponds to vortical structures at $St = 0.33, 0.18, \text{ and } 0.24$ for $T_u = 1.5\%, 5.0\% \text{ and } 10.0\%$ (Figs. 5.23c, 5.23g and 5.23k). These frequencies reveal the presence of multiple alternating structures distributed along the streamwise direction, characterized by opposite signs. For $T_u = 1.5\%$, these structures are observed to travel farther from the roof. However, with increasing FST intensity, their frequency decreases, and the structures remain closer to the roof while exhibiting an upward lifting motion. This upward lifting is consistent with the results of the spatial two-point autocorrelations observed in Fig. 5.15. The final category corresponds to the lowest frequency identified in the SPOD analysis: $St = 0.16, 0.09, 0.09, \text{ and } 0.13$ for $T_u = 1.5\%, 5.0\%, 10.0\% \text{ and } 15.0\%$,

respectively. For $T_u = 1.5\%$, $St = 0.16$ is observed as a subharmonic of the shedding frequency $St = 0.33$, indicating a secondary modulation of the primary vortex shedding process. The corresponding frequencies for $T_u = 5.0\%$, 10.0% , and 15.0% are associated with the emergence of elongated, low-frequency streaks that span the roof region and exert a pronounced influence on the slanted surface structures. The SPOD spectra reveal suppression of high-frequency modes (e.g., $St = 4.05$ at $T_u = 1.5\%$) and a shift toward lower frequencies (e.g., $St = 0.13$ at $T_u = 15.0\%$) with increasing FST intensity. This behavior is consistent with Chen et al.'s (2023a) observation that FST energizes the low-frequency structures while disrupting smaller-scale instabilities.

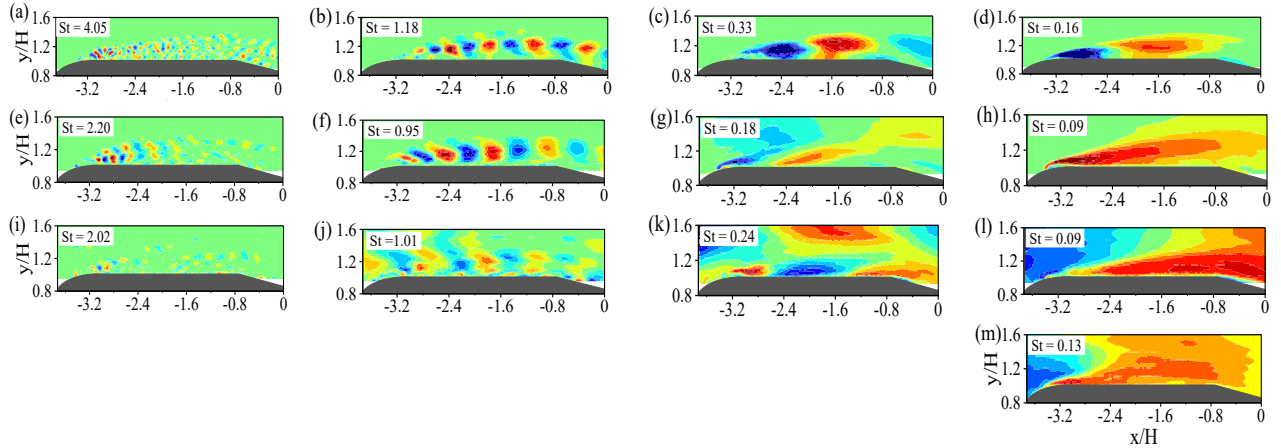


Figure 5.23 First POD mode at distinct frequencies (Fig. 5.22) for $T_u = 1.5\%$ [(a-d)]; $T_u = 5.0\%$ [(e-h)]; $T_u = 10.0\%$ [(i-l)]; $T_u = 15.0\%$ (m)

Figure 5.24 presents the vortical structures in the wake region at the distinct peak frequencies observed in Fig. 5.22. The wake region is characterized by $St = 0.33$, 0.30 , 0.30 , and 0.18 , for $T_u = 1.5\%$, 5.0% , 10.0% and 15.0% , respectively. The corresponding vortical structures are characterized by alternating positive and negative structures, resulting from the shear layer's oscillatory motion emanating from the slanted surface and base undersurface and convected downstream toward the ground. These alternating structures closely replicate von Kármán vortex shedding structures observed in the first two modes of streamwise velocity fluctuations by Siddiqui

& Agelin-Chaab (2022) and Sagharichi et al. (2023). The wake region is also characterized by $St = 1.18, 0.21, 0.18$, and 0.27 , for $T_u = 1.5\%, 5.0\%, 10.0\%$ and 15.0% , respectively. Figure 5.24e illustrates that at $T_u = 1.5\%$, the frequency of $St = 1.18$ in the wake region is characterized by a train of alternating positive and negative small-scale structures originating from the roof and shed into the wake. These structures, with an identical frequency observed over the roof (Fig. 5.23b), highlight a strong coupling between the flow dynamics of the roof and the wake region. As the turbulence intensity increases, additional disturbances are introduced, leading to more intricate interactions between vortices from the roof, slanted surface, and wake region. These interactions result in a more chaotic and irregular flow field, complicating the identification of distinct, coherent structures in the x - y plane alone.

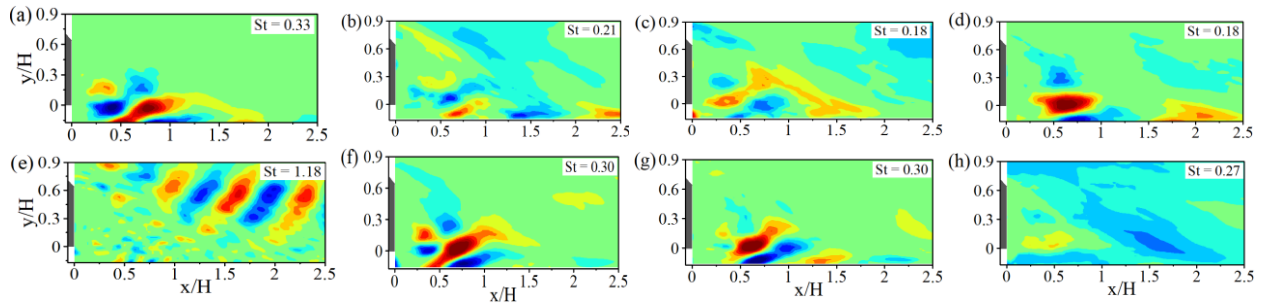


Figure 5.24 First POD mode at distinct frequencies (figure 22) for $T_u = 1.5\%$ [(a), (e)]; $T_u = 5.0\%$ [(b), (f)]; $T_u = 10.0\%$ [(c), (g)]; $T_u = 15.0\%$ [(d), (h)]

5.4.7 C-Pillar Vortex Characteristics

This section investigates the impact of FST intensity on the C-pillar flow characteristics over the slanted surface in the x - z plane. Previous studies by Wang et al. (2013) and Zhang et al. (2019) indicate that C-pillar vorticity can be identified by examining the mean wall-normal vorticity ($\omega_y = (\frac{\partial W}{\partial x} - \frac{\partial U}{\partial z})$) contours in the spanwise plane for $T_u = 1.5\%$ and $T_u = 15.0\%$ (Figs. 5.25a and 25b). The contours of mean wall-normal vorticity reveal three strip vortices labelled A, B, and C. Strip A forms due to the separation of the shear layer from the body's side surface. The middle

strip, C, originates from the side edge of the slanted surface and deflects toward the wake region as it evolves downstream, representing the C-pillar vortex. The C-pillar vortex induces the smaller strip, B (Zhang et al., 2019). Figures 5.25c and 5.25d present the contour of TKE, defined as $TKE = 0.5(\overline{u'u'} + \overline{w'w'})$ with peak values indicated on the contours. At $T_u = 15.0\%$, a more intense region of TKE is observed in the separated flow over the slanted surface. Compared to $T_u = 1.5\%$, the values of peak TKE for the C-pillar vortex and vortex B increase by 136% and 10%, respectively. Previous studies (Crabtree, 1987; Wang et al., 2013; Yu & Bingfu, 2021) have demonstrated that the C-pillar vortex plays a critical role in inducing the reattachment point over the slanted surface. Thus, the more energetic C-pillar vortex under the effect of FST intensity energizes the slanted surface shear layer, delaying reattachment further downstream.

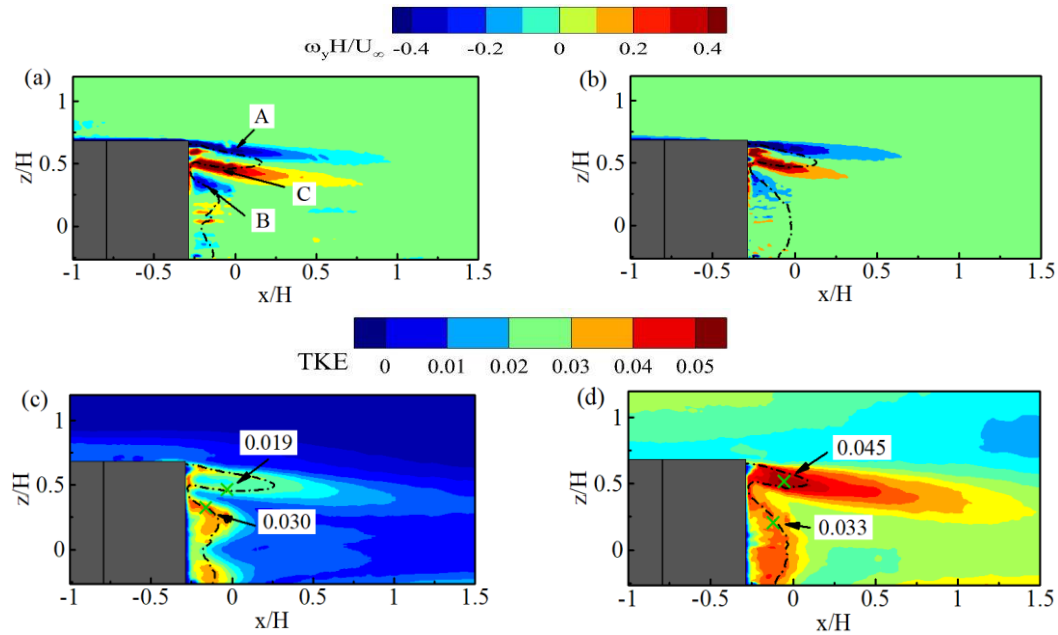
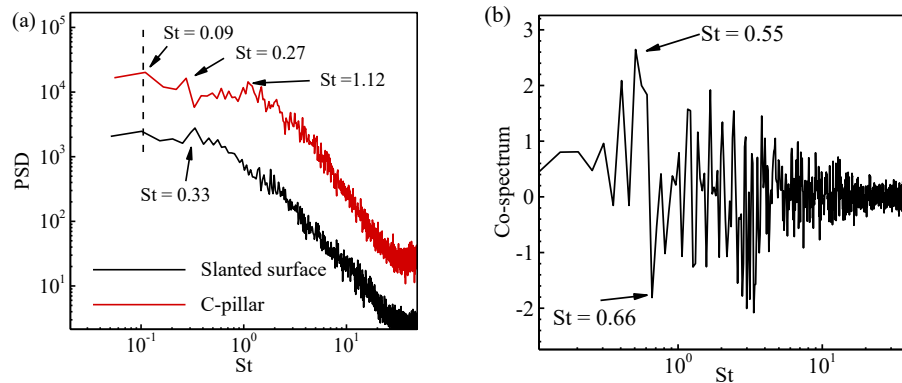


Figure 5.25 Contour of wall-normal mean vorticity [(a) and (b)] and TKE [(c) and (d)] in the spanwise plane for $T_u = 1.5\%$ [(a) and (c)] and $T_u = 15.0\%$ [(b) and (d)]

Figure 5.26 shows the frequency spectrum and the co-spectrum of streamwise fluctuation at $(X/H, Z/H) = (-0.1, 0.52)$ and $(X/H, Z/H) = (-0.1, 0)$ corresponding to locations within the C-pillar vortex and the separated flow over the slanted surface, respectively. As seen in Figure 5.26a, the frequency spectra of the C-pillar vortex for $T_u = 1.5\%$ shows distinct frequency peaks at $St = 0.09$ and 0.27 . The frequency of $St = 0.27$ agrees with the C-pillar vortex frequency of $St = 0.26$ observed by Heft et al. (2011). The co-spectrum of these two signals (Fig. 26b) at $T_u = 1.5\%$ shows two dominant peaks of $St = 0.55$ and $St = 0.66$, while decorrelates at high frequencies. The corresponding figure for $T_u = 15.0\%$ (Fig. 5.26c) possesses a dominant frequency of $St = 0.27$, and the co-spectrum of the two vortices (Fig. 5.26d) also exhibits a significant coherence at $St = 0.27$, indicating that the correlation between the frequency spectrum of the streamwise fluctuation signals increases with FST level. Hence, the increased FST level enhances the TKE energy of the C-pillar vortex and the separated shear layer and increases their spatiotemporal interaction, leading to more energetic flow structures over the slanted surface. As identified in the SPOD analysis, the energized C-pillar vortex with $St = 0.27$ sheds downstream while interacting with the wake region's upper and lower shear layer (Fig. 5.24h).



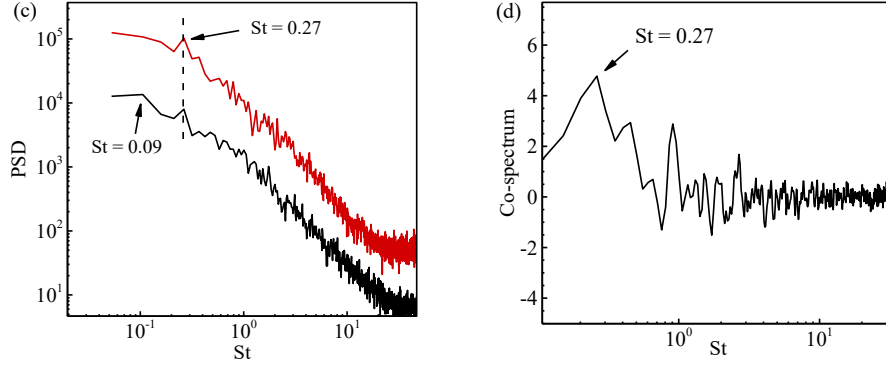


Figure 5.26 Frequency spectrum of the C-pillar vortex and separated flow from the slanted surface [(a) and (c)] and premultiplied co-spectrum [(b) and (d)] for $T_u = 1.5\%$ [(a) and (b)] and $T_u = 15.0\%$ [(c) and (d)]

5.5 Summary and Conclusion

The impact of freestream turbulence (FST) intensity on the flow dynamics around a high-drag Ahmed body was investigated using time-resolved particle image velocimetry (TR-PIV). The experiments were performed at a baseline level of $T_u = 1.5\%$, together with elevated FST levels of $T_u = 5.0\%$, 10.0% , and 15.0% generated using regular and fractal grids. The experimental data regarding mean flow, frequency spectra, spectral coherent spatial and temporal two-point correlation, and spectral proper orthogonal decomposition (SPOD) were analyzed.

Over the roof, FST intensity promotes shear layer reattachment and a monotonic reduction in the recirculation bubble size. The probability distribution of the reattachment point transitioned from a bimodal distribution at lower FST intensity to a unimodal behaviour at higher FST, indicating enhanced stability in flow attachment at higher FST intensities. Reynolds stresses and turbulent kinetic energy (TKE) decreased over the roof, with peaks shifting toward the leading edge at higher FST. Quadrant analysis showed that high FST intensity suppressed sweep and ejection events, contributing to a more stabilized shear layer. FST also suppressed both the Kelvin–Helmholtz (KH) instabilities near the leading edge and the roof bubble pulsation frequency, aligning with the shrinkage of the bubble at higher FST levels.

Over the slanted surface, the recirculation length of the slanted bubble initially increased with FST intensity but remained constant for $T_u \geq 10.0\%$. The increase in recirculation bubble size over the slanted surface was attributed to greater spatial and temporal correlations between the C-pillar vortex and the separated shear layer at higher FST intensities, reinforcing the interaction between these structures. Higher FST intensities also enhanced the temporal interaction between the C-pillar vortex and the upper shear layer in the wake region.

FST intensity did not significantly affect the recirculation length in the wake region. However, Reynolds stresses and TKE in the wake were significantly suppressed at higher FST levels. This suppression was attributed to reduced spectral coherence of the upper and lower shear layers, disrupting their flapping motion and causing a monotonic reduction in their interactions and vortex shedding frequency. SPOD analysis showed that coupling between the roof and wake flow dynamics was evident at $T_u = 1.5\%$, whereas this dynamic was absent at higher FST intensities.

This study found that at low FST intensity ($T_u = 1.5\%$), a coherent global instability mode ($St = 0.32$) links the roof bubble, slanted surface, and wake vortex shedding. This linkage allows roof-based flow control methods to effectively influence downstream flow. However, this linkage breaks down at higher FST levels. Designers should therefore shift flow control strategies from the roof to the slanted surface or wake region for more direct manipulation of dominant flow structures in highly turbulent conditions.

To better understand the complex interactions between the roof bubble, slanted surface, and wake under high FST intensities, future studies should employ simultaneous pressure/drag-velocity measurements to directly correlate bubble dynamics with drag forces. Implementing tomographic particle image velocimetry is also recommended to capture the three-dimensional flow structures, which become more prominent in turbulent conditions. Additionally, exploring the combined

effects of FST and crosswinds could clarify how turbulence alters wake dynamics and lateral forces, enhancing vehicle stability and fuel efficiency.

5.6 Reference

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Chapter 6: Freestream Turbulence Effects on Separating-reattaching Flow Induced by Simplified Road Vehicle with Square Leading Edge

6.1 Abstract

This study investigates the influence of freestream turbulence intensity (FST) on the spatiotemporal characteristics of turbulent separation around a slanted-back Ahmed body with a square leading edge using time-resolved particle image velocimetry (TR-PIV). The Reynolds number based on the freestream velocity and body height was $Re = 0.17 \times 10^5$. Four FST intensities, $T_u = 1.5\%$, 5.0% , 10.0% , and 15.0% were evaluated. Increasing FST intensity from $T_u = 1.5\%$ to 15.0% reduced the roof recirculation bubble length by 56% (from $1.85H$ to $0.82H$) and height by 32% (from $0.31H$ to $0.21H$), attributed to enhanced entrainment and an earlier shear-layer reattachment. In contrast, the wake's recirculation length was unaffected by FST. Over the roof, streamwise Reynolds stresses and turbulent kinetic energy (TKE) increased by FST intensity, driven by energy redistribution to low-frequency flapping motions ($St < 0.23$), while wall-normal and shear stress peaks showed minimal sensitivity. Spectral Proper Orthogonal Decomposition (SPOD) and quadrant-based analysis reveal that sweep events during bubble contraction amplify low-frequency flapping, with the anti-correlation between streamwise velocity fluctuations and reverse flow area strengthening to -0.72 at $T_u = 15.0\%$. In the wake, suppressed TKE by FST intensity resulted from diminished wall-normal Reynolds stresses caused by disrupted vortex interactions, accompanied by a monotonic reduction in vortex shedding frequencies. Wavelet and SPOD analyses further highlight the emergence of persistent C-pillar vortices, which progressively dominate the upper shear layer and disrupt classical vortex shedding. Spanwise measurements in the x - z planes confirmed that elevated FST intensities strengthen the C-pillar vortex, disrupt periodic shedding, and promote elongated vortical structures. These findings underscore the pivotal role of FST in modulating shear-layer behaviour, vortex dynamics, and turbulence statistics, offering critical insights for improving aerodynamic models and control strategies for bluff-body vehicles in real-world turbulent conditions.

6.2 Introduction

The aerodynamic performance of on-road vehicles, which account for nearly 30% of greenhouse gases (GHG), is critically tied to managing flow separation and wake dynamics under real-world turbulence conditions (Bellman et al., 2010). On-road vehicles commonly feature a bluff shape due to their functional design, which results in massively separated flow, complex wake dynamics, and significant pressure drag (Tunay et al., 2014; Liu et al., 2021). The Ahmed body (Ahmed et al., 1984), the canonical model for bluff-body aerodynamics, replicates the flow features of on-road vehicles. The flow around a high-drag Ahmed body (slanted angle of $\alpha = 25^\circ$) exhibits distinct features: hairpin vortices over the roof, a recirculation bubble on the slanted surface, C-pillar vortices (counter-rotating pairs shed from the slanted edges), and a low-pressure counter-rotating torus behind the vertical base (Ahmed et al., 1984; Wang et al., 2013; Zhang et al., 2015; Sagharichi & Tachie, 2025). Previous studies reported that the mean recirculation bubble, turbulent statistics, and unsteady dynamics of the separated shear layers around Ahmed body are sensitive to numerous factors such as Reynolds number (Thacker et al., 2012; Sagharichi et al., 2023), slanted angle (Wang et al., 2013; Tunay et al., 2014), aspect ratio (Venning et al., 2015; Venning et al., 2022), ground clearance (Wang et al., 2013; Grandemange et al., 2013), leading-edge configuration (Easanesan et al., 2020; Sagharichi et al., 2023; Sagharichi & Tachie, 2024), slanted surface configuration (Siddiqui & Agelin-Chaab, 2022), and incoming flow orientation (Haffner et al., 2020; Fan et al., 2022). However, these studies were conducted at freestream turbulence

(FST) intensities ($T_u = u_{rms}/U_\infty$, where $u_{rms} = \sqrt{\overline{u'^2}}$ is root-mean-square of the streamwise fluctuation velocity u' , $(\cdot)$ denotes time averaging, and U_∞ is freestream velocity) below $T_u = 2\%$, neglecting high-intensity turbulence ($T_u = 2\%$ to 16%) prevalent in real-world environments (Saunders & Mansour, 2000; Passaggia et al., 2021). This gap limits understanding of how

turbulence modulates flow dynamics and impedes the development of robust aerodynamic control strategies for practical applications.

Recently, there has been interest in the impact of turbulence intensity on the flow dynamics around the squared-back Ahmed body (Wang et al. 2020; Burton et al. 2021; Passaggia et al. 2021; Kang et al. 2021; Aleyasin et al. 2021; Chen et al. 2023). However, the influence of FST on slanted-back configurations (representative of fast-back vehicles) remains unexplored. Initial insights into FST effects on the slanted-back Ahmed body were provided by Zhang et al. (2015), who examined the effect of FST intensity on a rounded leading-edge Ahmed body at $T_u = 0.3\%$ and 7.8% . The study showed that increasing FST intensity leads to a reduction in the recirculation bubble size and suppression of vortex shedding over the roof. A dominant Strouhal number $St (= fH/U_\infty)$, where f is vortex shedding frequency, H is body height, and U_∞ is freestream velocity) $= 0.17$, associated with roof vortex shedding and bubble pulsation, emerged at $T_u = 0.3\%$ but vanished at $T_u = 7.8\%$. However, von Kármán shedding frequency in the wake remained unaffected by FST intensity. While advancing insights into FST effects, their narrow FST range and exclusive focus on spectral dynamics left open questions about spatiotemporal flow dynamics. Additionally, the study did not span a broad range of FST intensities, nor did it explore the role of FST intensity in the interaction between leading-edge and wake structures.

The recent work by Sagharichi & Tachie (2025) addressed these limitations by testing a rounded leading-edge high-drag Ahmed body across broader FST intensities of $T_u = 1.5\%$, 5.0% , 10.0% and 15.0% . Their results showed that increasing FST intensity from $T_u = 1.5\%$ to 15.0% resulted in a monotonic reduction in the roof recirculation bubble size, with the recirculation length (L_r , defined as the furthest streamwise extent where $U \leq 0$) decreasing from $0.90H$ to $0.32H$ and the bubble height shrinking from $0.08H$ to $0.01H$. This reduction was accompanied by an earlier

reattachment of the shear layer, shifting the probability distribution of the reattachment point from a bimodal pattern at $T_u=1.5\%$ to an unimodal distribution at higher FST levels. In the wake region, however, the recirculation length remained independent of FST intensity, approximately $L_r=0.56H$. A significant suppression of turbulence kinetic energy (TKE) and shear stress magnitudes over the roof at elevated FST levels, linked to the damping of sweep and ejection events. The hairpin packets emanating from the leading edge at $T_u=1.5\%$ were replaced by elongated streaks dominated by streamwise velocity fluctuations, which accelerated the transition of the laminar boundary layer to turbulent under higher FST intensity. Notably, the study highlighted a strong global instability with $St = 0.32$ between the roof and wake dynamics at low FST ($T_u = 1.5\%$), which vanished at higher intensities. Despite Zhang et al. (2015), it was shown that increasing FST intensity suppresses the wake vortex shedding frequency from $St = 0.32$ to 0.18 .

Despite recent progress in understanding bluff-body aerodynamics, the effect of FST intensity on shear-layer instabilities and wake modulation around a sharp leading-edge Ahmed body remains inadequately resolved. It is hypothesized that transitioning from a rounded to a sharp leading-edge configuration alters the shear layer's characteristics and its interaction with the three-dimensional unsteady vortical structures in the wake. Hence, a systematic investigation of sharp leading-edge Ahmed bodies under similar FST conditions is essential to isolate the role of leading-edge geometry on shear-layer receptivity and wake response to the FST intensity. Sagharichi & Tachie (2024a) explored the impact of FST intensities ($T_u = 1.5\%$, 5.0% , and 15.0%) on a slanted-back Ahmed body with a squared leading edge. Their findings highlighted distinct flow dynamics compared to rounded leading-edge configurations, notably a 78% increase in peak streamwise Reynolds normal stress as T_u rose from 1.5% to 15.0% was in sharp contrast to its suppression observed in rounded-edge counterparts (Sagharichi & Tachie, 2025). However, this study left

unresolved the underlying mechanisms driving this increase and provided limited insight into the broader spatiotemporal dynamics influenced by FST. Additionally, the study did not clarify which turbulence scale is responsible for the change in Reynolds normal stresses, nor the reduction in recirculation length on high FST intensities. Given that Reynolds stresses are intricately linked to turbulence production and energy dissipation, this knowledge gap hinders the development of accurate predictive models for sharp-edged configurations. Additionally, although the mean flow has been documented by Sagharichi & Tachie (2024a), how FST modulates vortex shedding, and space-time characteristics of coherent structures, remains poorly characterized. These aspects are essential for understanding how turbulence alters separated and reattached flow dynamics, which in turn affects aerodynamic forces and vehicle stability (Zhang et al., 2018).

These gaps motivate the authors to analyze how FST intensity modifies the spatiotemporal characteristics of flow around the square leading-edge Ahmed body. To achieve this objective, a square leading edge of Ahmed body with a slanted-back (with the slanted angle of $\alpha = 25^\circ$) was implemented. Three different passive grids, consisting of a regular and two fractal grids, were deployed at the inlet section of the test section to generate FST intensities of $T_u = 5.0\%$ 10.0% and 15.0% , and the results were compared with the baseline turbulence level of $T_u = 1.5\%$ that was generated in the test section without the grids. These FST intensities reflect conditions ranging from smooth to turbulent environments like traffic or wind gusts, as documented by Saunders & Mansour (2000).

Time-resolved PIV techniques are used to measure velocity in the flow around the body. The effects of FST intensity on turbulent statistics and transport phenomena are examined in terms of the mean velocities, Reynolds stresses, and TKE production terms. The effects of turbulence on the vortical structures are analyzed using reverse flow area and spectral proper orthogonal

decomposition (SPOD), and their temporal characteristics were assessed using frequency spectra, spectral coherence, and integral time scale. The remainder of this manuscript is structured as follows: Section II describes the experimental setup, including Ahmed body and turbulence-generating grids, as well as the measurement procedure. Section III presents a comparison of the test cases under varying FST intensities, and Section IV offers concluding remarks.

6.3 Methodology

The experiments were conducted in an open recirculating water channel at the Turbulence and Hydraulic Engineering Laboratory (THEL) at the University of Manitoba. This facility has been described in detail in (Fang & Tachie, 2019; Fang et al., 2022; Sagharichi et al., 2023), hence only the essential features are presented in this paper. The test section of the channel has dimensions of 6000 mm in length, 600 mm in width, and 450 mm in height. Bottom and side walls are constructed using 31.8 mm thick Super Abrasion Resistant® transparent acrylic plates of 31.8 mm thickness, allowing optical access to the test section. Water recirculation was achieved using an impeller pump with a maximum flow rate of 33,950 litres/minute, with the flow rate adjustable via a 30 kW variable speed motor. To achieve uniform flow and ensure the breakdown of large-scale turbulence before entering the test section, the channel includes a settling chamber equipped with perforated steel plates, a honeycomb structure, mesh screens, and a 4.88:1 converging section.

A 1:4 scale model of the full-size square leading-edge Ahmed body with a rear slant angle of $\alpha = 25^\circ$ was used in the experiments. Figure 6.1 presents a schematic representation of the body and the adopted Cartesian coordinate system. The origin of the coordinate system is located at the bottom of the rear base in the symmetry plane. The model measures 261 mm in length (L), 97 mm in width (B), and 72 mm in height (H) and is supported by four cylindrical struts, each with a

height (C) of 12.50 mm and a diameter (d) of 7.50 mm. The body was installed on a raised plate with a length of 42H that spanned the entire width of the test section and positioned horizontally 0.7H above the floor to control the growth of the boundary layer. The plate's leading and trailing edges are designed with sharp edges angled at 45° to prevent flow separation. In all cases, the distance between the body's leading edge and the raised plate edge was $x_{LL} = 2.77H$. In all experiments, the water level was maintained at $D = 435$ mm. The blockage ratio (defined as the body frontal area relative to the rectangular cross-stream area of the water column above the raised floor) was 3%, well below the 7.5% maximum recommended by Barlow et al. (1999) to minimize wall effects and ensure accurate flow measurements.

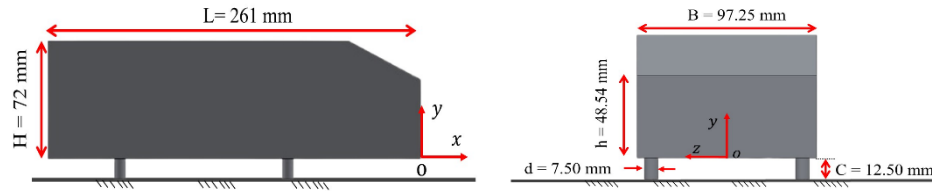


Figure 6.1 Drawings of Ahmed body

The freestream velocity was set to $U_{\infty} = 0.24$ m/s, which resulted in a Reynolds number of $Re = 0.17 \times 10^5$, where ν is the kinematic viscosity of water at $T = 20$ °C. The Froude number $(U_{\infty} / \sqrt{gD})$ where g is gravitational acceleration, was calculated to be 0.12. This low value is sufficient to ensure that free-surface effects do not influence the flow around the Ahmed body (Tunay et al., 2014; Sagharichi et al., 2023). The baseline FST intensity measured along the centerline of the channel (without any grid) was $T_u = 1.5\%$.

To produce the desired FST intensity levels, a regular grid with a solidity of $\sigma = 48\%$ (denoted as RG), and two fractal grids with blockage ratios of $\sigma = 32\%$ and 41% (denoted as FG32 and FG41, respectively) were used. These grids were cut using 6 mm sheets of stainless steel in a laser cutting facility. The detailed grids' geometrical specifications are documented in (Sagharichi & Tachie,

2025a). The schematics of the regular and fractal grids are presented in Fig. 6.2, and a summary of the grids' tested grid geometries is provided in Table 6.1. In Table 6.1, N represents iterations of the fractal patterns, L_0 is the maximum bar length in fractal grids (the bar length in the RG), and t_0 is the spanwise thickness of the largest bar in fractal grids (the bar thickness of RG), and t_r represents the thickness ratio (ratio of the largest bar to the thinnest bar).

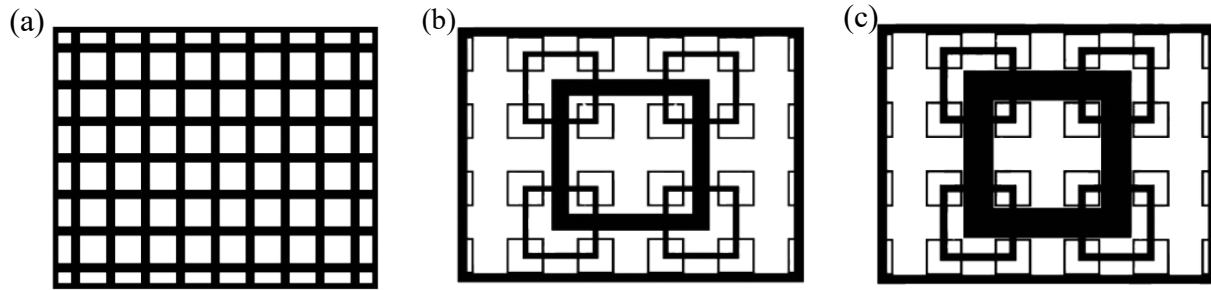


Figure 6.2 Turbulence-generating grids: RG (a), FG32 (b), and FG41(c)

Table 6.1 Grids' specifications

Parameters	RG	FG32	FG41
N	-	3	3
L_0/H	0.8	3.3	3.3
t_0/H	0.2	0.4	0.7
t_r	-	9.5	17.0
$\sigma \%$	48.0	32.0	41.0

The flow downstream of all grids was fully characterized before installing the Ahmed body, with these results documented in Sagharichi & Tachie (2025a). As shown in Fig. 6.3, the RG, FG32, and FG41 grids were placed at $x = 21.94H$, $20.69H$, and $19.30H$ upstream of the body, respectively. Further details have been provided in Table 2. At these distances, the turbulence is nearly homogeneous and isotropic (Sagharichi & Tachie, 2025a). The FST intensity levels at the Ahmed body's leading edge (measured in the absence of the body) were $T_u = 5.0\%$, 10.0% , and 15.0% for RG, FG32, and FG41, respectively. The corresponding integral length scales were $0.68H$, $1.07H$, and $1.0H$ for RG, FG32, and FG41, respectively. According to Castro & Haque (1988) and Li &

Melbourne (1995), when $0.4 < L_u/H < 4.0$, the integral length scale does not significantly affect the flow characteristics, including the mean pressure distribution on a rectangular plate. Given that the integral length scales in the current study are comparable to the body height, any variations in the grids' integral length scales are not expected to influence the flow dynamics. The boundary layer thickness was measured in the absence of the body at the location corresponding to the body's leading edge and was found to be $0.68H$, $0.79H$, $0.86H$, and $0.87H$ for FST intensities of 1.5%, 5.0%, 10.0%, and 15.0%, respectively.

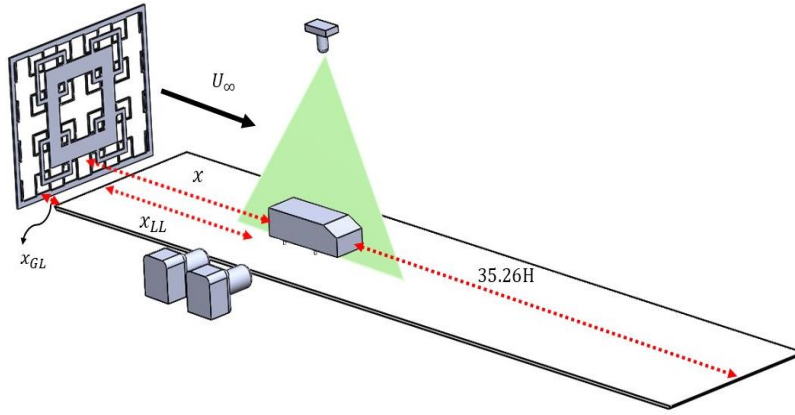


Figure 6.3 Schematic of the experimental setup

Table 6.2 Grid positions and turbulence parameters

Grid	T_u (%)	L_u/H	x_{LL}/H	x_{GL}/H
-	1.5	-	2.77	-
RG	5.0	0.68	2.77	19.16
FG32	10.0	1.07	2.77	17.92
FG41	15.0	1.0	2.77	16.53

6.3.1 Data Acquisition

Time-resolved particle image velocimetry (TR-PIV) was employed to measure the velocity vectors within the flow field. The Ahmed body model and raised floor were painted black to minimize

laser reflection noise. The flow was seeded with silver-coated hollow glass spheres, with a diameter of $10\text{ }\mu\text{m}$ (specific gravity of $\rho_p=1.4$) yielding a Stokes number of 0.73×10^{-5} well below the 0.05 threshold for accurate flow tracking (Samimy & Lele, 1991). The flow field was illuminated with a dual-cavity high-speed pulsed Nd:YLF laser with each pulse delivering a maximum energy of 30 mJ at a frequency of 1000 Hz and wavelength of 527 nm. The laser sheet thickness was set to 1 mm. The measurement was conducted in the x-y plane at the midspan of the test section ($Z/H = 0$), with the laser positioned above the water channel. To minimize free-surface distortions, a 9 mm-thick acrylic plate (585 mm long and spanning the entire section width) was submerged 2 mm below the laser sheet (Kumahor & Tachie, 2023; Sagharichi & Tachie, 2025). Measurements indicate that the boundary layer thickness on this plate was $\delta_p = 6\text{ mm}$ (Sagharichi & Tachie, 2025a); therefore, the effect of boundary confinement due to the surface plate on the present results is negligible. In the x-z plane, the laser was directed through the test section's sidewall, and measurements were acquired at two wall-normal locations, at the base mid-height ($y/H = 0.59$, hereafter referred to as H1) and over the slanted surface ($y/H = 0.89$, hereafter referred to as H2). Particle images were captured using Phantom VEO340L high-speed CMOS cameras, each with a resolution of 2560×1600 pixels. In the x-y plane, two cameras were utilized, each with a field of view of $288\text{ mm} \times 180\text{ mm}$ ($4.0H \times 2.50H$), arranged with a 10 mm overlap to achieve wider coverage. For the x-z planes, cameras with a field of view of $278\text{ mm} \times 174\text{ mm}$ ($3.86H \times 2.41H$) were employed. Specifically, a single camera was used at the H2 plane, while two cameras, each with the same field of view, were positioned with a 15 mm overlap for the H1 plane. The digital resolution was $112.5\text{ }\mu\text{m}$ per pixel and $108.2\text{ }\mu\text{m}$ per pixel in the x-y and x-z planes, respectively. Based on a convergence test, 60,000 instantaneous images were acquired per field of view in each plane at a sampling frequency of $f_{sp} = 803\text{ Hz}$. In the worst-case scenario (T_u

= 1.5%), the ratio of the sampling frequency to the vortex shedding frequency (f_{sp}/f) ensures 975 samples per shedding cycle, which is sufficient to resolve all dynamically important vortical structures. The total sampling time of $T = 74.7$ s captured approximately 62 shedding cycles, which corresponds to 268 characteristic time (H/U_∞), ensuring robust statistical convergence of mean and turbulent quantities.

The snapshots were post-processed using commercial software (Davis version 10.2.1) supplied by LaVision Inc.. A multi-pass cross-correlation algorithm was used for the velocity vector calculations (Willert & Gharib, 1991; Westerweel, 1997; Scarano & Riethmuller, 2000). A single initial interrogation area (IA) of $128 \text{ pixel} \times 128 \text{ pixel}$ with 50% overlap and four additional passes with an interrogation area of $24 \text{ pixel} \times 24 \text{ pixel}$ and with 75% overlap were used. The window deformation technique (Scarano, 2001) was applied in a multi-pass scheme, deforming and shifting interrogation windows based on predicted particle displacements to improve correlation accuracy by tracking identical particles across image pairs. The resulting vector spacing was $0.009H$ in each direction. A minimum correlation value of 0.5 for the primary correlation peak was imposed to ensure reliable correlations. Spurious vectors were removed using the universal outlier detection algorithm (Westerweel & Scarano, 2005) with a 5×5 neighbourhood median filter, and regions with fewer than five vectors were discarded. Spurious vectors were replaced using interpolation. Post-processing of PIV vectors was done using in-house MATLAB codes. Using the methods described by Sciacchitano & Wieneke (2016), the estimated uncertainties for the streamwise mean velocity, Reynolds normal, and shear stress with a 95% confidence level are less than $\pm 4.0\%$, $\pm 8.5\%$, and $\pm 5.2\%$, respectively.

A schematic of the PIV setup is depicted in Fig. 6.3. The instantaneous velocity component was decomposed into mean and fluctuating components using Reynolds decomposition, expressed as

$u = U + u'$, where U represents the mean velocity and u' denotes the fluctuating velocity. Throughout this paper, parameters are normalized relative to the model height and freestream velocity.

6.4 Results and Discussion

6.4.1 Mean Flow Field

Figure 6.4 presents the contours of normalized streamwise mean velocity (U/U_∞) around the Ahmed body, subjected to varying FST intensities of $T_u = 1.5\%$, 5.0% , 10.0% , and 15.0% . The subfigures are paired to illustrate flow evolution over the roof region (left column: (a), (c), (e), (g)) and the wake region (right column: (b), (d), (f), (h)), with superimposed mean streamlines (solid black lines) and the $U = 0$ isopleth (dashed line) which demarcates the recirculation bubble. The figures indicate consistent flow behaviour across all test cases. In each case, the flow separates at the leading edge, accelerates, and then reattaches to the roof to form the roof recirculation bubble. The figure shows that increasing FST intensity shrinks both the streamwise length and the height of the recirculation bubble over the roof, while its center shifts towards the leading edge. Specifically, the recirculation length is defined as the furthest streamwise extent where $U \leq 0$, as follows:

$$L_r = \max(x/H)_{U(x/H) \leq 0} \quad (6.1)$$

decreases from $1.85H$ at $T_u = 1.5\%$ to $1.49H$, $1.03H$ and $0.82H$ as FST intensity increases to $T_u = 5.0\%$, 10.0% and 15.0% , respectively. Meanwhile, the bubble size height reduces from $0.31H$ to $0.21H$ as FST intensity increases from $T_u = 1.5\%$ to 5.0% but remains unchanged as it further enhances to $T_u = 15.0\%$. That FST tends to shrink recirculation bubbles has been observed by previous researchers (Kiya & Sasaki, 1983; Kalter & Fernholz, 2001; Stevenson et al., 2016; Wang

et al., 2024; Sagharichi & Tachie, 2025). Stevenson et al. (2016) and Lander et al. (2016) have linked this earlier reattachment to the strength of entrainment mechanisms within the shear layer. As noted by Kiya & Sasaki (1983) and Lander et al. (2016), these entrainment mechanisms continuously deform the shear layer, pulling it closer to the surface. This result is an earlier reattachment of the flow to the roof, which reduces the size of the recirculation bubble. At $T_u = 1.5\%$ (Fig. 6.4a), the roof recirculation bubble is characterized by a maximum backflow of $U/U_\infty = -0.43$. As FST intensity increases, the maximum backflow decreases to $U/U_\infty = -0.39$, -0.36 , -0.28 at $T_u = 5.0\%$, 10.0% and 15.0% , respectively.

In the wake region, two recirculation bubbles form one over the other, with the top one forming due to the shear layer emanating from the slanted surface, and the lower one emanating from the body undersurface. This observation is in line with Wang et al. (2013), Tunay et al (2014), Venning et al. (2022), and Sagharichi & Tachie (2025) who reported similar behaviour in the wake region of the rounded leading edge high-drag Ahmed body. In contrast to the recirculation bubble over the roof, the length of the wake recirculation length ($L_r \approx 0.56H$) and maximum backflow ($U/U_\infty = -0.18$) are independent of FST intensity. This value agrees well with $L_r = 0.56H$ reported by Tunay et al. (2014) and Sagharichi & Tachie (2025) formed in the wake region of the rounded leading edge Ahmed body. This insensitivity suggests that the global wake topology is governed by the Ahmed body's geometry, rather than FST intensity and is consistent with previous studies on a wall-mounted square (Hearst et al., 2016), rectangular cylinder in freestream flow (Zhu et al., 2020), and a rounded leading edge Ahmed body (Sagharichi & Tachie, 2025) under elevated FST conditions. This trend is attributed to the dissipation of FST intensity along the body's surface and the shielding effect of the Ahmed body's geometry, which limits the influence of FST on the large-scale recirculation bubble in the wake (Chen et al., 2022; Sagharichi & Tachie, 2025).

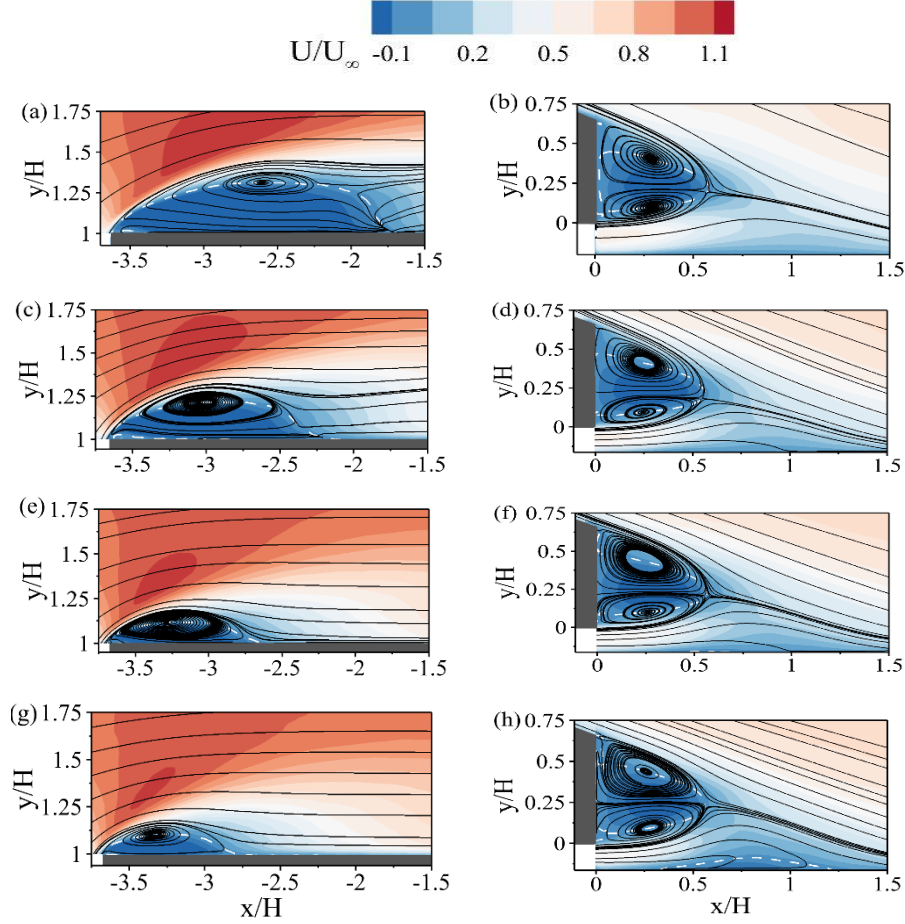


Figure 6.4 Contours of normalized streamwise mean velocity for $T_u = 1.5\%$ [(a), (b)], $T_u = 5.0\%$ [(c), (d)]; $T_u = 10.0\%$ [(e), (f)] and $T_u = 15.0\%$ [(g), (h)]. Mean streamlines are depicted using solid black lines, and the $U = 0$ isocontour using a dashed white line

As shown in Fig. 6.4, flow separation and recirculation phenomena over the Ahmed body are profoundly influenced by FST intensity. The introduction of FST modifies the mean shear characteristics, alters the strain rate dynamics, and suppresses the recirculation bubble. Central to understanding these dynamics is the decomposition of the mean shear tensor, S_{xy} , in the x - y plane. For spanwise-homogeneous flows, the 3D strain rate tensor simplifies to its planar components, with spanwise derivatives ($\partial U/\partial z$, $\partial V/\partial z$, etc.) vanishing (Fang & Tachie, 2020; Li et al., 2025). Under these conditions, S_{xy} is expressed as:

$$S_{xy} = \begin{bmatrix} \frac{\partial U}{\partial x} & \frac{1}{2}(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}) \\ \frac{1}{2}(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}) & \frac{\partial V}{\partial y} \end{bmatrix} = Q \begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix} Q^T \quad (6.2)$$

where σ_1 and σ_2 are eigenvalues representing the principal strain rates, and Q contains the eigenvectors defining the principal directions. Due to incompressibility ($\partial U/\partial x + \partial V/\partial y = 0$), the eigenvalues satisfy $\sigma_1 = -\sigma_2$, with $\sigma_1 > 0$ quantifying the magnitude of principal stretching. The first eigenvector in Q corresponds to the principal stretching direction, θ_p , confined to $[-90^\circ, 90^\circ]$.

Assuming small-scale vortices are convected by the mean flow, the salient features of the mean shear along the separating streamline are assessed in Fig. 6.5. As shown in Fig. 6.5a, the separating streamline for $T_u = 1.5\%$ and 5.0% sheds downstream without reattaching over the roof, while it reattaches at $x/H = -2.75$ and -2.55 for $T_u = 10.0\%$ and 15.0% , respectively. Fig. 6.5b shows that near the leading edge, strong shear layers induced by the sharp corner dominate the strain field. These layers exhibit pronounced velocity gradients ($\partial U/\partial x$ and $\partial V/\partial y$) that govern σ_1 and θ_p . While the magnitude of σ_1 at the leading edge is comparable across all FST intensities; increasing FST intensity suppresses σ_1 after the separation point, with the largest reduction observed near the reattachment points for $T_u = 15.0\%$. The reduction in principal stretch associated with a decrease in the recirculation bubble was also observed around rectangular cylinders submerged in the wall boundary layer (Li et al., 2025). The value of σ_1 for $T_u = 10.0\%$ and $T_u = 15.0\%$ increases after the reattachment point. This increase can be attributed to the presence of mean shear in the vicinity of the roof wall (Li et al., 2025). At the leading edge, the mean streamline separates at $\theta_u = 45^\circ$ for all test cases. At this point, irrespective of FST intensity, the principal stretching direction is almost vertical ($\theta_p = 90^\circ$). Along the separating streamline, θ_p continuously

decreases for $T_u = 1.5\%$ and $T_u = 5.0\%$, while it stabilizes at $\theta_p \approx 22^\circ$ at the reattachment point for $T_u = 10.0\%$ and $T_u = 15.0\%$, before plateauing at $\theta_p \approx 45^\circ$, resembling the behaviour observed in a canonical turbulent boundary layer (TBL) in which the $\partial U / \partial y$ is dominant (Fang & Tachie, 2020). It is also noted in Fig. 6.5c that for $T_u = 10.0\%$ and $T_u = 15.0\%$, as the mean streamline is deflected downward (at $x/H \in [-3.25, -2.75]$, corresponding to the rear part of the roof recirculation bubble) the direction of principal stretching also reduces abruptly (directed toward the wall). The abrupt drop in θ_p suggests that high FST pulls the shear layer toward the roof and aligns the stretching direction closer to the surface.

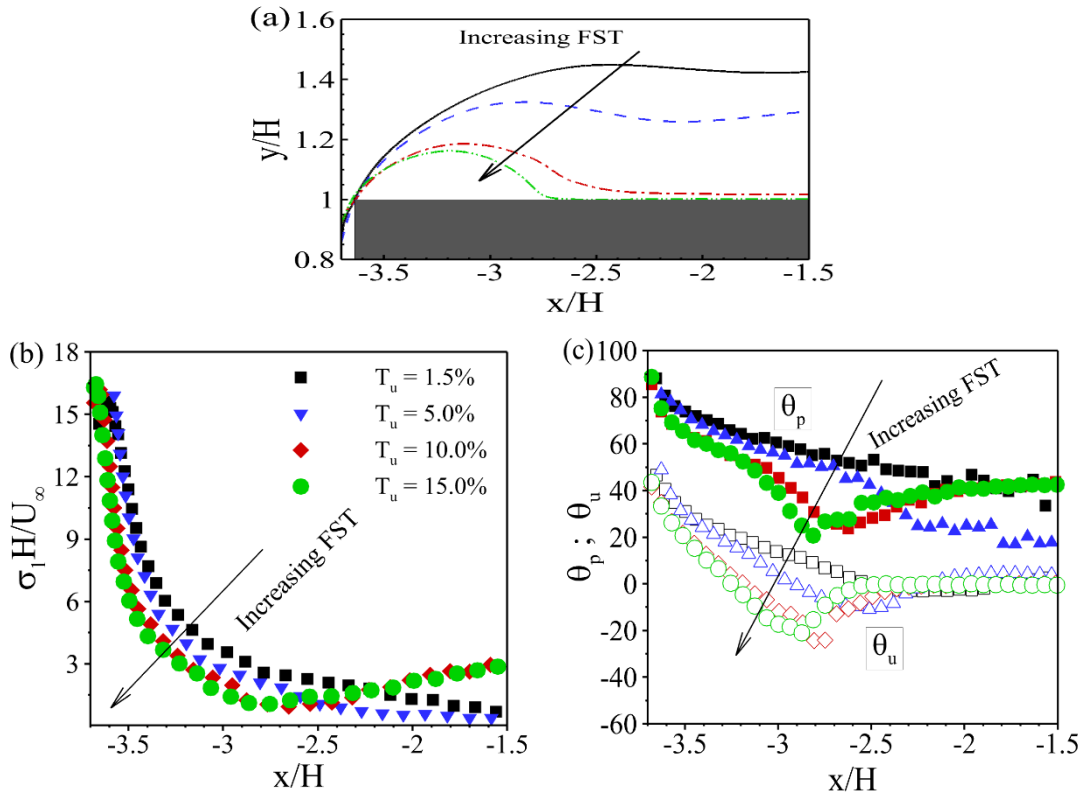


Figure 6.5 (a) Mean streamlines separate from the leading edge. (b) the principal stretching σ_1 along the separating streamline. (c) Angles (θ_p) of the principal stretching and mean velocity (θ_u)

Building on the insights from the mean shear and principal stretching dynamics along the separating streamline, we now examine the role of FST intensity on the evolution of the shear layer

interface over the roof. We calculate the shear layer interface ($y_{\Omega(x)}$) which is identifying the wall-normal position where the local mean spanwise vorticity decreases to $|\omega_z(x, y_{\Omega(x)})| = 0.01|\omega_z|_{\max}(x)$ (Cimarelli et al., 2024). A sensitivity analysis was conducted for thresholds of 0.005 and $0.02|\omega_z|_{\max}(x)$, which demonstrated that variations in the chosen cutoff produced less than a 2% change in the computed $y_{\Omega(x)}$. Figure 6.6 shows the streamwise evolution of the roof shear layer interface for various FST intensities. At the initial stage of shear layer development ($x/H < -3.2$), the streamwise evolution of the shear layer interface is remarkably consistent across all FST intensity levels. Beyond $x/H = -3.2$, the shear layer interface decreases more rapidly for higher FST intensities, indicating a monotonic deviation toward the roof. In contrast, lower FST intensities exhibit a more gradual decline. The rapid decrease in the shear layer interface height with increasing FST intensity reflects the folding of the shear layer interface toward the roof, which results in an earlier reattachment of the shear layer and a reduction in the recirculation bubble.

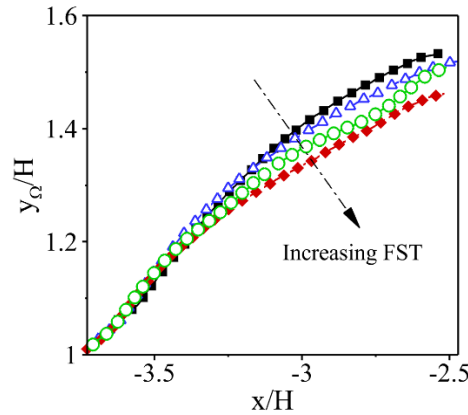


Figure 6.6 Streamwise evolution of the interface position

6.4.2 Reynolds Stresses and Temporal Scales

Figure 6.7 compares the streamwise evolution of the maximum streamwise Reynolds normal stress $(\overline{u'u'})_{\max}$, wall-normal Reynolds normal stress $(\overline{v'v'})_{\max}$, Reynolds shear stress $(\overline{u'v'})_{\max}$, and

turbulent kinetic energy $(TKE)_{\max}$ (defined as: $TKE = 0.5(\overline{u'u'} + \overline{v'v'})$) under varying FST intensities. Over the roof, for all FST intensities, the magnitude of $(\overline{u'u'})_{\max}$ dominates the Reynolds stresses, and the Reynolds shear stress is lower than that of the normal stress components. This trend is consistent with the findings of Moore et al. (2019) for flow around rectangular prisms with aspect ratios of 1, 3, and 5, as well as Sagharichi et al. (2025) for a rounded leading edge Ahmed body. $(\overline{u'u'})_{\max}$ profile exhibits a strong FST dependence. For instance, $(\overline{u'u'})_{\max}$ increases with FST intensity and its peak location shifts toward the leading edge. At $T_u = 1.5\%$, the peak value of $(\overline{u'u'})_{\max}$ reaches 0.13, which is 15%, 29%, and 46% lower than the corresponding peaks at $T_u = 5.0\%$, 10.0% , and 15.0% , respectively. This increase in $(\overline{u'u'})_{\max}$ with FST intensity is consistent with the findings of Castro & Haque (1988) for flow around a vertical flat plate subjected to elevated freestream turbulence. The upstream migration of the peak $(\overline{u'u'})_{\max}$ suggests that elevated FST triggers an earlier transition to turbulence, accelerating shear layer development (Kiya & Sasaki, 1983).

In contrast, the maximum wall-normal Reynolds normal stress and Reynolds shear stress over the roof show no sensitivity to FST intensity, with $(\overline{v'v'})_{\max} = 0.05$ and $(\overline{u'v'})_{\max} = 0.04$, regardless of FST intensity, even though their peak locations shift upstream as FST intensity increases. A similar trend was observed for the leading edge of a round-nosed plate subjected to the FST intensity of $T_u = 3\%$ and 7% (Stevenson et al., 2016). The figures also show that the magnitude of Reynolds stresses undergoes a sharp decline after the $x/H > -3.2$ and the decay rate turns out to be sharper for higher FST intensity. This behaviour was also observed over a vertical flat plate exposed to $T_u = 3\%$ (Castro & Haque, 1988) and is attributed to the shear sheltering effect, so that after a certain point, shear layer development no longer depends upon the external turbulence (Kalter & Fernholz, 2001). Additionally, this abrupt reduction implies a decoupling of the

streamwise and wall-normal velocity fluctuations under the effect of FST intensity (He et al., 2024). Especially the shear-stress correlation coefficient $\rho_{u'v'} = \overline{u'v'} / (\sqrt{\overline{u'u'}}\sqrt{\overline{v'v'}})$ along the trajectory of $(\overline{u'v'})_{\max}$ shows a declining trend with FST intensity. At $x/H = -1$, the correlation coefficient is $\rho_{u'v'} = -0.49, -0.49, -0.38, -0.33$ for $T_u = 1.5\%, 5.0\%, 10.0\%$, and 15.0% respectively (See subset in Fig. 6.7e). A similar observation was made by Hancock & Bradshaw (1983) for the flat plate boundary layer subjected to FST intensity. The curve of $(TKE)_{\max}$ displays qualitatively similar behaviour for all FST intensities. Each curve begins at a low TKE level, rises exponentially to a peak, and subsequently decreases. Its profile mirrors $(\overline{u'u'})_{\max}$ trend, which shows a consistent rise with increasing FST intensity, while its peak location shifts toward the leading edge. Moore et al. (2019) noted that vortex roll-up closely coincides with the peak $(TKE)_{\max}$. Hence, it can be conjectured that increasing FST intensity leads to a shift in the onset of vortex roll-up closer to the leading edge.

In the wake region, $(\overline{u'u'})_{\max}$ curves display an irregular trend with FST, with the highest $(\overline{u'u'})_{\max}$ occurs at $T_u = 5.0\%$ and the lowest at $T_u = 10.0\%$ and 15.0% . Increasing FST intensity, however, tends to reduce the peak value of $(\overline{u'v'})_{\max}$, $(\overline{v'v'})_{\max}$ and TKE. This trend is consistent with Li et al. (2022), who reported that high FST intensity ($T_u = 20.0\%$) weakens $(\overline{v'v'})_{\max}$ in the wake of a square cylinder due to reduced interaction of the shear layer in the wake region. Liu et al. (2021) reported that high concentrations of $(\overline{v'v'})_{\max}$ in the wake region of Ahmed body can be related to the interaction of periodic motions of the upper and lower shear layer, emanating from the slanted surface and body undersurface. Thus, the suppression of $(\overline{v'v'})_{\max}$ under high FST intensity can be attributed to the disruption of the periodical motion of shear layers by the elevated FST.

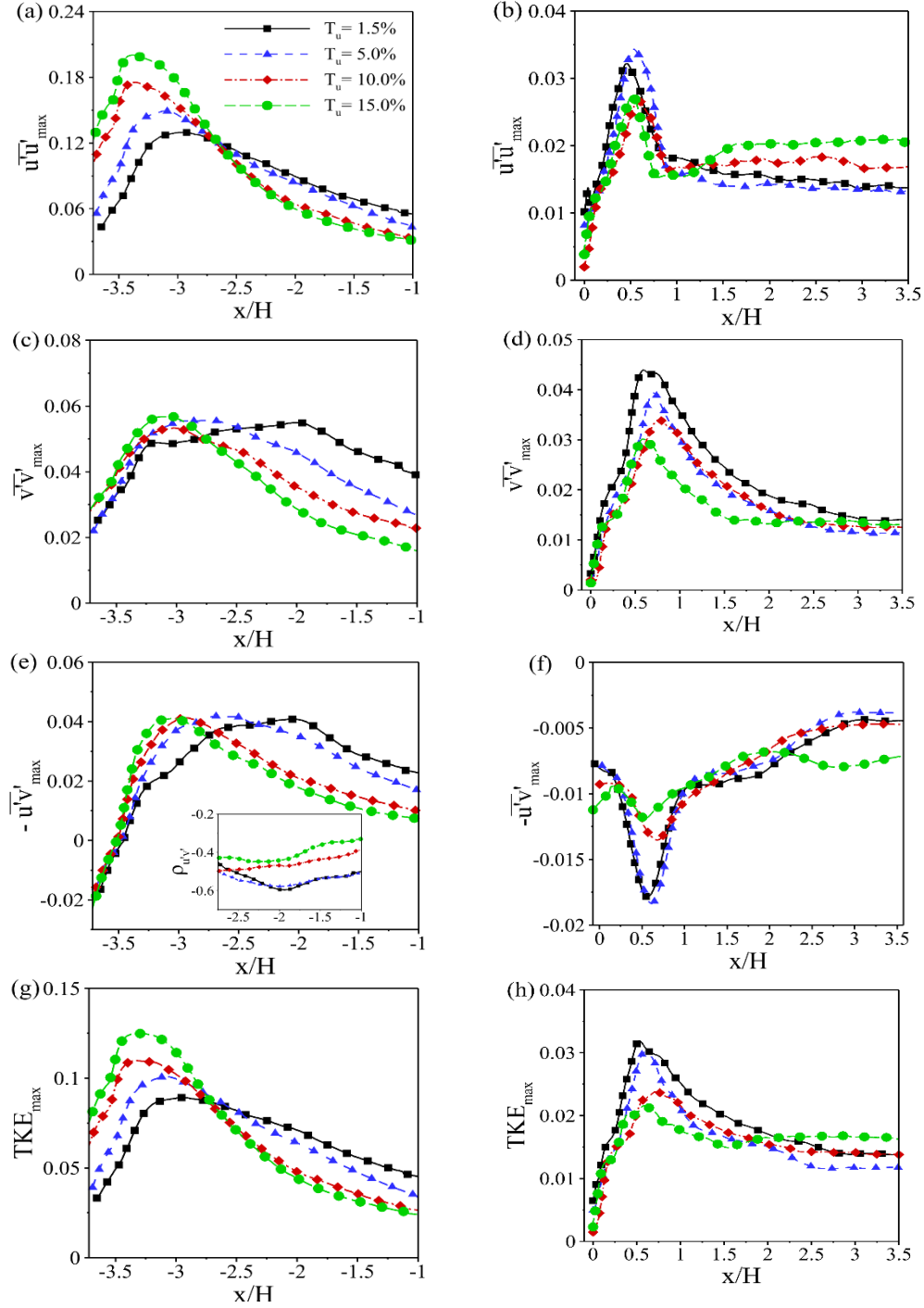


Figure 6.7 Streamwise evolution maximum Reynolds stresses and TKE over the roof [(a), (c), (e), (g)] and in the wake [(b), (d), (f), (h)]

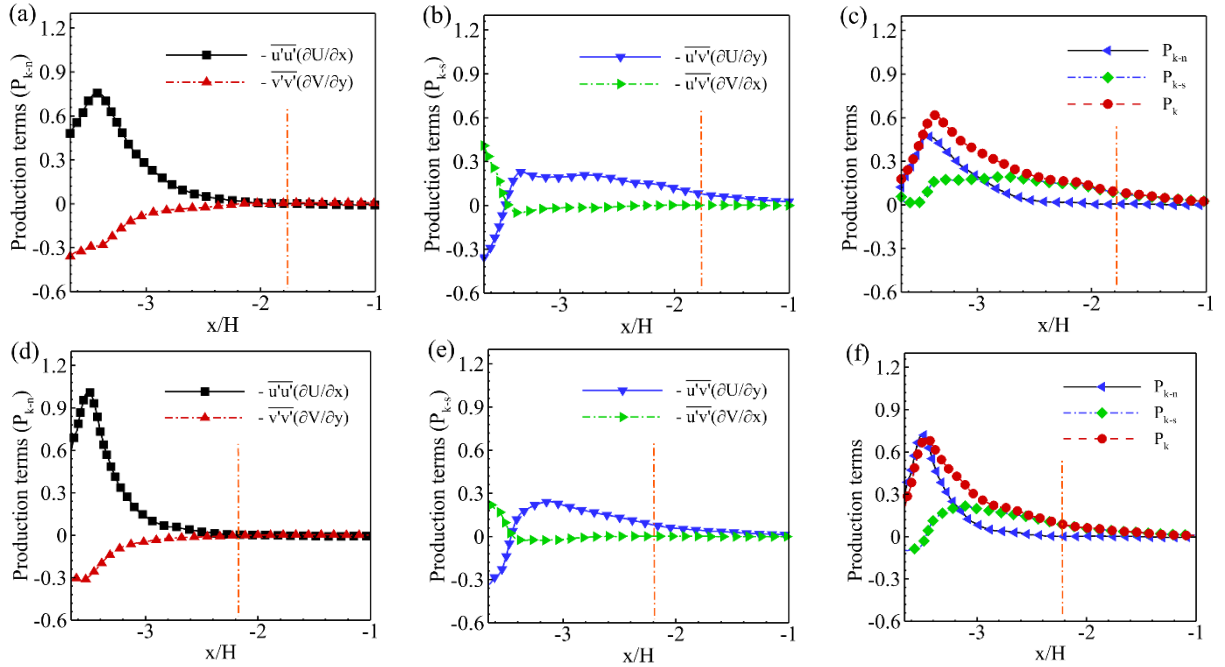
Having established how TKE varies with FST intensity, we now explore the underlying mechanisms influencing TKE production across various FST intensities. In this section, we evaluate the individual contributions of normal-stress and shear-stress terms to TKE production

by analyzing the production term (P_k). The normal stress contribution in TKE production (P_{k-n}), and shear stress production (P_{k-s}), and the total production term can be calculated as:

$$P_k = \underbrace{-\overline{u'u'} \frac{\partial U}{\partial x} - \overline{v'v'} \frac{\partial V}{\partial y}}_{P_{k-n}} - \underbrace{\overline{u'v'} \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right)}_{P_{k-s}} \quad (6.3)$$

Figure 6.8 shows profiles of each contribution of P_k along the shear layer (defined as the trajectory where $(TKE)_{\max}$ occurs). Irrespective of FST intensity, $-\overline{u'u'} \frac{\partial U}{\partial x}$ contributes the most to the overall amount of P_k , indicating that terms associated with streamwise mean velocity gradients and/or streamwise normal stresses are most responsible for the production of TKE. This observation aligns with the findings by Moore et al. (2019) and Chiarini et al. (2022) for a rectangular prism with an aspect ratio of 5. As FST intensity increases from 1.5% to 15%, the magnitude of this dominant normal stress term intensifies, and its peak location shifts upstream, a trend consistent with $(TKE)_{\max}$ curve observed in Fig. 6.7. After reaching its peak, the contribution of this term declines, becoming negligible by the reattachment point. In contrast, $-\overline{v'v'} \frac{\partial V}{\partial y}$ counteract $-\overline{u'u'} \frac{\partial U}{\partial x}$ contribution (because of incompressibility, $-\overline{v'v'} \frac{\partial V}{\partial y}$ and $-\overline{u'u'} \frac{\partial U}{\partial x}$ have an opposite sign) and positive $\frac{\partial V}{\partial y}$ across the roof shear layer, leads to the negative sign of $-\overline{v'v'} \frac{\partial V}{\partial y}$ along the shear layer. Cimorelli et al. (2019; 2020) showed that the negative sign of $-\overline{v'v'} \frac{\partial V}{\partial y}$ is a peculiar feature of sharp leading-edge geometries. Overall, the magnitude of $-\overline{v'v'} \frac{\partial V}{\partial y}$ is lower than $-\overline{u'u'} \frac{\partial U}{\partial x}$ which resulted from $\overline{u'u'} > \overline{v'v'}$ over the roof (See Fig. 6.7). In contrast to $-\overline{u'u'} \frac{\partial U}{\partial x}$, the magnitude of $-\overline{v'v'} \frac{\partial V}{\partial y}$ remains relatively insensitive to changes in FST intensity. The shear stress contributions exhibit distinct behaviours along the shear layer, divided into two regions. The first region ($x/H <$

-3.20), from the onset of the shear layer to $(TKE)_{\max}$ position, the shear stress terms counteract each other with $-\overline{u'v'} \frac{\partial V}{\partial x}$ and $-\overline{u'v'} \frac{\partial U}{\partial y}$ acts as the source (positive contribution) and sink (negative contribution), respectively. This trend agrees well with Cimarelli et al. (2019) and Chiarini et al. (2022) for separated flow from the leading edge of a rectangular cylinder subjected to freestream flow. At $T_u = 1.5\%$, these terms nearly cancel out each other, resulting in a zero contribution to TKE production (Fig. 6.8c). As FST intensity increases (from 5% to 15%), $-\overline{u'v'} \frac{\partial U}{\partial y}$ becomes dominant, causing the summed shear stress contribution to turn negative in this region. Beyond the position of $(TKE)_{\max}$ the contribution of $-\overline{u'v'} \frac{\partial V}{\partial x}$ becomes zero, while $-\overline{u'v'} \frac{\partial U}{\partial y}$ contribute to the positive production extending beyond the reattachment point. Consequently, the overall shear stress contribution becomes positive in this region, enhancing the total TKE production.



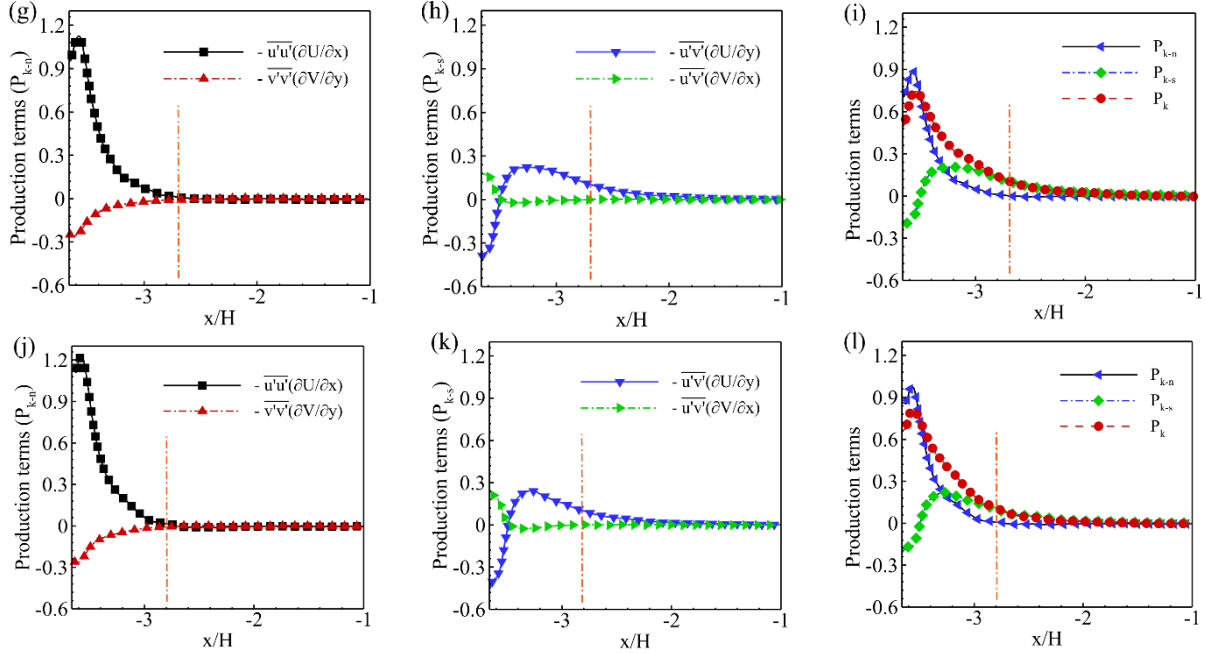


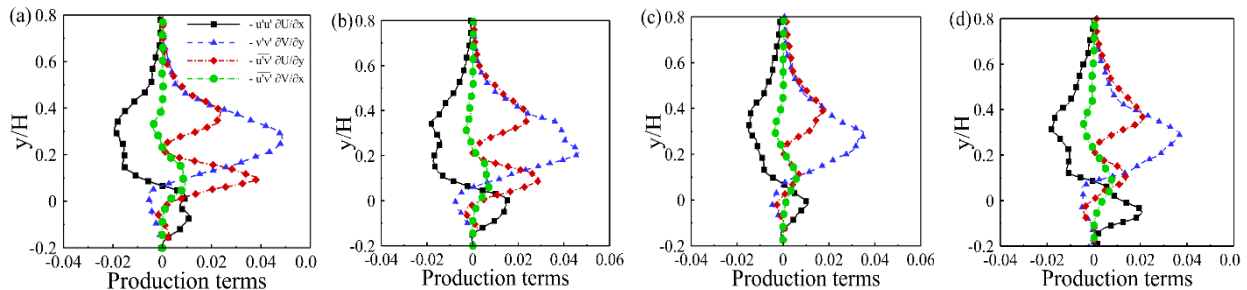
Figure 6.8 Turbulent production terms. [(a), (d), (g), and (j)] are profiles of normal stress contribution (P_{k-n}); [(b), (e), (h), and (k)] are profiles of shear stress contribution (P_{k-s}); in TKE production [(c), (f), (i), and (l)] represents the total production. Every third point is plotted. $T_u = 1.5\%$ [(a-c)], $T_u = 5.0\%$ [(d-f)]; $T_u = 10.0\%$ [(g-i)] and $T_u = 15.0\%$ [(j-l)]. The vertical dash-dot line marks the mean reattachment point

The mechanism of suppression of TKE in the wake region (See Fig. 6.7) under elevated FST intensity can be explained by TKE production. Figures 6.9a-d show the wall-normal distribution of terms contributing to P_k term at the location of $(TKE)_{\max}$ in the wake region. It is seen that the highest positive contribution in TKE stems from $-\overline{v'v'} \frac{\partial v}{\partial y}$, while it is counteracted by $-\overline{u'u'} \frac{\partial u}{\partial x}$. However, due to $\overline{v'v'} > \overline{u'u'}$ in the wake region, the sign of P_{k-n} is positive. Among shear stress production terms, $-\overline{u'v'} \frac{\partial u}{\partial y}$ is the dominant one, which is due to the intense $\partial u / \partial y$. Since both shear stress terms are positive, the overall shear stress term is the source of TKE in the wake region. At $T_u = 1.5\%$, the production of TKE is mainly due to shear stress, and it monotonically decreases as FST increases. However, increasing FST intensity does not affect the contribution from normal stresses P_{k-n} . Hence, the reduction in TKE in the wake region by FST intensity can be attributed to the suppression of shear stress production.

To evaluate how FST intensity suppresses the shear stress production in the wake region, a quadrant analysis was conducted following the methodology outlined by Willmarth & Lu (1972). At each point in the flow, the total stress $\overline{u'v'}$ was decomposed into contributions from each quadrant. The contribution from each quadrant to production by shear stress was then calculated as follows (Nolan et al. 2010):

$$P_i = -(\overline{u'v'})_i \left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \quad (6.4)$$

where $i = 1$ to 4 indicates the quadrant events, which are defined as outward interactions in quadrant 1 ($u' > 0$ and $v' > 0$), ejections in quadrant 2 ($u' < 0$ and $v' > 0$), inward interactions in quadrant 3 ($u' < 0$ and $v' < 0$), and sweeps in quadrant 4 ($u' > 0$ and $v' < 0$). Figures 6.9e-h show the quadrants' productions at $(TKE)_{\max}$ in the wake region. The figures are characterized by dual peaks which coincide with the location of the upper and lower recirculation bubbles, respectively (See Fig. 6.4). Thus, it can be inferred that the upper shear layer (dominated by ejection P_2 and sweep P_4) is linked to vorticity shed from the Ahmed body's slanted surface, while the lower shear layer (inward P_3 and outward P_1 interactions) corresponds to underbody-induced vorticity. In all test cases, P_3 is higher than the other terms, which suggests that turbulence production is driven by the impingement of low-momentum fluid onto the wall. While increasing FST intensity monotonically reduces the production of all quadrant terms, the reduction in the P_3 term is the most pronounced. Hence, it can be concluded that increasing FST intensity reduces the TKE energy by suppressing the inward interaction events.



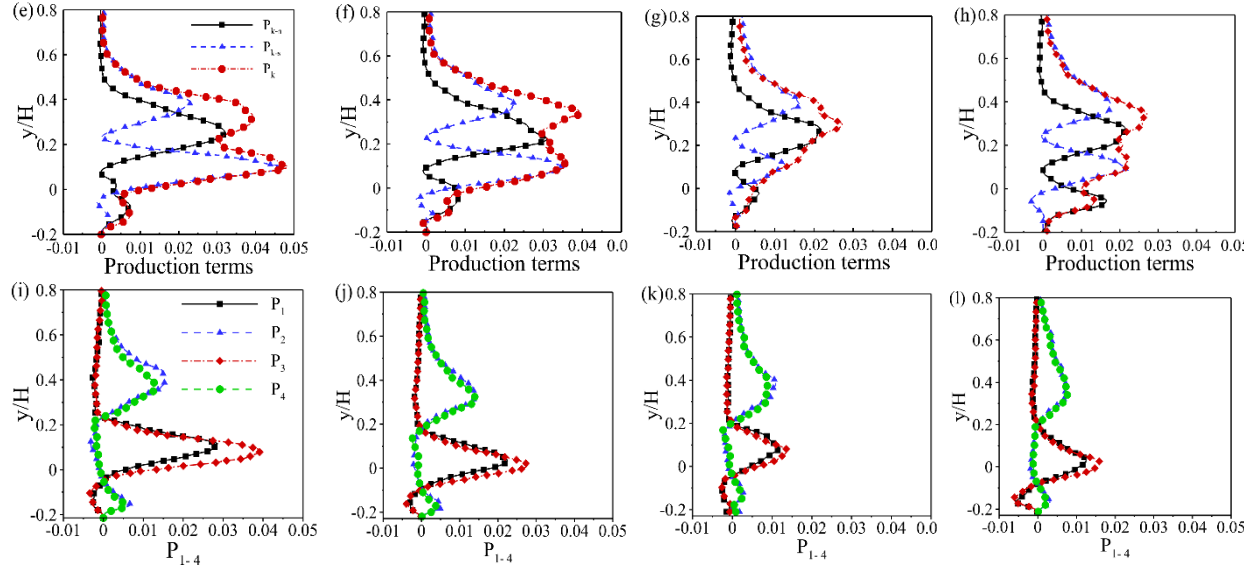


Figure 6.9 Normal and shear stress contribution on total TKE production [(a-h)] and production of quadrants [(i-l)] for $T_u = 1.5\%$ [(a), (e), and (i)]; $T_u = 5.0\%$ [(b), (f), and (j)]; $T_u = 10.0\%$ [(c), (g), and (k)]; $T_u = 15.0\%$ [(d), (h), and (l)]

Wallace et al. (1972) provided empirical evidence for the lifetimes of structures pertinent to each quadrant event. They determined the timescales for each quadrant using autocorrelations of quadrant-conditioned signals and found that the timescales for quadrant 2 (ejections) and quadrant 4 (sweeps) are significantly larger than those for quadrant 1 (outward interactions) and quadrant 3 (inward interactions). Thus, quadrant 1 and quadrant 3 events are shorter-lived, aligning with smaller-scale or more transient turbulent structures, while quadrant 2 and quadrant 4 structures are linked to longer-lasting, coherent structures. To understand the temporal mechanism involving the suppression of P_3 under high FST intensities in Fig. 6.9, integral time scales (τ) of vortical structures in the wake region were calculated. Following Tennekes & Lumley (1972), the integral time scale at a reference location (x_{ref}, y_{ref}) is calculated by integrating the temporal autocorrelation of velocity fluctuations from the time displacement (T) of zero to the point associated with the first zero correlation (T^*), as follows:

$$R(x_{\text{ref}}, y_{\text{ref}}, T) = \frac{\overline{u'(x_{\text{ref}}, y_{\text{ref}}, t)u'(x_{\text{ref}}, y_{\text{ref}}, t + T)}}{u_{\text{rms}}'^2(x_{\text{ref}}, y_{\text{ref}})} \quad (6.5)$$

$$\tau = \int_0^{T^*} R(x_{\text{ref}}, y_{\text{ref}}, T) dT \quad (6.6)$$

where t and T denote the reference time and the temporal separation, respectively. To take advantage of the whole-field time-resolved PIV measurements, the integral time scales of streamwise (τ_u) and wall-normal (τ_v) fluctuation velocities were determined at each vector point of the velocity field as presented in Fig. 6.10. The difference in topology between wall-normal and streamwise time scales underscores the pronounced anisotropy at large scales (Ouedraogo & Essel, 2023). The contours show the presence of larger integral time scales as FST intensity increases. Specifically, τ_u and τ_v increase from 0.63 to 1.45 and increase from 0.71 to 1.25, respectively, as FST intensity enhances from $T_u = 1.5\%$ to 15.0% . This trend aligns with Kiya & Sasaki (1985), who reported that the integral time scale around a blunt flat plate increases with FST intensity. This trend is consistent with the observed decrease in production from quadrant 1 and quadrant 3 events as FST intensity grows. Because these two quadrants are tied to short-lived, small-scale turbulent motions, their weakening contribution signifies a shift in the wake of transient, small-scale eddies. At $T_u = 1.5\%$, the location of elevated τ_v structure coincides with the location of $(\overline{v'v'})_{\text{max}}$ where the upper and lower shear layers interact. However, as FST intensity increases, this region shifts toward the base, and by $T_u = 15.0\%$, large-scale structures form near the base. These large time scales are attributed to the vortices in that are deflected backward after the interaction of the upper and lower shear layers.

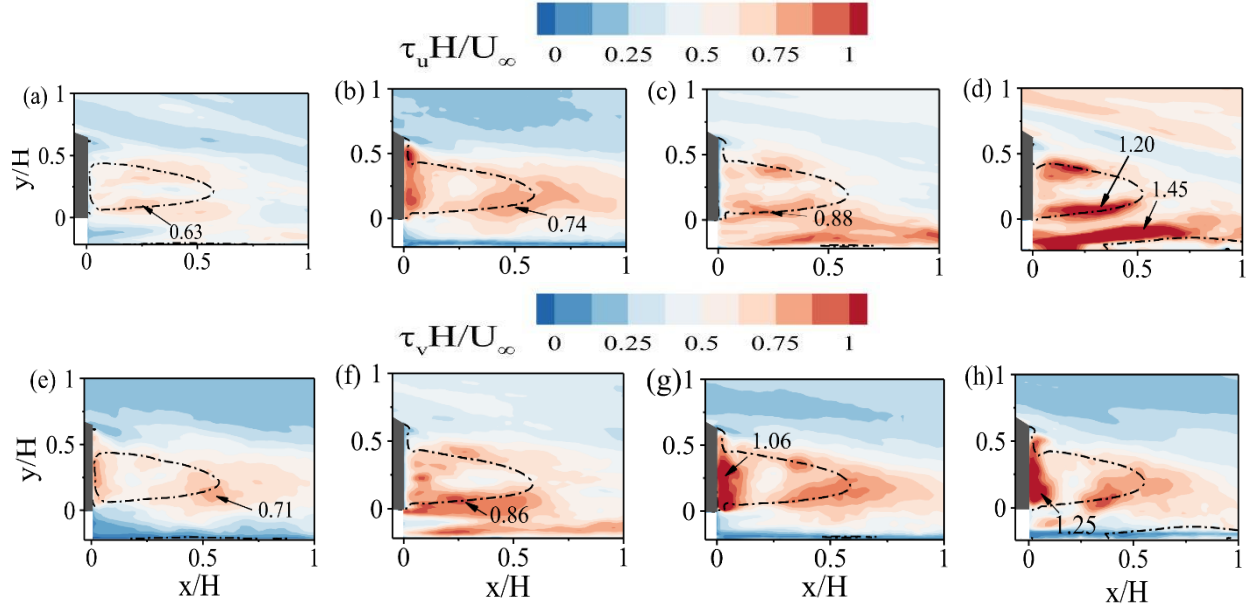


Figure 6.10 Contours of the streamwise [(a-d)] and wall-normal [(e-h)] integral time scales in the wake region. $T_u = 1.5\%$ [(a), (e)]; $T_u = 5.0\%$ [(b), (f)]; $T_u = 10.0\%$ [(c), (g)]; $T_u = 15.0\%$ [(d), (h)]

6.4.3 Frequency Spectrum

The temporal behaviour of the instantaneous shear layer is examined by analyzing the frequency spectra of streamwise fluctuation velocity. It is important to note that the spectral analysis in this study is carried out using Welch's overlapped window method (Welch 1967). Figure 6.11 shows the spectrum of streamwise and wall-normal fluctuation velocities at points $[x/H, y/H] = [-3.61, 1.08]$; $[-3.63, 1.06]$; $[-3.65, 1.05]$; $[-3.65, 1.04]$ for $T_u = 1.5\%$, 5.0% , 10.0% and 15.0% , respectively. The figure shows that this point is characterized by KH instability with $St = 4.63$, 5.32 , 4.54 , and 5.30 for $T_u = 1.5\%$, 5.0% , 10.0% and 15.0% , respectively. These frequencies are in excellent agreement with $St \approx 3.0 - 5.0$ reported over semi-submerged sharp-edge bluff bodies (Fang et al., 2022), over a flat plate (Kiya & Sasaki, 1983); and rectangular cylinders subjected to freestream flow (Moore et al., 2019).

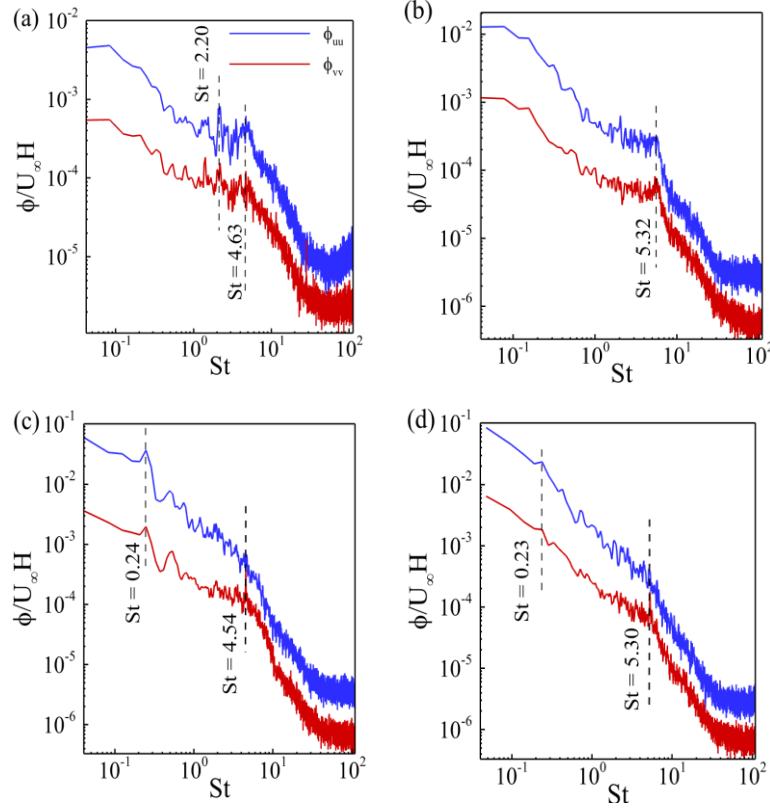


Figure 6.11 The frequency spectrum of streamwise (ϕ_{uu}) and wall-normal (ϕ_{vv}) fluctuation velocities at point $[x/H, y/H] = [-3.61, 1.08]$; $[-3.63, 1.06]$; $[-3.65, 1.05]$; $[-3.65, 1.04]$ for (a) $T_u = 1.5\%$, (b) 5.0% , (c) 10.0% and (d) 15.0% , respectively

Figure 6.12 characterizes the frequency spectrum of streamwise fluctuation velocities along the mean shear layer over the roof and the upper shear layer emanating from the slanted surface, which is shed into the wake region. Irrespective of FST intensity, the high-frequency vortices migrate to the lower frequencies, which start from the leading edge and cease at the midpoint of the recirculation bubble. Winant & Browand (1974), Moore et al. (2019), Fang et al. (2022), and Li & Wang (2024) noted that the migration of frequency arises from the recurrent pairing of vortices. Specifically, once the KH instability generates small-scale vortices, pairs of neighbouring vortices merge and mix, producing a new vortex that is twice the size and oscillates at half the original frequency. Multiple discrete frequencies are horizontally shed along the shear layer, and their energy fades earlier as FST intensity increases. This is not surprising as the mean shear layer moves

closer to the wall as FST intensity increases, so they fade out sooner under the wall proximity effect. Regardless of FST intensity, the shear layer over the roof is characterized by two distinct frequencies, $St \in [0.33 - 0.37]$ and 0.24, with the latter agreeing well with the reported Strouhal number, $St = 0.27$, found by Aleyasin et al. (2021) for flow around a cuboid at $Re = 2.26 \times 10^4$. At $T_u = 10.0\%$ and $T_u = 15.0\%$ the dominance of lower frequencies, $St = 0.16$ and 0.14 is apparent, respectively, which are not evident after the reattachment point. Interestingly, a Strouhal number of $St = 0.08$ appears at $T_u \geq 5.0\%$, and its spectral energy diminishes past the mean reattachment point. This frequency is close to $St = 0.09$ observed over a forward-facing step (Pearson et al., 2013). Considering that this frequency falls within $(0.08-0.2) U_\infty/L_r$ (Kiya & Sasaki, 1985) it can be concluded that it is related to the flapping motion of the recirculation bubble and indicates that the bubble expands and shrinks with a frequency whose value is roughly three to four times lower than the frequency of quasi-periodic vortex shedding in the separated shear layer ($St = 0.24$ and $0.34-0.37$). The spatial distribution of the energy spectrum of streamwise fluctuation velocity at this frequency shows an elevated region embracing the entire flow separation recirculation bubble. This observation agrees well with (Kiya & Sasaki, 1985) ‘The low-frequency unsteadiness is of large scale in the sense that it is felt everywhere in the separation bubble’. Interestingly, the flapping motion was not observed over the roof of the rounded leading edge of Ahmed body exposed to $T_u = 5.0\%$ to $T_u = 15.0\%$ (Sagharichi & Tachie, 2025). This absence can be attributed to the role of the leading edge in the flapping motion phenomena. It is believed that this type of low-frequency unsteadiness is a distinctive characteristic of flow separation over sharp edges and does not occur in separations over smooth leading edges (Cimorelli et al., 2020).

In the wake region, there is a monotonic reduction in shedding frequency from $St = 0.23$, 0.18 , 0.16 , and 0.14 for $T_u = 1.5\%$, 5.0% , 10.0% and $T_u = 15.0\%$ respectively. This suggests a strong

disruption of regular vortex shedding by the FST intensity. This reduction of 39% is less than the 44% reduction observed in the wake region of the rounded leading-edge Ahmed body exposed to the same level of FST intensity (Sagharichi & Tachie, 2025). The reduction of shedding frequency correlates with an increase in integral time scales shown in Fig. 6.10, confirming that FST promotes long-lived structures. The interruption of vortex shedding by the FST intensity is also responsible for the weaker wall-normal Reynolds stresses (and TKE) in the wake region (Fang et al., 2022).

To elucidate the mechanisms responsible for the interruption of vortex shedding, a wavelet analysis was performed using the Morlet wavelet formulation proposed by Morlet (1983). Figure 6.12 presents the resulting wavelet spectrum of the streamwise velocity fluctuations at the point of peak TKE within the wake. For $T_u = 1.5\%$ and 5.0% , the wavelet is persistent with respect to time, and fluctuates around the vortex shedding frequency, while the regular vortex shedding for $T_u = 10.0\%$ and 15.0% are disrupted by large-scale vortical structures characterized by $St = 0.08$ and 0.05 , respectively, introduced due to the enhanced FST intensity. The presence of these frequencies can be attributed to the disruption of regular vortex shedding by the C-pillar vortex in the wake region, as will be discussed in a later section. At $T_u = 10.0\%$ and 15.0% , wake vortex shedding frequencies of $St = 0.16$ and 0.14 , respectively, are also evident over the roof. Therefore, it can be inferred that the leading edge and wake vortices are shed at the same frequency, indicating the presence of frequency locking. Nakamura et al. (1991) made similar observations; Moore et al. (2019), Zhang et al. (2023), and Li et al. (2024) around rectangular cylinders. This trend is in sharp contrast with the existence of a global vortex shedding frequency at $T_u = 1.5\%$ and its disappearance for $T_u \geq 5.0\%$, around the rounded leading edge of Ahmed body at high FST

intensity (Sagharichi & Tachie, 2025) at the same Reynolds number. This discrepancy can be attributed to the role of the leading edge in the modulation of global vortex shedding frequency.

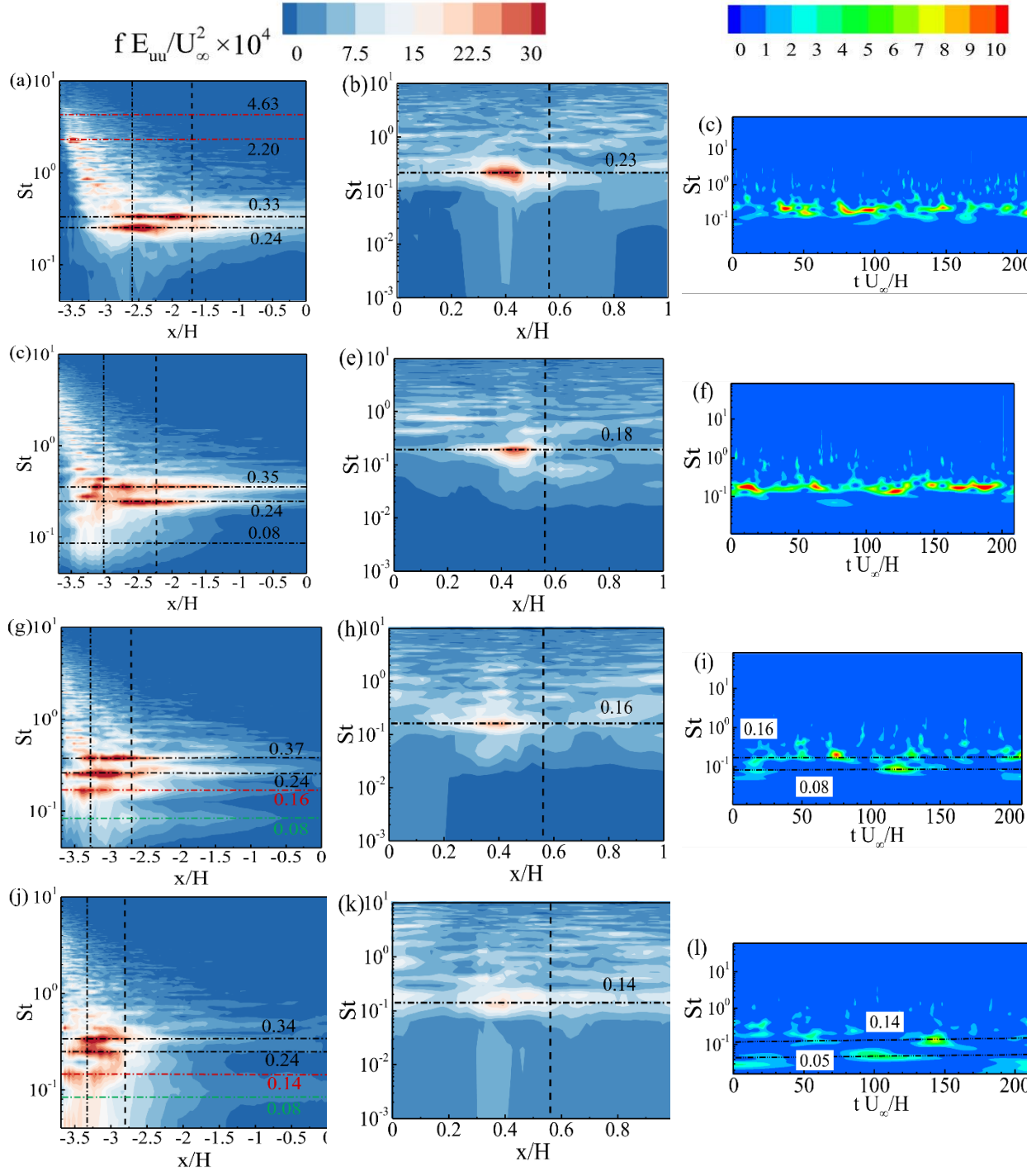


Figure 6.12 The Contours of the premultiplied frequency spectrum of streamwise fluctuating velocity (ϕ_{uu}) fluctuation velocities along the mean shear layer over the roof [(a), (c), (g), and (j)] and along the upper shear layer in the wake [(b),(e),(h) and (k)]. The wavelet frequency at max TKE in the

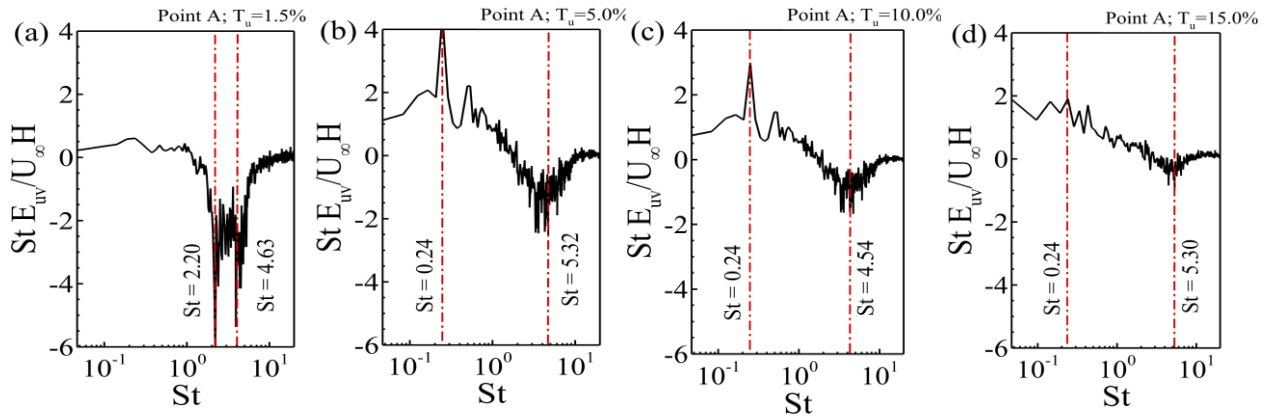
wake region [(c), (f),(i) and (l)]. $T_u = 1.5\%$ [(a-c)]; $T_u = 5.0\%$ [(c-f)]; $T_u = 10.0\%$ [(g-i)]; $T_u = 15.0\%$ [(j-l)]

6.4.4 Influence of Turbulence Scales on Roof TKE Production

As shown in Fig. 6.12, increasing FST intensity intensifies the low-frequency unsteadiness of the shear layer over the roof. These low-frequency structures superimpose onto the KH instabilities and vortex shedding, creating a multi-scale turbulence regime that redistributes energy across frequencies. To reveal the role of turbulence scales on TKE production over the roof, the premultiplied spectrum of streamwise and wall-normal fluctuation velocities (E_{uv}) at point A (the points used for identifying KH instability in Fig. 6.11), point B (at $(\overline{u'u'})_{\max}$ over the roof), point C (at $(\overline{v'v'})_{\max}$ over roof) calculated and the results are shown in Fig. 6.13. The sign of $-\overline{u'v'}$ determined by the alignment of fluctuating velocities with the mean shear ($\partial U / \partial y$) reveals whether turbulent motions are the source ($(-\overline{u'v'}) \partial U / \partial y > 0$) or sink ($(-\overline{u'v'}) \partial U / \partial y < 0$) of turbulence (Cimarelli et al., 2024).

At point A, the presence of two distinct time scales, each contributing to the Reynolds shear stresses with opposite signs, is evident. A range of small scales centred at the Strouhal number of $St = 2.20$ and 5.32 is found to contribute to positive Reynolds shear stresses ($-\overline{u'v'} > 0$). Meanwhile, a range of large time scales centred around $St = 0.24$ at $T_u = 5.0\%$ to 15.0% is found to contribute negatively ($-\overline{u'v'} < 0$) to the Reynolds shear stress. Considering the positive sign of the mean shear $\partial U / \partial y > 0$ over the roof, it implies that small and large eddies are, respectively, acting as TKE sources and sinks at point A. The observation of two opposing mechanisms of small-scale and large-scale turbulent structures in the vicinity of sharp leading-edge geometry agrees well with Cimarelli et al. (2019) and Cimarelli et al. (2024) for a rectangular prism subjected

to freestream flow. The observation explains the presence of negative shear stress production close to the leading edge at $T_u = 5.0\%$ to $T_u = 15.0\%$ in Fig. 6.8. At these FST intensities, turbulence scales pertinent to $St = 0.24$ possesses negative shear stress sign ($-\overline{u'v'} < 0$) and considered as a TKE sink, accordingly. As the shear layer evolves to points B (Figs 6.13e–h), small-scale vortices undergo pairing to form larger vortical structures (Moore et al., 2019). Consequently, the contribution from the small scales vanishes and the emergent larger eddies become the dominant positive source of Reynolds shear-stress production over the roof (Since the shear stress at these time scales is positive ($-\overline{u'v'} > 0$), they act as a source of TKE). The plots show the presence of wake frequencies ($St = 0.23, 0.18, 0.16$, and 0.14 for $T_u = 1.5\%, 5.0\%, 10.0\%$ and 15.0% , respectively) which have zero contribution up to $T_u = 10.0\%$, while is a sink of TKE at $T_u = 15.0\%$. Figures 6.13i–l show a systematic decrease in the frequency of structures pertinent to the TKE source with FST intensity, which agrees with the presence of large-scale structures over the roof at $T_u = 5.0\%$ to $T_u = 15.0\%$ (See Fig. 6.11). Hence, it can be concluded that FST shifts the dominant time scales pertinent to TKE production to larger values.



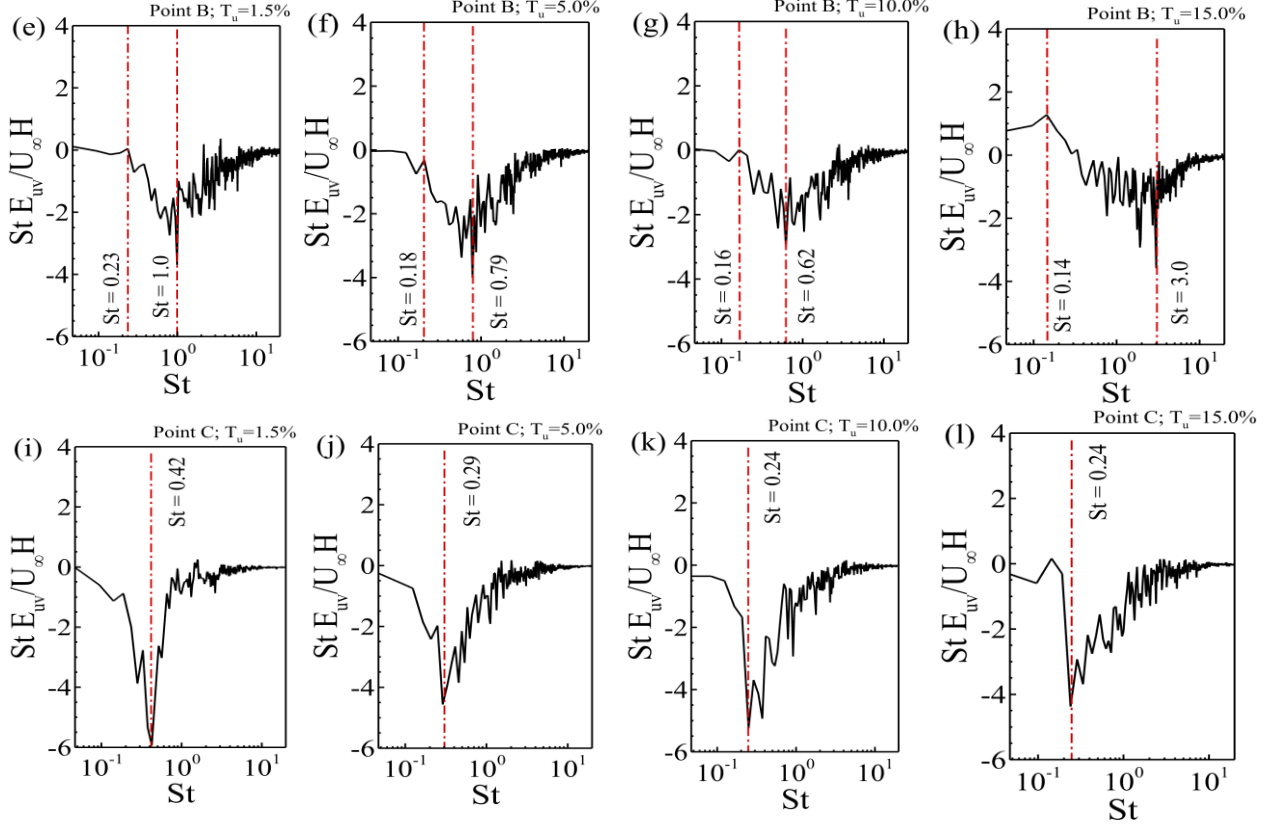


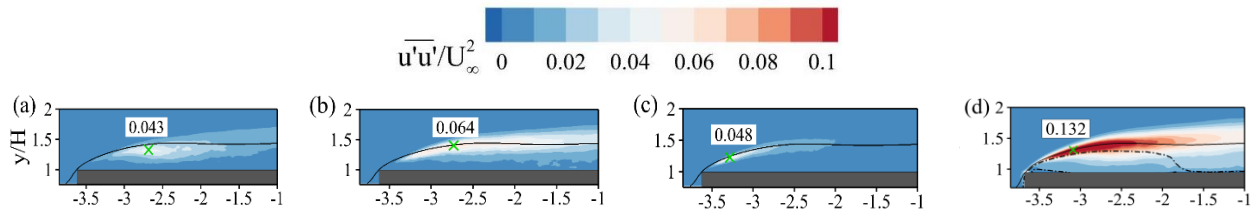
Figure 6.13 Premultiplied time cospectrum of the Reynolds shear stresses StE_{uv} evaluated in the point A [(a-d)]; point B [(e-h)]; point C [(i-l)]. $T_u = 1.5\%$ [(a), (e), (i)]; $T_u = 5.0\%$ [(b), (f), (j)]; $T_u = 10.0\%$ [(c), (g), (k)]; $T_u = 15.0\%$ [(d), (h), (l)]

In view of the variation of frequencies associated with positive TKE, following Fang & Tachie (2020) we examine the spatial characteristics of turbulence motions across different frequencies. To this end, turbulence motions for all FST intensities are partitioned into three frequency regimes based on Strouhal number: low-frequency (LF: $St < 0.23$), intermediate-frequency (IF: $0.23 \leq St \leq 1.15$), and high-frequency (HF: $St > 1.15$) and their respective influences are isolated by examining their contributions to the Reynolds stresses and TKE. These bands were selected for the following specific reasons: the low-frequency threshold is set to capture frequencies below the vortex shedding frequency observed at all FST intensities ($St = 0.24$), thereby isolating the contributions of low-frequency structures, while the high-frequency band encompasses the KH frequency (see Fig. 6.11). Alternative thresholds (e.g., $St < 0.12$, $0.12 \leq St \leq 2.20$, and $St > 2.20$)

yielded qualitatively similar results, confirming that the observed trends are intrinsic to FST modulation rather than arbitrary band selection.

Figure 6.14 quantifies the contributions of vortical structures related to the LF, IF, and HF bands to $\overline{u'u'}$. At $T_u = 1.5\%$, the IF band is dominant, while the LF and HF bands contribute equally. As FST intensity increases, the LF band progressively dominates, and by $T_u = 15.0\%$, it contributes to 47% of $(\overline{u'u'})_{\max}$. The contribution of the IF band shows an irregular trend with increasing FST intensity. While it decreases from $T_u = 1.5\%$ to 5.0%, its contribution saturates by further increasing FST intensity. The contribution of the HF band remains unchanged with increasing FST intensity.

The shift toward the significant contribution of the LF band in $(\overline{u'u'})_{\max}$ with increasing FST intensity explains the rise in maximum streamwise Reynolds stress. Hence, it can be concluded that the structures pertinent to $St < 0.23$ are primarily responsible for the progressive increase in peak streamwise Reynolds stress and TKE as FST intensity rises. It is also noted that the elevated region of maximum streamwise Reynolds normal stress in the LF band moves closer to the leading edge as FST intensity increases. This is consistent with Kiya & Sasaki (1985), who reported that increasing FST intensity induces larger vortices in regions downstream of the separation point of a blunt plate. Figure 6.14 complements this observation and shows that these vortices are more energetic at higher FST intensities.



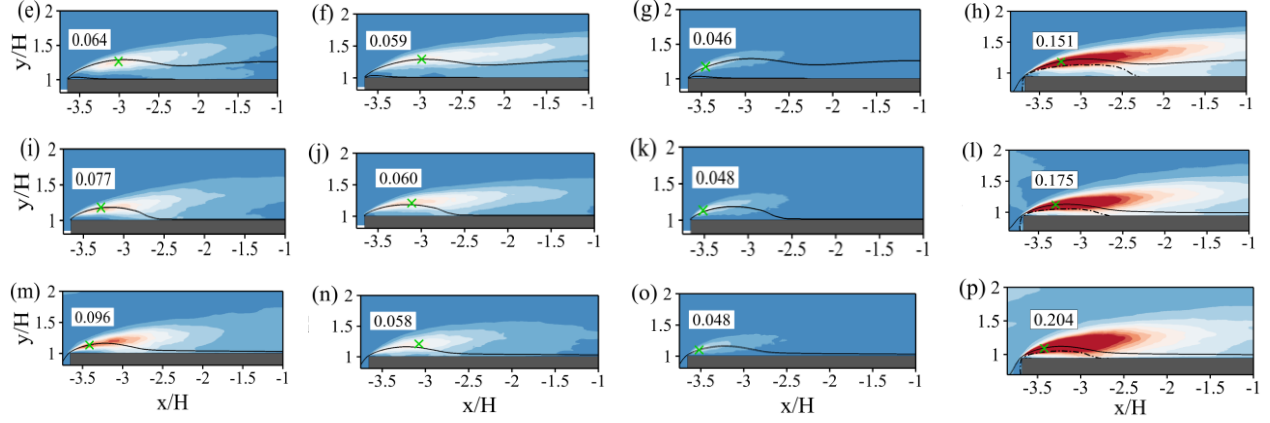


Figure 6.14 Contribution of [(a), (e), (i), (m)] LF, [(b), (f), (j), (n)] IF and [(c), (g), (k), (o)] HF bands to the [(d), (h), (l), (p)] streamwise Reynolds stress. [(a-d)] $T_u = 1.5\%$; [(e-h)] $T_u = 5.0\%$; [(i-l)] $T_u = 10.0\%$; [(m-p)] $T_u = 15.0\%$

Figure 6.15 shows the contributions of LF, IF, and HF motions to $\overline{v'v'}$ for various FST intensities. Overall, the magnitude of $(\overline{v'v'})_{\max}$ is lower than $(\overline{u'u'})_{\max}$ over the roof, which is consistent with Fig. 6.7. Unlike $\overline{u'u'}$ contours, $(\overline{v'v'})_{\max}$ are confined to the structures with IF bands across all FST intensity levels. Spatially, the contributions to $(\overline{v'v'})_{\max}$ vary across the flow domain. Near the leading edge, HF-band structures dominate, contributing most significantly to the $(\overline{v'v'})_{\max}$. In contrast, the magnitude of $(\overline{v'v'})_{\max}$ in the IF and LF bands peaked respectively in the aft part of the recirculation bubble and close to the reattachment point, irrespective of FST intensity. As FST intensity increases, a notable shift occurs in the relative contributions of the frequency bands: the LF and HF band contributions are suppressed, while the IF band contribution becomes more pronounced. This observation suggests that large-scale (LF) and small-scale (HF) structures negatively impact $(\overline{v'v'})_{\max}$ at higher FST levels. This behaviour aligns with findings from Castro & Haque (1988), who noted that earlier reattachment of the shear layer limits the growth of $\overline{v'v'}$ compared to $\overline{u'u'}$. This trend is confirmed in Fig. 6.15: as FST intensity increases, the earlier reattachment of the shear layer prevents $\overline{v'v'}$ from reaching values as high as those

observed for $\overline{u'u'}$, with the contributions from low-frequency (LF) and high-frequency (HF) bands being suppressed.

Comparing Figs. 6.14 and 6.15, one can observe the dual role of large-scale structures ($St < 0.23$) in TKE with FST intensity. By increasing FST, these vortical structures increase $(\overline{u'u'})_{\max}$ especially in the first half of the recirculation bubble, while it decreases $(\overline{v'v'})_{\max}$ near the reattachment point. The fact that $(\overline{u'u'})_{\max} > (\overline{v'v'})_{\max}$, it is concluded that the maximum TKE in the LF band over the roof increases monotonically with FST. In contrast, the TKE contribution from the IF band remains unaffected by FST. Meanwhile, the TKE magnitude pertaining to the HF decreases with rising FST intensity, indicating a shift in energy from smaller to larger scales. This behaviour is consistent with Castro & Haque (1988), who suggested that the FST intensity acts to concentrate the TKE in the larger-scale motions.

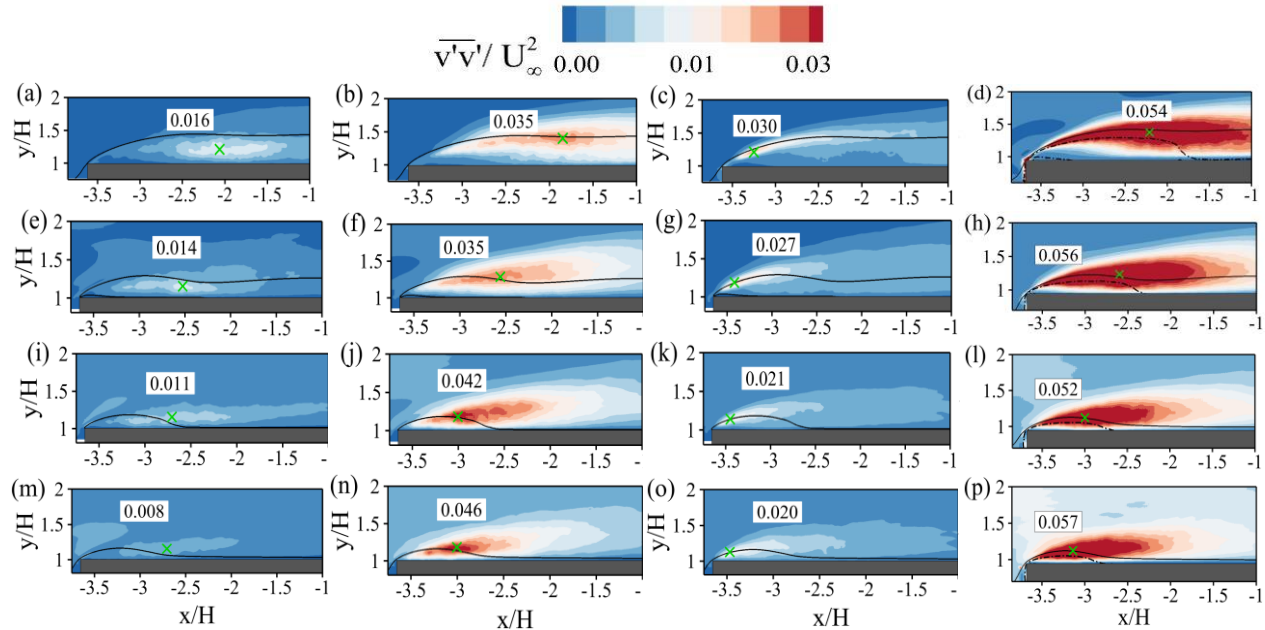
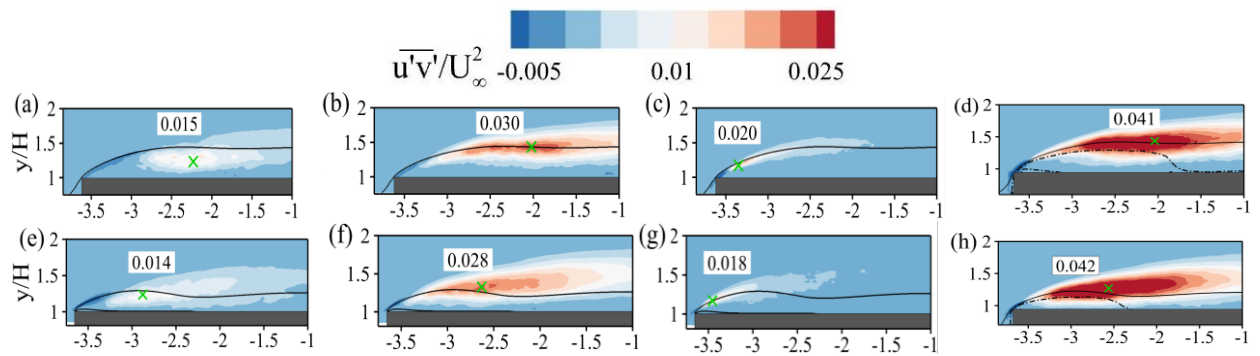


Figure 6.15 Contribution of [(a), (e), (i), (m)] LF; [(b), (f), (j), (n)] IF; and [(c), (g), (k), (o)] HF bands to the [(d), (h), (l), (p)] wall-normal Reynolds stress. [(a-d)] $T_u = 1.5\%$; [(e-h)] $T_u = 5.0\%$; [(i-l)] $T_u = 10.0\%$; [(m-p)] $T_u = 15.0\%$

Figure 6.16 elucidates the influence of LF, IF, and HF motions on the Reynolds shear stress ($-\overline{u'v'}$) over the roof under FST intensities. The results highlight a pronounced dependence of shear stress contributions on both frequency band and FST intensity. For all FST intensities, IF bands show strong positive values (indicating $-\overline{u'v'} > 0$, a source of TKE as $\partial U / \partial y > 0$) at points B and C. This dominance of intermediate scales aligns with Fig. 6.13, where the vortical structures pertinent to $St \in [0.24-1.0]$ are responsible for $-\overline{u'v'} > 0$, hence TKE source. This positive contribution of shear stress to TKE results from the entrainment of upstream flow towards the wall at a speed greater than the mean (Q_4) or ejection of mean momentum away from the wall due to upward burst events (Q_2) (Tafti & Vanka, 1991). Similarly, Stevenson et al. (2016) reported strong positive contributions in TKE from both Q_2 and Q_4 for a rounded leading-edge plate subjected to elevated FST intensity. As FST intensity increases, $(-\overline{u'v'})_{\max}$ in all bands progressively decreases. The positive values of $-\overline{u'v'}$ in the HF band confined to areas near the separation point, which is linked to the TKE source of small-scale turbulent structures (See Fig. 6.13). In contrast, near the leading edge, the vortical structure linked to the LF band has a negative contribution ($-\overline{u'v'} < 0$, a sink of TKE), and it becomes more pronounced as FST increases. This trend is consistent with Fig. 6.13, where at point A, large scales acted as energy sinks for $T_u \geq 5.0\%$ (See Fig. 6.13). It is also noted that the positive peak magnitude of the LF band occurs close to the reattachment point.



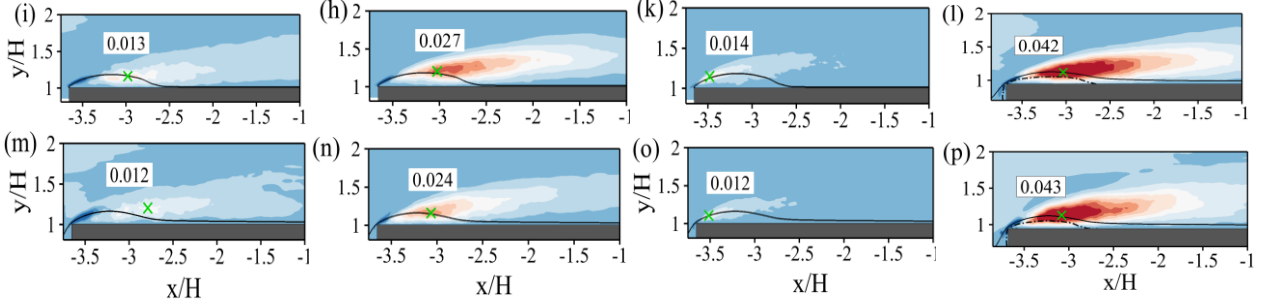


Figure 6.16. Contribution of [(a), (e), (i), (m)] LF; [(b), (f), (j), (n)] IF; and [(c), (g), (k), (o)] HF bands to the [(d), (h), (l), (p)] Reynolds shear stress. [(a-d)] $T_u = 1.5\%$; [(e-h)] $T_u = 5.0\%$; [(i-l)] $T_u = 10.0\%$; [(m-p)] $T_u = 15.0\%$

6.4.5 Spatiotemporal Characteristics of the Recirculation Bubble

As shown in Fig. 6.4, the recirculation length over the roof is affected by FST intensity. Therefore, it is expected that the flapping motion of the reverse-flow region will exhibit high receptivity to changes in FST intensity. In line with the approach of Pearson et al. (2013) and Graziani et al. (2018), we use the area of reverse flow (defined as the total area where the streamwise velocity component u is negative) at any given instant to quantify the instantaneous size of recirculation bubbles. The method proposed by Pearson et al. (2013) is employed to calculate the variation in the instantaneous reverse flow area $A(t)$, as shown below:

$$A(t) = \int \xi(u(x, y, t)) dx dy \quad (6.7)$$

$$\xi(p) = \begin{cases} 1, & p < 0 \\ 0, & p \geq 0 \end{cases} \quad (6.8)$$

where $u(x, y, t)$ represents the instantaneous streamwise velocity, and $\xi(p)$ is the detector function based on the event p . The analysis was conducted over the roof with the masked region of $x/H \in [-3.69, -0.7]$ and $y/H \in [1.0, 2.2]$, as well as the wake region with the masked region of $x/H \in [0, 1.0]$ and $y/H \in [-0.17, 0.85]$ for each test case. These regions were carefully selected to encompass the roof and wake recirculation bubbles. The mean reverse flow area (A_{mean}) was calculated from the instantaneous reverse flow area for all 60000 samples, and the fluctuation reverse flow is

defined as $A' = A - A_{\text{mean}}$. The normalized mean reverse flow area A_{mean}/H^2 and the root mean square of reverse flow area fluctuations A'_{rms}/H^2 and $A'_{\text{rms}}/A_{\text{mean}}$, over the roof and wake region are presented in Figs. 6.17a and 6.17b, respectively.

Figure 6.17a shows that increasing FST monotonically decreases the A_{mean}/H^2 and A'_{rms}/H^2 over the roof. This trend is consistent with the reduction in the recirculation length over the roof (see Fig. 6.4). However, $A'_{\text{rms}}/A_{\text{mean}}$ monotonically increases with FST intensity. In the wake region, A_{mean}/H^2 , and A'_{rms}/H^2 and $A'_{\text{rms}}/A_{\text{mean}}$ remains unchanged as FST increases from $T_u = 1.5\%$ to $T_u = 10.0\%$ ($A_{\text{mean}}/H^2 \approx 0.2$, $A'_{\text{rms}}/H^2 \approx 0.03$ and $A'_{\text{rms}}/A_{\text{mean}} \approx 0.16$). However, a slight increase is observed when FST intensity reaches $T_u = 15.0\%$, with A'_{rms}/H^2 and $A'_{\text{rms}}/A_{\text{mean}}$ increasing to approximately 0.04 and 0.19, respectively. This subtle shift suggests that, unlike the roof region, the wake's reverse flow area is less sensitive to FST enhancement up to moderate intensities.

The probability density function (PDF) of the fluctuations in the reverse flow area A'/A'_{rms} over the roof and in the wake region is shown in Figs. 6.17c and 6.17d, respectively. In these figures, the expansion and contraction of the reverse flow area can be identified by positive and negative A'/A_{rms} , respectively. The figure shows that by increasing FST intensity, the probability of contraction events increases, which implies that the recirculation bubble tends to shrink more frequently under higher turbulence conditions. This trend can be attributed to the presence of large-scale flapping motion, as Kiya & Sasaki (1985) observed that the presence of this large-scale unsteadiness leads to enhancement of the shrinkage rate compared with the enlargement rate.

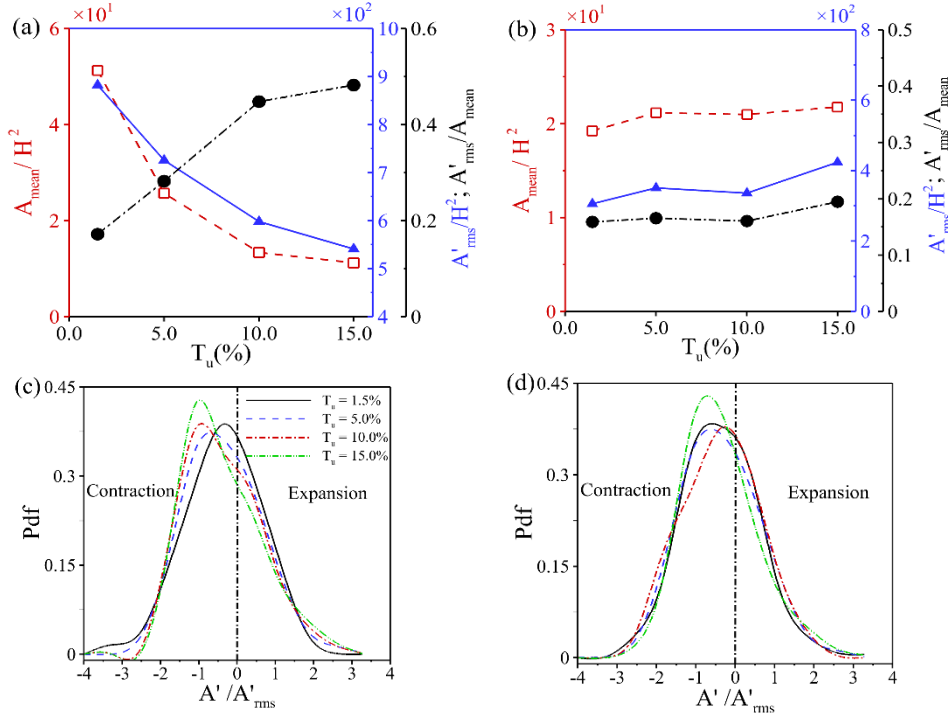


Figure 6.17 Variations of the mean reverse flow area A_{mean}/H^2 and the root mean square of reverse flow area fluctuations A'_{rms}/H^2 [(a, b)] and the probability density function (PDF) of reverse flow area fluctuations A'/A'_{rms} over the roof [(a,c)] and wake region [(b),(d)]

To investigate the relationship between recirculation bubble contraction/expansion events and TKE production, conditional averaging was conducted at the location of maximum TKE. The TKE production for each quadrant (P_1 to P_4) was computed, with results displayed in Fig. 6.18.

As FST intensity increases, the production terms P_4 (positive contribution from sweep events, where high-speed fluid moves toward the wall) and P_1 (negative contribution from outward interactions, where low-speed fluid moves away from the wall) become more prominent. Meanwhile, the minor contributions of P_2 (ejections) and P_3 (inward interactions) at $T_u = 1.5\%$ diminishes to negligible levels by $T_u = 15.0\%$. At $T_u = 15.0\%$, P_4 accounts for nearly 100% of the positive TKE production during contraction events, highlighting its dominance under high-FST conditions. This aligns with Fang & Wang (2024), who attributed low-frequency flapping motion in flow separation to sweep events near the separating streamline's crest, where vertical vortices

drive high-speed fluid toward the wall, enhancing TKE production via an amplified lift-up mechanism. The sharper rise in P_4 at higher FST suggests that large-scale turbulent structures (LF bands), triggered by elevated FST, contract the recirculation bubble and boost TKE production primarily through P_4 . During expansion events, P_2 and P_3 dominate across all FST intensities, with P_2 (ejections, where low-speed fluid lifts away from the wall) emerging as the primary contributor. Contributions from P_1 and P_4 fade as FST intensifies, and by $T_u = 15.0\%$, P_2 drives TKE production in expansion, promoting bubble elongation through upward turbulent bursts. This corroborates Fang & Wang's (2024) observations of vertical vortices in the recirculation bubble's first half, which lift low-speed fluid and sustain flapping motion. This shows that as FST intensity increases, the mechanisms governing the expansion and contraction of the recirculation bubble become increasingly segregated, with ejection events (P_2) predominantly driving expansion and sweep events (P_4) driving contraction. These findings suggest that FST could be leveraged in flow control strategies to modulate recirculation bubble dynamics, offering potential applications in vehicle aerodynamics for drag reduction or stability enhancement.

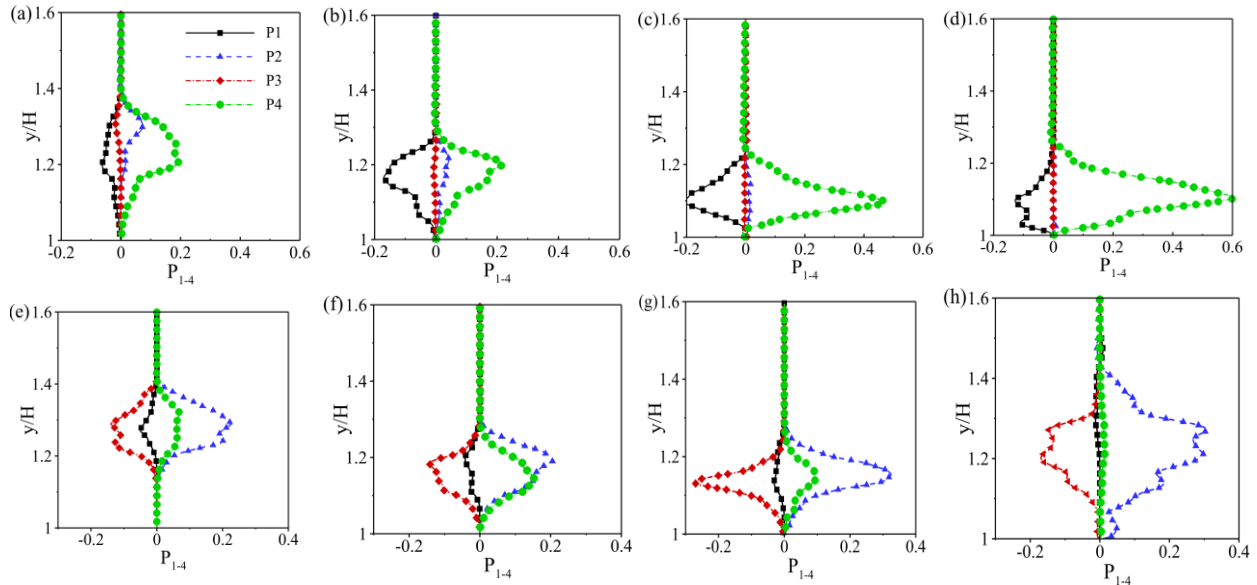


Figure 6.18 Conditional averaging of production of quadrants for contraction [(a-d)]; and expansion events [(e-h)]. $T_u = 1.5\%$ [(a), (e)]; $T_u = 5.0\%$ [(b), (f)], $T_u = 10.0\%$ [(c), (g)] and $T_u = 15.0\%$ [(d), (h)]

6.4.5.1 Synchronization of u' and Reverse Flow Dynamics

Thus far, our analysis has demonstrated that an increase in FST intensity significantly influences the spatiotemporal flow characteristics over a roof by amplifying the streamwise Reynolds normal stress, $\overline{u'u'}$, due to the presence of large-scale structures. This observation motivates an investigation into the effect of FST intensity on the relationship between the local peak of $\overline{u'u'}$ at LF band (derived from a low-pass filtered u' signal, retaining frequencies lower than the fundamental shedding frequency (i.e., Strouhal numbers $St < 0.23$ for all FST intensities)) and the fluctuations in the reverse flow area over the roof (derived from a low-pass filtered A' signal, retaining frequencies corresponding to Strouhal numbers $St < 0.23$). Figure 6.19 presents a comparison of the temporal evolution, cross-correlation, and joint probability density function (JPDF) of low-pass filtered u' and A' signals. The results show that for $T_u \geq 5.0\%$ there is a strong negative correlation between u' and A' . Quantitatively, the cross-correlation coefficient, defined as $\overline{u'A'}/u'_{\text{rms}}A'_{\text{rms}}$, is -0.48, -0.77, -0.77, and -0.72 at zero lag for FST intensities of $T_u = 1.5\%$, 5.0%, 10.0%, and 15.0%, respectively. The magnitude of the cross-correlation coefficient for $T_u \geq 5.0\%$ is close to -0.74 observed for the forward-facing step submerged in a thick, turbulent boundary layer at local turbulence intensity of 14.5% Fang & Tachie (2020). This negative correlation in the LF band aligns with earlier findings (See Fig. 6.14), where large-scale structures ($St < 0.23$) dominate $(\overline{u'u'})_{\text{max}}$ at higher FST, suggesting that LF-driven streamwise fluctuations actively modulate the recirculation bubble's size. The JPDF analysis provides additional support for this narrative by showing that, at $T_u = 1.5\%$, the highest joint probability of u' and A' aligns along the horizontal axis, suggesting a relatively balanced interaction. However, as FST intensity increases to $T_u = 5.0\%$ and 10.0%, the peak probability shifts toward the second and fourth quadrants. This shift implies that an increase (decrease) in u' corresponds closely with a

contraction (expansion) of the recirculation bubble, which highlights a dynamic interplay between streamwise velocity fluctuations and reverse flow area. At $T_u = 15.0\%$, the JPDF has the probability concentrating predominantly in Q_4 . This suggests that in the LF band, the dominant mechanism governing the flow at this turbulence level is an enhanced u' , which effectively suppresses the recirculation bubble, thereby reducing its spatial extent. This dynamic interplay reflects the LF band's role in contraction, consistent with sweep events (P_4) dominating TKE production during bubble shrinkage (See Fig. 6.18).

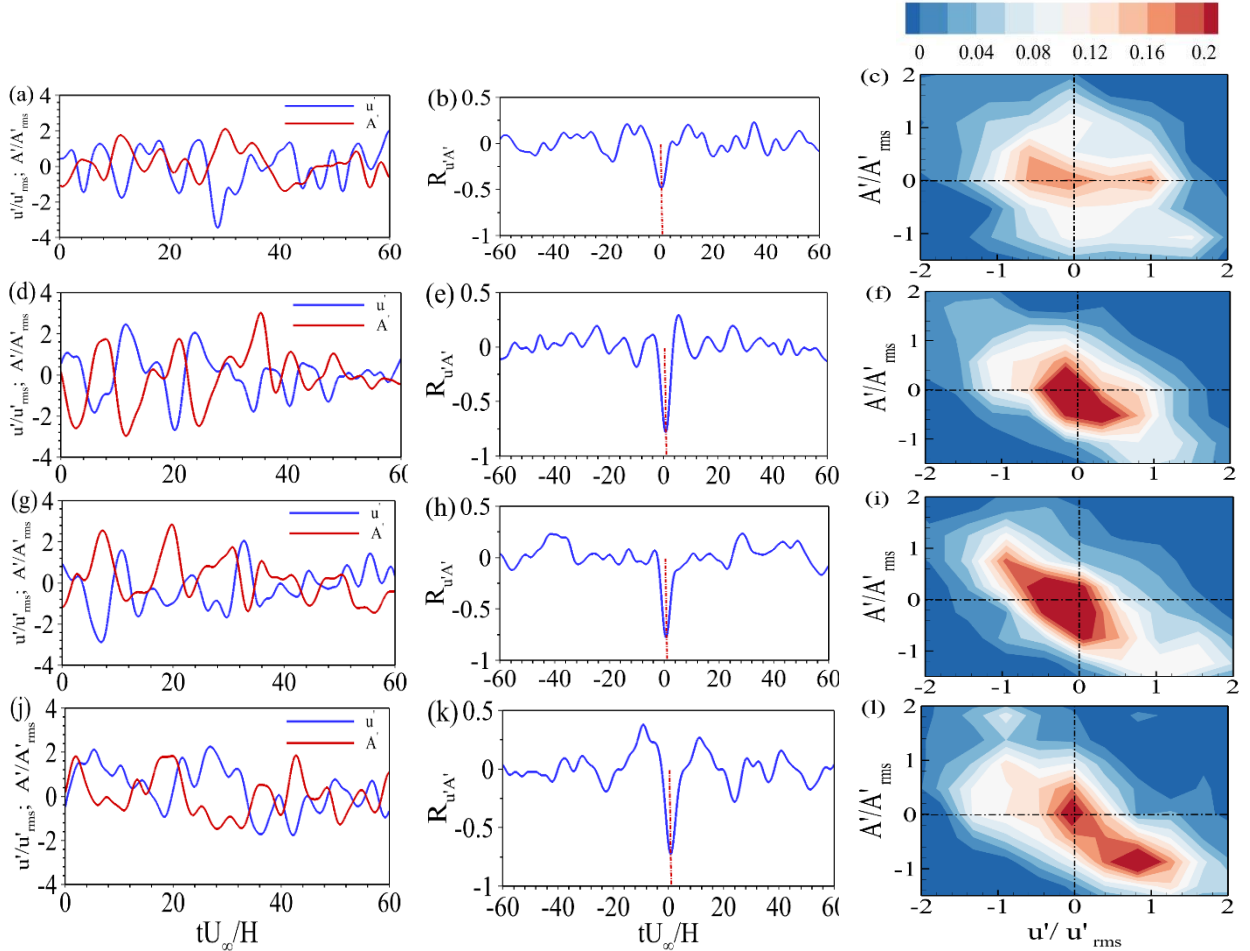
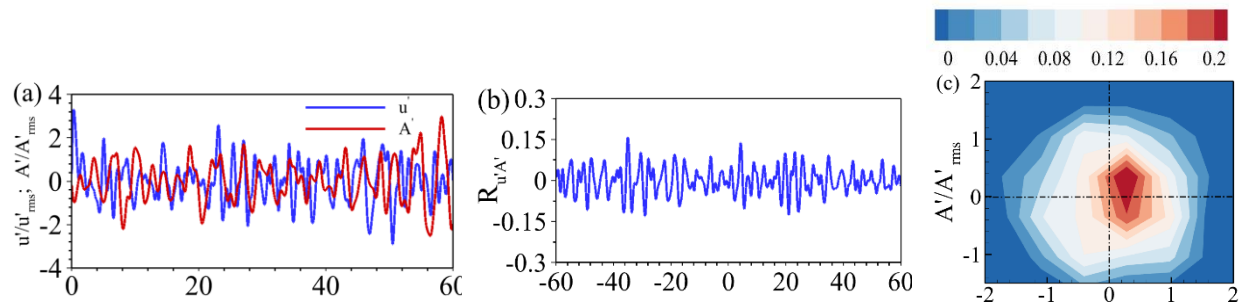


Figure 6.19 Time evolution of u' filtered and A' filtered signals [(a), (d), (g) and (j)]; Cross-correlation between u' filtered and A' filtered over roof [(b), (e), (h) and (k)] and JPDF of u' filtered and A' filtered signals. $T_u = 1.5\%$ [(a-c)]; $T_u = 5.0\%$ [(d-f)]; $T_u = 10.0\%$ [(g-i)]; $T_u = 15.0\%$ [(j-l)]. The signals were low-pass filtered (retaining frequencies corresponding to Strouhal numbers $St < 0.23$)

A complementary analysis was conducted to isolate the role of intermediate-frequency (IF: $0.23 \leq St \leq 1.15$) and high-frequency (HF: $St > 1.15$) structures on the contraction/expansion of the roof recirculation bubble across all FST intensities. Drawing on the spectral bands defined in Part D (see Fig. 6.13 and the band thresholds in Fig. 6.14), we filtered the u' and A' signals to retain $0.23 < St < 6.0$, and then performed the same temporal, cross-correlation, and JPFD analyses. Figure 6.20 illustrates the results for $T_u = 1.5\%$ and $T_u = 15.0\%$ (results for $T_u = 5.0\%$ and 10.0% follow the same pattern and are omitted for brevity). As shown, no statistically significant correlation emerged between IF/HF-filtered u' and A' signals at either turbulence level, in stark contrast to the strong LF-band coupling documented in Fig. 6.19. Consequently, we conclude that the intermediate and small-scale vortical motions play a negligible role in driving recirculation bubble motions. Consequently, the contraction or expansion of the recirculation bubble is a direct outcome of the interaction between these large-scale motions and the mean flow, rather than a cumulative effect of smaller-scale turbulence. This hierarchy of influence underscores that the energy content and spatial footprint of LF eddies ($St < 0.23$), established in Fig. 6.14, govern the unsteady separation dynamics. These insights sharpen our understanding of turbulence–roof flow interactions and suggest that flow-control strategies should target LF scales to manipulate recirculation bubble behavior, with clear ramifications for aerodynamic surface design under varying upstream turbulence.



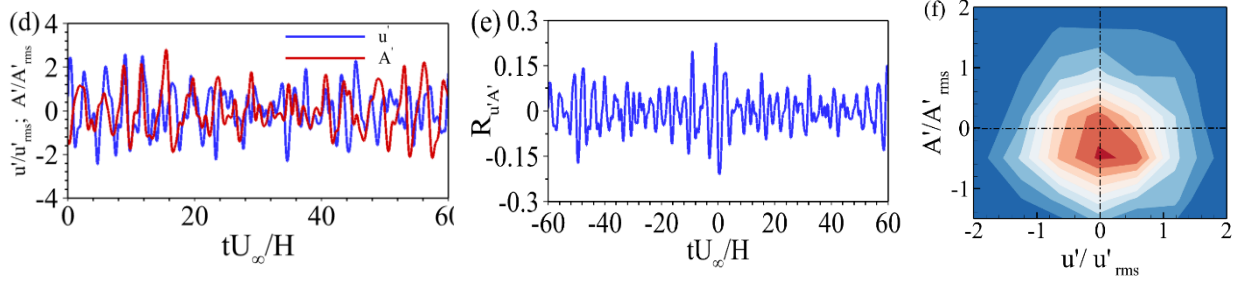


Figure 6.20 Time evolution of u' filtered and A' filtered signals [(a), (d)]; Cross-correlation between u' filtered and A' filtered over roof [(b), (e)] and JPFD of u' filtered and A' filtered signals. $T_u = 1.5\%$ [(a-c)]; $T_u = 15.0\%$. The signals were low-pass filtered (retaining frequencies corresponding to Strouhal numbers $0.23 < St < 6.0$)

6.4.6 Spectral Proper Orthogonal Decomposition (SPOD)

Thus far, it has been shown that increasing FST has a significant impact on the temporal behaviour and dominant frequencies of the flow structures around the Ahmed body. To examine the dynamics of the vortical structures linked to these dominant frequencies, Spectral Proper Orthogonal Decomposition (SPOD) is applied. This study follows the SPOD methodology described in detail by Towne et al. (2018). In this approach, the fluctuating velocity field is decomposed as:

$$u'(x, y, t) = \sum_{j=1}^{\infty} \sum_{m=1}^{\infty} \phi_j^m(x, y) a_j^m e^{-i\omega_j t} + c. c., \quad (6.9)$$

The indices “j” and “m” represent the frequency and mode number, respectively. The term ϕ_j^m denotes the orthogonal spatial eigenfunctions (modes), while a_j^m refers to their corresponding temporal coefficients. The wavenumber is defined as $\omega_j = 2\pi f_j$ where $i = \sqrt{-1}$ and “c.c.” stands for the complex conjugate.

For this analysis, a total of 60,000 samples were divided into ten blocks of 6,000 images. A Fast Fourier Transform (FFT) was applied to each block using Welch’s overlapped window technique (Welch 1967). The FFT window size, N_w , was set to 5400, resulting in a frequency resolution of 0.15 Hz. Next, for each selected dominant frequency, the snapshot Proper Orthogonal

Decomposition (POD) method (Sirovich, 1987) was applied to the FFT data using Singular Value Decomposition (SVD) (Meyer et al., 2007; Fang & Tachie, 2019). SVD computes the modes and their associated eigenvalues (λ), which quantify the energy content of each mode. These modes are then ranked in descending order of energy, with the leading modes capturing the most energetic flow structures.

Figure 6.21 illustrates the energy contribution of the first ten SPOD modes for FST intensities in the roof and wake regions. Over the roof, mode one accounts for 38% of the TKE at an FST intensity of $T_u = 1.5\%$, increasing to 41%, 44%, and 49% for $T_u = 5.0\%$, 10.0% , and 15.0% , respectively, while the second mode contributes 13%, 12%, 15%, and 16%, respectively. In the wake region, the contribution from the first mode (32%, 31%, 29%, and 28% for $T_u = 1.5\%$ to 15.0% , respectively) is comparatively lower than observed over the roof.

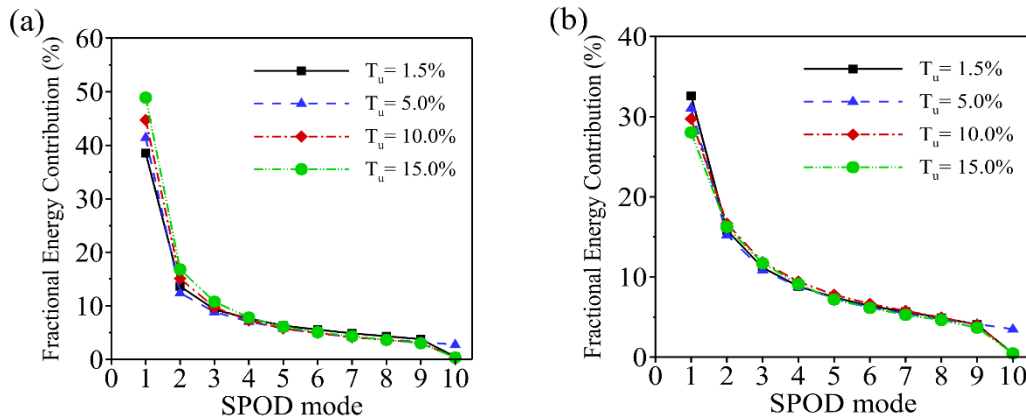


Figure 6.21 The energy contribution of SPOD modes. (a) Over the roof and (b) wake region

Figure 6.22 presents a comparison of the premultiplied frequency spectra corresponding to the first two SPOD modes over the roof and the first mode in the wake region. The dominant frequency identified by SPOD coincides with that observed using the frequency of streamwise fluctuation velocity in Fig. 6.12. Over the roof, increasing FST intensity energizes the LF band ($St < 0.23$) in

the first mode. However, no change is observed in the energy level of the wake region frequency distribution.

Figure 6.22a shows that the first mode of $T_u = 1.5\%$ can be characterized by the co-shedding of vortical structures with $St = 0.24$ and 0.36 . These values are comparable with $(0.5-0.6) U_\infty / L_r$, reported by Kiya & Sasaki (1985) and Cherry et al. (1984), who attributed these frequencies to the quasi-periodic vortex shedding in the separated shear layer. Comparable frequencies are also observed in the first POD mode of $T_u = 5.0\%$ and 10.0% ($St = 0.23, 0.35$ for $T_u = 5.0\%$, and $St = 0.24, 0.37$ for $T_u = 10.0\%$). At $T_u = 15.0\%$, the corresponding frequency $St = 0.33$ has been broadened. A similar broadness of peak frequency spectrum was observed by Zhang et al. (2015) and Hearst et al. (2016) for flow around the Ahmed body and surface-mounted square cylinder, and was attributed to the reduction of periodicity spanwise vortices due to the FST intensity (Mannini et al. 2017). In all cases, there is evidence of low-frequency motion structures of $St = 0.12$ or $T_u = 1.5\%$, 0.08 for $T_u = 5.0\%$ and 10.0% , and 0.09 for $T_u = 15.0\%$. This low frequency corresponds to $St_L (= fL_r / U_\infty) \in [0.08-0.2]$ for all test cases, which are in excellent agreement with the universal frequency range related to the flapping motion of the shear layer (Kiya & Sasaki, 1983a; Hudy et al., 2003; Fang & Wang, 2024). The identification of flapping motion in the first SPOD mode is consistent with Chiatto et al. (2021) and Abdul-Salam et al. (2024) for flow over a backward-facing ramp and rectangular cylinder, respectively.

In the wake region, Figure 6.22e-h shows a monotonic reduction in the dominant Strouhal number with increasing FST intensity. Specifically, the peak frequency shifts from $St = 0.23$ to $St = 0.14$ as the FST intensity increases from 1.5% to 15.0% . Additionally, the amplitude of this peak diminishes with higher FST intensity, indicating a suppression of coherent structures at higher

turbulence levels. These frequencies were also identified using the frequency spectrum of fluctuation velocity in Fig. 6.12.

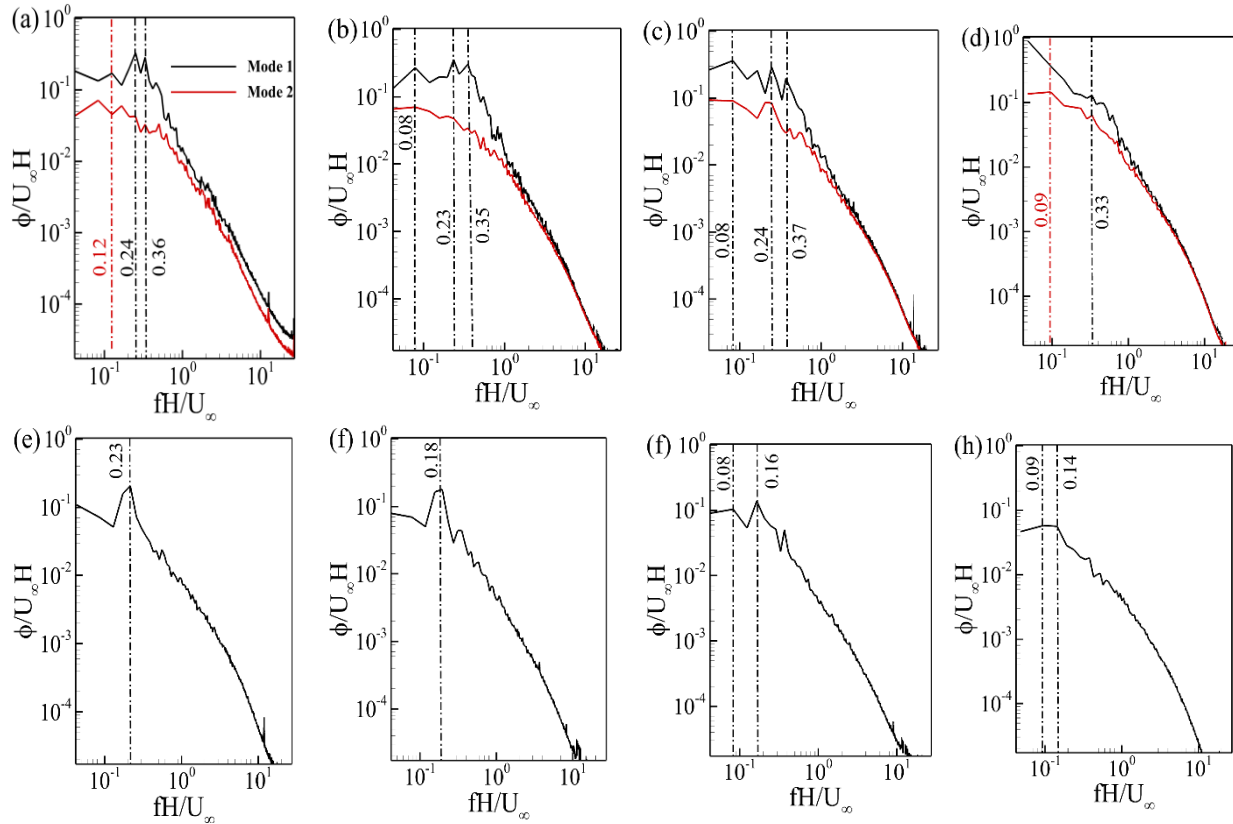


Figure 6.22 Premultiplied frequency spectra of the first and second SPOD modes over the roof [(a-d)] and wake region [(e-h)]. [(a), (e)] $T_u = 1.5\%$, [(b), (f)] $T_u = 5.0\%$, [(c), (g)] $T_u = 10.0\%$, and [(d), (h)] $T_u = 15.0\%$. The vertical dash-dotted lines mark characteristic frequencies of the modes

Figure 6.23 compares the vortical structures pertinent to the low-frequency motion across the different test cases by examining the streamwise (ϕ_u) and wall-normal components (ϕ_v) at the dominant frequencies of $St = 0.08$ and 0.09 for all FST intensities. Due to the periodic nature of these coherent structures, the complete phase evolution of these motions was reconstructed using both the real and imaginary parts of the SPOD modes. This reconstruction allows for a full-cycle visualization of the coherent structures. The animations illustrating the full-phase evolution of these vortex shedding motions are provided in supplementary videos 1-4. The mechanism pertinent

to $St = 0.12$, 0.08 , and 0.09 is described as a flapping motion. In general, these modes exhibit consecutive positive or negative long patches of streamwise fluctuating velocity which encompass the recirculation bubble over the roof. Similar to the findings of Fang & Wang (2024), supplementary movies reveal that the unsteadiness in the reattaching shear layer is influenced by the passage of large-scale organized vortices through the reattachment zone. These coherent structures, akin to the flapping motion, strongly interact with the recirculation bubble, causing notable variations in the size of the recirculation bubble. Similar flapping motions were observed by Tafti & Vanka (1991) in their study of flow separation over a long rectangular bluff body, backward-facing step flows (Eaton & Johnston 1982; Driver et al. 1987), over the slanted surface of Ahmed body (Thacker et al. 2013), forward-backward-facing step geometries (Largeau & Moriniere 2006), rectangular cylinder (Abdul-Salam et al., 2024) and pressure-induced turbulent recirculation bubble (Mohammed-Taifour & Weiss, 2016; Malmir et al., 2024). The presence of flapping motion structures in flows with turbulence intensity ($T_u > 1.5\%$) can be related to the higher TKE over the body roof at high FST intensities (See Fig. 6.7), and is consistent with Castro & Haque (1988) who observed an enhancement of the flapping motion in the separated shear layer around a flat plate under elevated levels of FST. Fang & Wang (2024) showed that the low-frequency flapping motion is associated with elevated TKE at low frequencies, particularly within the recirculation bubble. Ma & Schröder (2017) similarly linked flapping motion to regions of elevated TKE. Both studies indicate that this energy is primarily associated with large-scale sweep- and ejection-like motions. Specifically, Fang & Wang (2024) demonstrated that in the second half of the recirculation bubble, the flapping motion extracts energy from the mean shear through the production term involving the Reynolds shear stress, thereby enhancing it within the aft portion of the recirculation bubble.

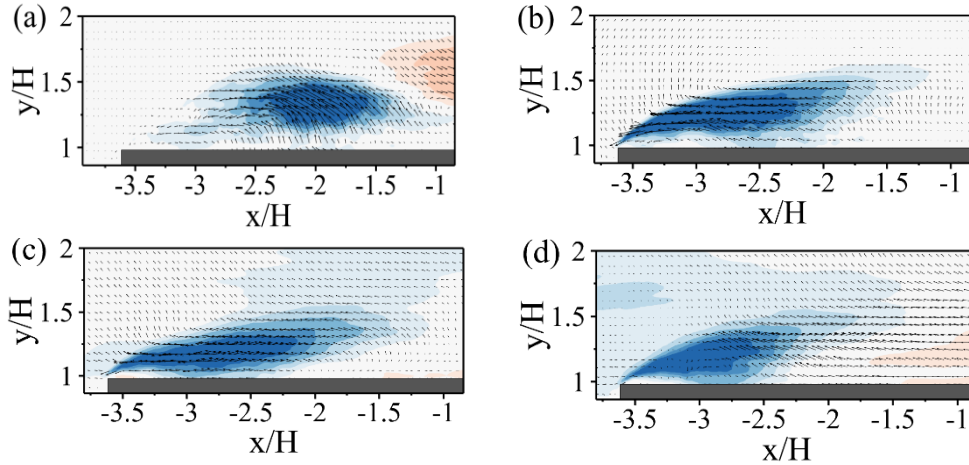


Figure 6.23 Contours of streamwise components of dominant Strouhal numbers $St = 0.12, 0.08, 0.08,$ and 0.09 for (a) $T_u = 1.5\%$, (b) 5.0% , (c) 10.0% and 15.0%

Figure 6.24 shows spatial structures pertaining to $St = 0.24, 0.23, 0.24$ observed in the spectra of $T_u = 1.5\%, 5.0\%$ and 10.0% , respectively. The figure shows alternating streamwise velocity fluctuations advected in the streamwise direction. These structures are counter-rotating, and as a result, they induce strong modal velocities in the region between them. The supplementary movies 5-7 show that as the phase angle increases, they gradually grow. However, for higher FST intensities, the process of enlarging vortices occurs closer to the body's leading edge. Multiplying the wavelength by its corresponding mode frequency (Riches et al., 2018; Fang et al., 2022) yields a convective velocity of $0.52U_\infty$, independent of FST intensity. This result is in excellent agreement with the $0.50U_\infty$ convective velocity measured for vortical structures over a flat plate (Kiya & Sasaki, 1985), $0.48U_\infty$ reported for a rectangular cylinder (aspect ratio 5) in uniform flow (Bruno et al., 2010), and $0.5-0.7U_\infty$ over a facing-forward step (Podvin & Fraigneau, 2024). Furthermore, the observed insensitivity of convective velocity to FST intensity is consistent with Mannini et al. (2017), who found a convective velocity of approximately $0.40U_\infty$ for FST levels of $T_u = 0.7\%$ and 8.6% around the rectangular cylinder. The supplementary videos also show that the vortical structures lose coherence sooner under the influence of high FST intensity.

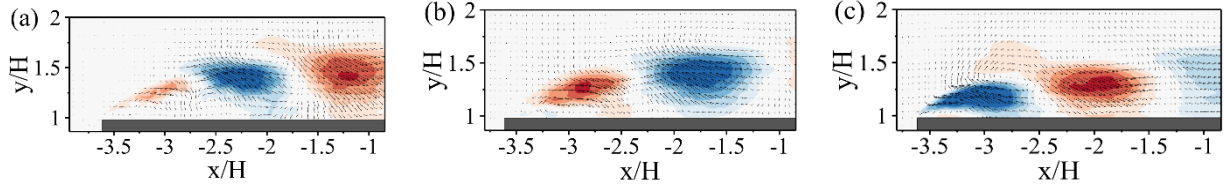


Figure 6.24 Contours of streamwise components of dominant Strouhal numbers $St = 0.24, 0.23$, and 0.24 for (a) $T_u = 1.5\%$, (b) 5.0% and (c) 10.0%

Figure 6.25 shows that the structures based on the streamwise fluctuation velocity related to the $St = 0.36, 0.35, 0.37, 0.33$ can be related to the large alternating structures advected in the streamwise direction (please see supplementary videos 8-11). At $T_u = 1.5\%$, the plot shows a coherent train of alternating high- and low-speed streaks (shown in red and blue). Each structure emerges as early as $x/H \sim -3.1$ and develop further downstream. At $T_u = 5.0\%$, the same alternating high- and low-speed streaks emerging from the square edge, but their behaviour has noticeably changed compared to the $T_u = 1.5\%$ case. The streaks begin to distort almost immediately after they form, and by $T_u = 15.0\%$, the freestream injects energetic fluctuations into the shear layer as soon as it separates. Similar structures have been observed as the first POD modes of flow over semi-submerged bluff bodies (Fang et al., 2022), backward-facing step (Ma & Schröder, 2017); forward-facing step (Fang et al., 2019; Podvin & Fraigneau, 2024)

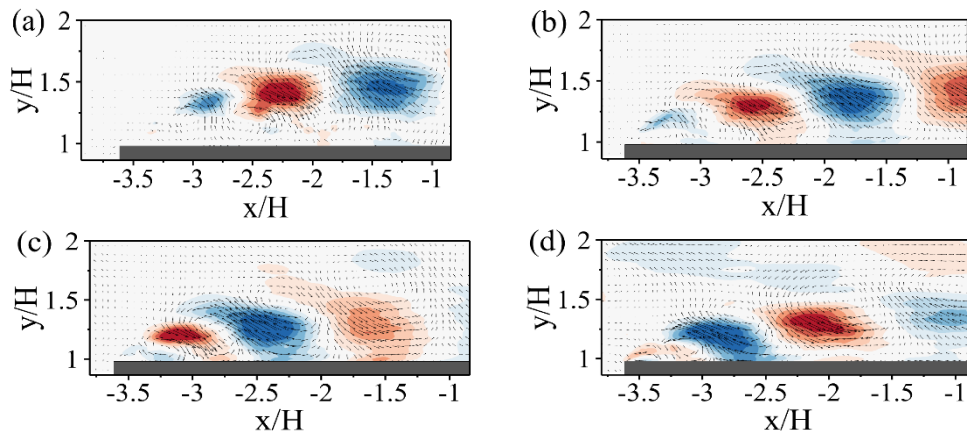


Figure 6.25 Contours of streamwise components of dominant Strouhal numbers $St = 0.36, 0.35, 0.37$, and 0.33 for (a) $T_u = 1.5\%$, (b) 5.0% , (c) 10.0% , (d) 15.0%

Figure 6.26 illustrates the first SPOD modes associated with vortex shedding at $St = 0.23, 0.18, 0.16$, and 0.14 , corresponding to $T_u = 1.5\%, 5.0\%, 10.0\%$, and 15.0% , respectively, in the wake region. The wake region is marked by alternating vortex shedding, evident in the succession of positive and negative fluctuations, exhibiting periodic oscillatory behaviour in the spanwise direction. Such alternating regions of positive and negative structures have also been reported in Ahmed bodies' wake regions (Aleyasin et al., 2021; Siddiqui & Agelin-Chaab, 2022; Sagharichi et al., 2023). The alternating regions stem from the upper and lower shear layers, denoted as A and B, respectively. The vortical structure C and D arises from the interaction of shear layers B and A and are deflected toward the wall due to the downwash from the slanted surface. Regardless of FST intensity, the evolution of vortical structures in the wake region follows a distinct cycle: At the onset of the shedding cycle, shear layers of opposite signs emanate from the slanted surface and body undersurface. Subsequently, the upper and lower recirculation bubbles (structures A and B) grow progressively due to continuous fluid entrainment. These structures converge at a position corresponding to the recirculation length. Concurrently, separated vortical structures (C and D, detached from the lower and upper shear layers, respectively) are advected downstream, with their peak intensity gradually decaying. The observed cycle aligns with the phase-resolved vortical structure reconstructions reported by Liu et al. (2021). Analysis of SPOD animations (see supplementary videos 12-15) reveals that increasing FST intensity enhances shear layers A and B. Their interaction gives rise to a persistent structure D, which, at $T_u = 15.0\%$, attains a strength comparable to shear layer A. As structure D evolves downstream and approaches the wall, it entrains structure C, impeding its downstream progression. Consequently, structure C becomes stagnant, interfering with the newly formed structure B in the subsequent cycle. This disruption

perturbs the regular vortex shedding, leading to a reduction in shedding frequency as FST intensity increases.

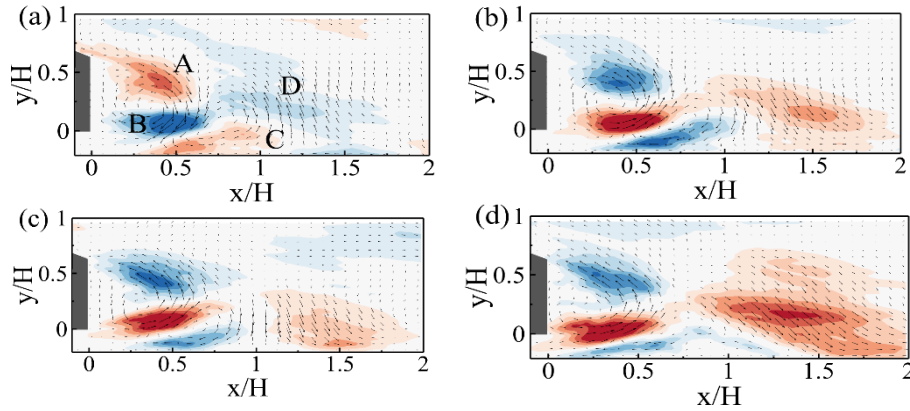


Figure 6.26 Contours of streamwise components of dominant Strouhal numbers $St = 0.23, 0.18, 0.16$, and 0.14 for (a) $T_u = 1.5\%$, (b) 5.0% , (c) 10.0% , (d) 15.0%

Figure 6.27 shows the SPOD structures related to the $St = 0.08$ and 0.09 , which were only observed for $T_u = 10.0\%$ and 15.0% , respectively. This plot provides insight into the reason for the higher persistence of structure D emanating from the upper shear layer. The figure, along with supplementary videos 16 and 17, shows that at $T_u = 10.0\%$ and 15.0% , an elongated structure emanating from the slanted surface combines with the upper shear layer while being shed toward the wall. A similar elongated structure was also observed by Sagharichi & Tachie (2025), who reported that increasing FST intensity energizes the C-pillar vortex, which sheds downstream while interacting with the upper shear layer. Hence, it disrupts the periodic motion of the upper shear layer. This leads to the lack of interaction with the upper shear layer; the lower shear layer maintains its strength, and long-lived structure forms near the wall. This behaviour agrees with the formation of a long-lived structure observed in Fig. 6.10.

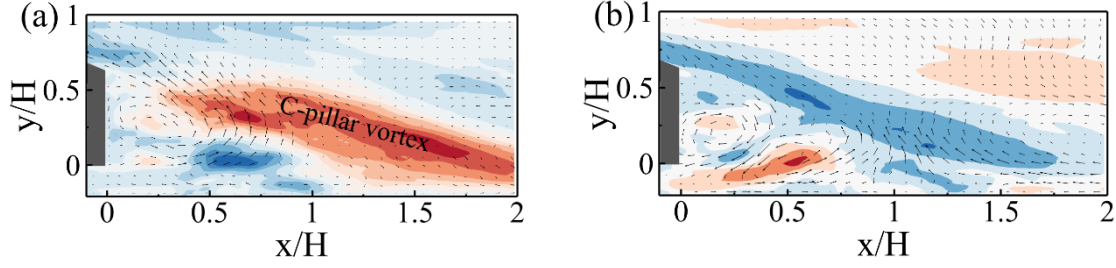


Figure 6.27 Contours of streamwise components of dominant Strouhal numbers $St = 0.08, 0.09$ for (a) $T_u = 10.0\%$, (b) 15.0%

6.4.7 Flow Characteristics in the x-z Planes

Due to the three-dimensional nature of the flow around the Ahmed body, streamwise-spanwise planes (H1 and H2) are employed to provide further insights into the effect of FST intensity on mean flow characteristics and vortex-shedding behaviour. The spanwise planes were carefully selected to explore the C-pillar vortex and wake recirculation bubble formed near the base region.

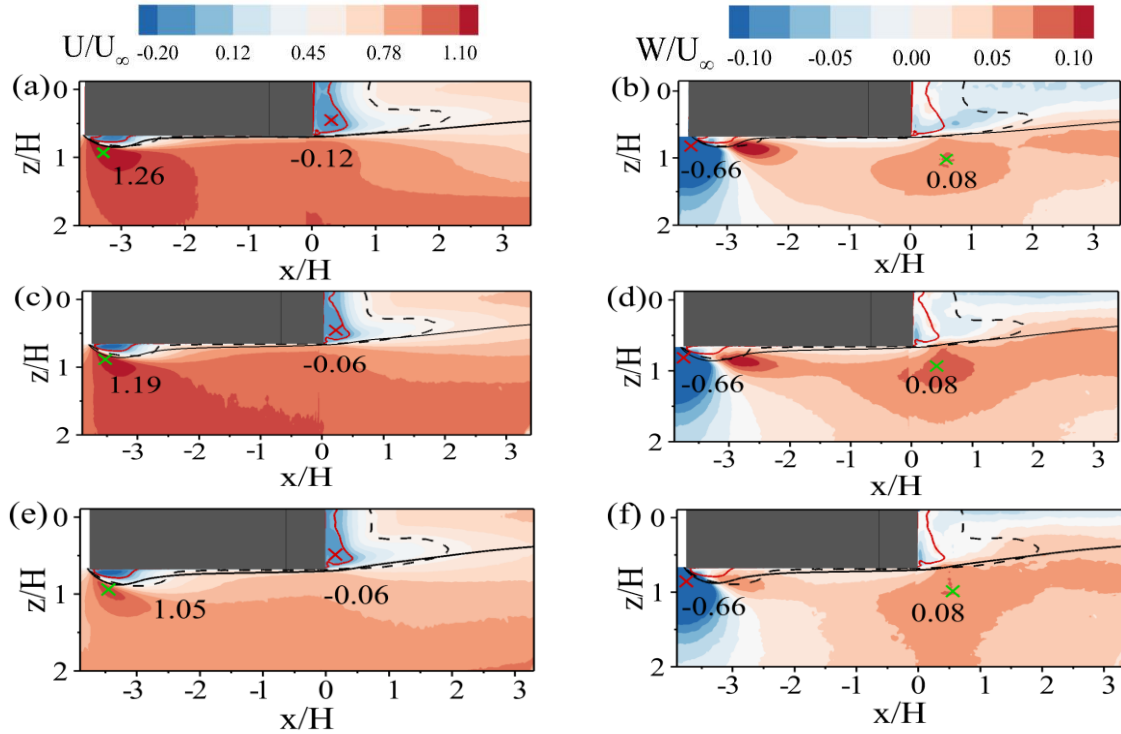
6.4.7.1 Mean Flow Field in Plane H1

Figure 6.28 shows the contours of the streamwise mean velocity (U) and spanwise mean velocity (W) in the spanwise plane of H1. The mean streamline separating from the side surface and isopleths of the recirculation bubble, where $U/U_\infty = 0$ and 0.5 , are also superimposed on the plots. The maximum and minimum magnitudes of each velocity are indicated in each figure. As the incoming flow impinges on the sharp edge, it separates and subsequently reattaches near the leading edge, forming a recirculation bubble with a recirculation length of $L_r \approx 0.72H, 0.69H, 0.68H, 0.58H$ for $T_u = 1.5\%, 5.0\%, 10.0\%$ and 15.0% , respectively. This reduction in the recirculation bubble with increasing FST intensity mirrors the behaviour observed over the roof and suggests that higher turbulence promotes earlier reattachment of the separated flow. Irrespective of the FST intensity, the recirculation bubble in the wake varies across the spanwise

direction, with L_r being larger at the side edges and reaching its minimum in the midspan plane.

This topological structure aligns with Venning et al. (2015), who proposed that the toroidal structure in the wake region of the Ahmed body exhibits a horseshoe shape.

The plots also show that the elevated region of streamwise velocity decreases monotonically with increasing FST intensity. The maximum backflow velocity in the wake region is $U/U_\infty = -0.12$ for $T_u = 1.5\%$, while decreases to $U/U_\infty = -0.06$ for $T_u \geq 5.0\%$. This reduction in reverse flow strength suggests that turbulence mitigates the intensity of the recirculation. The magnitude of spanwise velocity near the leading edge is lower than the streamwise velocity and remains insensitive to FST intensity till $T_u = 10.0\%$, after which it decreases. The W velocity on the side surface of the body increases before deviating toward the wake region. The magnitude of the elevated spanwise velocity remains $W/U_\infty = 0.08$, irrespective of FST intensity.



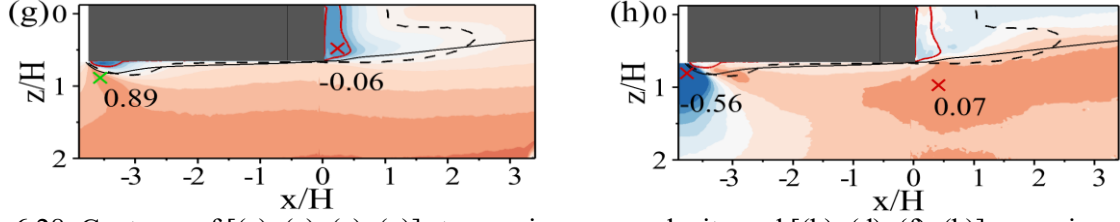


Figure 6.28 Contours of [(a), (c), (e), (g)] streamwise mean velocity and [(b), (d), (f), (h)] spanwise mean velocity in the H2 plane. Superimposed are the mean separating streamlines and the isopleth of the recirculation bubble (red solid line) which bounds the reverse flow region. The black dashed line represents $U/U_\infty = 0.5$. [(a), (b)] $T_u = 1.5\%$, [(c), (d)] $T_u = 5.0\%$, [(e), (f)] $T_u = 10.0\%$ [(g), (h)] $T_u = 15.0\%$

Contours of the Reynolds stresses ($\overline{u'u'}$, $\overline{w'w'}$, $-\overline{u'w'}$) are presented in Fig. 6.29. Consistent with Fig. 6.7, $\overline{u'u'}$ is enhanced in the separated shear layer near the leading edge. In this region, $\overline{w'w'}$ and $-\overline{u'w'}$ increases with increasing FST intensity from $T_u = 1.5\%$ to $T_u = 5.0\%$, while remaining constant for $T_u \geq 5.0\%$. The side surface shear layer in the wake region is less intense within the wake behind the body, and the Reynolds stress magnitude is independent of FST intensity.

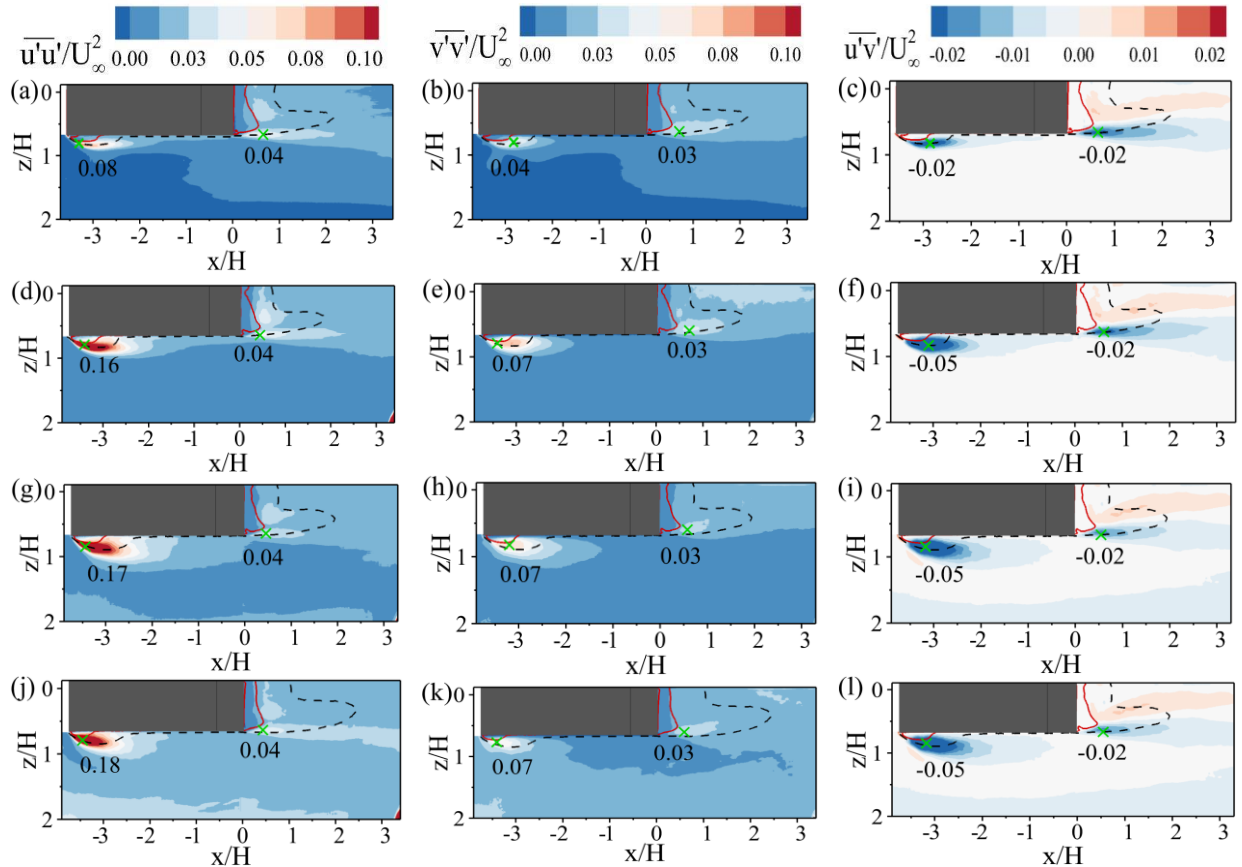


Figure 6.29 Contours of [(a),(d),(g),(j)] $\overline{u'u'}$, [(b),(e),(h),(k)] $\overline{w'w'}$ and [(c),(f),(i),(l)] $-\overline{u'w'}$ in the H1 plane. Superimposed is the isopleth of the recirculation bubble (red solid line), which bounds the reverse flow region. The black dashed line represents $U/U_\infty = 0.5$. [(a),(b)] $T_u = 1.5\%$, [(c),(d)] $T_u = 5.0\%$, [(e),(f)] $T_u = 10.0\%$, [(g),(h)] $T_u = 15.0\%$

6.4.7.2 Vortex Shedding Frequency

Figure 6.30 presents the premultiplied frequency spectra of the streamwise fluctuation velocity at the location of maximum $\overline{u'u'}$ for both the leading edge (Fig. 6.30a) and the wake shear layers (Fig. 6.30b). In Fig. 6.30a, the Strouhal number associated with vortex shedding is observed to switch between $St = 0.18$, 0.36 , and 0.72 , which tend to increase with increasing FST intensity. Notably, the frequency corresponding to $St = 0.36$ falls within the range $St \in [0.33-0.37]$ observed over the roof in the x-y plane. Two peaks are identifiable in the wake shear layer across all levels of FST intensity (Fig. 6.30b). The one at $St = 0.36$ is the same as measured in the leading edge shear layer, and the other occurs at $St = 0.54$ and 0.57 for $T_u = 5.0\%$, and 10.0% , respectively. The occurrence of the peak $St = 0.36$ in the wake region and near the leading edge may be ascribed to the intermittent lock-in of vortex shedding in these regions. While an alternative scenario, advection and impingement of upstream vortices could also play a role.

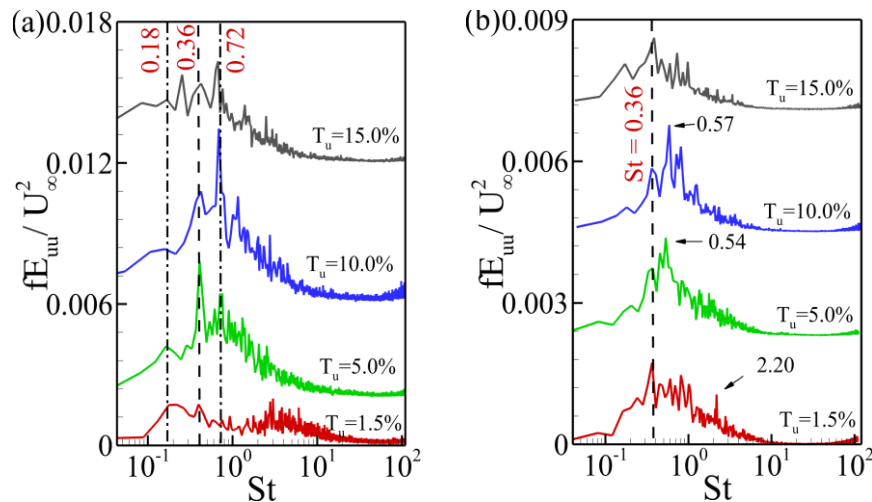


Figure 6.30 Spectra of streamwise velocity fluctuations at maximum $\overline{u'u'}$ (a) leading edge (b) wake region

To investigate the influence of FST intensity on the linear correlation between the roof and wake regions at the frequency corresponding to $St = 0.36$, the spectral coherence of the frequency spectrum is analyzed. Using the method outlined by Antonia et al. (1993), the coherence magnitude between two synchronized signals, signal i , the streamwise velocity fluctuations over the roof, and signal j , those in the wake shear layer is calculated as:

$$\gamma_{ij}(f) = \frac{|P_{ij}(f)|^2}{P_{ii}(f) \times P_{jj}(f)} \quad (6.10)$$

where $P_{ij}(f)$ is the cross-spectrum and P_{ii} and P_{jj} are the auto-spectra of signals i and j . The spectral coherence, varying between 0 and 1, highlights the frequencies at which signals exhibit the strongest correlation (Thacker et al., 2013). By examining $\gamma_{ij}(f)$ at $St = 0.36$, we assess whether FST intensity enhances the correlation, potentially due to stronger vortex shedding lock-in across these regions.

Figure 6.31 shows the spectral coherence of the frequency spectrum at maximum $\overline{u'u'}$ at the leading edge and wake region for all test cases. The figure reveals that increasing FST intensity intensifies the coherence of distinct peaks $St \leq 0.36$. Specifically, the coherence related to the $St = 0.36$ increases from $\gamma = 0.18$ to 0.28, 0.29 and 0.36 for $T_u = 1.5\%$, 5.0%, 10.0% and 15.0%, respectively. The observation suggests that at $St = 0.36$, vortex shedding in the wake region is locked in with the frequency of vortices originating from the upstream cylinder, and the degree of coherence between the leading edge and wake region increases with FST intensity.

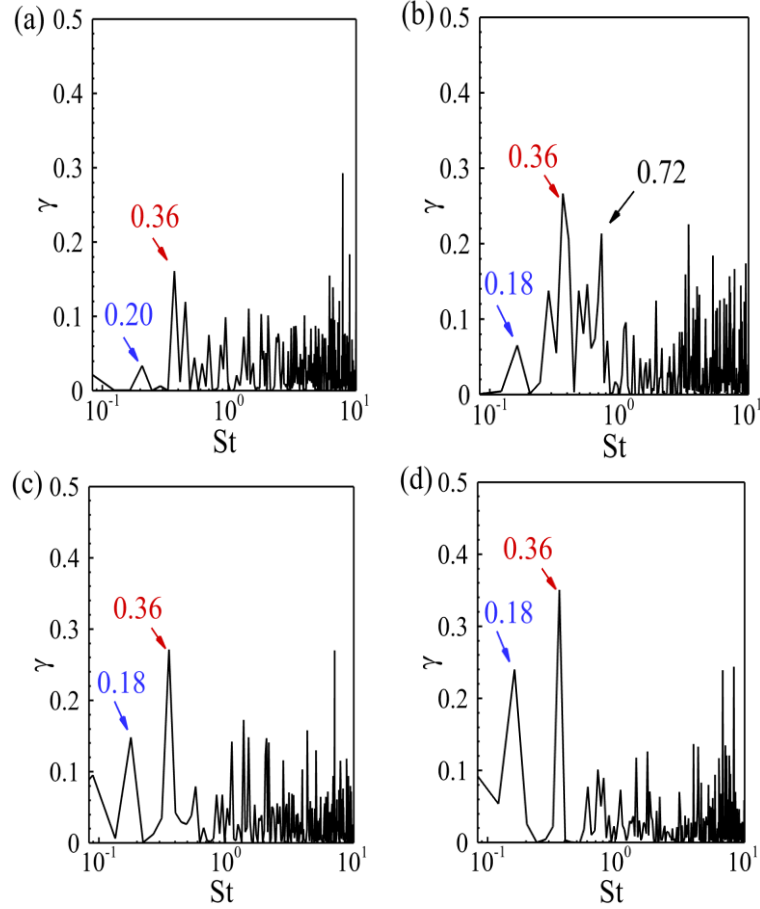


Figure 6.31 The spectral coherence between points $(x/H, z/H) = (-3.40, -0.80)$ and wake region $(x/H, z/H) = (0.33, -0.61)$ for $T_u = 1.5\%$ (a), $T_u = 1.5\%$ (b) and $T_u = 15.0\%$ (c)

6.4.7.3 Mean Flow Field in Plane H2

Figure 6.32 presents the contours of the streamwise and spanwise mean velocities at plane H2 for $T_u = 1.5\%$ and $T_u = 15.0\%$. The mean streamlines are superimposed on the contours of the streamwise mean velocity. The figure shows the three-dimensionality of the flow by displaying variations in the mean flow pattern across the spanwise direction. A comparison of Fig. 6.32a and 6.32b reveal a more pronounced deviation of flow streamlines near the ends of the body into the wake region at $T_u = 1.5\%$. This suggests a higher level of interaction between the shear layers in this region. Figure 6.32c illustrates the profile of the streamwise mean velocity in the spanwise direction at $x/H = 0.5$. The profile shows a greater velocity deficit in the wake region of the body

exposed to $T_u = 15.0\%$. Additionally, the contours of the spanwise mean velocity (Figs. 6.32d and 6.32e) show that the maximum spanwise velocity for lower FST intensity is $W/U_\infty = 0.20$, which is higher than $W/U_\infty = 0.16$ observed for the higher FST intensity. This confirms that lower FST intensity is associated with a stronger spanwise velocity component in the wake region.

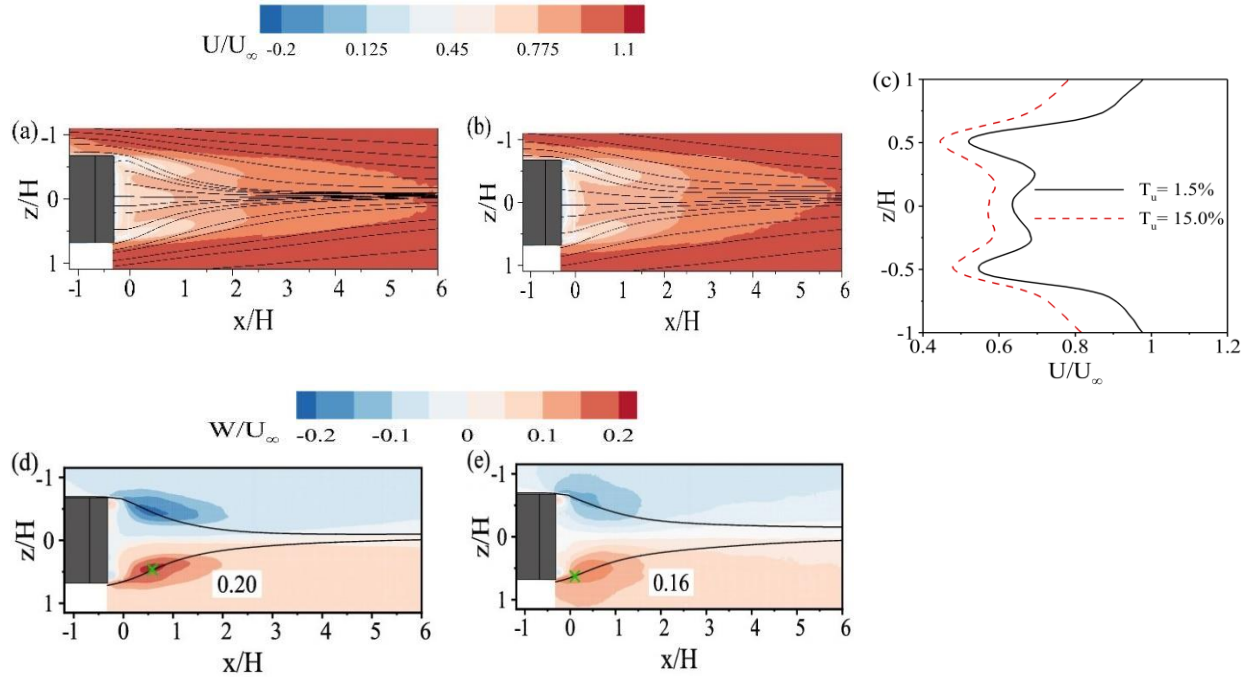


Figure 6.32 Contour of streamwise mean velocity for $T_u = 1.5\%$ (a) and $T_u = 15.0\%$ (b); One-dimensional profile of the streamwise mean velocity in the spanwise direction at $x/H = 0.5$ (c); Contour of spanwise mean velocity for $T_u = 1.5\%$ (d) and $T_u = 15.0\%$ (e)

6.4.7.4 Proper Orthogonal Decomposition

To investigate how FST intensity influences the wake dynamics and vortex shedding patterns of most energetic structures around the body, POD is employed in plane H2 to extract the coherent vortical structures and their associated shedding frequencies (Van Oudheusden et al., 2005; Essel et al., 2021; Sagharichi & Tachie, 2024). The POD algorithm was performed using the snapshot technique introduced by Sirovich (1987) and detailed in Fang & Tachie (2019). The POD analysis was performed in the region of $x/H \in [-0.9, 2.5]$ and $y/H \in [-1.2, 1.2]$.

The fractional and cumulative energy of the first 100 modes are displayed in Fig. 6.33. Increasing FST intensity boosts the energy captured by the first few modes while widening the energy gap between the first two POD modes. Notably, the first two modes at $T_u = 1.5\%$ captures 25.1% of the TKE, while this increases to 27.4% at $T_u = 15.0\%$. The higher similarity between the energy captured by the first two POD modes at lower FST intensity suggests a stronger correlation between these modes, indicative of a more stable vortex-shedding mechanism. This observation aligns with previous studies on Ahmed bodies (Siddiqui & Agelin-Chaab, 2022; Sagharichi et al., 2023) and finite wall-mounted cylinders (Essel et al., 2023), where the first two modes were closely linked to vortex shedding. Beyond the second mode, the energy contribution diminishes significantly. Furthermore, the cumulative energy distribution shows a higher overall energy captured at $T_u = 15.0\%$, which indicates that higher FST intensity enhances the dominance of the largest coherent structures.

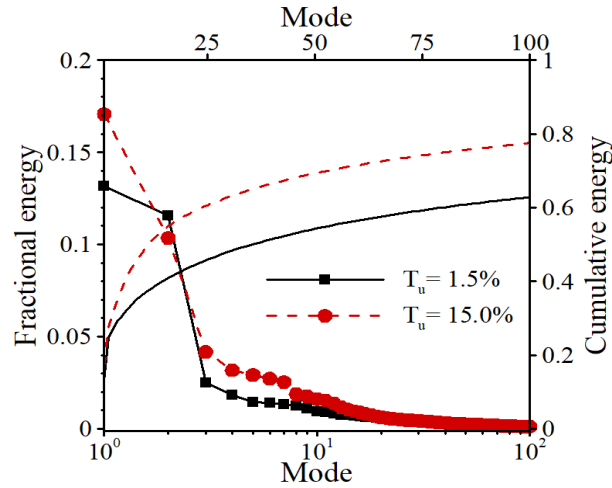
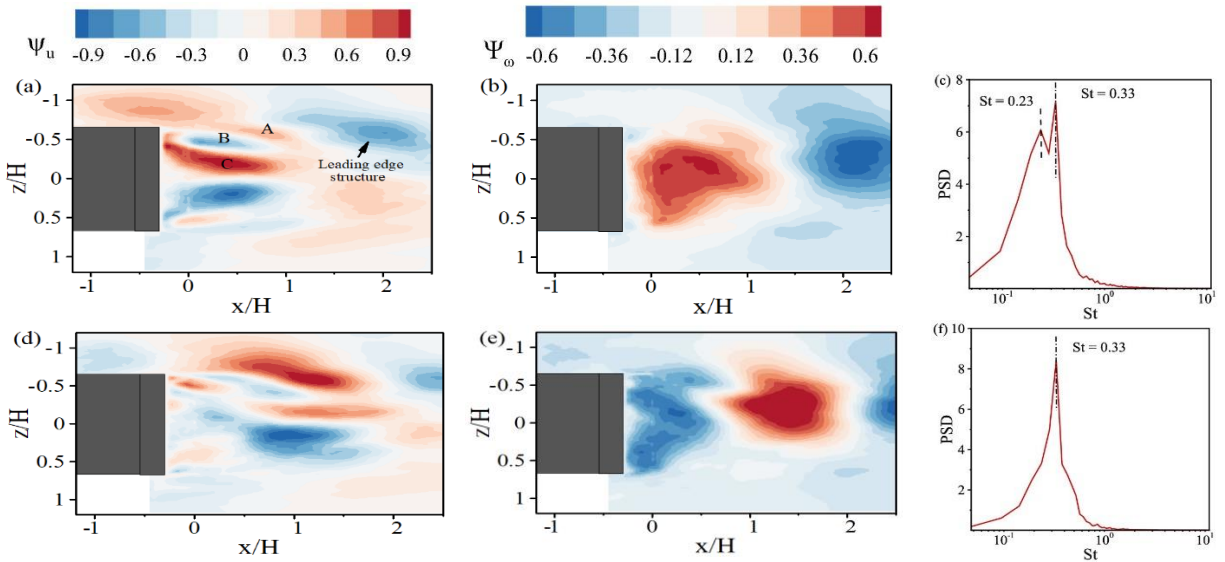


Figure 6.33 Relative and cumulative TKE captured by POD modes

The spatial distribution of streamwise and spanwise velocity fluctuation for mode 1 and mode 2 is used to visualize the coherent structures. Figures 6.34a and 6.34d display three distinct vortices labelled "A", "B" and "C". Vortex "A" forms due to the shear layer separating from the body side surface. Vortex "B" originating from the side edge of the slanted surface, curves inward as it sheds

downstream and is identified as the C-pillar vortex, and vortex "C" is induced by the C-pillar vortex (Wang et al., 2013; Zhang et al., 2019). The spanwise distribution of POD mode 1 and mode 2 at $T_u = 1.5\%$ (Figs. 6.34b and 6.34e) is characterized by alternate positive and negative structures, an indication of the vortex shedding phenomena (Sagharichi et al., 2023). The spectra of the temporal POD coefficient in this FST intensity set at $St = 0.33$, which was also identified as the vortex shedding of the shear layer separating from the leading edge in the x-y plane (See Fig. 6.12). In contrast, the streamwise distribution of the first two POD modes for $T_u = 15.0\%$ (Figs. 6.34g and 6.34j) highlights the dominance of an elongated C-pillar vortex, indicating that higher FST intensity leads to the strengthening of this vortex structure. This observation is in accordance with the dominance of the C-pillar vortex in the wake region in the x-y plane (Fig. 6.27) at $T_u = 15.0\%$. Accordingly, the spanwise distribution in this FST intensity lacks a regular pattern of vortex shedding. The spectra of the POD coefficients in this FST intensity are $St = 0.09$, which was also identified in the wake region of the body in the x-y region as the frequency of the C-pillar vortex.



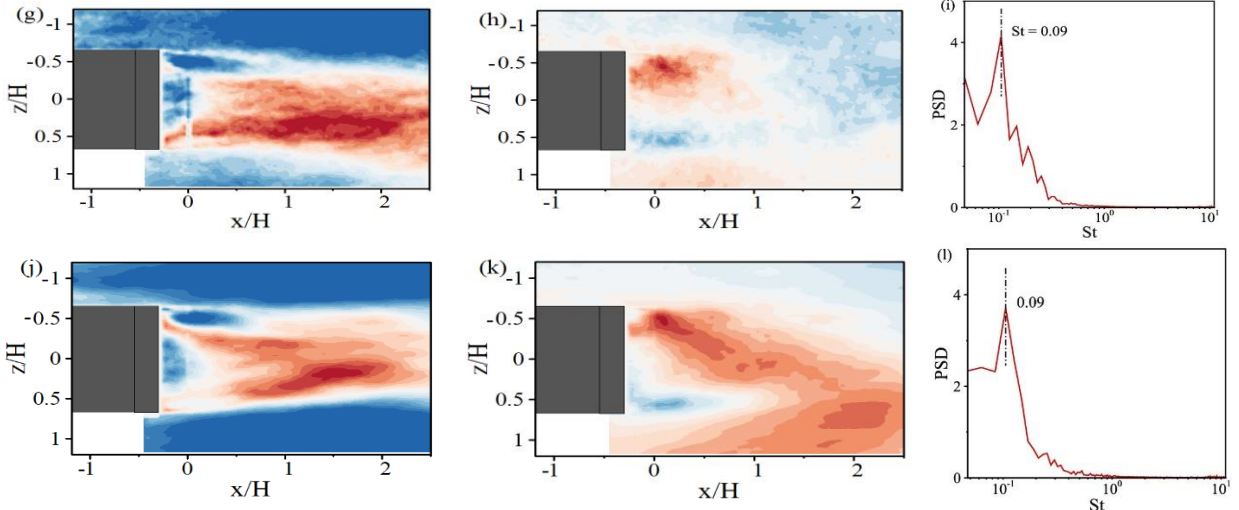


Figure 6.34 Contours of streamwise [(a),(d),(g) and (j)] and spanwise [(b),(e),(h) and (k)] of first [(a), (b),(g) and (h)] and second [(d),(e),(j) and (k)] POD modes for $T_u = 1.5\%$ [(a-f)] and $T_u = 15.0\%$ [(g-l)]. The corresponding premultiplied frequency spectra of each mode are shown in the right column

6.5 Summary

This study has presented a thorough investigation of how free-stream turbulence (FST) intensity influences the spatiotemporal characteristics of turbulent separation and reattachment around a slanted-back Ahmed body with a square leading edge, at $Re = 0.17 \times 10^5$. Four turbulence levels ($T_u = 1.5\%$, 5.0% , 10.0% , and 15.0%) were generated using a combination of no-grid (baseline), a regular grid, and two fractal grids. Time-resolved particle image velocimetry (TR-PIV) was employed to measure the instantaneous velocity fields over the x - y and two x - z planes. The primary findings are summarized below.

The results demonstrate that increasing FST intensity profoundly alters the flow dynamics over the roof. As T_u increases from 1.5% to 15.0% , the roof recirculation bubble length decreases monotonically from $L_r = 1.85H$ to $0.82H$, and its height drops from $0.31H$ to $0.21H$. In contrast, the wake's recirculation length remains constant ($L_r \approx 0.56 H$) and its velocity deficit shows negligible variation with FST intensity. By decomposing the mean-shear tensor along the

separation streamline, it was shown that the principal stretching rate downstream of the sharp leading edge remains comparable at all FST intensities near separation, but is subsequently suppressed for $T_u \geq 10\%$. The associated principal-stretching direction rapidly reorients toward the roof at high FST intensity, whereas for lower turbulence it continues to decrease more gradually. Additionally, the identified shear-layer interface height collapses more rapidly toward the roof as FST intensity rises. It was concluded that higher FST intensity pulls the shear layer downward earlier, causing reattachment to occur sooner and shrinking the recirculation bubble.

Over the roof, the peak streamwise Reynolds normal stress increases by 46% as FST intensity rises from 1.5% to 15.0%, and its location migrates upstream toward the leading edge. The increase in streamwise Reynolds normal stress with FST intensity is driven by energy redistribution toward low-frequency motions ($St < 0.23$). In contrast, wall-normal Reynolds stresses remain insensitive to FST, confined to medium-frequency vortex shedding processes ($0.23 \leq St \leq 1.15$) for all FST intensities. The roof's maximum turbulent kinetic energy rises sharply with turbulence intensity, and this amplification is driven primarily by enhanced production via the streamwise stress term, while the wall-normal stress term remains small and nearly constant. The production in the wake region is dominated by the shear stress production, but its magnitude decreases steadily as FST intensity increases. Quadrant analysis in the wake highlights that TKE suppression was linked to reduced inward interaction events, with sweep events dominating turbulence production. The integral time scale and quadrant analysis showed that elevated turbulence preferentially suppresses the short-lived, small-scale inward-interaction structures responsible for the wake's shear-layer unsteadiness. In the wake, the classical vortex-shedding frequency at $St = 0.23$ ($T_u = 1.5\%$) reduces monotonically to $St = 0.18$ ($T_u = 5.0\%$), $St = 0.16$ ($T_u = 10.0\%$), and $St = 0.14$ ($T_u = 15.0\%$). The wavelet analyses reveal that regular shedding at these Strouhal numbers is intermittently disrupted

by large-scale vortical structures associated with C-pillar vortices forming along the slanted edges at high FST intensities.

The synchronization between low-frequency streamwise Reynolds stress fluctuations and reverse flow area fluctuation over the roof shows a strong correlation at $T_u \geq 5.0\%$. Joint probability density function analysis confirms that higher FST intensity enhances contraction events increasingly dominant at $T_u = 15.0\%$. In contrast, intermediate and small-scale structures ($0.23 < St < 6.0$) exhibit negligible influence on bubble dynamics, underscoring the primacy of large-scale motions in FST-modulated flows.

Both spectral analysis and Spectral Proper Orthogonal Decomposition (SPOD) revealed that, regardless of free-stream turbulence intensity, a large-scale flapping motion consistently developed over the body roof. The flapping motion is driven by large-scale sweep events during bubble contraction, contributing 100% of positive TKE production at $T_u = 15.0\%$, while ejection events govern expansion but contribute less to TKE.

In the wake, FST monotonically suppresses vortex shedding frequency, reducing the dominant Strouhal number from $St = 0.23$ to 0.14 as T_u increases from 1.5% to 15.0% . This suppression is linked to the emergence of a persistent C-pillar vortex, which interacts with the upper shear layer, disrupting regular vortex shedding and promoting long-lived structures near the wall. This behaviour was confirmed using spanwise measurements in the x - z planes, which showed that elevated FST intensities strengthen the C-pillar vortex and promote elongated vortical structures. The spanwise-plane measurements also revealed frequency locking near the side-surface shear layers originating from both the leading edge and the wake region, and this effect intensified as the FST intensity increased.

6.6 References

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Chapter 7: Conclusions and Recommendations for Future Studies

This chapter summarizes the key findings of the research on the effect of freestream turbulence (FST) on the flow structure around the Ahmed body and provides recommendations for future studies. The study utilized experimental techniques to investigate flow characteristics under varying turbulence intensities, offering insights into the spatiotemporal flow characteristics around the slanted-back Ahmed body.

7.1 Research Summary and Major Findings

This thesis examined the influence of freestream turbulence (FST) on the flow structure around a slanted-back Ahmed body with a 25° slant angle. Two leading-edge configurations were studied: squared (SL) and rounded (RL). Particle image velocimetry (PIV) was employed in a water channel to capture detailed flow characteristics. Passive grids, including a regular grid and two fractal grids with varying mesh sizes, generated FST intensities ranging from 5.0% to 15.0%, with integral length scales between $0.29H$ and $1.07H$ (where H is the height of the Ahmed body). These conditions were compared to a baseline turbulence intensity of 1.5% without grids. The major findings are summarized as follows:

7.1.1 Effect of Leading-Edge Shape at Low Turbulence

The first part of the thesis focused on a comparison of flow dynamics around the body induced by different leading-edge shapes: squared leading-edge and rounded leading-edge bodies at the baseline FST intensity of 1.5%. The spatiotemporal characteristics of flow separations around the bodies were investigated using double-frame and time-resolved particle image velocimetry. The Ahmed body used in this study has a $\frac{1}{4}$ scale of the original model introduced by Ahmed et al.

(1984) with a slanted surface angle of 25° . Comprehensive measurements were performed for two Reynolds numbers of $Re = 0.17 \times 10^5$ and $Re = 0.36 \times 10^5$ at x-y and x-z measurement planes. The mean velocity contours revealed that three distinct bubbles are formed around the bodies, over the roof, the slanted surface, and the wake region. While the results showed a degree of Reynolds independence in the SL body, the length of the recirculation bubble over the body was smaller in the RL body, and its extension became smaller as the Reynolds number increased. A higher downwash flow was observed behind the RL body than that of the SL body. A thicker separated shear layer was emanating from the leading edge of the SL body than in the RL case. However, the thickness of this shear layer was insensitive to the Reynolds number for both bodies. A higher level of Reynolds normal and shear stresses was observed behind the RL case compared with the SL one, which indicated that the interactions between the lower and upper shear layers of the RL body are more intense compared to the SL one. Near the leading edge, the Kelvin–Helmholtz instability observed over the bodies at $St = 4.4$ and 4.2 for SL, and $St = 4.3$ and 5.5 for RL bodies at $Re = 0.17 \times 10^5$ and $Re = 0.36 \times 10^5$ respectively. It was also observed that the frequency of the separated shear layer migrates from high to low values through the vortex pairing mechanism. Analysis of shedding frequencies and convective velocities using POD coefficients over the body roof revealed a higher shedding frequency and convective velocity over the SL body ($St = 0.36$, and $U_c \approx 0.72U_\infty$) compared with $St = 0.33$ and $U_c \approx 0.47U_\infty$ over the RL roof. In contrast, in the wake region, the RL body exhibited higher values: $St = 0.33$ and $U_c \approx 0.76U_\infty$, compared to the SL body: $St = 0.23$ and $U_c \approx 0.62U_\infty$. The cross-correlation analysis of reverse flow area fluctuations revealed that for the RL body, expansions or contractions of the leading-edge separation bubble tend to occur simultaneously with similar changes in the wake separation region.

In contrast, the SL body more frequently exhibited the opposite behaviour, where expansion in one region corresponded with contraction in the other.

7.1.2 Impact of Elevated FST on the Flow Around the RL and SL Body

The impact of FST intensity on the flow dynamics around rounded and squared leading-edge Ahmed bodies was investigated using time-resolved particle image velocimetry (TR-PIV) at $Re = 0.17 \times 10^5$. The experiments were performed at a baseline level of $T_u = 1.5\%$, with elevated FST levels of $T_u = 5.0\%$, 10.0% , and 15.0% generated using regular and fractal grids.

Roof dynamics: For both geometries, increasing FST intensity consistently reduced the size of the roof recirculation bubble, evidenced by a decrease in recirculation length from $0.90H$ to $0.32H$ for the RL body and from $1.85H$ to $0.82H$ for the square leading-edge SL body, as FST rose from $T_u = 1.5\%$ to 15.0% . This reduction reflects improved flow reattachment stability, corroborated by the probability distribution of the reattachment point shifting from a bimodal pattern at lower FST to an unimodal one at higher intensities. Quadrant analysis further revealed that elevated FST suppressed sweep (Q_4) and ejection (Q_2) events, stabilizing the shear layer over the roof in both configurations. For the RL body, Reynolds stresses and turbulent kinetic energy (TKE) diminished with increasing FST, indicating a suppression of turbulent fluctuations. In contrast, the SL body exhibited an increase in streamwise Reynolds stress and TKE, with peak values rising by 46% from $T_u = 1.5\%$ to 15.0% , attributed to energy redistribution toward low-frequency motions ($St < 0.23$). Despite these differences, peak turbulence locations shifted upstream toward the leading edge in both cases, signalling an earlier transition to turbulence. Regarding vortical structures, FST suppressed Kelvin–Helmholtz (KH) instabilities and associated vortical structures near the RL body’s leading edge, transforming positive and negative structures (Q_2 and Q_4 events) into

elongated, coherent structures spanning the roof bubble, as revealed by space-time correlation analysis. Conversely, for the SL body, KH instabilities persisted with a slight increase in vortical structure frequency, and elevated FST intensity amplified low-frequency flapping motion, characterized by periodic bubble growth and shrinkage.

Slanted surface dynamics: The analysis of flow over the slanted surface of the RL body showed that increasing FST intensity promotes the recirculation length but remains constant for $T_u \geq 10.0\%$. The recirculation bubble over the slanted surface enlarged with increasing FST intensity. This was attributed to stronger spatial and temporal correlations between the C-pillar vortex and the separated shear layer, reinforcing their interaction. Additionally, higher FST levels intensified the temporal coupling between the C-pillar vortex and the upper shear layer in the wake region.

Wake region: In the wake region, the recirculation length remained constant at $0.56H$ for both RL and SL bodies across all FST intensities, unaffected by leading-edge shape or turbulence levels, due to the shielding effect of the Ahmed body's geometry. However, elevated FST disrupted regular vortex shedding and fostered long-lived, near-wall flow structures. For both configurations, TKE in the wake was significantly suppressed at higher FST, linked to reduced spectral coherence between the upper and lower shear layers, which weakened their flapping motion and reduced wake vortex shedding frequency. This effect was more pronounced in the SL body, where wake vortex shedding frequency dropped from $St = 0.23$ to 0.14 (a 39% reduction) compared to $St = 0.33$ to 0.27 (an 18% reduction) for the RL body as FST increased from $T_u = 1.5\%$ to 15.0% . The reduction in TKE with FST intensity in the wake region of the SL body was linked to reduced shear stress production and diminished inward interaction events (Q_3) identified through quadrant analysis. In the RL body, higher FST intensified temporal coupling between the C-pillar vortex and the upper shear layer, disrupting shedding coherence. Similarly, in the SL body,

SPOD analysis revealed a persistent C-pillar vortex merging with the upper shear layer at $T_u \geq 10.0\%$, impeding lower shear layer interactions and sustaining near-wall structures, as evidenced by increased integral time scales.

7.2 Recommendations for Future Studies

Based on the research outcomes, the following recommendations are proposed to advance the understanding of FST effects on bluff body aerodynamics:

1. **Investigation of Different Slant Angles:** The current research focused on a 25° slant angle. Studying other angles, especially near the critical angle of approximately 30° , where flow topology changes significantly, could reveal how FST interacts with varying wake configurations.
2. **Active Flow Control Techniques:** Implementing active flow control methods, such as synthetic jets or plasma actuators, alongside varying FST levels could demonstrate how these control strategies perform under realistic, turbulent inflow conditions, revealing their effectiveness and robustness in real-world aerodynamic applications.
3. **Three-Dimensional Flow Analysis:** To better understand the complex interactions between the roof bubble, slanted surface, and wake under high FST intensities, future studies should employ simultaneous pressure/drag-velocity measurements to directly correlate bubble dynamics with drag forces. Implementing tomographic particle image velocimetry is also recommended to capture the three-dimensional flow structures, which become more prominent in turbulent conditions.
4. **Practical Impact and Application Prospects:** This study showed that there is a link between the recirculation dynamics of the roof bubble, slanted surface, and alternating vortex-shedding motion in the wake region of RL body at $T_u = 1.5\%$, and a possible global

instability mode that governs flow reattachment and wake vortex shedding. However, this linkage vanished at higher FST intensities. The disruption of this linkage has significant implications for flow control strategies. At low FST ($T_u = 1.5\%$), flow control techniques applied over the roof, such as vortex generators, steady blowing, or surface modifications (Zhang et al. 2018) can effectively manipulate the roof bubble to influence downstream flow, including the slanted surface and wake, due to the coherent global mode. However, at high FST intensities ($T_u > 1.5\%$), the loss of this coherence suggests that roof-based flow controls may have diminished effectiveness in altering downstream flow structures. This insight advises designers to reconsider traditional flow control approaches in turbulent environments, potentially shifting focus to control methods that target the slanted surface or wake directly under high FST conditions.

5. **Impact of Cross-wind, Unsteady Flow:** In real road conditions, moving vehicles are exposed to unsteady flow conditions due to road irregularities, wind gusts, and varying traffic flow. These dynamic effects can significantly alter the flow dynamics in the rear face region. Yaw angle (the angle of incident flow to the body) has an unsteady, variable nature in real driving conditions, particularly during gusty crosswinds. These yaw angles introduce significant complexities in the flow and contribute to increased aerodynamic drag. Howell (2015) demonstrated that yaw angles significantly affect pressure drag. The author noted, "The drag coefficient increase at yaw should be considered when evaluating the performance of passenger cars. The drag rise with yaw may negate the benefits for a car with a low drag coefficient as defined at zero yaw only." This is confirmed by McArthur et al. (2018), who proved that in crosswind conditions, three-dimensional separations along the edges generate streamwise vortices that interact with the rear face structures and

contribute to induced drag. Hence, exploring the combined effects of FST and crosswinds is recommended as it could clarify how turbulence alters wake dynamics and lateral forces, enhancing vehicle stability and fuel efficiency.

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