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ANALYSIS OF THE SENSOR SIGNAL FROM A VORTEX FLOWMETER TOT RECOVER INFORMATION REGARDING THE FLOW REGIMES

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1 Introduction

The paper discusses the effects of non-standard flow regimes on the performance of vortex flowmeters and the methods of analysing the vortex sensor signal to detect the presence of these spurious conditions in the flow, and swirling flow in particular.

This study shows that the amplitude and frequency fluctuations embedded in vortex sensor signals carry much useful information about system conditions and fluid flow regimes which can seriously impair the accuracy of measurement. The necessary signal information can be recovered by analysing the unconditioned raw vortex sensor signal i.e. utilizing data regarding fluctuations in signal amplitude and periodicity.

2 Background

The vortex flowmeter has become established throughout the process industries for the measurement of liquid and gas flows, principally because of its wide rangeability, and its linear relationship between frequency and volumetric flow rate, but also because there are no moving parts liable to deteriorate in service. Furthermore, the same *K* factor applies for liquid and gases.

It has not been generally recognised that the basic characteristics of the primary transducer of the vortex flowmeter are governed by two distinct laws of fluid mechanic. The principal characteristic is the shedding of vortices from a bluff body, to produce a Von Karman Vortex Street, in which the shedding frequency has a nearly linear relationship with the velocity of the flowing fluid.

The vortex street produces an oscillating pressure difference downstream of the bluff body and, provided that the presence of vortices can be sensed reliably, the vortex shedding frequency is described by the Strouhal Number, St, which typically depends on the Reynolds Number being greater than about 10,000.

The most widely used method for detecting the shedding of the vortices involves sensing the change in fluid pressure caused by the transit of vortices past two fixed points immediately downstream of the of the point on the bluff body where they are shed. A differential pressure sensor is widely used but other techniques can be found, such as those in which inductive, capacitance, or strain gauge techniques are used to sense the oscillatory changes in the fluid pressure.

The vortex shedding body itself constitutes a change in the cross section of the conduit in which the fluid is flowing, and the second law governing the behaviour of the vortex flowmeter is that the differential pressure developed across it varies in accordance with Bernoulli's theorem. Hence the pressure drop across the vortex shedding body is a function of the square of the flow velocity as well as the density of the flowing fluid.

However, the vortex flowmeter is very dependent on being able to sense vortices reliably and this, in turn, is influenced by the flow regime in which the flowmeter is operating. Hence the shedding frequency is sensitive to spurious flow regimes such as flow pulsation and swirling flow, as well as to flow regimes where the Reynolds number is lower than about 10,000, which results in an unstable and unreliable sensor signal. In a steady flow regime and when a differential pressure sensor is used to detect vortices, the sensor signal from the vortex flowmeter is characterised by variations in periodicity of as much as ±10% and even wider fluctuations in amplitude.

Nevertheless, the *rms* amplitude V_{rms} of the vortex signal may be calculated by

$$V_{rms} = \sqrt{\frac{\sum_{n=1}^{N} x^2(n)}{N}}$$

where *x(n)* is sampled sensor data, and *N* is the number of sampled data points.

Hitherto, it has been customary to condition the sensor signal so that these amplitude fluctuations are eliminated and only the frequency information is utilised in determining the volumetric flow rate. If however, the amplitude information is recovered, information regarding both the volumetric flow rate and the fluid density can be recovered by applying Bernoulli's theorem.

This study has demonstrated that the effects of flow pulsation and swirling flow on the signal from a vortex flowmeter, in which the vortices are detected by a differential pressure sensor of the piezoelectric type, can be identified by analysis of the sensor signal.. The experimental results show that the response of this type of flowmeter is strongly affected by swirling flow that, depending on the degree of swirl, can cause errors of up to 50% in measured flow rate. However, the presence of swirling flow is detectable by analysing the unconditioned vortex signal.

Similarly, flow pulsation has a significant effect on vortex flowmeter by modulating the sensor signal with the frequency of the pulsation and its harmonics. This causes the vortex amplitude to fluctuate more than for recommended flow conditions, and creates weak harmonics throughout its frequency spectrum. Under extreme conditions, the vortex shedding can be made to lock on to the pulsations.

In all the experimental measurements, the unconditioned vortex sensor signal was sampled at 8 kHz for 16 seconds using an A/D data acquisition card. The data was then stored in digital format and analysed by a signal processing programme to identify the useful features.

3 Flow loop facilities and test conditions

The flow rig at the University of Sussex has three separate flow loops with different line sizes. The 1.5" and 2" loops can be configured in either horizontal or vertical planes, but the 100 mm loop is only available in the vertical plane. The flow loops are built using PVC pipework, some of which is transparent so that, when the flow is seeded, the flow regime can be observed. All the various flowmeters are fitted with adapters for screwed PVC unions, as are all the other in-line components such as bends and elbows, pressure and temperature tapping points, flow diversion valves etc. This facilitates reconfiguration of the flow loops to meet alternative experimental requirements.

The main water supply is drawn from a very large storage tank on the roof of the building about 20 meters above the laboratory floor, providing a static head pressure of 1.20 bar (gauge). However, the flow in each loop can also be accelerated by pumps that are driven by 2-pole motors controlled by individual variable speed drives. Under test, the water is drawn from the storage tank on the roof down to the laboratory where it flows through the loops and is discharged to a large reservoir in the basement of the building, from where it is pumped back to the storage tank, thereby providing a stable head pressure for the flow loops.

In both the 1.5" and 2" flow loops, there are two straight horizontal pipe test sections – a lower and an upper section – where flowmeters can be installed. Laws type flow conditioners are installed close to the start of each of these test sections to assist in developing a fully developed flow profile. They are normally located as close as possible to the start of the straight pipe test sections. An electromagnetic flowmeter and a multi-beam ultrasonic transit time flowmeter are installed in the 1.5" and 2" flow loops respectively, and used as reference meters to monitor fluid flow rates for all measurements. Figure 1 shows the arrangement of a loop.

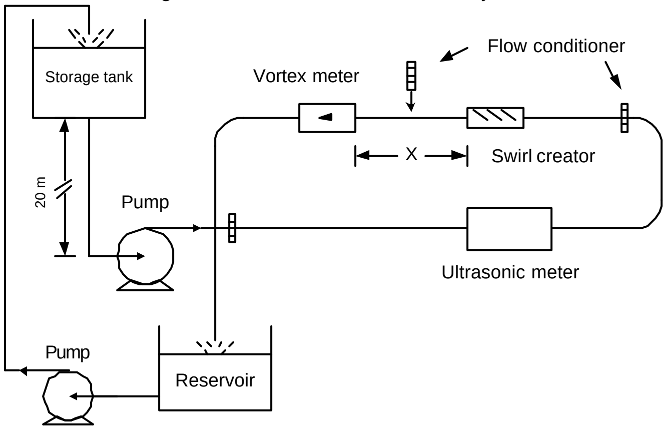

Figure 1. Flow loop diagram

4 Experimental results

4.1 Swirling flow condition

The swirling flow conditions were created by a generator with four fixed blades set at 45° with respect to the axis of the pipe. This was located upstream of the flowmeter under test at different lengths X of 10, 24, 40 and 60 pipe diameters (D) upstream of vortex flowmeter.

The water flow rates were varied in discrete steps in the range from 240 to 450 l/min for each position of swirl generator. A flow conditioner was inserted at 15 D upstream of vortex flowmeter when swirl generator was located at 40 D and 60 D upstream of vortex flowmeter, to demonstrate the effectiveness of the flow conditioner in re-establishing a fully developed flow profile from the swirling flow created by the swirl generator.

A typical vortex sensor signal is shown in the time and frequency domains in Figure 2 . When swirl is introduced into the flow, it has a strong influence on the vortex shedding signal in which signal amplitude decreases and vortex shedding frequency becomes unstable, as shown as examples in Figure 3 and 4.

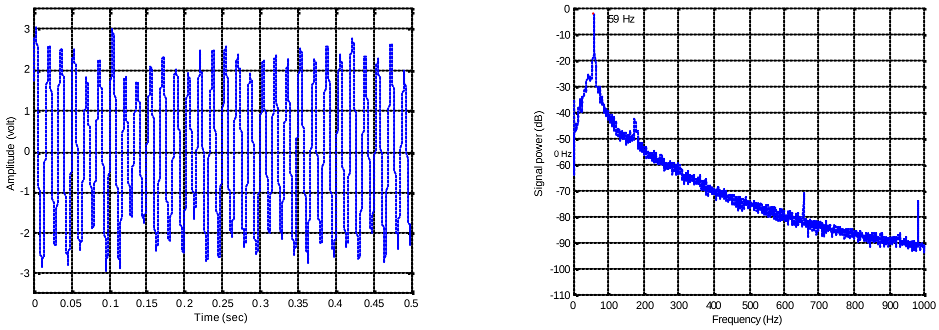

Figure 2. Vortex signal response in healthy condition

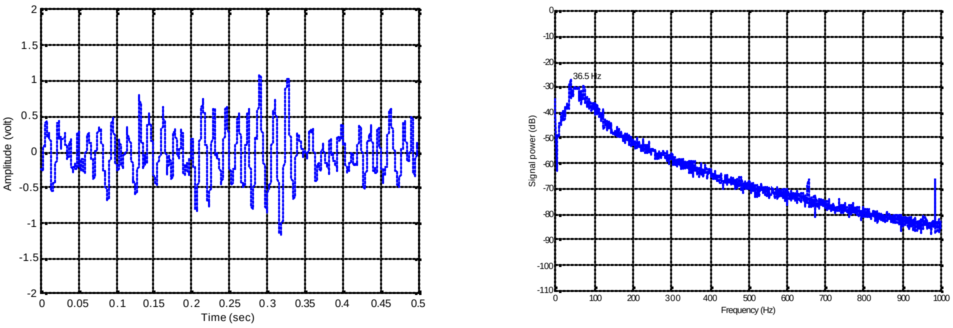

Figure 3. Vortex signal response under swirl condition
(swirl generator at 24 D upstream)

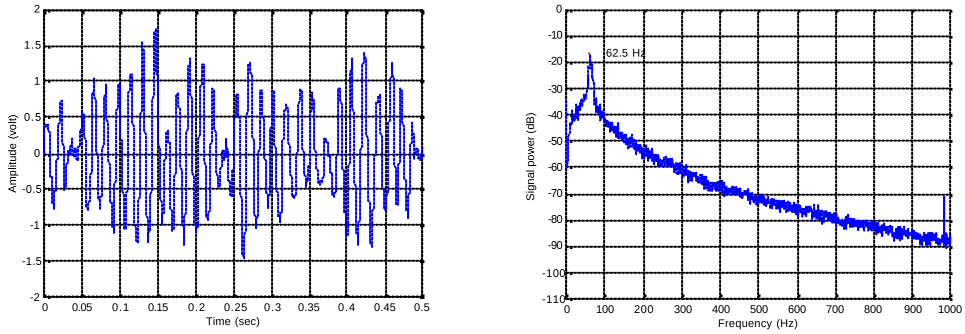

Figure 4. Vortex signal response under swirl condition (swirl generator at 60 D upstream)

Using these examples, the signal analysis techniques can be applied to recover useful information from unconditioned sensor signal. For a range of different swirl conditions, the signal amplitude, the shedding frequency, the power spectrum density, and the maximum power spectrum peak (in both linear and logarithmic scales) can be plotted against water flow rates to provide independent sets of data regarding the effect of swirl as shown in Figure 6 to 8.

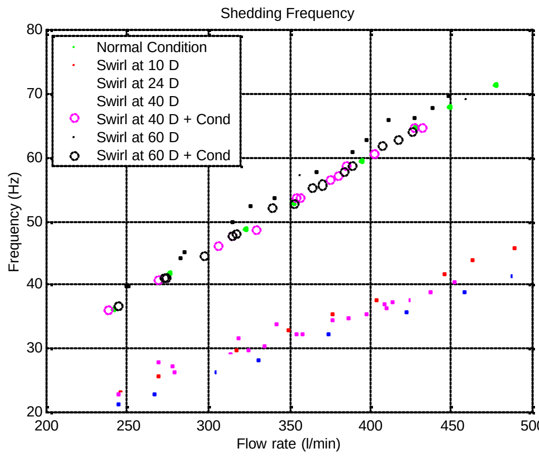

Figure 5. Vortex shedding frequency at different swirl conditions

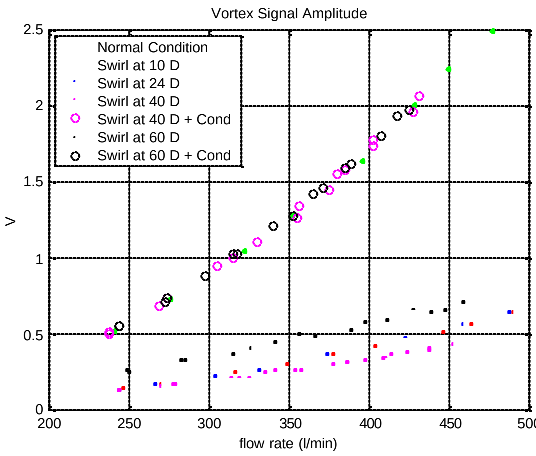

Figure 6. Vortex signal amplitude at different swirl conditions

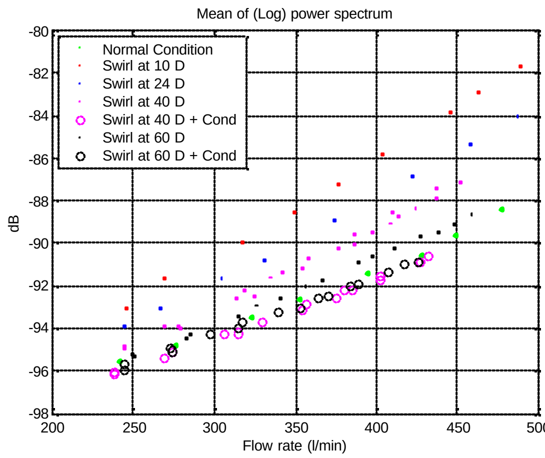

Figure 7. Mean of (log) power spectrum under different swirl conditions

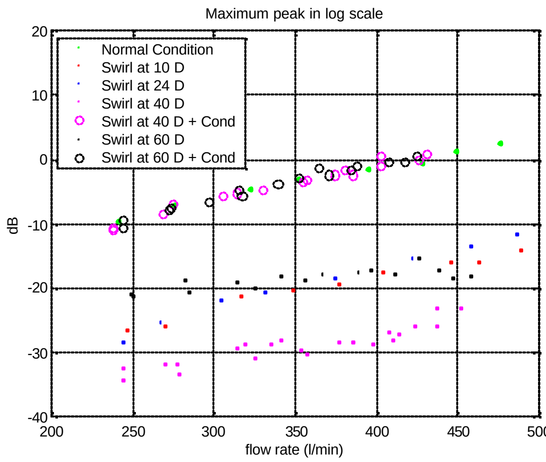

Figure 8. Maximum peak of (log) power spectrum under different swirl conditions

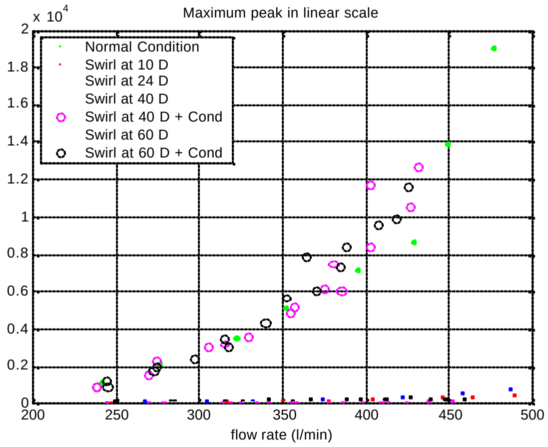

Figure 9. Maximum peak of power spectrum at different swirl conditions

Figures 5 and 6 clearly show that it is possible to discriminate between a healthy flow regime and one in which there is swirling flow by studying two distinct features of the vortex signal, namely the amplitude and the shedding frequency. The presence of swirling flow causes the meter *K* factor to become unreliable although, as shown in Figure 5, if a 60 D length of straight pipe is introduced upstream of the flowmeter, this can help to stabilise the meter *K* factor.

Figure 6 shows that under normal conditions, the vortex signal amplitude has a square law relation with water flow rate according to Bernoulli's theorem, but that if swirling flow is introduced into the flow, vortex signal amplitude will fall away progressively (more than 50%) from the level under normal conditions, even when the upstream pipe meets the recommended length of 60 D. It also shows the ability of the Laws flow conditioner

Figure 7 shows that swirl creates high frequency fluctuations in the vortex signal that can be seen in the increase of noise level in the power spectrum density plots. In other words, it reduces signal to noise ratio (SNR). The increase of noise level can imply that there is a higher degree of swirl present in the flow.

The maximum peak in the power spectrum of the vortex shedding signal in either linear and logarithmic scales (Figure 8 and 9) also identifies the presence of swirl in the flow, compared with a good flow regime, where it falls away progressively from the level for a healthy flow regime to a spurious low value for a non-standard flow regime.

However, the flow conditioner can be used to minimise the effect of swirl, as shown in the test results. Other tests have shown that the adverse effects of asymmetric or distorted flow velocity profiles can be greatly reduced by the inclusion of flow conditioners.

4.2 Pulsating flow

The configuration of the flow loop for tests of pulsating flow is shown in Figure 10. Flow pulsation was induced by a bellows attached to the main conduit by a 'T' piece and driven by an electromagnet over a range of frequencies by an external oscillator and power amplifier. The oscillator was positioned at 40 D upstream of the vortex meter. Using a 1.5" vortex flowmeter in which the vortices were detected by a piezoelectric differential pressure sensor, a series of tests was carried out during which the water flow rate was maintained constant at 175 l/min and the frequency of the flow pulsation was varied from 0 Hz to 140 Hz in discrete steps.

The results for the effect of pulsating flows on both time series and frequency response measurements of the vortex sensor signal are shown in Figures 11 to 16. The influence of the external excitation frequency can be seen clearly in both time and frequency domains. In time series signal, the vortex signal amplitude is modulated by the external pulsation frequency. This can be seen in the signal envelope, especially at low frequency excitation. In the frequency response, there are peaks on either side of the main vortex shedding frequency, for example at 25.25 Hz pulsation frequency there are two distinct peaks, one at 31.5 Hz and the other at 81.75 Hz, on either side of the main shedding frequency peak frequency at 56.75 Hz (Figure 13).

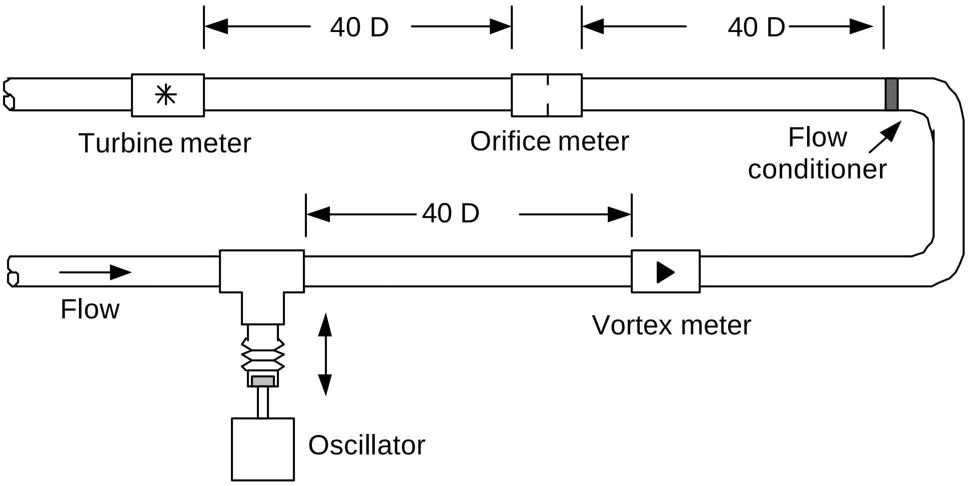

Figure 10. Configuration for flow pulsation tests

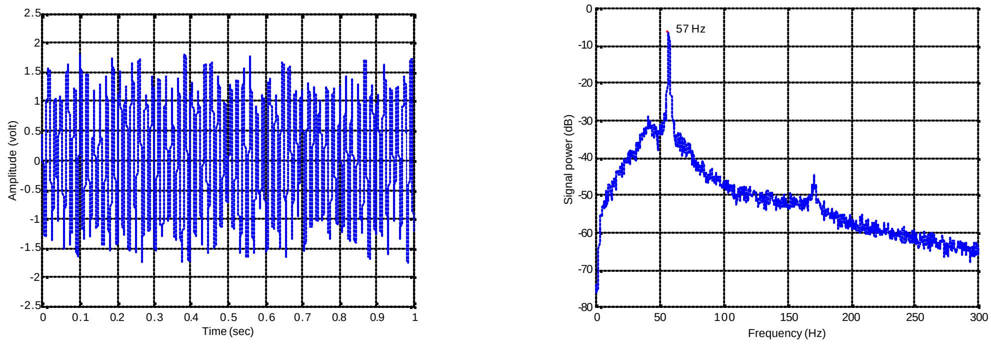

Figure 11 Time and frequency response of vortex signal under normal conditions

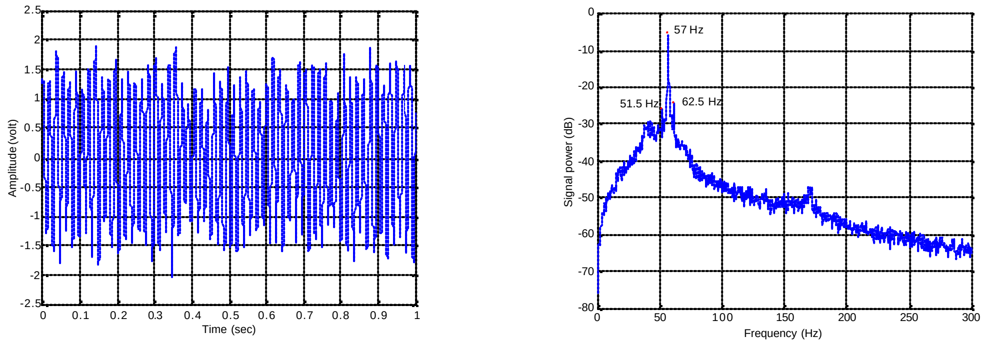

Figure 12 Time and frequency response of vortex signal at 4.5 Hz pulsation frequency

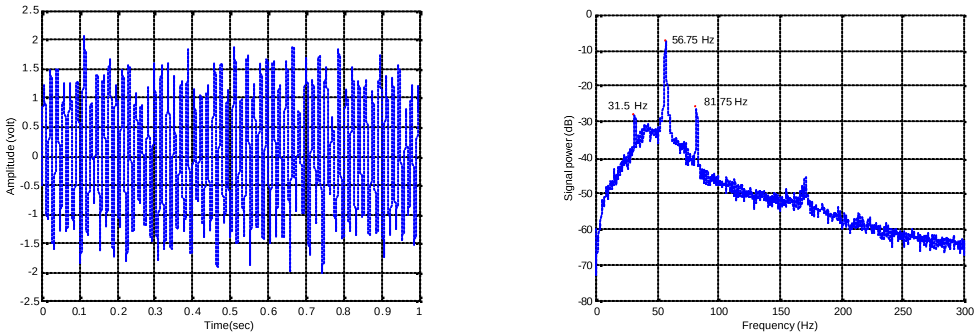

Figure 13. Time and frequency response of vortex signal at 25.25 Hz pulsation frequency

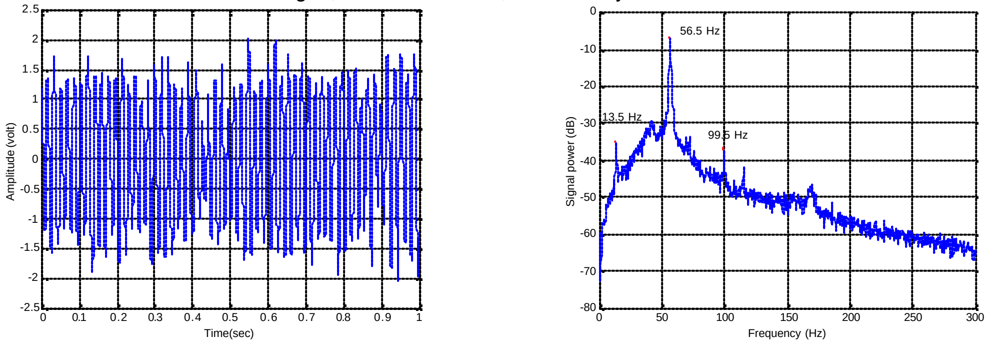

Figure 14. Time and frequency response of vortex signal at 43 Hz pulsation frequency

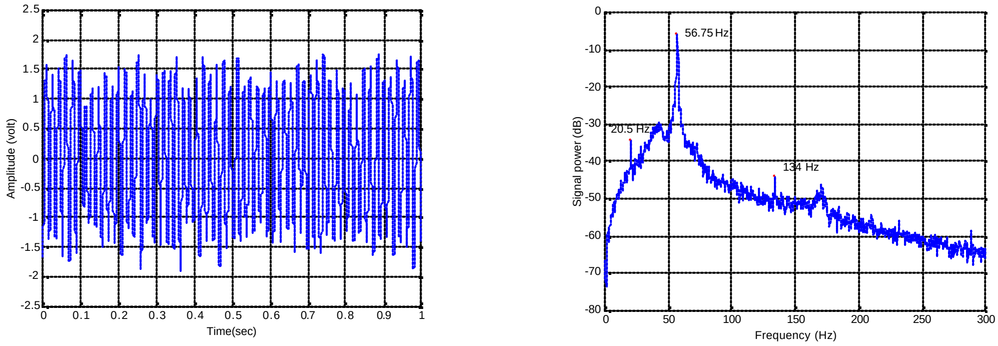

Figure 15. Time and frequency response of vortex signal at 77.25 Hz pulsation frequency

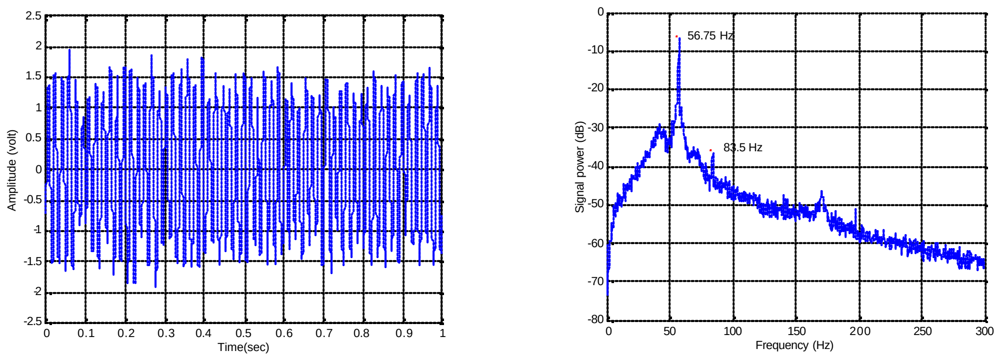

Figure 16. Time and frequency response of vortex signal at 140.25 Hz pulsation frequency

However, the results using power spectrum analysis do not show any strong influence of flow modulation frequency on the main vortex shedding frequency, when compared with the effects on a turbine flowmeter and a orifice plate/differential pressure flowmeter, both of which were installed in series downstream of the vortex flowmeter and therefore exposed to the same flow test conditions [6].

5 Conclusion

This paper shows that the unconditioned vortex sensor signal carries much useful information regarding the flow regime under which the flowmeter is operating. In this context, two non-standard flow regimes – swirling flow and pulsating flow – have been studied. The asymmetric flow profile caused especially by swirl has a very strong effect on vortex shedding frequency. It has been demonstrated that unacceptable errors can arise without any warning in spite of employing the recommended lengths of straight pipe both upstream and downstream of the flowmeter. However, this type of fault can be identified by analysis of the unconditioned sensor signal. The laboratory results show that the amplitude of vortex signal is critically influenced by the presence of swirl in the flow, and results in the shedding frequency becoming unreliable.

Conversely, the results of pulsating flow driven from an external source do not appear to have a significant impact on the vortex signals, including the frequency response of vortex flowmeter. There is, of course, modulation of the main vortex shedding frequency due to the frequency of the imposed pulsation but, when comparing results taken simultaneously from two other different types of flowmeter connected in series in the same test loop and whose measurement data was gathered simultaneously with that from the vortex flowmeter, the influence of flow pulsation seemed to be far more dominant on their sensor signals than on the signal from the vortex flowmeter.

On the other hand, this study did not take account of the signal conditioning provided by manufacturers in their vortex flowmeters and therefore we cannot draw any conclusions regarding the performance of this type of flowmeter under pulsating flow, especially in terms of its measurement accuracy.

6 References

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