THE REDUCTION OF DRAG OF TWO-DIMENSIONAL BLUNT-BASED BODIES BY BLOWING

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by

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To

My wife Mimi

whose never ending encouragement made this thesis possible.

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LIST OF NOTATION

a	lateral spacing of vortices in a vortex street.
b	width of the mixing zone.
C_d	$\frac{D}{\frac{1}{2}\rho_\infty U_\infty^2 d}$, drag coefficient.
C_p	$\frac{P-P_\infty}{\frac{1}{2}\rho U_\infty^2}$, pressure coefficient.
C_{Pb}	base pressure coefficient.
$C_{P_{sep}}$	pressure coefficient at separation.
$C_{P_{step}}$	pressure coefficient for a step.
$\overline{C_p}$	average pressure coefficient.
C_μ	$\frac{U_{bl} \cdot W_{sl}}{U_\infty t_{max}}$, bleed coefficient.
c	proportionality factor.
C_M	$\frac{2t_{max}}{h} C_\mu^2$, momentum coefficient.
D	drag.
D_{pr}	$\oint pdy$, pressure force.
d	body height.
$\frac{db}{dx}$	rate of spread
F	streamwise force.
f	$\frac{F}{\frac{1}{2}\rho U_\infty^2 t_{max}}$, streamwise force coefficient.

G_d	$\left\|\frac{\Delta C_d}{\Delta C_\mu}\right\|_{lin}$	, drag gain over the approximately linear portion of a C_d-C_μ curve.
h	base height.	
h_s	transversal spacing of vortices	
L_d	diffusion length.	
L_f	length of formation region.	
l_e	entrainment length	
l_{spin}	spinning length	
l_{form}	formation length	
M	bleed momentum	
$\dot{m}_{bl}$	bleed mass flow rate	
N	vortex shedding frequency on one side of the vortex street.	
p	static pressure	
Re	$\frac{U_\infty \text{ x body length}}{\nu}$, Reynolds number	
r	= velocity ratio	
S	$\frac{N \cdot h}{U_{sep}}$, strouhal number	
s	step height.	
t_{max}	model maximum thickness	
U,u	velocities	
v	perturbation velocity.	
W_{sl}'	total width of "open" part of the base	

X,Y	coordinates for models.
x,y	coordinates for shearlayers.
γ	boat-tail angle.
Γ	vortex strength
δ	boundary layer thickness.
Δ	finite change in a quantity.
ε	eddy or effective viscosity.
ϵ	vortex transfer fraction.
η	y/x, similarity variable.
ν	kinematic viscosity.
ρ	fluid density.
ϕ_b	base cylinder diameter.
χ	experimental constant.

SUMMARY

The effect of changes in the base geometry and the bleedvents on the drag of blunt-based bodies is investigated at high Reynolds numbers ($Re \approx 10^5$). A maximum drag coefficient $C_d = .640$ and a minimum of $C_d = .270$ is found for very small bleedrates. The previously found drag gain with bleed of $G_d = 3.0$ could be improved to $G_d = 74.0$. Drag variations could be related to the flow pattern in the near wake by means of two newly defined length scales l_e and l_{spin} through the use of a newly developed streamer method. A uniformly valid correlation between l_e and l_{spin} is found which is thought to make the formation of vortex streets behind bluff objects dependent on l_e only.

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1. General Introduction

The present study of the drag reduction by blowing is part of a programme concerned with a system for the speed stabilization of a windtunnel, using fluidic devices.

The invention in 1960, of the first fluid amplifiers opened the way for a rapidly expanding new technology now commonly known as fluidics, or fluid amplification. These devices made possible the development of control-and logic systems using only the properties of moving fluids - "pure fluid" systems.

The attractive feature of many now known fluidic devices is that they contain no moving parts and can operate under widely varying environmental conditions giving rise to the expectation of prolonged life and dependability of the systems. In all the devices, use is made of interaction of jets and phenomena relating to separated-and re-attached flows. The application of common sense and imagination to combining these principles has played and still plays an extremely important role in the conception of new fluidic devices and control systems; the investigation here presented is a result of such a development.

It was thought that an automatic windtunnel speed stabilization system using the fluidic principle of no moving parts, would have distinct advantages over partly electrical, partly mechanical systems. The fluidic system basically senses the windtunnel speed and counteracts any changes in the speed by varying the aerodynamic resistance of the tunnel circuit.

The realization of the system requires the development of a number of devices, namely:

- a speedsensor
- a comparator
- power amplifier
- variable tunnel resistance.

Of these devices the speedsensor incorporating the comparator has been completed and the no-load static performance investigated (Ref. 1). The power amplifier is under investigation. The variable resistance is proposed to be brought about by two methods: (1) variation of the drag of blunt bodies by means of base bleed, (2) diffuser efficiency control by inducing local separation by blowing. The air supply for the resistances and part of the power amplifier is to be taken from the settling chamber of the windtunnel itself, making those parts of the system independent of external power.

A more detailed description of the speed stabilization system is presented in appendix A.

2. The Reduction of the Drag of Cylindrical Blunt Based Bodies by Blowing.

2.1 Introduction

It is well known that ill-streamlined bodies show a considerable drag compared to well-streamlined bodies. This effect is caused by the inability of the boundary layer to remain attached to the body in the presence of high adverse pressure gradients over the rear part of the body. The flow therefore separates from the body leaving a so called "dead air" region behind the body and a wake which may be periodic. This "dead air" region, having a low pressure, creates a high drag.

Although these effects were extensively reported in the early days of fluid dynamics by Prandtl, von Kármán, Kirchoff, Helmholtz and others, they remained of academic interest only - blunt shapes were simply avoided in aerodynamic design - until quite recently.

Extensive research (Ref. 2) into the drag reduction at supersonic and transonic speeds resulted in the use of airfoils with cut-off trailing edges. Although advantageous at high speeds, they gave rise to a considerable penalty in aerodynamic efficiency at subsonic speeds due to the low lift and high drag characteristics. The high drag is mainly due to the low pressure region immediately behind the body called the base drag. Reduction of the base drag was found to be obtained by a continuous injection of fluid from the base of bodies and even relatively low bleed-rates were found to be effective (Ref. 3,4). For use in the speed stabilization system, however, these bleedrates would be high compared to the tunnel mass flow, requiring the search for even more effective bleed modes.

From studying the effects of changes in the geometry of the base and bleedvents, insight into more efficient means of drag reduction by base bleed is anticipated so that higher drag gain, $|\Delta C_d/\Delta C_\mu|$, than demonstrated in References 3 and 4, can be obtained.

2.2. Review of Previous Work

Although quite a complete review of research on the separated flows behind bluff bodies was presented in 1962 by Nash (Ref. 2), more recent work is of sufficient importance to be reviewed and its connection with older work noted.

Investigations by Prandtl (Ref. 5) on the flow around bluff objects showed that the flow pattern changed very significantly with Reynolds number. At extremely low Reynolds number ($Re \approx 1$), a flow pattern like the potential flow was observed. A slightly higher Reynolds number up to $Re \approx 50$, was characterized by the separation of the laminar boundary layer, well before the rear stagnation point, forming a stable forced vortex pair (Fig. 1[a]). Increasing the Reynolds number beyond $Re \approx 50$ resulted in the vortex pair becoming unstable and the well-known vortex street was formed. This vortex street could be observed for Reynolds numbers beyond the critical value-transition to turbulent boundary layers and turbulent separation - as high as $Re \approx 10^5$ (Ref. 6). Beyond that the value the vortex street broke down and the wake became a periodic.

A close approximation of the behaviour of periodic vortex streets was given by von Kårmån using a potential flow solution. He found a unique relationship between the geometry of the vortex street, the strength of the individual vortices and the velocity with which the vortex street moves downstream with respect to the body (Fig. 1[b]).

$$U_s = \frac{\Gamma_s}{2a} \tanh \frac{\pi h_s}{a} , \qquad (1)$$

where: U_s = velocity of the vortex street relative to the body,

Γ_s = strength of each of the vortices in the street

a, h_s = lateral and transversal spacing of the vortices respectively.

Stability investigations on different geometrical configurations of periodic vortex streets revealed that only one stable condition exists, namely when:

$$\sin\left(\frac{\pi h_s}{2}\right) = 1,$$

$$\text{or} \quad \frac{h_s}{a} = 0.281 \quad . \qquad (2)$$

Carrying through a time averaged drag calculation by momentum considerations it was found (Ref. 6) that the drag coefficient is given by:

$$C_d = \frac{D}{\frac{1}{2}\rho U_\infty^2 d} = \frac{a}{d}\left[1.59\,\frac{U_s}{U_\infty} - 0.63\left(\frac{U_s}{U_\infty}\right)^2\right], \qquad (3)$$

where: C_d = drag coefficient, D = drag

U_∞ = free stream velocity

$$\frac{U_s}{U_\infty} = \frac{N \cdot a}{U_\infty}, \qquad (4)$$

N = vortex shedding frequency on one side

$$\Gamma_s = 2\sqrt{2}\,aU_s, \qquad (5)$$

ρ = density

d = body height.

Measurements of the frequency and spacing ratio only are needed to calculate the drag.

A method for predicting the frequency and spacing ratio for a given body shape, however, was not available. Attempts to calculate the drag of bluff body shapes resulted in the Helmholtz-Kirchoff free streamline theory. Basic assumptions of this theory were that in the average the hightly turbulent wake could be replaced by a dead-air region at ambient pressure being separated from the free stream by the free shear layers. These free shear layers were replaced by free streamlines springing from the separation points. For bodies with fixed separation points such as flat plates normal to the stream the potential flow solution obtained by the free streamline theory yielded forebody pressure distributions which resembled the measured distributions. However, the drag values obtained were not in agreement with the observations. Only quite recently (1954) Roshko (Ref. 7) succeeded in obtaining a more satisfactory potential flow solution for the periodic flow around bluff body shapes by joining the free-streamline solution to the von Kårmån vortex street as illustrated in Fig. 2. But this solution is also semi-emperical in that one parameter, namely the vortex transfer fraction ϵ has to be determined from experiments. This parameter represents the fraction of the vorticity, shed from the separation points, which enters the vortex street. The rate of flow of vorticity in one shear layer may be found (Ref. 3,4) to be.

$$\frac{d\Gamma}{dt} = \frac{U_1^2 - U_2^2}{2}, \qquad (6)$$

where:

U_2 = velocity on the outside of the free shear layer,

U_1 = velocity on the inside of the free shear layer.

The rate of flow of vorticity in one half of the von Kårmån vortex street is simply

$$\frac{d\Gamma_s}{dt} = N \cdot \Gamma_s \qquad (7)$$

The vortex transfer fraction is therefore

$$\epsilon = \frac{d\Gamma_s}{dt} \Big/ \frac{d\Gamma}{dt} = \frac{2N \cdot \Gamma_s}{U_1^2 - U_2^2} \qquad (8)$$

Using experimentally determined values of ϵ by Fage and Johansen (Ref. 8), Roshko (Ref. 7) was able to compute fairly accurate base pressures and base drags for certain body shapes.

The vortex transfer fraction ϵ in fact describes quantitatively the transformation of the free shear layers into concentrated vortices and the cancellation of part of the vorticity shed from the separation points by dissipative action in the near wake. It is especially processes like

- entrainment in the shear layers and vortices
- mixing and rolling up of the shear layers,
- dissipation in the near wake

which determine the character of the flow, but which are still very little understood.

Since then, some light has been shed on the problem. It was demonstrated in 1962 by Abernathy and Kronauer (Ref. 9) that two vortex layers which are free to interact are unstable and break down into concentrated vortices. Hence steady reversed flow bubbles behind bluff bodies cannot exist in the presence of disturbances as created by turbulent free shear layers - turbulent wakes are inherently unstable - but may exist in the case of almost disturbance free laminar shear layers (extremely low Reynolds numbers). The mechanics of the formation of eddies for relatively high Reynolds numbers was discussed by Gerrard in 1966 (Ref. 10). He suggested that two characteristic lengths in the near wake determine the structure of the vortex street.

(a) The scale of the formation region L_f, measured as the horizontal distance between the separation points and the point where irrotational fluid is first drawn across the wake axis

(b) The width to which the shear layers diffuse before they come together L_d.

These two lengths determine respectively the frequency of shedding and the strength of the vortices. Fig. 3 shows a schematic of the formation process according to Gerrard. The free shearlayer I begins to roll up. The other shearlayer and some irrotational fluid which is gradually entrained in the formation process starts to be drawn into the formation region by the forming vortex I. This fluid is distributed into the directions a, b and c. Part a is entrained by the vortex I, part b by the shearlayer I while part c enters the formation region. As soon as the shearlayers - bearing vorticity of opposite sign - come together, less circulation from the shearlayer I enters vortex I. Finally it is cut-off from shearlayer I and vortex I is shed from the body. Vortex II is then beginning to form. Roshko (Ref. 7.) defined the universal Strouhal number (non-dimensional frequency) as

$$S = \frac{N \cdot d}{U_{sep}} \qquad (9)$$

where $$U_{sep} = U_\infty \sqrt{1-C_{P_{sep}}} \qquad (9^a)$$

and U_{sep} = velocity in the free stream at the separation point

C_{Psep} = pressure at separation point.