THE UNIVERSITY OF MANITOBA

A MASS FLOWMETER FOR PARTICULATE SOLIDS

by

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A Thesis

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IN THE NAME OF ALMIGHTY GOD,

THE MAGNIFICENT, THE MERCIFUL.

ABSTRACT

This research was conducted as a second phase of investigations of capabilities and limitations of microwave Doppler radar as a flow monitor for particulate solids. Experiments were performed to extract information from the Doppler signal about the average bulk density of particulate solids, an important parameter in monitoring the mass flow rate. Different flow fields were employed including the circular and ring cross-section flow fields to study the effect of the distribution of solid material in the flow field. Monostatic free space configuration was used throughout the experiments.

Two different Doppler signal processing systems, namely, an analog (on line), and a digital (off line), were used to determine the RMS values of the Doppler signals and hence radar cross-sections of columns of wheat, moving through a plastic pipe. A commerically available tape recorder was used for recording Doppler signals from the bulk flow of granular materials and metallic calibrating spheres. The recorded data were subsequently processed by a digital computer. Radar cross-sections of various metallic calibrating spheres were determined theoretically as well as experimentally and used for calibration of the radar system. A computer program was developed for analysis of Doppler signals.

The relationship between the average bulk density of the column of wheat moving continuously through a pipe and RMS values of Doppler signals and hence their radar cross-sections was developed and verified experimentally. Experimental results of radar cross-section as a function of the average bulk density of wheat are presented.

As a result of this research it was concluded that a Doppler radar, used as a flow monitor, has an excellent capability for monitoring the flow rate of particulate solids without disturbing the monitored system. When the cross-section area of the flow field is known, this flowmeter can be used to monitor the mass flow rate of particulate solids continuously with good accuracy and without causing any obstruction in the flow field.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

A_{av}	Average cross-sectional area of the flow field
A_e	Equivalent antenna aperture
A_{RMS}	RMS value of the Doppler signal scattered by a target
$A_{o_{RMS}}$	RMS value of the Doppler signal scattered by a calibrating sphere
D	Kernel density of a single particle
D_{av}	Average bulk density
E_i	Magnitude of the incident electric field
E_r	Magnitude of the reflected electric field
F	Shape factor
$\|K\|^2$	A factor which depends upon the electromagnetic properties of the flow field
L	Elongation factor
L_a	Length of the flow field in the direction of antenna beam
M	Moisture content
M_{av}	Average mass flow rate
N	Number of particles
N_s	Number of samples
P_r	Power received
P_t	Power transmitted
P_{ro}	Power scattered by a calibrating sphere
R	Radar range
$S_x(f)$	Frequency content of a time varying signal
T	Time period of flow
T_1	Temperature
T_w	Time window
U	Velocity component

V	Volume of the target
V_{av}	Average velocity of the flow field
W_R	Uncertainty in the result
W	Weight of the material
$W_{D_{av}}$	Uncertainty in the average bulk density
$X(t)$	Time dependent signal
a	Correction factor
a_o	Radius of the sphere
c	Velocity of propagation of electromagnetic waves
c_o	Velocity of sound waves in the fluid
d	Diameter of a single particle
e	A factor defining the third axis of a spheroid
f	Value of data points
f_o	Frequency of transmission
f_d	Doppler frequency
f_{di}	Instantaneous Doppler frequency
h	Altitude of right circular cone
n	Constant time interval between consecutive data points
v	Velocity of the target
w_1	Uncertainty in the weight of material
w_2	Uncertainty in the time period of flow
w_3	Uncertainty in measurement of velocity
w_4	Uncertainty in measurement of cross-sectional area of the flow field
x_1, x_{n-1}, x_n	Independent variables

Δf_d	Bandwidth of the Doppler frequency spectrum
$\Delta\theta_2$	Two way 3dB antenna beamwidth
Δt	Time interval between samples
$\Delta\omega$	Difference between the transmitted and the received angular frequencies
Δd	Error in measurement of the diameter of sphere
α	Angle between the transmitting beam and the direction of the velocity vector
β	Angle between the receiving beam and the direction of the velocity vector
ε'	Dielectric constant
ε''	Loss factor
θ	Viewing angle
λ	Free space wavelength
σ	Backscattering radar cross-section of the target
σ_{av}	Average radar cross-section of the target
σ_o	Radar cross-section of the calibrating sphere
δ_{f_d}	Standard deviation of the instantaneous Doppler frequency
ω	Angular frequency of the scattered sound wave
ω_o	Angular frequency of the incident sound wave
RCS	Radar cross-section
RMS	Root mean square value

CHAPTER I

INTRODUCTION

The subject of flow metering of particulate solids dates back a few decades. Several efforts have been made in the past to design and develop practical flowmeters for monitoring the mass flow rate of granular materials. However, none of the flowmeters developed so far, proved to be suitable for applications, which require an inexpensive and accurate flowmeter for measuring the mass flow rate of particulate solids. With the advancement in agricultural technology, and other areas of engineering, there has been an increasing need for some means of measuring flow rates of particulate solids. From harvesting of grain to the point of consumption, a flowmeter may potentially play an important role in enabling the Government authorities to obtain more accurate and earlier estimates of national yield, which would be helpful in planning and have a settling effect on the new cereal market. The information obtained would also be helpful to individual farmers who could compare their yields arising from different grain varieties, fertilizer applications, cultivations techniques etc., and could plan their future contracts more accurately. Flowmeters are also needed to weigh grain as it is loaded onto trucks or ships or delivered into grain driers. In sugar, fertilizer, cement, paper and other chemical industries there has been a growing need for a measuring device for solid materials, because of the fact that the quality of the final product and the performance of the plant depend to a large extent upon precise measurements.

Several flowmeters, based on various principles of operation, have been developed in the past. By far, continuous weighing is one of the most commonly utilized methods of measuring the flow rates of particulate solids. The principle of change of angular momentum of the measured material has also been utilized by different authors to monitor the mass flow rate of granular materials. A spiral vane flowmeter, for measuring the volumetric flow rate of particulate solids moving through vertical ducts, is another reported device. Optical methods for detecting and measuring the volumetric flow rates of powders have been practised in the past. Nucleonic methods for monitoring the mass flow rate of granular solids, is another contribution towards the solution of this problem. Recently, laser anemometers and ultrasonic flowmeters have been introduced for measuring the velocity of flow fields, without introducing any mechanical probe into the flow field. The microwave Doppler flowmeter technique for particulate solids was first suggested by Ellerbruch and Parker. Harris made some qualitative studies on applications of this technique to the flow metering of particulate solids. The first quantitative studies of this technique were made by Hamid to monitor velocity of granular materials falling freely under gravity. The detailed review of the subject is presented in Chapter II.

During the last few years, the increasing demand for more accurate solid flow measurements has exceeded the capability of the existing flowmeters for particulate solids. None of the existing flowmeters, however, is suitable for the applications, which require a compact, inexpensive device to measure a high flow rate continuously, and without causing any obstruction in the conveying system.

The aim of this work was to investigate further capabilities and limitations of the Doppler radar flowmeter for continuous and contactless measurements of particulate solids. The particular objective of this work was to analyse the Doppler signal and to retrieve useful information about the average bulk density of the granular materials moving through a pipe. When the cross-sectional area of flow is known, the average mass flow rate can be determined easily by multiplying the average bulk density by the average bulk velocity and by the cross-section area of the flow field.

CHAPTER II

REVIEW OF LITERATURE

Monitoring mass flow rate of particulate solids with high accuracy has been a major problem in many areas of engineering. The complete solution awaits mainly the development of an accurate mass flowmeter, which is by no means a trivial task. A brief review is given here indicating the basic problems in monitoring the mass flow rate of granular materials and some of the contributions made in its solution. The capabilities and limitations of microwave Doppler flow monitor and other noncontact flow measuring systems, for example, ultrasonic flowmeters and laser anemometers are discussed in some detail.

Although the basic principles used for monitoring the mass flow rate of fluids apply equally well to granular materials, typical sensors usually obstruct the flow of the material, change the flow pattern, assist the formation of blockages and therefore limit practical use of the modified forms of fluid flowmeters for granular materials. The relatively high resistance to shear forces of granular material compared to that of fluids further explains the lag of flow measurement techniques for granular materials. However, a few devices and techniques exist to measure the flow rate of particulate solids. None of the existing flowmeters is suitable for applications which require a compact, inexpensive and noncontact device for measurements at high flow rates in difficult, hostile environments and inaccessible situations.

Flowmeters based on the principle of weighing the material continuously are the most common devices for monitoring the mass flow rate of granular and powdered materials. The material passing a fixed point on a conveyor belt or through a hopper can be weighed. (Beck _et al_., 1969).

Early methods of weighing on a conveyor belt contained a pivoted arm restored to the equilibrium position by weights. The restoring force was thus proportional to the weight of material on the belt. (Kirwan and Demler, 1955). Modern instruments employ load cells to measure the weight of the material on the belt, and a tachometer generator to measure the speed of the belt. (Valenti, 1961 and Craven, 1964). Continuous weighing is an accurate method of measuring solid flow rates on a belt conveyor. As these flowmeters contain moving parts, a fair amount of care is required to maintain the required accuracy. These methods are not in general suitable for pneumatic conveyors.

The principle of momentum change of the measured material has also been used in the past to measure the mass flow rate of particulate solids. A flowmeter working on this principle has been developed and reported. (Dean, 1955). The meter incorporates an inclined plate attached to a rigid beam, pivoted about a point near its centre. The material falls onto the inclined plate and the moment is measured by a force balance unit. If the velocity of the material is constant, the force on the plate is proportional to the mass flow rate. This device, however, can only be used for dense materials, falling freely under gravity. Moreover, it can cause obstruction in the conveying system. Recently, a combine harvester discharge meter employing the same principle has been developed in NIAE, Silsoe. (Hooper et al., 1973). The meter incorporates an impact plate in the form of a funnel through which the grain falls, and the force exerted on the funnel is a measure of the flow rate of grain. The meter gave good results for wheat and rather poor results for barley. The poor results for barley may be due to formation of blockages in the conveying system because freshly harvested barley is usually not clean and may contain roughages. This