DESIGN OF A NOVEL LOW COST VORTEX FLOWMETER

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

The accurate measurement of flowrate of a fluid through a pipeline is one of the most important requirements in any process plant in order to run the plant with optimum efficiency at lesser cost. There are various effects like the effect of energy associated with a flowing fluid through a pipeline, Doppler effect and effect of speed of the fluid suction pump on the flowrate etc., which have been utilised in designing the various flowmeters [8, 26, 58, 86, 101, 187, 272, 273]. In the vortex flowmeter, the effect of a blunt obstruction post to the flowing fluid through a pipeline has been utilised [26, 86, 98, 260]. In this instrument, it has been established experimentally that the frequency of the vortices produced behind a blunt post inserted into a flowing fluid is linearly proportional to the velocity of the fluid. Hence, the volume flowrate of the fluid is directly proportional to the frequency.

In the conventional vortex flowmeters [86, 98, 260] the frequency of vortices is sensed by a capacitive or piezo-resistive sensor, where a mechanical diaphragm or similar device is used as a primary sensing element behind the blunt post. Hence, the performance of the instrument may be assumed to depend on the sensitivity of the mechanical diaphragm as well as the secondary sensing element like strain gauge, piezo resistance etc. In the present investigation, a direct action type frequency and pressure sensing element has been developed using an inductive pickup. In this case, the change of reluctance of a magnetic circuit due to the vortices produced behind the blunt post has been sensed by the pickup coil. The design aspects of the flowhead and the signal conditioner are described. The

developed flowmeter has been calibrated in a half-inch water flowline by direct water collection method. A non-linearity is observed in the calibration curve and this is linearised by a microprocessor based piece wise linearisation technique. The experimental results before and after linearisation are reported.

6.2 METHOD OF APPROACH

When a blunt post is inserted into a fluid flowing through a pipeline, vortices are produced on the downstream side of the post and, under turbulent condition when the Renold’s Number exceeds 10,000, the vortex shedding frequency \( f \) is given by the relation [26, 86, 98, 260],

\[
f = \frac{N_s V}{d} \tag{6.1}
\]

where \( V \) is the velocity of the fluid, \( d \) is the characteristic dimension of the blunt post and \( N_s \) is an experimentally determined number, which is nearly constant.

Hence the volume flowrate \( Q \) through the pipeline of cross sectional area \( A_0 \) is proportional to the vortex-shedding frequency and is given by

\[
Q = \frac{A_0 d}{N_s} f. \tag{6.2}
\]

This vortex shedding frequency is sensed by an inductive pick-up, as shown in Figure 6.1.
It consists of a blunt post made of non-magnetic material and a flexible thin strip of magnetic material behind the post, both mounted in a flowhead tube of non-magnetic material. The upper end of the flexible strip is fixed at a suitable location in the upper part of the flowtube just behind the blunt post, while the lower part touches a fixed magnetic material post at the diametrically opposite location below the upper part, so that the flexible strip and the fixed post close the magnetic circuit of the two inductive pick-up coils through their common core material, as shown in Figure 6.1. The core material is laminated and surrounds the flowtube. When any one of the pick-up coils is excited with the DC or AC signal, a magnetic flux passes through the flexible strip. When there is no flow of liquid through the pipe, the flux is maximum since the reluctance of the magnetic circuit is minimum. Now when the liquid flows through the pipe, vortices are produced behind the blunt post and a change of the vortex shedding frequency and pressure occurs with the increase of flowrate. As a result, the tip of the flexible strip is displaced from the fixed post and vibrates about some mean position. Since the decrease of pressure in the downstream side of blunt post with respect to that in the upstream side increases with the increase of flowrate so the frequency of oscillation as well as the maximum displacement of the tip of the flexible strip
will increase with the increase of flowrate. The variation of this maximum

displacement produces the change of reluctance of the magnetic circuit.

Let the effective permeability, length and cross-section of the laminated core,
flexible strip and fixed magnetic post be respectively \( \mu_1, l_1, A_1 \), \( \mu_2, l_2, A_2 \) and
\( \mu_3, l_3, A_3 \), where the sum of \( l_2 \) and \( l_3 \) is approximately equal to the pipe
diameter. Hence, the net reluctance of the magnetic circuit when there is no flow
is given by

\[
R_0 = \left[ \frac{\frac{l_1}{\mu_1 A_1} + \frac{l_2}{\mu_2 A_2} + \frac{l_3}{\mu_3 A_3}}{\mu_0} \right]
\]  

(6.3)

Let the permeability of the liquid be \( \mu \) and the maximum and minimum gaps
between the flexible strip and fixed post due to the fluctuation of vortex shedding
pressure at the vortex shedding frequency \( f \) be \( x_1 \) and \( x_2 \), respectively. Hence, the
reluctance of the magnetic circuit at the maximum gap \( x_1 \) is given by

\[
R_1 = \left[ \frac{\frac{l_1}{\mu_1 A_1} + \frac{l_2}{\mu_2 A_2} + \frac{l_3}{\mu_3 A_3} + \left( \frac{x_1}{\mu A} \right)}{\mu_0} \right]
\]

or

\[
R_1 = R_0 + \left( \frac{x_1}{\mu_0 \mu A} \right)
\]

(6.4)

where \( A \) is the contact area between flexible strip and fixed post. Similarly, the
reluctance for the minimum gap \( x_2 \) is

\[
R_2 = \left[ R_0 + \left( \frac{x_2}{\mu_0 \mu A} \right) \right]
\]

(6.5)
Hence, the self inductances $L_1$ and $L_2$ have the primary excitation coil of $n_1$ turns for the maximum and minimum gaps which are respectively given by

$$L_1 = \frac{n_1^2}{R_1} = \frac{\mu_0 \mu A n_1^2}{(\mu_0 \mu A R_0 + x_1)} = \frac{K_1}{(K_2 + x_1)}$$

(6.6)

and

$$L_2 = \frac{K_1}{(K_2 + x_2)}$$

(6.7)

where

$$K_1 = \mu_0 \mu A n_1^2$$

(6.8)

and

$$K_2 = \mu_0 \mu A R_0.$$  

(6.9)

Let the current passing through the excitation coil from a stabilised sinusoidal source at a frequency $f_0 = \frac{\omega_0}{2\pi}$ Hz, be $i = i_m \sin \omega_0 t$. Hence the AC flux for the maximum and minimum gap conditions are given by

$$\Phi_1 = L_1 i = L_1 i_m \sin \omega_0 t = \Phi_{1m} \sin \omega_0 t$$

(6.10)

and

$$\Phi_2 = L_2 i = L_2 i_m \sin \omega_0 t = \Phi_{2m} \sin \omega_0 t$$

(6.11)
where

\[ \Phi_{1m} = L_1 i_m \quad \text{and} \quad \Phi_{2m} = L_2 i_m. \]  

(6.12)

Hence the r.m.s value of the induced emf in the secondary pickup coil for these two flux waves are given by

\[ e'_1 = 4.44 n_2 f_0 \Phi_{1m}, \]  

(6.13)

and

\[ e'_2 = 4.44 n_2 f_0 \Phi_{2m}, \]  

(6.14)

where \( n_2 \) = Number of turns of the secondary pickup coil.

So the change in the induced emf in the secondary pickup coil is given by

\[ \Delta e = e'_1 - e'_2 = 4.44 n_2 f_0 (\Phi_{1m} - \Phi_{2m}). \]  

(6.15)

From the equations (6.6), (6.7), (6.8), (6.9) and (6.12) the above equation is reduced to

\[ \Delta e = 4.44 n_2 f_0 (L_1 - L_2) i_m \]

or

\[ \Delta e = 4.44 n_2 f_0 \left[ \frac{K_1}{(K_2 + x_1)} - \frac{K_1}{(K_2 + x_2)} \right] i_m \]
If the minimum gap \( \Delta x_2 \) is assumed to be negligible, then the above equation (6.16) is reduced to

\[
\Delta e = -4.44 n_2 f_0 \left( \frac{K_1}{K_2} \right) \left( \frac{x_1}{K_2 + x_1} \right) i_m. \tag{6.17}
\]

Since \( x_1 \) is generally very small, so the above equation (6.17) may be written as

\[
\Delta e = -4.44 n_2 f_0 \left( \frac{K_1}{K_2} \right) x_1 \left( 1 - \frac{x_1}{K_2} \right) i_m.
\]

or

\[
\Delta e = 4.44 n_2 f_0 \left( \frac{K_1}{K_2} \right) \left( -x_1 + \frac{x_1^2}{K_2} \right) i_m. \tag{6.18}
\]

Now the signal conditioner output voltage \( V_0 \) is linearly related with \( \Delta e \) so that the input small AC voltage signal is converted into large DC voltage signal in the range of 1-5 volts. Hence, the signal conditioner output voltage \( V_0 \) may be given by

\[
V_0 = K_0 \Delta e + K_C
\]

where

\[
K_C = \text{Constant},
\]
or

\[ V_0 = 4.44 n_3 f_0 K_0 \left( \frac{K_1}{K_2} \right) \left( -x_1 + \frac{x_1^2}{K_2} \right) i_0 + K_C. \] (6.19)

Now the vibration of the flexible strip due to the fluctuation of the vortex pressure at the vortex frequency \( f \) may be assumed to be equivalent to a simple harmonic oscillator of frequency \( f \) and the displacement of the free tip of the strip at any instant \( t \) may be given by the following equation

\[ x = a \sin 2\pi f t \] (6.20)

where \( f \) denotes the vortex shedding frequency and \( a \) is a constant.

Since \( x \) is very small so the above equation may be written as

\[ x = 2\pi a f t. \] (6.21)

Combining the equations (6.2) and (6.21) we get

\[ x = 2\pi a \left( \frac{N_p}{A_0 d} \right) Q, \] (6.22)

Hence the displacement \( x_i \) at a particular instant \( t_i \) may be given by,

\[ x_i = C Q \] (6.23).

where

\[ C = 2\pi a t_i \left( \frac{N_p}{A_0 d} \right) = \text{constant}. \]
Combining the equations (6.19) and (6.23) we get

\[ V_0 = 4.44 n_3 f_0 K_0 \left( \frac{K_1}{K_2} \right) \left( \frac{C Q^2}{K_2} - Q \right) i_m + K_c \]

or

\[ V_0 = \alpha Q^2 + \beta Q + K_c \quad \text{(6.24)} \]

where \( \alpha = 4.44 n_3 f_0 K_0 \left( \frac{K_1}{K_2} \right)^2 C^2 i_m \) \quad \text{(6.25)}

and

\[ \beta = -4.44 n_3 f_0 K_0 \left( \frac{K_1}{K_2} \right) C i_m \quad \text{(6.26)} \]

Hence the output voltage is non-linearly related with the volume flowrate and, under certain experimental conditions, it may have a parabolic relation with flowrate as shown in equation (6.24).

6.3 DESIGN

The design of the flowhead involves the selection of a suitable non-magnetic material for the flowhead tube and blunt post and the magnetic material for the flexible strip, the fixed post and the core of the pick-up coil. The flexible strip should have sufficient strength so that it can withstand the fluid pressure in the pipeline within elastic limit and the core material should be laminated. The pick-up coils should be designed so that the sensitivity of the instrument is appreciably high.
In the present project, a hard PVC tube of 12 mm internal diameter and 100 cm length with flange connections at both ends was used. The blunt post of obstruction width 8 mm with a triangular cross section, as shown in Figure 6.1, was selected. This post was inserted at the mid position of the flowhead tube.

The flexible magnetic stainless steel strip of width 7.5 mm was used. The fixed post in the reluctance path of the pick-up coils was selected to be the magnetic stainless steel rod of rectangular cross section. The L shaped laminated strip was used as the core material and 500 turn coils of 36 SWG super enameled copper wires were used as the excitation and pick-up coils.

6.4 SIGNAL CONDITIONER

As mentioned in the earlier section, the AC voltage induced in the secondary pick-up coil due to the AC excitation voltage in the primary coil is measured in the proposed vortex flow sensor. The schematic block diagram of microprocessor based inductive pick-up vortex flowmeter is shown in Figure 6.2.

![Schematic diagram of the signal conditioner of an inductive pick-up vortex flowmeter](image)

Figure 6.2: Schematic diagram of the signal conditioner of an inductive pick-up vortex flowmeter
The signal conditioning circuit of the inductive flowmeter was designed as shown in Figure 6.3. The primary inductive coil is excited by sinusoidal alternating voltage of magnitude 5 V AC with frequency 1 kHz. The AC voltage induced in the secondary pickup coil 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 $R_9$. The amplified AC voltage is converted then to DC voltage by precision rectifier using $IC_4$, $D_1$, $D_2$ and $C_3$. $C_3$ and $R_{10}$ are acting as filter circuit of the rectifier block. But there may be DC offset which may affect the output voltage. This can be nullified at the stage $IC_5$ where positive or negative offset can be added to the output DC value. $IC_6$ is acting as DC output signal buffer. The entire circuit is tuned to give output signal 0-5 volt DC from zero to maximum flow of liquid. This output voltage from $IC_6$ is then fed to A/D converter of the experimental microprocessor kit, Micro-friend $ILC\ V2$, supplied by Dynalog Micro Systems, India.

Figure 6.3: Schematic diagram of the signal conditioner of an inductive pickup vortex flowmeter
This model has high performance Intel 8085A CPU operating at 3 MHz, 16 K powerful monitor, Firmware expandable up to 32 K, 64 K user RAM, versatile key board, display controller using IC 8279, in-built 6 digit seven segment display, on board 8 channel ADC and DAC with 8 bit resolution etc., and many other features, which are very suitable for the development system. This microprocessor is used for linearisation of non-linear input, local display of level in engineering unit and generation of linearised DC output analog voltage. This DC output voltage is then fed to IC\(_7\), that is, XTR110, precision voltage to current transmitter IC\(_7\). The output of this section is 4 mA to 20 mA DC that may be used for remote monitoring, recording and controlling purpose. The final output of the flowmeter is 4 mA to 20 mA DC that varies proportionately with liquid flow.

6.5 LINEARISATION

From the experimental results, the characteristic curve obtained by plotting the output voltage against actual flowrate was found to be non-linear. The output signal of the flowmeter requires linearisation. There are various methods available to linearise the signal. Lookup table and piecewise linearisation technique are normally used for microprocessor-based linearisation. In the present project, piecewise linearisation technique by the ILCV2 8085 microprocessor is adopted. A/D converter of 8 bits resolution digitises the analog signal. The operating flowchart of ADC conversion program is shown in Figure 6.4a.

For the entire output against flowrate, an experimentally determined graphical plot was divided into four 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. Therefore, these small piecewise linear zones need modification of their slope and intercept values to fit into desired 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 6.4b and Figure 6.4c. The accuracy of the linearisation depends on the number of zones selected. Higher the number of zones, higher is the accuracy in linearisation.

Figure 6.4a: Flowchart of ADC programming of microprocessor based flowmeter
Figure 6.4b: Main programme flowchart for linearisation of vortex flowmeter
Figure 6.4c: Flowchart continued for linearisation, display and D/A conversion
6.6 EXPERIMENT

The experiment was performed with the experimental setup as shown in Figure 6.5. The flowrate through the pipeline was changed in steps and at each step the actual flow was measured by the direct collection method for a known interval of time and also the corresponding flowmeter output in volts was measured by a 4$rac{4}{5}$ digit TX3 true RMS digital multimeter. The experimental data are shown in TABLE 6.1.

![Experimental setup](image)

**Figure 6.5:** Experimental setup used to study the vortex flowmeter

These experimental data were linearised by the microprocessor using piecewise linearisation technique as explained earlier. The experimental graphs obtained before and after linearisation are shown in Figure 6.6. From the experimental data obtained before linearisation, the bestfit parabolic curve was plotted by using MAT LAB version 6.5 as shown in same Figure 6.6. With respect to the actual
values as per this bestfit parabolic curve, the percentage errors of the observed data are calculated, which are shown in TABLE 6.1. The percentage error curve before linearisation is shown in Figure 6.7 and it is observed that the percentage error lies within tolerable limits.

![Figure 6.6: Characteristics of the vortex flowmeter before and after linearisation](image)

*Figure 6.6: Characteristics of the vortex flowmeter before and after linearisation*
6.7 DISCUSSIONS

The output DC voltage versus flow characteristic of the flowmeter obtained from experiment, as shown in Figure 6.6, indicates that the output voltage non-linearly varies with the flowrate. The experiment was performed repeatedly under the same experimental conditions in both increasing and decreasing modes and almost identical results were obtained. Comparing the experimental graphs as shown in Figure 6.6 with the equations (6.17), (6.18) and (6.24), it may be concluded that the nature of graph \( Y = 0.0099 X^2 + 0.0559 X + 1.0223 \) almost follows the equation (6.24). The percentage error of the measured data from the bestfit parabolic curve is also found to be within tolerable limits. So the proposed modified inductive technique of measurement of vortex flowmeter appears to follow the parabolic curve as shown in equation (6.24). Hence, the assumption that the maximum displacement of the flexible strip is directly proportional to the
flowrate, as shown in equation (6.23), may be assumed to be valid. The technique is very simple and involves low cost of materials. Moreover, the instruments may be designed to have larger life period as compared to other similar instruments.
TABLE 6.1: Experimental data for static characteristic of vortex flowmeter before and after linearisation

<table>
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<tr>
<th>Sl. No.</th>
<th>Water flow (X)</th>
<th>The flowmeter output before linearisation</th>
<th>Output after linearisation</th>
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<td>SET-I (Decreasing)</td>
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<tr>
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