CHAPTER 7
CHAPTER 7

EXPERIMENTAL INVESTIGATIONS TO LOCATE THE OPTIMUM POSITIONS FOR PRESSURE SENSING IN A VORTEX SHEDDING FLOWMETER

7.1 Literature Review of the Vortex Shedding Flowmeter

Studying the geometrical shapes of vortex shedders in conjunction with the vortex shedding phenomenon continues to be an active research area. Igarashi [23] compared the vortex shedding characteristics of six bluff bodies in different cross-sectional shapes and concluded that a circular cylinder with blowing and suction can enhance the quality of the vortex shedding signal significantly. El Wahed and Sproston [24] compared the vortex shedding signals of a number of vortex shedders and Miau et al [25] have developed a T-shaped vortex shedder with the goal of improving the quality of the vortex shedding signal measured. Signal quality and performance have been studied experimentally with various bluff bodies by Bentley and Nichols [26]. To sense the presence of fluctuations induced by the vortex shedding process, one may consider a strain gauge type sensor, flush mounted on the surface of vortex shedder [27] or a piezoelectric sensor accommodated in the bluff body [28]. The flow-past-shedders of rectangular, elliptical and T-shaped cross-section have also been studied [29-31]. Amadi Echendu et al [32] have advocated a new approach, which involves a detailed analysis of the unconditioned signal from the sensor prior to the conventional signal conditioning. The results obtained from this approach open opportunities for the development of alternative signal conditioners and transmitters, which not only enhance the quality of the measurement of output from a vortex flow meter but also make it possible to use the flow meter for monitoring the condition of the plant.

Most of the commercial vortex shedding flowmeters rely on a known relationship between the vortex shedding frequency and the mass flow needing a regular and well-defined vortex structure as well as a shedding mechanism. However in most known current designs, the pressure sensors are included into the bluff body, imposing severe restrictions on the shape of the body. This results in rather irregular pressure signature of the vortex system, leading to problems in the signal processing. Von Lavante E., et al
[33] has numerically investigated the flow about the bluff body in a vortex shedding flowmeter using a Navier-Stokes solver, capable of handling unsteady, compressible and viscous flows in two dimensional and three dimensional geometries. The computations are compared with experimental results obtained by ultrasonic measurements downstream of the bluff body. Several different body shapes are studied, trying to optimize the resulting pressure signature downstream of the body. Conclusions regarding an aerodynamically optimal shape of the bluff body are made.

Experiments were performed to study the response of a vortex flowmeter to structural vibrations due to impulsive forces applied on the pipe. Vortex shedding signals obtained by a piezoelectric sensor embedded in a vortex shedder were examined [34]. Major findings are described as follows. First, by improving the design of the piezoelectric sensor, the sensor sensitivity to structural vibrations could be reduced. Specifically speaking, the noise component due to impulsive force with level upto 13.8 KN could be removed effectively from the output. Second, by applying repetitive impulsive forces on the pipe, characterized by a frequency greater than the vortex shedding frequency, the quality of vortex shedding signals measured was degraded substantially.

The vortex shedding flowmeter is recommended for use with relatively clean liquids, high pressure gases and vapours but is not recommended for high viscosity liquids. S. Goujon – Durand [35] has conducted experiments to study the dependence of the linearity of the vortex meter [36] on the fluid viscosity.

Experimental work has been performed inorder to gain a better understanding of the flow around vortex flow meters in perturbed flow conditions. As part of a larger study, extensive results on the effect of pulsatile flow conditions, with and without acoustic coupling, on the dynamic behaviour and the resulting metering errors have been presented [37]. These measurements were performed on various water tunnels and aerodynamic facilities in rectangular (2D) or circular (3D) tunnel sections incorporating the same bluff body geometry. The 3 D case corresponds to an industrial flowmeter. The measurement techniques consist of flow visualization and image processing, unsteady velocity and pressure measurements, and finally signal analysis. The effect of
Reynolds number, pulsation (frequency and amplitude) and acoustic characteristics of the facility on the lock-on phenomenon were studied and analysed.

A configuration of a ring type bluff body situated in a circular pipe is suggested as a design of a vortex flow meter [38]. Experiments were carried out to test a series of ring-type bluff models. Major efforts are focused upon a group of the ring type vortex shedders whose vortex shedding process is strongly influenced by the presence of the wall. Results obtained suggest the appropriate sizes of rings for which the vortex shedding frequency can be clearly measured either on the pipe wall or at the centre of the pipe.

The fluid dynamics of flow over an axisymmetric bluff body in a circular pipe are surveyed for circular disks and rings. One important feature found is that shedding vortices convecting in the wake may induce flow near the wall in unsteady, periodic motion. This finding indicates that the vortex shedding frequency can be obtained with a sensor situated on the surface of the pipe wall. Guidelines for the optimal sizes of the vortex shedders and the optimal streamwise locations of the frequency sensors are suggested [39].

A new type of vortex shedding meter [40] has been developed, in which the bluff body is in the form of an annular ring with a T-shaped cross section. Because this is axisymmetric it disturbs the flow much less than a transverse bluff body. This leads to a meter which is considerably more repeatable, and hence potentially more accurate, than a conventional vortex meter. It also has excellent linearity, and an exceptionally low pressure drop.

Examination of the performance of a large number of dual bluff body combinations leads to the conclusion that optimum repeatability of vortex shedding may be obtained with combinations satisfying certain basic conditions. Once possible condition is the coincidence of the positions of maximum vortex strength for the individual bluff bodies which made up the combination. J.P. Bentley and R.A. Benson [41] describe the results of a test of the above principle using rectangular bluff bodies.
J.T. Turner et al [42] review the process, stretching over several years and with contributions from several workers, by which an improved body shape for use in vortex shedding meters was designed and tested. A priori knowledge of the fluid mechanics involved in vortex shedding, supplemented by information obtained from observation (flow visualization) and measurement (spectral analysis), was used to direct the design process. Particular attention was focused on stabilizing the vortex shedding so that signal dropout and unnecessary limitations to the operating range could be attacked at their source.

A method of flow measurement is described by J. Coulthard & Y. Yan [43] based on using a vortex wake as a flow tracer shed from a low blockage-ratio bluff body, the velocity of which is measured by cross-correlation. Preliminary comparisons are made between measurements of the vortex shedding frequency and the vortex wake transit time between the two ultrasonic beams to determine the flow rates. Whilst preliminary results are confined to a 50 mm diameter sensing head, there is no upper limit to pipe size using the same suitably extended bluff body.

J Coulthard and Y. Yan [44], investigate the effects of different types of bluff body on the ultrasonic vortex wake transit time measurement technique for flow metering. Comparisons are made between results obtained from three different bluff bodies of low blockage ratio.

M. Takamoto, et al [45] have made numerous measurements of the effects of pipe fitting on vortex shedding flowmeters as a contribution to flow metering standards. A water test line of 150 mm diameter is used in the experiments covering a Reynolds number range of about $2 \times 10^5$ to $10^6$. The effects of six kinds of piping configurations are examined at various upstream straight pipe lengths and all four kinds of liquid vortex shedding flowmeters, which were commercially available in Japan, are tested. The vortex shedding flowmeters are compared with a turbine meter in experiments designed to evaluate reproducibility of measurements. It is found that the magnitude of each installation effect strongly depends on the design of the flowmeter. The experimental results are presented in detail and a table is given of the minimum upstream straight
pipe lengths needed to suppress the effects to <0.5% for each of the tested flowmeters. This can be used as guidance in the installation of vortex shedding flowmeters.

K.AI-Asmi & I.P. Castro [46] have presented a selection of the results of an extensive experimental study of the effects of in-line, periodic flow oscillations on the character of vortex shedding from sharp edged bluff bodies. Attention is concentrated on how oscillation amplitude and the body shape alter the range of reduced velocity, Ur, over which lock-in conditions occur – i.e. conditions under which changes in the upstream mean velocity no longer lead to changes in the vortex shedding frequency. Ur is defined as Uo/Nd, where d is the body cross stream width, Uo is the upstream velocity and N is the oscillation frequency. It is demonstrated that with all other parameters fixed, some body shapes are much more susceptible to lock-in than others. Of the four shapes tested, the two most commonly used in industrial vortex flowmeters (triangular and T-shaped cross sections) are the most likely to suffer from measurement errors due to in-line flow oscillations. The additional effects of high obstacle blockage and small spanwise aspect ratio are also discussed in the context of oscillatory flow.

A.Laneville et.al [47] have reported their experimental investigation on the signal quality of a hot film anemometer located in the vicinity of a vortex flowmeter exposed to different levels of swirling flow.

A passive signal processing technique has been described by Webster et al [48] for the recovery of the frequency of large amplitude oscillatory measurements from interferometric fibre optic sensors. The technique was developed for vortex shedding flowmeters, and was evaluated by them and compared with other signal processing schemes.

Miau, J.J. et al [49] have suggested that the vortex shedding frequency could be clearly sensed by a pressure transducer installed on the pipe wall in the region of the maximum pressure fluctuation. This resulted in a design where the sensor of a vortex flowmeter can be removed from the flow field.
7.2 Experimental Investigations

The photograph of the vortex shedding flowmeter is shown in Fig. 7.1 and that of the bluff body is shown in Fig. 7.2. The schematic of the bluff body is shown in Fig. 7.3. The bluff body is made of brass and has trapezoidal cross section. The experimental setup consisting of a blower, a 150 mm vortex shedding flow meter and the electronic instruments is shown in figure 7.4. The shape of the bluff body, positions of pressure sensing holes and their selection during each set of tests are explained with the help of figure 7.3 and table 7.1. The electronic circuits used in the study set up with the strain gauge sensors is shown in figure 7.5.

7.2.2 Description of instruments used

7.2.2.1 Strain gauge differential pressure transducer

This transducer [Make: 'Sensym', Model : SLPO10DD4; Range : 250 mm Water column] consists of a diaphragm fixed with four strain gauges connected in bridge form. The strain gauge bridge is excited with a regulated 5 volts supply. As a constant voltage excites the sensor, many sensors can be connected to the same biasing source.

7.2.2.2 The Amplifier and Biasing Circuit

The amplifiers are based on AD 625 instrumentation amplifier. No kind of filtering is used in the circuit in order to study the quality of raw signals.

7.2.2.3 The Data Acquisition System (DAS)

The PC based DAS uses computer add-on card having a maximum of 64 channels and a maximum throughput (ie. product of number of channels selected and sampling rate per channel) of 1.25 Mega-samples per second.

The software is prepared using LabVIEW graphical user interface package. The online software configures the DAS card to sample two channels, each at a rate of 2500 samples per second & 2500 samples per channel, and displays the waveforms, power
Fig. 7.1 Photograph of Vortex shedding Flowmeter
Fig. 7.2 Photograph of the bluff body of the vortex shedding flowmeter
Cross-section of Bluff-body

Height of Bluff-body
Vertical spacing of holes on the Bluff-body
Horizontal spacing of holes along the flow axis

Pressure line R of Tube-pair C
Pressure line R of Tube-pair B
Pressure line R of Tube-pair A

Pressure line L of Tube-pair C
Pressure line L of Tube-pair B
Pressure line L of Tube-pair A

Hole A-1-R
Hole A-2-R
Hole C-1-R
Hole B-1-R
Hole A-3-R
Hole A-4-R
Hole A-5-R
Hole A-6-R
Hole A-7-R

Hole A-1-L
Hole A-2-L
Hole C-1-L
Hole B-1-L
Hole A-3-L
Hole A-4-L
Hole A-5-L
Hole A-6-L
Hole A-7-L

Flow axis

Height of Bluff-body
Vertical spacing of holes on the Bluff-body
Horizontal spacing of holes along the flow axis

Fig. 7.3: The Shape of Bluff-body and the Positions of Pressure Sensing Holes
**Table 7.1 Relationship between Test numbers and Tube pairs used in the Vortex meter study**

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Tube Pairs used</th>
<th>IDENTITY NUMBERS OF HOLES (L &amp; R) OPENED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>A &amp; B</td>
<td>Tube Pair A: 3, Tube Pair B: 1, Tube Pair C: *Hole Pair</td>
</tr>
<tr>
<td>Test 2</td>
<td>B &amp; C</td>
<td>Tube Pair A: 1, Tube Pair B: 1, Tube Pair C: 1</td>
</tr>
<tr>
<td>Test 3</td>
<td>A &amp; C</td>
<td>Tube Pair A: 1, Tube Pair B: *Hole Pair, Tube Pair C: 1</td>
</tr>
<tr>
<td>Test 4</td>
<td>A &amp; C</td>
<td>Tube Pair A: 2, Tube Pair B: *Hole Pair, Tube Pair C: 1</td>
</tr>
<tr>
<td>Test 5</td>
<td>A &amp; C</td>
<td>Tube Pair A: 3, Tube Pair B: *Hole Pair, Tube Pair C: 1</td>
</tr>
<tr>
<td>Test 6</td>
<td>A &amp; C</td>
<td>Tube Pair A: 4, Tube Pair B: *Hole Pair, Tube Pair C: 1</td>
</tr>
<tr>
<td>Test 7</td>
<td>A &amp; C</td>
<td>Tube Pair A: 5, Tube Pair B: *Hole Pair, Tube Pair C: 1</td>
</tr>
<tr>
<td>Test 8</td>
<td>A &amp; C</td>
<td>Tube Pair A: 6, Tube Pair B: *Hole Pair, Tube Pair C: 1</td>
</tr>
<tr>
<td>Test 9</td>
<td>A &amp; C</td>
<td>Tube Pair A: 7, Tube Pair B: *Hole Pair, Tube Pair C: 1</td>
</tr>
<tr>
<td>Test 10</td>
<td>A &amp; C</td>
<td>Tube Pair A: 3, Tube Pair B: *Hole Pair, Tube Pair C: 1</td>
</tr>
<tr>
<td>Test 11</td>
<td>A &amp; C</td>
<td>Tube Pair A: 1,4,7, Tube Pair B: *Hole Pair, Tube Pair C: 1</td>
</tr>
<tr>
<td>Test 12</td>
<td>A &amp; C</td>
<td>Tube Pair A: 1,2,3,4,5,6,7, Tube Pair B: *Hole Pair, Tube Pair C: 1</td>
</tr>
</tbody>
</table>

* Hole pair 3 under Tube pair A means vortex sensing holes are A-3-L & A-3-R

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* 1.5kW, 3φ 2850rpm Blower

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**Fig. 7.4: Schematic of Experimental Setup for study of Vortex meter**

[Diagram of experimental setup with labels and dimensions]
Fig. 7.5: Electronic circuits used in the study setup
spectrum and the peak frequency. This software runs continuously and also has provision to save data of 5 seconds, whenever required. The offline software displays the waveforms, power spectrum and peak frequency using the data saved by the online software.

7.3 The Testing Procedure

The sensing holes on the bluff body are selected, by blinding the unwanted sensing holes, and the sensors are fixed. The online software is started, which displays the peak frequency component of the pressure waveform along with the waveform & power spectrum. The blower is started and its inlet is adjusted (by partially closing the suction side of the blower using perforated sheets, which are held in position by the suction force of blower) till the software displays the required peak frequency. Then the software is enabled to save the data of 5 seconds in duration. The procedure is repeated for different peak-frequencies. The relationship between vortex frequency in Hz, flow rate in m$^3$/h and Reynolds number is given in Table 7.2.

<table>
<thead>
<tr>
<th>Vortex frequency (Hz)</th>
<th>Flow rate m$^3$/h</th>
<th>Reynolds No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>1742</td>
<td>2.562E + 05</td>
</tr>
<tr>
<td>115</td>
<td>1532</td>
<td>2.524E + 05</td>
</tr>
<tr>
<td>100</td>
<td>1332</td>
<td>1.959E + 05</td>
</tr>
<tr>
<td>85</td>
<td>1140</td>
<td>1.677E + 05</td>
</tr>
<tr>
<td>70</td>
<td>939</td>
<td>1.381E + 05</td>
</tr>
<tr>
<td>55</td>
<td>728</td>
<td>1.071E + 05</td>
</tr>
<tr>
<td>40</td>
<td>538</td>
<td>7.914E + 04</td>
</tr>
<tr>
<td>30</td>
<td>395</td>
<td>5.810E + 04</td>
</tr>
<tr>
<td>25</td>
<td>329</td>
<td>4.840E + 04</td>
</tr>
<tr>
<td>20</td>
<td>269</td>
<td>3.957E + 04</td>
</tr>
<tr>
<td>15</td>
<td>200</td>
<td>2.942E + 04</td>
</tr>
<tr>
<td>10</td>
<td>136</td>
<td>2.001E + 04</td>
</tr>
</tbody>
</table>

Table 7.2 - The relationship between vortex frequency, flow rate and Reynolds No.

7.4 Test Results and Discussions

12 tests as shown in Table 7.1 were conducted with each test conducted at frequencies (in Hz) of 10, 15, 20, 25, 30, 40, 55, 70, 85, 100, 115 and 130; thus a total of 12 x 12 = 144
waveforms and 144 RMS spectra were captured as shown in Figs. 7.6 to 7.17 and were analysed. The quality factor defined as below

\[
\frac{(B/D)}{(A/C)}
\]

[where \(B\) and \(D\) are RMS value of peak frequency component and overall RMS value respectively of the waveforms from sensor –2; similarly \(A\) and \(C\) are those of waveforms from sensor – 1] was calculated for all the waveforms acquired. Table 7.3 gives the quality factors obtained for each of the 144 tests. With strain gauge sensors connected to the upstream (ie. near to the 40 mm base of bluff body) and down stream (ie. near to the 7.5 mm base of bluff body) sensing positions on the bluff body (refer Tests 1 to 12 in Table 7.1), waveforms from the sensor connected to upstream are having less distortion/noise compared to the waveforms from the other downstream locations. In other words, waveforms obtained from tube pair C are better than those from tube pair B or tube pair A and waveforms from tube pair B are better than those from tube pair A in the critical frequency range of 10 Hz to 40 Hz. At frequencies above 40 Hz the signals are of good quality and shape for processing.

In the test 1 for the port combination A3 & B1 (see Fig. 7.6(a) and 7.6(b)) the quality factor varies from 1.795 to 1.037 for the frequency range of 10 Hz to 40 Hz. The quality factor of value above 1 indicates that the signal waveforms obtained from port B1 are of better quality when compared to those from port A3. In the above test for the frequency range 55 Hz to 130 Hz also the quality factor varies from 1.001 to 1.017.

In the test 2 for the port combination B1 and C1 (see Fig. 7.7(a) and 7.7(b)) the quality factor varies from 1.115 to 1.022 for the frequency range of 10 Hz to 40 Hz indicating that the signal waveforms from C1 are of better quality when compared to those from port B1.

In all the tests with numbers 3 to 12 for the critical frequency range of 10 Hz to 40 Hz the quality factor is above 1 (varies from 1.001 to 2.215) indicating that the signal waveforms obtained from port C1 are of better quality when compared to those from ports A1, A2, A3,A4,A5,A6,A7,A3&A4, A1&A4&A7 and A1 to A7. This implies that multiport pressure sensing (refer tests 10 to 12 in Table 7.1) does not provide any significant
improvement in the quality of the waveforms, hence a single pair of holes is good enough.

The peak amplitudes of RMS spectra from port B1 are slightly higher than those from port A3 in test No. 1 and those from port C1 are also slightly higher than those from ports B1 and A3 (in the test Nos. 2 and 5 respectively) in the critical frequency range of 10Hz to 40 Hz.

Thus from test 1, 2 and 5 we infer that the port B1 is better than port A3 and port C1 is better than port B1 for signal processing in the critical frequency range of 10Hz to 40 Hz.

The quality factor varies from 0.983 to 0.998 for the following port combinations and frequencies.

B1&C1 at frequencies 130 Hz to 55 Hz (Test No. 2)
A6&C1 at frequencies 100 Hz to 70 Hz (Test No. 8)
A7&C1 at frequencies 85 Hz and 70 Hz (Test No. 9)
A all & C1 at frequencies 130 Hz to 55 Hz (Test No.12)

Though the quality factor is very slightly less than one for the above tests it is not of much significance as at frequencies of at and above 55 Hz the wave forms are well developed and are of good quality and shape for signal processing.

If the flow rate is decreased below 10 Hz of vortex shedding frequency, the other frequency components (power supply noise of 50 Hz, blower noise in the order of hundreds of hertz etc.) are dominating.
<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Test No.</th>
<th>Test ID</th>
<th>Flow rate (m³/h)</th>
<th>Peak vortex Frequency in Hz</th>
<th>Quality factor</th>
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<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>A3+B1@130</td>
<td>1742</td>
<td>130.0</td>
<td>1.001</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>A3+B1@115</td>
<td>1532</td>
<td>114.4</td>
<td>1.007</td>
</tr>
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<td>3</td>
<td>1</td>
<td>A3+B1@100</td>
<td>1332</td>
<td>99.4</td>
<td>1.016</td>
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<tr>
<td>4</td>
<td>1</td>
<td>A3+B1@085</td>
<td>1140</td>
<td>85.1</td>
<td>1.017</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>A3+B1@070</td>
<td>939</td>
<td>70.0</td>
<td>1.010</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>A3+B1@055</td>
<td>728</td>
<td>54.3</td>
<td>1.011</td>
</tr>
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<td>9</td>
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<td>24.6</td>
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<td>12</td>
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<td>13</td>
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<td>B1+C1@130</td>
<td>1716</td>
<td>128.0</td>
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<td>1484</td>
<td>110.7</td>
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**Interpretation of Test ID**

For example consider A3+C1@085. A3 before '+' indicates that hole pair A3R & A3L are sensing ports of sensor 1 and C1 after '+' indicates that the hole pair C1R & C1L are sensing ports of sensor 2. @085 indicates that the approximate vortex shedding frequency during the test was 85 Hz.
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Figure 7.6(a): Waveforms and RMS spectra obtained for Test 1 in the vortex frequency range of 130 Hz to 55 Hz
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Figure 7.13(b): Waveforms and RMS spectra obtained for Test 8 in the vortex frequency range of 40 Hz to 10 Hz
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Figure 7.14(b): Waveforms and RMS spectra obtained for Test 9 in the vortex frequency range of 40 Hz to 10 Hz
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Figure 7.15(b): Waveforms and RMS spectra obtained for Test 10 in the vortex frequency range of 40 Hz to 10 Hz
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Figure 7.16(b): Waveforms and RMS spectra obtained for Test 11 in the vortex frequency range of 40 Hz to 10 Hz
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Figure 7.17(b): Waveforms and RMS spectra obtained for Test 12 in the vortex frequency range of 40 Hz to 10 Hz