The Study of Conductive Inner Lining of the Electromagnetic Flowmeter (EMF) on the Output

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Abstract. The lining of traditional electromagnetic flow sensor is insulated. But this limits the use of electromagnetic flowmeter. This paper presents a new type of electromagnetic flowmeter, which can measure the conductivity of pipe wall. The circuit is designed to compensate the sensor output induced potential. The stability and reliability of the new electromagnetic flowmeter are verified in theory and experiment.

1. Introduction
Because of its reliability and stability, electromagnetic flowmeter (EMF) is widely used in industrial control process. Its obstruction-less structure and linear flow characteristics are of great advantage in this field. Shercliff’s [1] book on the EMFM given the basic theory. Zhang [2] gave the semi analytical solution of weight function of electromagnetic flowmeter. Baker [3] gave the 2D analysis method of electromagnetic flowmeter. Bevir [4] gives the concept of virtual current and analyzes the basic theory of electromagnetic flowmeter. Baker [5] developed the concept of virtual current and improved the calculation accuracy.

In some high temperature or corrosive applications, the insulation lining of electromagnetic flowmeter limits its use. But the insulation lining effectively prevents the short circuit of current and improves the accuracy of measurement. Some of the results of this paper are also suitable for the wear analysis of insulating lining.

This paper presents a new type of electromagnetic flowmeter. The insulation lining in the sensor is removed, the servo technology is adopted, the compensation circuit is designed, and the output signal reliability is improved.

2. Theory of EMFM with conductive Pipe Wall
2.1. Insulation pipe wall
The theory of traditional electromagnetic flowmeter proposed by shercliff [1], Baker [6] and Bevir [4] is summarized.

Maxwell’s equations for a flow conductor are given in the following form:

\[ \nabla \times \frac{B}{\mu \mu_0} = j \]  \hspace{1cm} (1)

\[ \nabla \times E = -\frac{\partial B}{\partial t} \]  \hspace{1cm} (2)

\[ \nabla \cdot B = 0 \]  \hspace{1cm} (3)

\[ j = \sigma(E + \nu \times B) \]  \hspace{1cm} (4)
In addition, the following two equations involving the flow and its acceleration are applicable
\[ \nabla \cdot \mathbf{v} = 0 \]  
(5)
\[ \rho \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla p + j \times \mathbf{B} + \mathbf{F} \]  
(6)
In the foregoing equations the MKS system has been used; magnetic flux density is \( \mathbf{B} \); \( \mu \) is magnetic permeability; \( \mu_0 \) is magnetic permeability of free space; virtual current density is \( j \); electric field is \( \mathbf{E} \); time is \( t \); \( \sigma \) is fluid electrical conductivity; \( \mathbf{v} \) is fluid density; \( \rho \) is fluid density; \( p \) is pressure; \( \mathbf{F} \) is frictional shear.
We shall apply Equations (1) to (6).
To find a useful solution to the foregoing equations, we take as starting point the following assumptions:
Steady conditions to that
\[ \frac{\partial}{\partial t} = 0 \]  
(7)
According to Equations (2) and (7)
\[ \nabla \times \mathbf{E} = 0 \quad \text{or} \quad \mathbf{E} = -\nabla U \]  
(8)
If, then, we eliminate \( j \) between Equation (1) and (4) by taking the curl of each, we obtain
\[ \nabla^2 \mathbf{B} = -\sigma \mu_0 \left\{ (\mathbf{BV}) \mathbf{v} - (\mathbf{vV}) \mathbf{B} \right\} \]  
(9)
The following components of \( \mathbf{B} \) are consistent with both Equations (10) and (9)
\( B_x = \text{const}; \)
Physically, it seems simpler to work with the electric potential \( U \). Therefore we take the divergence of Equation (7) and obtain
\[ \nabla^2 U = \nabla \cdot j \mathbf{B} \]  
(10)
Equation (10) is valid for any axially directed velocity distribution.
The boundary condition on the pipe wall is
\[ j_n = 0 \]  
(11)
2.2. Non-insulation pipe wall
Now, in fully developed turbulent flow the velocity distribution is axially symmetric, and this distribution we shall now assume.
If \( r \) and \( \theta \) are used to denote unite vectors in the \( r \) and \( \theta \) directions, respectively, we have,
\[ j = r \sin \theta + \theta \cos \theta \]  
(12)
And, from Equation (11), we have
\[ \nabla \cdot j \mathbf{B}_z = \frac{B_z}{r} \left[ \frac{\partial}{\partial r} \left( r v \sin \theta \right) + \frac{\partial}{\partial \theta} \left( v \cos \theta \right) \right] = B_z \frac{v}{r} \sin \theta \]  
(13)
then,
\[ \frac{\partial^2 U}{\partial r^2} + \frac{1}{r} \frac{\partial U}{\partial r} + \frac{1}{r^2} \frac{\partial^2 U}{\partial \theta^2} = B_z \frac{v}{r} \sin \theta \]  
(14)
As a particular solution for the potential field within the fluid, we try
\[ U_j = F(r) \sin \theta \]  
(15)
First we insert this solution in Equation (15) and then perform the integrations indicated
\[ F'(r) + \frac{F(r)}{r} = B_z \frac{v}{r} \]  
(16)
\[ F'(r) + \frac{F(r)}{r} = B_z \frac{v}{r} \]  
(17)
\[ F'(r) + \frac{F(r)}{r} = B_z \frac{v}{r} + K \]  
(18)
\[ [rF(r)] = B_z \frac{v}{r} r + Kr \]  
(19)
\[ rF(r) = B_z \int_0^r v(r) rdr + K \frac{r^2}{2} \]  
(20)
At \( r=R_i \) the fluid velocity is necessarily zero. Thus from Equation (21).We have
\[ F'(R_i) + \frac{F(R_i)}{R_i} = K \]  
(21)
Also, Equation (20) may be rewritten in terms of the mean volumetric velocity $\bar{v}$, to give

$$\frac{F(R_o)}{R_o} = B\bar{v} + \frac{K}{2}$$  \hspace{1cm} (22)$$

The integration constant $K$ can now be eliminated from Equations (21) and (22) to give

$$F(R_o) = B\bar{v}R_o + RF'(R_o)$$  \hspace{1cm} (23)$$

The boundary conditions to be applied at the interface between the fluid and the non-insulation pipe wall are as follows:

1. The continuity of the normal component of the current

$$\sigma_f(E_n)_f = \sigma_w(E_n)_w$$  \hspace{1cm} (24)$$

2. The continuity of the transverse component of the electric-field vector

$$(E_n)_f + \tau\sigma_f(E_n)_f = (E_n)_w$$  \hspace{1cm} (25)$$

Turning now to the electric potential within the pipe wall, we try the particular solution

$$U_w = G(r)\sin\theta$$  \hspace{1cm} (26)$$

Since this potential must satisfy Equation (19) with $v(r)=0$, we have

$$G'(r) + \frac{G(r)}{r} - \frac{G(r)}{r^2} = 0$$  \hspace{1cm} (27)$$

Now at $r=R_o$, the radial component of electric field vector must vanish. By manipulations similar to those performed earlier we easily deduce that

$$G(r) = \frac{G(R_o)}{2}(\frac{r}{R_o} + \frac{R_o}{r})$$  \hspace{1cm} (28)$$

We proceed next to match the fluid and wall solutions at the interface according to Equations (27) and (28). Equation (26) will be satisfied if

$$\sigma_f F'(R_o) = \sigma_w G(R_o)$$  \hspace{1cm} (29)$$

Equation (27) will be satisfied if

$$F(R_o) = G(R_o)$$  \hspace{1cm} (30)$$

Put $F(R_o)$ and $F'(R_o)$ in terms of $G(R_o)$ and $G'(R_o)$ in Equation (26), we obtain

$$\frac{G(R_o)}{2}(\frac{R_o}{R_w} + \frac{R_w}{R_o}) = B\bar{v}R_o + \frac{\sigma_w G(R_o)}{\sigma_f} \left(\frac{1}{R_o} - \frac{R_o}{R_w}\right)$$  \hspace{1cm} (31)$$

According to Equation (29) the maximum potential difference at the outside of the pipe wall will be

$$U = U_e\left(\frac{R_o}{R_w}, \pi/2\right) - U_e'\left(\frac{R_o}{R_w}, -\pi/2\right).$$

Therefore

$$U = 2B\bar{v}R_o\left[\frac{1+\sigma_f}{\sigma_f} + \frac{R_w^2 - R_0^2}{R(R_w^2 + R_0^2)}\right] = 2BvR_o\left[\frac{1+\sigma_f}{\sigma_f} + \frac{R_w^2 - R_0^2}{R(R_w^2 + R_0^2)}\right]$$  \hspace{1cm} (32)$$

Assuming a higher conductivity of the fluid from Equation (32):

1. The conductivity has a certain influence on the output signal of the sensor.
2. The output of the sensor is affected by the conductivity of the liquid.
3. The larger the radius of the sensor, the greater the effect of liquid conductivity on the sensor output.
4. The thicker the tube wall is, the greater the influence of the conductivity of the tube wall on the sensor output is.

3. **The transmitter**

Electric current electrodes (CE), feedback electrodes (FE), earthing electrodes (GE), signal electrodes (SE) and potential electrodes (PE) as shown in **Fig. 1.** Converter circuit is shown in **Fig. 2.**
The excitation current is constant amplitude current and low frequency (50 / 16Hz). The input impedance of the first stage amplifier should be high enough. Used to guarantee signal compensation. The conductivity of liquid is more than 5-10 μs / cm. The impedance between electrodes is estimated to be 500-1000k Ω. In order to make the load effect less than 0.01%, the input impedance should be greater than 1010 Ω. The voltage following circuit is used in the first stage amplifier.

**Figure 3** Servo amplifier. The servo amplifier needs high current gain.

**4. Experimental Results and Discussion**

**Figure 4** shows display the relationship between measured fluid flow and output voltage (liquid conductivity $\sigma_f = 163 \mu\text{S/cm}$). And temperature is 18°C, the exciting magnetic field distribution $B$ is
81e^{-4} T.

We can see form Fig. 4 that without applied wall potential, compared with the theoretical value, the output voltage decreases about 60%, but it can be increased to 99% of the theoretical value under the action of wall potential.

Figure 5 shows the effect of fluid conductivity $\sigma_f$ at constant flow rate. And temperature is 18°C, the exciting magnetic field distribution $B$ is 81e^{-4} T, mean flow velocity is 0.8 m/s.

5. Conclusions
The conclusions are as follows:
(1) By increasing the tube wall voltage of the electromagnetic flow sensor, the boundary conditions equivalent to the non-conductive tube wall can be obtained.
(2) By using the servo circuit, the equivalent boundary conditions of the metal pipe wall and the insulating pipe wall are realized.
(3) The experimental results verify the theoretical analysis.

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