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Research Article

Measurement and control systems for an imaging electromagnetic flow metre

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ABSTRACT

Electromagnetic flow metres based on the principles of Faraday's laws of induction have been used successfully in many industries. The conventional electromagnetic flow metre can measure the mean liquid velocity in axisymmetric single phase flows. However, in order to achieve velocity profile measurements in single phase flows with non-uniform velocity profiles, a novel imaging electromagnetic flow metre (IEF) has been developed which is described in this paper. The novel electromagnetic flow metre which is based on the 'weight value' theory to reconstruct velocity profiles is interfaced with a 'Microrobotics VM1' microcontroller as a stand-alone unit. The work undertaken in the paper demonstrates that an imaging electromagnetic flow metre for liquid velocity profile measurement is an instrument that is highly suited for control via a microcontroller.

1. Introduction

Electromagnetic flow metres have been used for several decades, with the basic principles being derived from Faraday's laws of induction. Conventional 2-electrode electromagnetic flow metres (EMFMs) have been used successfully in a variety of industries for measuring volumetric flow rates of conducting fluids in single phase pipe flows. At present, a conventional 2-electrode EMFM can measure the volumetric flow rate of a single phase flow with relatively high accuracy (about $\pm 0.25\%$ of reading) provided that the velocity profile is axisymmetric [1]. However highly non-uniform velocity profiles are often encountered, e.g. just downstream of partially open valves. The axial flow velocity just downstream of a gate valve varies principally in the direction of the valve stem, with the maximum velocities occurring behind the open part of the valve and the minimum velocities behind the closed part of the valve. In such non-uniform velocity profiles the accuracy of the conventional EMFM can be seriously affected [2,3]. One method for improving the accuracy of the volumetric flow rate estimate is to measure the axial velocity profile with the 'Imaging Electromagnetic Flow metering' (IEF) technique described in this paper and then to use this profile to determine the mean flow velocity in the cross-section. Previous researchers e.g. [4–7] have proposed techniques to obtain velocity profiles in the flow cross-section but few practical devices have emerged. In view of the above, the main objective of this paper is to describe a new non-intrusive electromagnetic flow metering technique for measuring the axial velocity profile of single phase flows of conducting fluids. In Section 3 of this paper the mechanical and electrical designs of an IEF device are described, as well as the relevant signal detection and processing methods.

In Section 4 of the paper, a microcontroller is introduced as the processing core of the IEF to achieve the functions of driving the magnetic field, acquiring voltage data from the electrode array, matrix inversion to calculate the velocity profile and data display.

Section 5 presents experimental results of local axial velocity distributions obtained from the IEF device under a variety of different flow conditions and includes comparisons with reference local axial velocity measurements obtained from a Pitot-static tube.

2. Background theory

An alternative approach to accurate volumetric flow rate measurement in highly non-uniform single phase flows was proposed by authors such as Horner [8] who described a six electrode electromagnetic flow metre which is insensitive to the flow velocity profile. However, this type of flow metre cannot provide information on the local axial velocity distribution in the flow cross-section unlike the IEF device presented in this paper.

The essential theory of EMFMs states that charged particles in a conducting material which move in a magnetic field experience a Lorentz force acting in a direction perpendicular to both the

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material's motion and the applied magnetic field. Williams [9] applied a uniform transverse magnetic field perpendicular to the line joining the electrodes and the fluid motion and his experiments revealed that for a uniform velocity profile the flow rate is directly proportional to the voltage measured between the two electrodes. Subsequently Shercliff [10] showed that the local current density **j** in the fluid is governed by Ohm's law in the form

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \tag{1}$$

where σ is the local fluid conductivity, **v** is the local fluid velocity, and **B** is the local magnetic flux density. The expression $(\mathbf{v} \times \mathbf{B})$ represents the local electric field induced by the fluid motion, whereas **E** is the electric field due to charges distributed in and around the fluid. For fluids where the conductivity is constant (such as the single phase flows under consideration in this paper) Shercliff [10] simplified Eq. (1) to show that the distribution of the electrical potential ϕ in the flow cross-section can be obtained by solving

$$\nabla^2 \phi = \nabla(\mathbf{v} \times \mathbf{B}) \tag{2}$$

For a circular cross-section flow channel bounded by a number of electrodes, with a uniform magnetic field of flux density B normal to the axial flow direction, it can be shown with reference to [10] that, in a steady flow, a solution to Eq. (2) which gives the potential difference U_j between the jth pair of electrodes is of the form

$$U_j = \frac{2B}{\pi a} \iint v(x,y) W(x,y)_j dx\, dy \tag{3}$$

where $v(x,y)$ is the steady local axial flow velocity at the point (x,y) in the flow cross-section, $W(x,y)_j$ is a so-called 'weight value' relating the contribution of $v(x,y)$ to U_j and a is the internal radius of the flow channel. Let us now assume that the flow cross-section is divided into N large regions (Fig. 1(c)) and that the axial flow velocity in the ith such region is constant and equal to v_i (i.e. for a given region the axial flow velocity does not vary within that region). Let us further suppose that N potential difference measurements U_j are made between independent pairs of electrodes on the boundary. From these assumptions, and by discretising Eq. (3), the following relationship is obtained between the jth potential difference measurement U_j and the ith steady axial velocity v_i.

$$U_j = \frac{2B}{\pi a} \sum_{i=1}^{N} v_i w_{ij} A_i \tag{4}$$

Here A_i represents the cross-sectional area of the ith region and the term w_{ij} is the weight value which relates the steady flow velocity in the ith region to the jth potential difference measurement. Provided that the required N^2 weight values are known [11] Eq. (4) can be manipulated to enable the steady axial flow velocity v_i in each of the N regions to be determined from the N potential difference measurements U_j ($j = 1$ to N) made on the boundary of the flow cross-section. This process for calculating the velocity in each of the regions can be expressed by the matrix equation

$$\mathbf{V} = \frac{\pi a}{2B} [\mathbf{WA}]^{-1} \mathbf{U} \tag{5}$$

where **V** is an $N \times 1$ matrix containing the required velocities, **W** is an $N \times N$ matrix containing the weight values w_{ij}, **A** is a diagonal matrix containing the cross-sectional areas of the regions and **U** is an $N \times 1$ matrix containing the N boundary potential difference measurements. Since many pipe flows are turbulent the question now arises as to what is meant by a 'steady' axial velocity v_i in a given region in turbulent flow. Texts on fluid mechanics e.g. [12] state that in a turbulent flow, when the velocity over a given 'averaging' time remains constant, the flow is termed steady. For the flows relevant to the present investigation this averaging time is approximately 7 s (see Sections 3.4 and 4.2). Consequently, when using the techniques described in this paper the measured potential differences U_j must be averaged over at least this time period in order for repeatable velocities v_i to be obtained from one averaging period to the next. Note that Eq. (4) is strictly only valid if the steady local velocity in each of the N large regions is the same everywhere in a given region. However results presented in [11] show

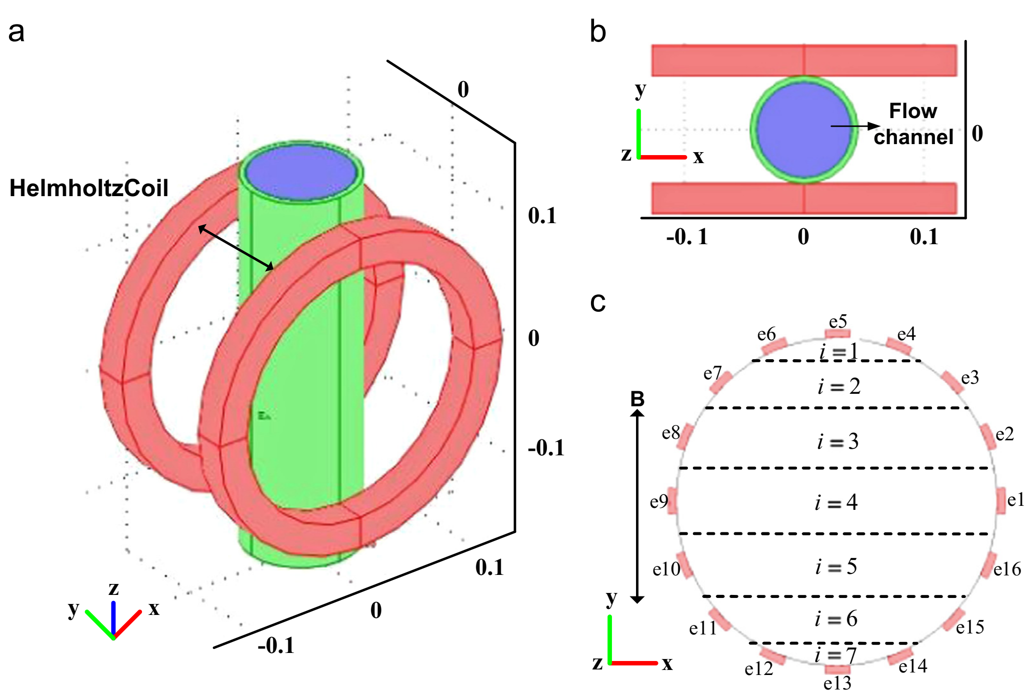

Fig. 1. Model of Finite Element Simulation. (a) 3D model, (b) view on x–y plane and (c) schematic diagram of the flow regions, index i denotes region number (the seven regions and the boundary electrodes denoted as e1–e16).