DESIGN OF A NOVEL BRIDGE TYPE FLOWMETER FOR A CONDUCTING LIQUID

A dissertation submitted in partial fulfillment for the degree of Doctor of Philosophy in Applied Physics (Measurements and Instrumentation) under The University of Calcutta
CHAPTER VII

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7.1 INTRODUCTION

The measurement of volume flowrate of a conducting liquid is generally done in the process industries by using electromagnetic flowmeters [26, 56, 73, 141, 202], since this technique is very simple as compared to other methods. There are other techniques of this flow measurement [26, 73, 82, 141, 212, 218] like absorption type, turbine type, coriolis force type, target type, vortex type etc. But for conducting liquid flow measurement, the electromagnetic flow measurement technique is much easier and less costly as compared to the other measurements. In this technique, an intense magnetic field is produced in the selected region of the flowtube by means of two coils excited from an AC or a DC source. Two sensing electrodes are placed on the diametrically opposite positions inside the tube in contact with the flowing liquid. The flowing liquid induces an e.m.f between the electrodes, which is directly proportional to the flow.

In the present investigation, a novel technique of measurement of flow of a conducting liquid has been described. In this technique, no excitation coil is required. This technique consists of four metal electrodes inserted into the selected zone of the flow, which are always in contact with the liquid and produce no obstruction to the liquid flow. This electrode system is excited from an AC source and the output signal has been found to be linearly related with the liquid flow under streamline condition along with a small non-linear zone at turbulent condition.

This output voltage has been amplified by an instrumentation amplifier and then rectified. The offset or zero adjustment network controls the offset of the rectified
signal. This signal is then further amplified to voltage signal in the range of 0-5 volts and the non-linear zone is linearised by a microprocessor based piece wise linearisation technique. The digital output signal of microprocessor is first converted into analog signal and then into 4 - 20 mA current signal for transmission. The design of the flowhead and the calibration data before and after linearisation are reported here. The experimental data are almost found to conform to the theoretical equations.

7.2 ANALYSIS

When two metal electrodes are immersed in a conducting liquid, the polarisation effect [196, 226, 234, 241, 249] at each electrode produces an electric double layer at each metal liquid interface across which there exists a difference in potential along with polarisation impedance. If a very small value of sinusoidal voltage signal is applied across the electrodes, then this AC voltage signal is superimposed with the half-cell potential [234] at each electrode and accordingly the flow of ions from one electrode to the other is obtained. The electric current due to these flow of ions may be opposed by the DC polarization impedance and the ohmic impedance of the liquid between the two electrodes. Again, if there is a flow of liquid from one electrode to the other, then the flow of a liquid element along with the ions may be opposed by the viscous effect of the liquid produced by the velocity gradient. Hence, the net impedance between the electrodes defined as the ratio of the supply voltage to the current may be assumed to be dependent on the electrode polarisation effect, ohmic effect and the velocity gradient of the liquid [234, 241, 249]. The DC polarisation effect non-linearly depends [241] on the electric current density and frequency of excitation and ohmic effect may be assumed constant for a particular system.

When a liquid flows through a pipeline, there exists a velocity gradient across the cross section of the pipeline, which depends on the flowrate of the liquid if the polarisation effect and ohmic effect are assumed to be constant. In the present investigation, the effect of four electrodes inserted into a conducting liquid
flowing through the pipeline with proper insulation at the diametrically opposite positions is studied. Since impedance is always found to exist between any two of these electrodes, the four electrodes may be assumed to be equivalent to four lumped impedances as shown in Figure 7.1.

![Figure 7.1: Lumped parameter equivalent impedance network between four electrodes](image)

Now when a conducting liquid flows through the horizontal pipe under the streamline condition, it may be assumed to have no component of its velocity along any diameter, since it is perpendicular to the length of the pipeline. Hence, the lumped parameter impedance $Z_1$ between the diametrically opposite electrodes $A$ & $C$ and $Z_3$ between the similar electrodes $B$ & $D$ may remain constant but the effective lumped impedance $Z_2$ between $C$ & $D$ or $Z_4$ between $A$ & $B$ tends to change due to the velocity gradient among the liquid layers between the electrodes.

Hence, if any two diagonally opposite electrodes be supplied from a very small value sinusoidal stabilised AC source, then the output across the other two electrodes may change due to the flow of the conducting liquid following the Wheatstone bridge network principle. So, for a small value supply voltage $V_s$ at a fixed frequency applied between $A$ and $D$ and for a very high input impedance of the measuring circuit, the bridge output voltage signal $V_0$ may be given by
\[ V_o = \frac{(Z_2 Z_4 - Z_1 Z_3)}{(Z_1 + Z_4)(Z_2 + Z_3)} V_s. \]  \hspace{1cm} (7.1)

For a very small value of AC voltage \( V_o \) and for the identical electrodes \( Z_1 = Z_3 \) and \( Z_2 = Z_4 \).

Let at any flow rate \( Q_0 \) of the liquid, \( Z_1 = Z_3 = Z_c, \ Z_2 = Z_4 = Z_0 \) and at any other flow rate \( Q \) slightly different from \( Q_0 \), the value of \( Z_0 \) be changed to \( Z_Q \).

Hence the Taylor Series Expansion of \( Z_Q \) may be given by

\[ Z_Q = Z_0 + \left( \frac{\partial}{\partial Q} Z_Q \right)_{Q_0} \Delta Q + \left( \frac{\partial^2}{\partial Q^2} Z_Q \right)_{Q_0} \Delta Q^2 + \cdots \quad (7.2) \]

where

\[ \Delta Q = Q - Q_0. \]

Let

\[ \left( \frac{\partial}{\partial Q} Z_Q \right)_{Q_0} = \mu \quad \text{and} \quad \left( \frac{\partial^2}{\partial Q^2} Z_Q \right)_{Q_0} = \beta. \]

Hence

\[ Z_Q = Z_0 + \mu \Delta Q + \beta \Delta Q^2 + \cdots . \quad (7.3) \]

Under streamline conditions, the value of \( \beta \) and the co-efficient of higher order terms may be assumed to be very small. Hence, for very small change (\( \Delta Q \)) of flowrate, \( Z_Q \) may be given by

\[ Z_Q = Z_0 + \mu \Delta Q. \quad (7.4) \]
Hence, putting $Z_1 = Z_3 = Z_C$ and $Z_2 = Z_4 = Z_Q$ in equation number (7.1), the bridge output voltage for a liquid flow rate $Q$ is given by

$$V_0 = \frac{(Z_Q - Z_C)}{(Z_C + Z_Q)} V_s.$$  \hspace{1cm} (7.5)

From the equation numbers (7.4) and (7.5) we get

$$V_0 = \frac{(Z_0 + \mu \Delta Q - Z_C)}{(Z_C + Z_0 + \mu \Delta Q)} V_s$$

or

$$V_0 = \frac{(Z_0 - Z_C + \mu \Delta Q)}{(Z_0 + Z_C)} \left[1 + \frac{\mu \Delta Q}{Z_0 + Z_C}\right] V_s$$

or

$$V_0 = \frac{Z_0 - Z_C}{Z_0 + Z_C} \left[1 + \frac{\mu \Delta Q}{(Z_0 - Z_C)}\right] \left[1 - \frac{\mu \Delta Q}{(Z_0 + Z_C)}\right] V_s$$

or

$$V_0 = \frac{Z_0 - Z_C}{Z_0 + Z_C} \left[1 + \frac{\mu \Delta Q}{(Z_0 - Z_C)}\right] \frac{\mu \Delta Q}{(Z_0 + Z_C)} \left[\frac{\mu \Delta Q^2}{(Z_0 - Z_C)(Z_0 + Z_C)}\right] V_s$$

or

$$V_0 = \frac{Z_0 - Z_C}{Z_0 + Z_C} \left[1 + \frac{(Z_0 + Z_C - Z_0 + Z_C)\mu \Delta Q}{(Z_0 - Z_C)(Z_0 + Z_C)}\right] \frac{\mu \Delta Q^2}{(Z_0 + Z_C)(Z_0 - Z_C)} V_s$$
or \[ V_0 = \left( \frac{Z_0 - Z_C}{Z_0 + Z_C} \right) \left[ 1 + \frac{2Z_C \mu \Delta Q}{(Z_0 - Z_C)(Z_0 + Z_C)} - \frac{\mu^2 \Delta Q^2}{(Z_0 + Z_C)^2} \right] V_s \]

or \[ V_0 = \left[ \frac{Z_0 - Z_C}{Z_0 + Z_C} + \frac{2Z_C \mu}{(Z_0 + Z_C)^2} \Delta Q - \frac{\mu^2}{(Z_0 + Z_C)^2} \Delta Q^2 \right] V_s \]

or \[ V_0 = K_1 + K_2 \Delta Q - K_3 \Delta Q^2 \] (7.6)

where

\[ K_1 = \left( \frac{Z_0 - Z_C}{Z_0 + Z_C} \right) V_s \] (7.7)

\[ K_2 = \frac{2 \mu Z_C}{(Z_0 + Z_C)^2} V_s \] (7.8)

\[ K_3 = \frac{\mu^2}{(Z_0 + Z_C)^2} V_s \] (7.9)

Under the streamline conditions, the term \( K_3 = \frac{\mu^2}{(Z_0 + Z_C)^2} V_s \) may be assumed to be very small and hence for a very small change \( \Delta Q \) of flow rate, the equation number (7.6) may be written as

\[ V_0 = K_1 + K_2 \Delta Q \] (7.10)

or

\[ V_0 = K_1 + K_2 (Q - Q_0) \] (7.11)

Hence the bridge output voltage is linearly related with the incremental change in flowrate under the streamline condition. Under no flow condition \( Q_0 = 0 \) and for
electrode separation along the pipeline equal to the pipe diameter, \( Z_0 = Z_C \).

Hence \( K_x = 0 \) and the equation number (7.11) is reduced to

\[
V_0 = K_2 Q.
\] (7.12)

Thus the bridge output voltage is linearly related with flowrate when the flowrate is very small and streamline.

Under the turbulent condition, the equation number (7.3) may be given as

\[
Z_Q = Z_0 + \mu \Delta Q + \beta \Delta Q^2.
\]

Hence from equation (7.5) the bridge output voltage is given by

\[
V_0 = \left[ \frac{Z_0 + \mu \Delta Q + \beta \Delta Q^2 - Z_C}{Z_0 + \mu \Delta Q + \beta \Delta Q^2 + Z_C} \right] V_s.
\] (7.13)

So under turbulent condition, the bridge output voltage may be non-linearly related with the incremental change of flow rate. Therefore, \( Z_0 + Z_C \gg \mu \Delta Q + \beta \Delta Q^2 \). So the bridge output voltage under turbulent condition may be given by

\[
V_0 = \left[ \frac{(Z_0 - Z_C) + \mu \Delta Q + \beta \Delta Q^2}{(Z_0 + Z_C)} \right] \left[ 1 - \frac{\mu \Delta Q + \beta \Delta Q^2}{(Z_0 + Z_C)} \right] V_s
\]

or

\[
V_0 = \left[ \frac{(Z_0 - Z_C) + \mu \Delta Q + \beta \Delta Q^2}{(Z_0 + Z_C)} \right] \left[ \frac{\mu \Delta Q - \mu \Delta Q^3}{(Z_0 + Z_C)^2} \right] V_s
\]
or \[ V_0 = K_1 + K_2 \Delta Q + K_3 \Delta Q^2 - K_4 \Delta Q^3 - K_5 \Delta Q^4 \] (7.14)

where \( K_1 = \left( \frac{Z_0 - Z_C}{Z_0 + Z_C} \right) V_s \)

\[ K_2 = \frac{2 \mu Z_C}{(Z_0 + Z_C)^2} \ V_s \] (7.15)

\[ K_3 = \frac{2 Z_C \beta - \mu^2}{(Z_0 + Z_C)^2} \ V_s \] (7.16)

\[ K_3 = \frac{2 \mu \beta}{(Z_0 + Z_C)^2} \ V_s \] (7.17)

Since \( \mu \) and \( \beta \) are small \( K_4 \) and \( K_5 \) may be negligible and hence the above equation number (7.14) may be written as

\[ V_0 = K_1 + K_2 \Delta Q + K_3 \Delta Q^2. \] (7.18)

Hence the relation between the bridge output voltage and the incremental change of flowrate may be assumed to be parabolic under some conditions of turbulent flow.

### 7.3 DESIGN

The design of the flowhead is very simple as shown in Figure 7.2. It involves only the selection of the electrode material, which is chemically inert to the flowing liquid. In the present design, the flowrate of water through a one inch pipeline has
been measured. Hence the electrode material is selected to be stainless steel. Since outside and inside diameter of the pipe are 25 mm and 20 mm respectively, length of each electrode is selected to be 15 mm with 2 mm insertion depth. The diameter of each electrode is selected to be 4 mm. These selections are made on a trial basis so that the obstruction to the flow is minimum.

Each electrode is covered with PVC sleeve and is fitted with a 2 mm terminal screw. Each electrode is then mounted on the flowhead along its line of symmetry through a proper hole so that the electrode may be inserted with tight shut up condition and there is no water leakage at the operating pressure. The small gap is sealed with araldite. The length of the flowhead is selected to be three feet with flange connections at both ends of internal diameter exactly equal to that of the pipeline. The flowhead is connected with the pipeline through insulating gasket of Teflon sheet.

![Flowhead of the bridge flowmeter](image)

**Figure 7.2: Flowhead of the bridge flowmeter**

### 7.4 SIGNAL CONDITIONER

The lumped parameter bridge circuit is supplied from a Wein bridge oscillator at 1000 Hz. Any two diagonal electrodes are taken as the bridge supply nodal points and the other two diagonal electrodes as the bridge output nodal points. The signal conditioning circuit of the bridge type flowmeter was designed as shown in Figure 7.3. The bridge output voltage signal due to change in liquid flow is fed to precision true differential amplifier constructed using Burr brown INA101KP.
integrated circuit. The gain of the amplifier is adjustable by the trimpot $R_s$. The rest part of the circuit is as described in Figure 6.3 in the earlier Chapter-VI.

![Schematic diagram of the signal conditioner circuit of the bridge type flowmeter](image)

**Figure 7.3:** Schematic diagram of the signal conditioner circuit of the bridge type flowmeter

### 7.5 LINEARISATION

The experimental graph as shown in Figure 7.5 is found to be non-linear with a linear zone over a large portion of the calibration characteristics of the flow transducer. It is linearised by using the piece wise linearisation technique with the software programme by an ILCV2 8085 microprocessor. The operating flowchart of ADC conversion program is shown in Figure 7.4a. For the entire output against flowrate, experimentally determined graphical plot was divided into two parts. Each part is considered a straight line but with different slope and intercept. The basic aim is to transfer these piecewise linear zones to a reference straight line.
From the experimental data this linear part is found to approximately satisfy the equation $Y = 0.61X + 0.7$, where $Y$ denotes the flowmeter output in volt and $X$ denotes the flowrate in liter per minute and the data in the non-linear zone of the experimental graph are converted into the corresponding data in the linear zone by the microprocessor. Therefore, these small piecewise linear zones need modification of their slope and intercept values to fit into desire reference output straight line. After data acquisition, the microprocessor first finds out the operating zone in which the data fall. Then it will modify the data with desired slope and intercept values. The mathematical calculations are performed by the microprocessor as per procedure shown in the main program flowchart Figure 7.4b and Figure 7.4c. The linearised data are displayed in the microprocessor in liter/min.

![Flowchart of ADC programming of microprocessor based flowmeter](Figure 7.4a)

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Figure 7.4b: Main programme flowchart for linearisation of vortex flowmeter
7.6 EXPERIMENTAL RESULTS

The experiment was performed by using tap water with the experimental setup as shown in Figure 7.5. The flow through the pipeline is increased in small steps and in each step the actual flow was measured by the direct collection method for a known interval of time and the signal conditioner output in volts was measured by a 4 4/5 digit TX3 true RMS digital multimeter and the microprocessor output are noted in both increasing and decreasing modes as shown in TABLE 7.1. The static calibration graphs obtained from the experiment for the signal conditioner output and microprocessor output after linearisation are as shown in Figure 7.6.
Figure 7.5: Experimental setup of the bridge type flowmeter

Figure 7.6: Calibration curve for bridge type flowmeter before and after linearisation
7.7 DISCUSSIONS

The repeatability of the experimental data in the increasing and decreasing modes were found to be satisfactory. The calibration graph reveals that the nature of the graph is linear over a large portion of the operating zone. The non-linearity may be due to the turbulence effect of flow. The nature of the graph appears to follow the theoretically derived equations (7.11) and (7.18). The technique is very simple and requires no magnetic excitation field coils as in the case of an electromagnetic flowmeter and, hence, it is very low cost.
### Table 7.1: Experimental data of the bridge type flow meter before and after linearisation

<table>
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<tr>
<th>Sl. No.</th>
<th>Water flow ( (X) )</th>
<th>Signal Conditioner Output</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit–→ L/min</td>
<td>SET-I</td>
</tr>
<tr>
<td></td>
<td>volts</td>
<td>Increasing</td>
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<tr>
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<td>Signal Conditioner Output</td>
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