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Electromagnetic flow meters for open channels: Current state and development prospects

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ABSTRACT

Electromagnetic method to measure water flow has been known for nearly 180 years. This paper presents how the method has undergone development and describes in detail the most common electromagnetic flowmeters used for open channels. It also presents specific methods of signal processing used in this type of flowmeters. The analysis is associated directly with the relevant types of induced magnetic field. Some of the analyzed types of magnetic fields considered are sine waves and bipolar rectangular fields. The concept of low-energy electromagnetic flow meter was introduced as part of deliberations concerning current development trends.

1. Introduction

Electromagnetic flowmeters have been researched and subject of analysis for over 180 years. Their indisputable advantages earned them a permanent place on the flow measurement market, even though competitive methods achieve comparable performance. In the area of closed and open measurement channels, the main competitor of the electromagnetic flowmeter is an ultrasonic flowmeter, which in many aspects has comparable properties, especially with regards to measurements taken in pipelines. Since introduction of the Doppler profile gauge, the ultrasonic method of measurements in open channels has become a serious alternative to electromagnetic methods. By giving an overview of different solutions, this paper attempts to systematize and structure the knowledge concerning application of electromagnetic flow measurement method in open flow channels.

2. Mathematical model of electromagnetic flow meter

Faraday's law is the principle behind electromagnetic flow meters. It associates electric potential φ induced in the measurement zone with both liquid velocity vector, $\vec{\vartheta}$ and magnetic flux density, $\vec{\mathbf{B}}$ (Fig. 2.1).

Some of the electric and magnetic properties of the environment need to be assumed in order to describe how an electromagnetic flowmeter operates [1]. Those assumptions are as follows:

- Flowing liquid is characterized by magnetic permeability $\mu=\mu_0$.
- Water conductivity, γ_w, and conductivity of channel bed, γ_g, are isotropic and they are not functions of magnetic field and water velocity. The Hall effect is excluded.
- The type of flow and applied field excludes self-induction.
- Velocity vector of a liquid, $\vec{\vartheta}$ has only one component (rectilinear flow) in the area of magnetic field e.g. ϑ_y and $\partial\vartheta_y/\partial_y=0$.

Analysis of distribution of magnetic field can be then limited to the stationary state because its commutation frequency is low. All assumptions were taken to simplify the analysis and do not affect practical application of electromagnetic methods. Shercliff [2] had described the basic equation in his electromagnetic flowmeter theory,

$$\mathrm{div}(\gamma \mathrm{grad}\varphi) = \mathrm{div}\gamma\left(\vec{\vartheta} \times \vec{\mathbf{B}}\right), \tag{2.1}$$

where γ is electric conductivity.

Voltage, U_e, induced between two electrodes e_1 and e_2 of the flowmeter, (Fig. 2.1) is given by

$$U_e = \varphi_{e_1} - \varphi_{e_2} = \int_V \vec{\vartheta} \times \left(\vec{\boldsymbol{B}} \times \vec{\boldsymbol{J}}\right) dv, \tag{2.2}$$

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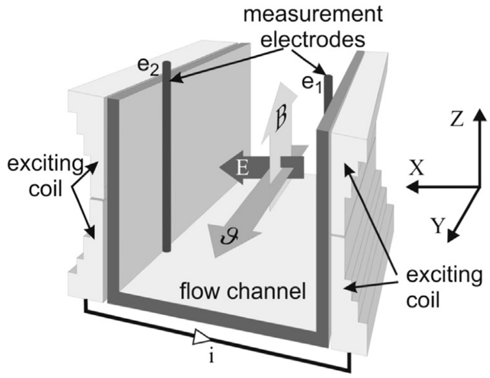

Fig. 2.1. The idea of the electromagnetic flow measurement method in open flow channel.

where V denotes the volume of measurement zone, $\vec{J}$ denotes a virtual density current vector, and φ_e denotes electric potential of an electrode.

Here $\vec{J}$ is a "virtual current" i.e. current density set up in the liquid by driving an imaginary, unit current into electrode 1 and out of electrode 2. Bevir [3] named $\vec{J}$ the "virtual current" in order to distinguish it from currents existing in working flowmeters. The magnitude and distribution of virtual current $\vec{J}$ depends on geometry of flow channel, the shape of electrodes, and conductivity of the liquid and channel walls. If the excitation coil of the flowmeter generates a field such that

$$rot\left(\vec{B} \times \vec{J}\right) = rot\left(\vec{W}\right) = 0, \tag{2.3}$$

where $\vec{W} = \vec{B} \times \vec{J}$ is known as the weight vector [3] over the entire domain V, then the voltage between electrodes is proportional to mean velocity of unspecified flow $\vec{\vartheta}_m$. This kind of flowmeter is considered as "ideal".

The final potential difference (U_e), using weight vector ($\vec{W}$), which is perceived as an extension of Shercliff's weight function [2], is expressed as follows:

$$U_e = \int_V \vec{W} \times \vec{\vartheta}\, dv \tag{2.4}$$

According to our assumptions, flow is rectilinear $\left(\vec{\vartheta} = [0,\ \vartheta_y(x, z), 0]\right)$ and vector $\vec{W}$ may be written as a scalar W. Then Eq. (2.2) may be reduced to (2.5)

$$U_e = \int_S \vartheta_y W(x, z) \mathrm{d}s. \tag{2.5}$$

here S is the cross-section of flow channel and $W(x, z)$ is the rectilinear weight function [34,35], given by

$$W(x, z) = \int_{-\infty}^{+\infty} W_y dy, \tag{2.6}$$

where

$$W_y(x, y, z) = B_Z J_X - B_X J_Z. \tag{2.7}$$

1. W_y is the component of W. $W(x,z)$ is a measure of the response to rectilinear flow at a given point (x, z) in cross section of the flow channel.
2. The condition for an "ideal" flowmeter (2.3) may be reduced to

$$W(x, z) = \int_{-\infty}^{+\infty} W_y dy = const.$$

In an ideal flowmeter, the measurement signal does not depend on water level in neither flow channel nor velocity vector distribution. An ideal flowmeter features a rectangular cross-section, insulating walls, long uniform magnetic field and two infinitely conducting long electrodes spanning two opposite walls [4]. This configuration of electrodes generates a uniform virtual current. Should magnetic flux density $\vec{\mathbf{B}}$ be uniform, the weight vector $\vec{\mathbf{W}}$ is also uniform and consequently the output signal (electrode potential) is independent on the shape of velocity profile. As shown in for instance [5], circular flow meters with point electrodes could not be ideal as long as velocity distribution is unspecified.

3. Historical overview

The very first attempts to measure water flow using the electromagnetic method had been carried out in the nineteenth century by Faraday, who tried to measure flow of the river Thames. Another attempt at flow measurement was made nearly 100 years later. In 1915, Smith and Slepian were granted a patent for an electromagnetic velocity meter used by vessels [6] and Young et al. [7] tried to measure flow of a river. The operating principle of a flowmeter is based on analysis of magnetic and electric fields carried out by Williams [8]. Kolin [9] was probably first to suggest use of such a system in measuring flow in closed channels. The result of efforts initiated in 1936 was a patent for an electromagnetic flowmeter granted in 1939. That system used a constant magnetic field generated by a permanent magnet or an electromagnet powered by direct current. One of the very first industrial flow meters was Tobiflux developed in the Netherlands. It uses a coil of special shape and an iron core to increase induction of magnetic circuit. This made it possible to reduce dimensions of exciting coil-based solutions and improve stability of metrological parameters of the flowmeter. A company named Foxboro filed in 1952 for a patent, where they proposed the use of air coils and a simplified generation of magnetic field. The first flowmeter based on this approach was used in 1954 and since then electromagnetic flowmeters technology has underwent steady development. The demand generated by the processing industry drove rapid development of electromagnetic flowmeters solutions. Flow measurement was a serious problem in the paper industry, due to the density of the medium. The solution came in form of an electromagnetic flowmeter which does not generate additional increase of hydraulic resistance in the system, ensures correct measurement of the flow of suspensions and is relatively resistant to environmental factors.

First attempts to apply the electromagnetic method to measure currents in rivers, as mentioned earlier were unsuccessful due to imperfections of measurement techniques. Between 1851 and 1918, Young and Gerrard [7] made further attempts after Faraday's work in the English Channel. That point on, there are no studies that would prove advancement of methods for electromagnetic flow measurement in rivers. Thurlemann [10] mentioned in his analysis of a rectangular flowmeter that potentially it could be used in measuring flow of rivers. Development of modern electronics (during the 60s) sparked a renewed interest in this method. In 1967, Engel published his paper [11] where he described how to use electromagnetic method of flow measurement in open channels. Engel in his deliberations considered a channel with a rectangular cross section and placed electrodes on opposite banks of the channel. He established a uniform magnetic field over the entire area where measurements were taken. In order to measure flow, both the velocity and water level had to be measured. Engel proposed a measurement method utilizing an interesting relationship between amplitude of the voltage induced in the conductor loop and a water level. The loop consists of a liquid and electrodes. In 1970, Gils in [12] introduced an electromagnetic flow meter system installed in a drainage channel in Bad Rehburg (Germany). Characteristic feature of the system was the use of cross- coil system to excite an artificial magnetic field. Hence a variable magnetic field could be generated in two perpendicular directions,