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Coil shape optimization of the electromagnetic flowmeter for different flow profiles

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ABSTRACT

The precision of the electromagnetic flowmeter (EMF) suffers from the impact of the flow profiles. The typical idea is to construct an ideal magnetic field, in order to make the sensitivity of measurement area to be a constant. In the case of the ideal magnetic field, the potential difference between the two picking-up electrodes is linearly related to the mean velocity of the flow in the pipe, i.e. the flow rate. The necessary and sufficient conditions for the ideal magnetic field in the electromagnetic flowmeters were established in the paper. The EMF with ideal magnetic field is immune to the impact of the profiles. However, in the case of typical electrode configurations, e.g. point electrodes, the ideal magnetic field does not exist. As the alternative to the ideal magnetic field, the excitation coils were optimized to minimize the non-uniform of the sensitivity distribution in the measurement area. Numerical simulations were used to optimize the excitation coils in three dimensional cases. Two parameters of the excitation coils were optimized. Phantoms of the EMF with optimized excitation coils were constructed. Experimental results validated the performance the optimized excitation coils. Compared with the EMFs with commercially available coils, the EMF with optimum excitation coils was less sensitive to the flow profiles, especially in the cases of flows nearby a U-shaped pipe.

1. Introduction

As one of the most commonly used flowmeters in various industrial applications, the electromagnetic flowmeters (EMF) usually possess a high precision and cause no pressure loss. Based on the Faraday's Law, the EMFs usually use two picking up electrodes to measure the variations of induced electrical potentials, which are generated by the moving electrical conductive fluid in the magnetic field [1,2]. For its high precision and absence of no moving part, EMF appears extensively in the water system as well as food, pharmaceutical and other process industries. EMFs can be classified into several categories, e.g. circular pipe EMF and rectangular pipe EMF in terms of the shape of pipe cross-section, small diameter EMF ($D < 50$ mm, here, D refers to the diameter), median diameter EMF (65 mm $< D <$ 250 mm) and large diameter EMF ($D > 300$ mm) in terms of the diameters of the measured pipes [3]. In typical industrial applications, the EMFs are of circular cross-sections. In the EMF, two excitation coils are positioned around the pipe to generate a magnetic field, as shown in Fig. 1. Two picking-up electrodes are located at the two ends of the diameter of the cross-section of the interior pipe wall, so that the flow-induced voltage can be detected.

The Faraday's Law indicates that the measured electrical potential difference is determined by both the electrode configuration and magnetic flux distribution in the measured area. In the ideal case, the potential difference is expected to be linearly related to the average velocity of the measured flow, i.e. the flow rate of the flow. Usually, the flow rate can be considered to be immune to the velocity profile of the flow, especially when the flow has been fully developed. In this case, the velocity can be considered to be axisymmetrically distributed, and the EMF with uniform magnetic distribution can yield a high precision result of the volumetric flow rate in a single phase flow with an error within 0.5%. However, the fully developed flow requires a long straight pipe, usually of five to ten times of the pipe diameter, installed before the EMF. As a result, an increase in the installation difficulties and costs is necessary. Moreover, in the industrial applications, valves and elbows are frequently used in the flow system, and the practical flow condition becomes extremely complicated and hard to predict. Typically, asymmetrically distributed flow profiles occurs both in the downstream and upstream of these devices [4]. For EMF of small diameter, the length of straight pipe can be more easily satisfied compared with those of extremely large diameter, e.g. several meters, which often appears in hydraulic engineering. For example, the South-to-North water diversion project in China uses many large diameter pipes, in order to redistribute

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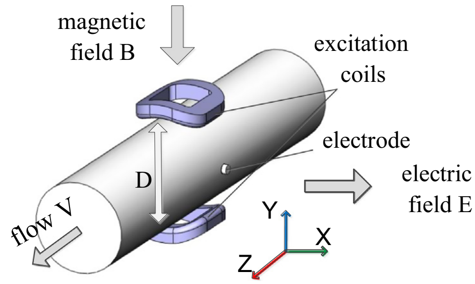

Fig. 1. The principle of conventional EMF.

water resources among different regions of the country. In this case (not limited to), requirement of long straight pipe becomes unrealistic, and the flow velocity distribution can hardly be guaranteed to be axisymmetrical, and consequently results in an unpredicted measurement error. As a result, the EMF is required to be immune to the flow velocity distribution. In the past few decades, great efforts have been made to develop the flow-profile-insensitive EMFs [5–10]. Usually, the problem was handled either by modifying the weight function distribution or designing the magnetic field distribution. When the magnetic field is fixed, e.g. a uniform magnetic field, the weight function only depends on the electrodes and the structure of pipe. In this case, geometric parameters of the electrodes were selected to be optimized, especially in an EMF with multi-electrodes. The multi-electrode EMF is insensitive to the flow profile by using a number of point electrodes, usually more than eight electrodes, which results in at expense of more complexity in both manufacturing and signal processing. Large size electrodes can also be used to reduce the impact of flow profiles [11]. However, the inevitable contamination of the electrodes distorts the measurement precision. Insulated electrode of large surface area can be used to avoid the contamination. The insulated electrodes and a quasi-uniform magnetic field can be used together to reduce the distortion caused by the velocity distribution of the flowing liquid [12], whereas the complexity of the processing circuit is increased to pick up the weak signal introduced by the insulated electrodes.

When the configuration of the electrodes is predetermined for facilitation of industrial production, the excitation coil was typically modified to generate an expected magnetic field distribution. Several possible excitation coil shapes have been proposed for the EMF with point electrodes, especially to deal with rectilinear distorted flow profiles [13]. An optimum excitation coil for open channel EMF was reported to be independent on the water level [14]. It was restricted to the case of a rectangular pipe, long electrodes and uniformly distributed magnetic field. However, for the commonly used EMF, a pair of point electrodes, two excitation coils and a circular insulated pipe were typically used. The excitation coils were usually of a saddle-shape, because they could improve the performance of the flowmeter by rending it less sensitive to asymmetric velocity profiles [15].

In the paper, the sufficient and necessary conditions for the ideal magnetic field and the weight function were established. For the facilitation of industrial production, the excitation coil of a saddle-shape was optimized to decrease the impact of the flow profiles.

2. Fundamentals

According to Ohm' Law, the current flow in the conductive fluid can be expressed as

$$\vec{j} = \sigma(\vec{E} + \vec{V} \times \vec{B}) \tag{1}$$

where $\vec{j}$ denotes the current density vector, σ the fluid conductivity, $\vec{E}$ the electric field vector under the stationary conditions, $\vec{V}$ the flow velocity vector, $\vec{B}$ the magnetic flux density vector, respectively. The term $\vec{V} \times \vec{B}$ represents the induced voltage generated by the fluid motion [13].

When the EMFs were applied to measure the flow rate of a single phase flow in a pipe, the applied external magnetic field is usually treated to be static, the permeability and the conductivity of the flow are considered to be homogenous, and both the displacement current and the Hall Effect can be ignored. As a result, according to the Maxwell's Equation and Ohm' Law shown in Eq. (1), the governing equation of the EMF is derived as follows [1],

$$\nabla^2 U = \nabla(\vec{V} \times \vec{B}) \tag{2}$$

where, U denotes the electric potential distribution within the insulated pipe. However, the differential equation is solved analytically with proper boundary conditions only in some simplified cases such as uniformly distributed magnetic field or velocity. The analytic solution becomes extremely difficult to obtain when the condition is more complicated [16].

The induced voltage can be calculated by utilizing the Green's Formula [13] and the introduction of the "virtual current"[17]. In the case of stationary fluid and the absence of the magnetic field, the virtual current was generated by passing unit DC current into one electrode and extracting it from the other. The virtual current describes the contribution of each part of moving fluid to voltage collected between two point electrodes [18], namely,

$$\Delta U = \int_{\Omega} [(\vec{B} \times \vec{j_v})\vec{V}]\mathrm{d}\Omega \tag{3}$$

where Ω indicates the integration volume, $\vec{j_v}$ the "virtual current", ΔU the induced voltage picked up between two point electrodes. In real applications, both laminar and turbulent flows can be assumed to be rectilinear, namely, only the velocity component in the direction along the pipe axis appears in the measurement. Eq. (3) can be rewritten as

$$\begin{aligned}\Delta U &= \iiint (\vec{B} \times \vec{j_v})_z V_z dxdydz \\ &= \iiint [B_x (j_v)_y - B_y (j_v)_x] V_z dxdydz\end{aligned} \tag{4}$$

Here, the magnetic flux density vector $\vec{B}$ and the virtual current vector $\vec{j_v}$ are depicted in the form of its x- and y- components, respectively. The virtual current $\vec{j_v}$ is also denoted as the weight function w, i.e. $w = \vec{j_v}$. Eq. (4) underpins the following result, i.e.

$$\Delta U = \iiint (B_x w_y - B_y w_x) V_z dxdydz \tag{5}$$

where w_x and w_y refer to the x- and y- component of the weight function[19].

On the cross-section where the electrodes are located (the cross-section is defined as the electrode plane for writing convenience), the z-components of both the magnetic field and the weight function vanishes. If the EMF is immune to the flow profile, the item in the integration in Eq. (5) should satisfy,

$$B_x w_y - B_y w_x = c \tag{6}$$

Here, c represents a constant.

In the case of the electromagnetic flowmeter, the magnetic field can be considered as DC magnetic field, while the free current density is zero. It means that

$$\nabla \times B = 0 \tag{7}$$

Moreover, the magnetic flux B also satisfies

$$\nabla B = 0 \tag{8}$$