flotek.g 2017-İnnovative Solutions in Flow Measurement and Control- Oil,Water and Gas¨
$August 28-30, 2017, FCRI, Palakkad, Kerala, India$

Modelling of Electromagnetic Flowmeter for Reduction of Eddy Current Effect

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***Abstract*—The electromagnetic flowmeter is a versatile, compact and a popular instrument widely used for accurate measurement of closed conduit flow measurement. It works on the principle of the electromagnetic induction due to flow of liquid in a magnetic field. Magnetic excitation is often established using ac mains (at 50/60 Hz) for convenience. But the introduction of an alternating magnetic field has the disadvantage of generating an alternating magnetic flux through the loop formed by the electrode leads and the conduction path. The alternating magnetic field also has the drawback of generating induced emf or currents(known as eddy current) in the metal parts of the meter. This current in turn produces its own magnetic field in the metal parts which opposes the original magnetic field rendering the mesurement of EMF or flow less accurate than it ought to be. The induced EMF and eddy current effect in the electromanetic flowmeter have been controlled by a two dimensional modelling apprach. An effort has been made in this paper to model the electromagnetic meter numerically to alleviate the effect of induced magnetic field. The modelled flowmeter has been validated in primary standard calibration rig at CWPRS to ascertain the accuracy of the proposed model.**

***Index Terms*—Electromagnetic flowmeter, Eddy Current, Induced EMF, Electro Motive Force, Electromagnetic Induction**

1. INTRODUCTION

The basic idea of the electromagnetic flowmeter for measureing fluid flow in pipes [**?**] is imposition of external magneticment field perpendicular to the pipe carrying fluid flow. If the fluid contains mobile electric charges these are displaced (with respect to the fluid) due to the Lorentz-force. The accumulated charges form a space charge density and an electric field is induced which prevents further charge separation. The electric potential or voltage(Figure.1) can be measured using galvanic or capacitive coupling. In ideal cases the measured voltage is proportional to the flow rate in the tube. This phenomena is called Magneto Hydro Dynamic (MHD) effect.

The modelling of induced EMF and eddy-current effects in electromagnetic flowmeters is not extensive as has been found in the litratures. Sanderson et.al [**?**] noted that the magnetic field inside a thin cylinder is different both in phase and magnitude from the external field.It was attributed due to the eddy currents [**?**]induced in the wall, which give rise to a secondary flux density inside the cylinder . But it does not take into account the reflection of the external field of the cylinder by the core nor does it take account of eddy currents in the core. Both of these effects are important as we will see in this paper.

Works by Xu and others [**?**] give an account of empirical modelling of the effects of induced EMFs and eddy currents (and effectively of hysteresis) under sine wave operation of an electromagnetic flowmeter(EM) . The in-phase and quadrature components of the electrode signal are measured for frequencies in the range 50-180 Hz, flow rates q in the range 0 to 2 l/s and magnet currents I in the range 7 to 35 mA. These measurements are used to calculate the coefficients in polynomial expansions of the signal components in the variables f and q (for a fixed magnet current) and in the variables I and q (for a fixed frequency). Thus empirical formulae for the in-phase and quadrature compo-

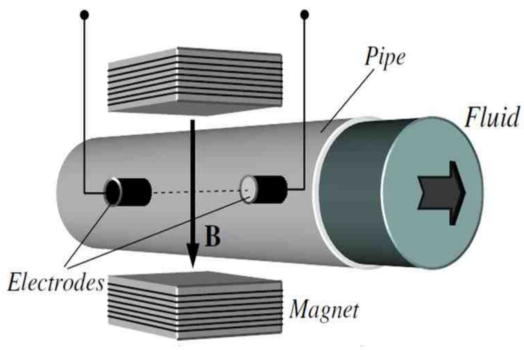

Fig. 1: Principle of operation of the electromagnetic flow meter

nents of the electrode signal are obtained. These can be used to convert future electrode signals from the same meter (operated under any frequency and magnet current within the range studied) into a measure of flow rate.

2. DIFFICULTIES IN MEASUREMENT OF ELECTRIC SIGNAL

It is a well known fact that the electromagnetic flowmeter has been encountered with a number of problems that make it hard to improve accuracy much beyond the 1.0% level in the best site conditions. The sensed signal is small (of the order of 100 mV),and there is significant $\frac{1}{f}$noise and electrode electrochemical activity. The variability of fluid resistivity can cause errors due to potential divider effects. With contacting electrodes there is the problem of unwanted electrochemical (cell like) contact potentials which, even though the electrodes are of the same material, do not cancel out completely because of unavoidable differences in their surface conditions. This can cause an unwanted signal comparable to (or larger than) the flow signal one is trying to be measured. The presence of this unwanted signal (which is generally a slowly changing semi dc signal) leads one to work with an alternating magnetic field. across the liquid.

The induced EMF produces an unwanted signal and can be removed by accurate positioning of the electrode leads in the plane of symmetry of the meter, but in practice a residual signal always remains. Phase-sensitive detection has been employed to suppress this signal. Which is an alternating current operation be in phase quadrature with the flow signal and in square-wave operation should be present only shortly after the magnet current changes in value. The introduction of an alternating magnetic field also has the disadvantage of generating eddy currents in the metal parts of the meter (the meter tube and magnet core) and eddy currents in the liquid. Eddy currents in the metal parts cause phase-shifting of the magnetic field rendering the phase-sensitive detection less accurate than it might otherwise be. Eddy currents in the liquid can flow in and out of each electrode through its surface impedance producing an inter-electrode signal difficult to separate from the flow signal and apt to change with electrode surface conditions. Inaccuracies due to induced EMFs and to eddy currents are naturally greater the higher the frequency of operation.

Another consideration is the response time to flow change.In low-frequency operation (e.g. at 3 Hz) this response is slow. Whereas with high-frequency operation (e.g. 50 Hz), speed of response can be faster. So a trade-off has to be made between requirements for accuracy and speed of response.

The authors consider that the accuracy and speed of response of electromagnetic flowmeters will only be increased by operating them at high frequencies (in the range 10 Hz-1 kHz). To remove errors due to eddy currents it is proposed:

- To model induced EMF and eddy-current effects
- To confirm the accuracy of the modelling using experimental measurements

3. ONE DIMENSIONAL MODEL OF AN ELECTROMAGNETIC FLOW METER

When the magnetic field is of form $\mathbf{B}sinwt$, the sensor output of electromagnetic flowmeter is

$$u(t) = c_1qBsinwt + c_2wBcoswt \qquad (1)$$

where B is magnetic flux density, q is the flow rate, c_1 and c_2 are constants, and w is the exciting angular frequency, that is, $w = 2\pi f$. Since the magnetic flux density is proportional to the exciting current, Eq.1 becomes

$$u(t) = c_3qIsinwt + c_4wIcoswt \qquad (2)$$

where I is the amplitude of exciting current, and c_3 and c_4 are constants.

However, there are problems exist in this signal model. The first one is that the effects of some factors have not been considered, for example, the effect of eddy current that is induced in the body of the flowmeter or adjacent structure. The second one is that the quantitative relationship among the sensor output, flow rate, and exciting signal could not be determined. This is because we only carry out the qualitative analysis according to Faradays law and some assumptions. In practice, the interaction between the electromagnetic field and the fluid field is complex.

4. TWO DIMENSIONAL MODEL OF EM FLOWMETER

This paper presents an analytical $2D$ field theory model of an electromagnetic flow meter which will help calculation of eddy currents in the meter tube and a coaxial (cylindrical) magnet core. The model meter has point electrodes and a coil winding on the inside surface of the core (thus producing a uniform magnetic field in the tube interior).

But operation at any frequency is allowed and the effects of eddy currents on the predicted flow signal and coil impedance are calculated. The theory employed (linear Maxwell equations with neglect of displacement currents) is very similar to that employed in predicting losses due to eddy currents in transformer plates or in predicting effects of eddy currents on electromagnet coil impedance . In the present paper, to simplify the theory as much as possible, the meter tube and magnet core are modelled as infinitely thin. This requires working out the correct boundary conditions to employ across these material surfaces. The modelling of thin conducting sheets by material surfaces has been used before in connection with finite element solutions of eddy current problems.

Although the model is simplified in many ways it nonetheless seems to grasp the essential processes going on in the electromagnetic flowmeter associated with eddy currents in the metal parts. This is demonstrated by applying the model to a 20 inch fullbore electromagnetic flowmeter and comparing model predictions of the coil impedance and of the amplitude and phase of the central magnetic field with measured values of the same quantities over the frequency range 10 Hz to 1 kHz.

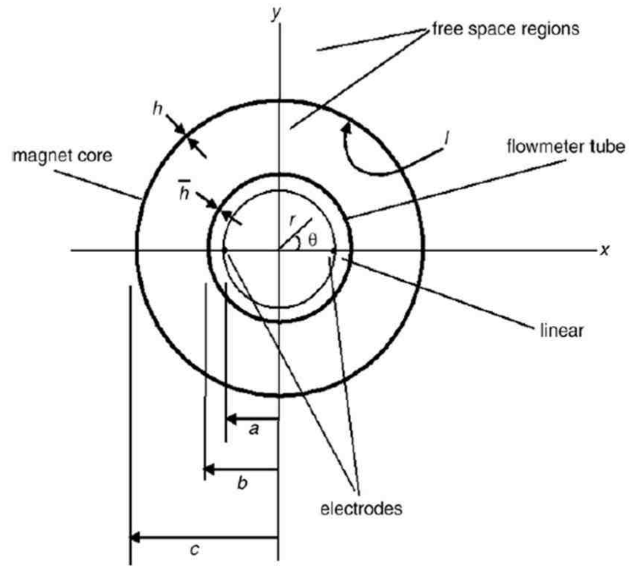

Fig. 2: Two Dimensional Model of an Electromagnetic Flowmeter

A. Description of the Model

The model shown in Fig.2 consists of two metallic cylindrical shells modelled as infinitely thin cylindrical material surfaces. One cylindrical surface at radius $r = b$ represents the metallic flowmeter tube with constant thickness h, conductivity $\bar{\sigma}$ and permeability $\bar{\mu}$, the other at $r = c$ represents the magnet core with constant thickness$h$, conductivity σ and permeability μ. The cylindrical surface at $r = c$ has an inner surface (z-directed) current of density I (amps per unit length of the circumference). The model is linear and the fields are supposed to vary sinusoidally in time. We use the complex notation with unwritten factor e^{jwt} where $w(= 2\pi f)$ is the angular frequency. We take the current density$I$ to be real and given by

$$I = -I_0 coswt; I_0 > 0 \tag{3}$$

so as to produce a uniform magnetic flux B_0 in the y-direction inside the flowmeter tube. The metallic flowmeter tube has a liner of insulating material occupying the region $a \leq r \leq b$ and point electrodes are present at $\theta = 0, \pi$;on the inside surface r= a of the liner. The liner, electrodes, and liquid (in the region$r \leq a$) are assumed to have a negligible effect on the magnetic field. The current density I is considered to be due to a '$cos\theta$ winding', that is, to many (very thin) wires parallel to the z-axis laid on the inside of the cylindrical surface on $r = c$ each carrying a (small) current I_c the density n of wires (the number of wires per unit length of the circumference) being given by

$$n = -n_0 cos\theta; n_0 > 0 \tag{4}$$

negative n signifying current flow in the negative z-direction. Each wire carrying current in the positive z-direction is connected at each end to a corresponding wire on the other side (opposite value of the x-coordinate) carrying current in the negative z-direction. This connection is made via circumferential wires at the remote ends of the magnet (at large $\mod z$j). In this way two coils are formed. The wires for $0 \leq \theta \leq \pi$ form the 'top coil' and the wires for $0 \leq \theta \leq 2\pi$ form the 'bottom coil'. The number N of turns in each coil is by (4)

$$N = -\int_0^{\pi/2} ncd\theta = -n_0 I_c \theta \tag{5}$$

and the current density in (3) is, by (5),

$$I = -I_0 cos\theta = nI_c = -n_0 I_c cos\theta \tag{6}$$

giving the relation

$$I_0 = \frac{N}{c} I_c \tag{7}$$

B. Determination of Magnetic Field

In the spaces within, around and between the cylindrical surfaces (at $r = b$ and $r = c$ in Fig.2 the magnetic field $\mathbf{H}$ is curl free and can be written as the gradient of a scalar potential ϕ. In the polar coordinates in Fig.2 the$2D\phi$ has the form

$$\phi = I_0 A_r \sin\theta, r \leq b \tag{8}$$

$$\phi = I_0(Cr + D(C^2/r)\sin\theta, b \leq r \leq c \tag{9}$$

$$\phi = I_0 B(C^2/r)\sin\theta, r \geq c \tag{10}$$

where A; B; C and D are dimensionless constants. The two boundary conditions across each cylindrical surface give four equations from which the constants A; B; C and D in equations (8)to (10)can be calculated. The boundary conditions at $r = c$ (where the cylindrical surface possesses strong local reaction $-cf$.

$$\begin{aligned} &B_r\|_{r=c+} + B_r\|_{r=c-} = \\ &K\frac{\partial}{c\partial\theta}(H_\theta\|_{r=c+} - H_\theta\|_{r=c-} - I) \end{aligned} \tag{11}$$

$$\begin{aligned} &B_r\|_{r=c+} + B_r\|_{r=c-} = \\ &L\frac{\partial}{c\partial\theta}(H_\theta\|_{r=c+} + H_\theta\|_{r=c-} + I) \end{aligned} \tag{12}$$

$$\begin{aligned} &(1+m^2)\frac{\partial^2}{b^2\partial\theta^2}(B_r\|_{r=b+} + B_r\|_{r=b-}) = \\ &\bar{K}\frac{\partial}{b\partial}(H_\theta\|_{r=b+} - H_\theta\|_{r=b-}) \end{aligned} \tag{13}$$

Letting δ and $\bar{\delta}$ represent the 'skin depths' of the shell materials, i.e. putting

$\delta = \sqrt{\frac{2}{\sigma\rho w}}$ and $\bar{\delta} = \sqrt{\frac{2}{\bar{\sigma}\bar{\rho}\bar{w}}}$
the constants K and L are given in (11) and the constants$\bar{K}$,$\bar{L}$ and m are given with $h, \sigma, \rho and \delta$ replaced by the inner surface parameters $\bar{h}, \bar{\sigma}, \bar{\rho} and \bar{\delta}$ respectively. Expressing H_θ and $B_r.(\rho_0 H_r)$in terms of ϕ as given by (6) and substituting the results into (7)-(10) we obtain four equations for the constants A, B, C and D which can be written in the dimensionless form

$$B(1-K') - C(1-K') + D(1+K') = -K' \tag{14}$$

$$B(1-L') - C(1-L') - D(1+L') = -L' \tag{15}$$

$$\begin{aligned} &-A(1-(m^2/b^2)-\bar{K}') - C(1-(m^2/b^2)- \\ &\bar{K}') + D(1-(m^2/b^2)-\bar{K}')(c^2/b^2) = 0 \end{aligned} \tag{16}$$

$$A(1-L') - C(1-L') - D(1+L')(c^2/b^2) = 0 \tag{17}$$

where

$$K' = \frac{K}{\mu_0 c} = \frac{\mu\delta(1 + \exp^{\frac{-(1+jh)}{\delta}})}{(1+j)\mu_0 c(1 - \exp(\frac{-(1+j)h}{\delta}))} \tag{18}$$

Similarly $\bar{L}', m$ can be determined.

C. Determination of Coil Impedance

The impedance of the electromagnet (from the point of view of driving the coils) is calculated assuming a finite (but long) length l of wires in the z-direction in Fig.2 and neglecting fringing of the magnetic field near the remote ends of the coil (at $z = +/-\frac{1}{2}$).

Consider the magnetic flux through the top coil. The flux
$B_r\|_{r=c-} = cd\theta l$
through the element of arc $cd\theta$ in the first quadrant in Fig. 3 fluxes all the turns of the upper coil from θ 0 to θ (the polar angle position of the element $cd\theta$). Hence it causes a flux through the upper coil of magnitude

$$d\phi = B_r\|_{r=c-}cd\theta l \int_0^\theta (-n)cd\theta \qquad (19)$$

The radial component of the flux density is,

$$B_r\|_{r=c-} = -\mu_0 \frac{N}{c} I_c(C-D)\sin\theta \qquad (20)$$

Hence the net flux through the top coil is

$$\phi = -\frac{\pi}{2}\mu_0 \frac{N}{c} I_c(C-D)\sin\theta \qquad (21)$$

where use has been made of equation(3). This causes a back-EMF

$$E = jw\pi/2\mu_0 N^2 l I_c(D-C) \qquad (22)$$

Hence if R is the resistance of the wire of the top coil, the impedance Z (from the point of view of driving the electromagnet) is

$$Z = \frac{V}{I_c} = R + 2jw\pi N^2 l\mu_0(D-C) \qquad (23)$$

for series and for parallel and

$$Z = \frac{V}{2I_c} = R/2 + jw/2\pi N^2 l\mu_0(D-C) \qquad (24)$$

Hence if$R$ is the resistance of the wire of the top coil, the impedance Z (from the point of view of driving the electromagnet) is

where V is the voltage applied to the terminals of the electromagnet and the two values of Z are for the cases in which the top and bottom coils are connected in series or in parallel. In łq(16), $D-C$ is generally complex, its real part reflecting coil inductance and its imaginary part reflecting eddy-current losses in the metallic shells.

D. Calculation of Inter-Electrode Potential

As is well known the flow signal (open circuit inter-electrode potential) due to asymmetric flow of the liquid is

$$U = 2vB_0a \qquad (25)$$

where v is the mean flow velocity (the total flow rate Q being $v\pi a2$). Using B_0 gives

$$U = -\frac{2}{\pi}\frac{N}{ac} I_c\mu_0 AQ \qquad (26)$$

The present model also allows the calculation of the so-called transformer signal U_t i.e. the EMF induced in the loop formed by the electrode leads and the conduction path across the liquid. As the electrodes are assumed to be infinitely small this conduction path may be taken as the straight line joining the electrodes and the transformer signal is then given by

$$U_t = -jw \int_0^\alpha Bd\alpha \qquad (27)$$

where d is a directed element of surface area of the total area of a surface (any surface) bounded by the loop formed by the electrode wires and the straight line joining the electrodes. In practice the electrode units extend out from the liquid to the outer surface of the flow meter tube where wires connected to them are taken directly around the tube to the point considered.

5. INSTRUMENTATION FOR THE FLOW METER

The instrumentation for the input and output circuit for designing the two dimensional model flow meter is given below in Fig.3. The excitation signal which is a sine wave given to the DAC converter and it then passes through the low pass filter F_1 to remove the high frequency components. The availability of output as voltage or current depends upon the corresponding feedback signals V_{sence} or I_{sense}.

6. RESULTS AND DISCUSSIONS

The model-validation experiments were performed using a standard 20 inch fullbore electromagnetic flow meter (Model SR100P) installed on

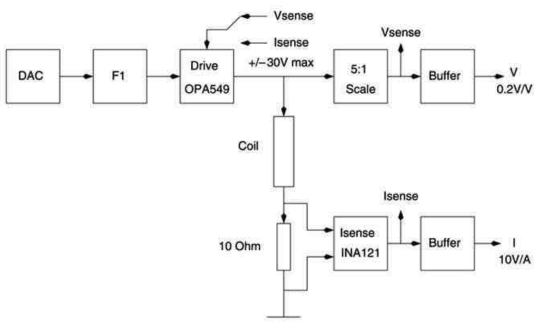

Fig. 3: Schematic of the Instrumentations

the CWPRS volumetric test bench to determine the effectiveness of the modelling . This flow meter and its associated IMT25 transmitter are built for low frequency square-wave operation. Hence new electronics setup were designed to enable ac excitation over the desired frequency range, i.e. up to 1 kHz.The result of the two dimensional modelled compared with that of a unmodelled flow meter with the standard flow as reference flow (determined by primary flow measurement method). The result obtained from the test set up is given in the table 1 and in figure 4 .

Reference Flow Rate (Cum/Sec)	Modelled Meter Flow Rate(Cum/Sec)	Non Modelled Flow Rate (Cum/Sec)
160.458	160.071	158.373
187.364	187.719	186.071
215.553	215.143	214.779
255.005	255.969	254.853

TABLE I: Reference Flow, Modelled and Unmodelled Flowmeter Readings

7. CONCLUSIONS

The two dimensional model derived to reduce the effect of eddy currents in an electromagnetic flow meter under ac drive conditions. The model successfully predicts, at a level of accuracy higher than 0.5% or better and has been validated. The new model gives the flow which is more accurate than that of unmodelled. Thus the proposed model is more realistic prediction of the typical magnetic flow meter.

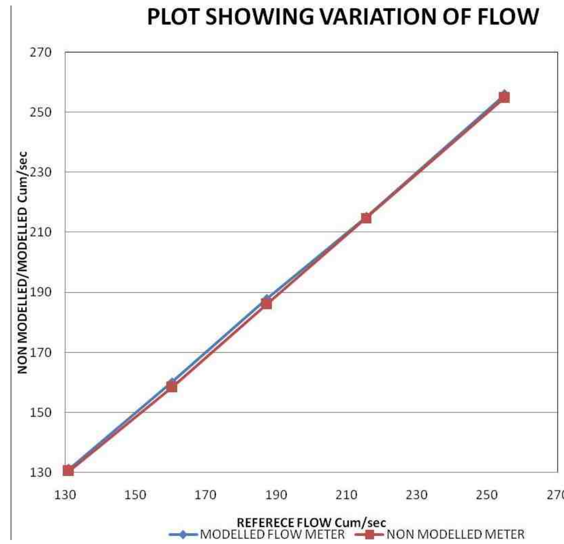

Fig. 4: Comparison of Modelled and Unmodelled Flow meter Reading

8. ACKNOWLEDGEMENTS

Authors express their sincere gratitude to Dr.(Mrs.) B.V.Bhosekar, Director, CWPRS for permitting to publish the paper and her constant encouragement for such work. Authors also place on record their thankfulness to Shri T.Nagendra, Scientist-E for his valuable suggestion and help during preparation of the paper. The assistance rendered by the staffs of HMC division during instrumentation setup is also worth to mention.

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