

Analysis of the sensor signal from a turbine flowmeter to recover information regarding the flow regimes

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1 Introduction

The paper discusses the identification of turbine flowmeter fault conditions by recovering additional information from the unconditioned sensor signal. Turbine flowmeters are characterised by their high accuracy, excellent repeatability, good linearity and wide operating range.

However, they are very sensitive to the change of flow regime and system conditions, which can degrade the flowmeter performance and, in particular, the accuracy of measurement. Four general fault conditions – erosion or damaged of the rotor blades, swirling flow, pulsating flow and two-phase flow - have been simulated and studied. The laboratory experiments provide very strong evidence that there is much useful information embedded in the sensor signal that can be recovered and used to identify the operational status of the flowmeter.

The experimental results show that additional information regarding attributes and features of flowmeter itself, as well as its operational status and the condition of the flow regime in which it is operating, can be recovered by analysis of the unconditioned sensor signal.

2 Background

The turbine flowmeter is a velocity measuring instrument in which the sensor signal is in the frequency domain. When fluid flows through the flowmeter, it imparts momentum to the rotor causing it to spin. At constant flow rate, the driving torque generated by the fluid impacting on to the blades exactly balances the resistive drag resulting from bearing, viscous and sensor retarding forces. The rotational speed of the rotor is proportional to the volumetric flow rate of the fluid through the meter and, in the majority of cases, rotation of the rotor is sensed electromagnetically. As successive rotor blades approach and pass the sensor, a quasi-sinusoidal signal is generated. This is usually converted into a train of pulses by the associated signal conditioning circuits, so that each pulse corresponds to the passage of a discrete volume of fluid. Variations in the radial length of individual rotor blades are reflected in the amplitude of the sensor signal but they are repetitive and usually small.

The signal from the sensor is nearly sinusoidal but is, nevertheless, rich in harmonics due to the slightly differing geometry of individual blades, so that small changes in the radial length and angular spacing of individual blades generate distinctive pulses, but the pattern repeats itself for each revolution of the rotor. The geometrical differences in rotor blade spacing can be identified by plotting the zero-crossing times for successive pairs of blades and the tiny fluctuations in the groups of these signals represent transient fluctuations in the flow regime. If rotor blade geometry is altered, the effect is immediately apparent in the unconditioned sensor signal.

In this study, the effect of changing rotor blade geometry by reducing the radial length of a single rotor blade first by 0.010, and then by a further 0.010 to 0.020 inches was measured. Then the effect of reducing the length of an adjacent blade by 0.010 inch was observed, after which the length of the blade on the opposite side of the first blade was reduced by 0.009 inch and the effect observed. The effects of these changes is clearly shown in the time series of the sensor signal by the reduction in the

amplitude of the particular pulses generated by affected blades, and also by the appearance of increased amplitudes of the harmonics in the frequency spectrum of the signal compared with the signal of a 'healthy' rotor.

The effect of chamfering the leading and trailing edge of a rotor blade was also studied. Rather surprisingly, the former has little effect on the meter factor but the later has a distinct effect on both the meter factor and linearity.

Disturbed flow regimes have an adverse effect on the performance of turbine flowmeter, but some of these conditions can be detected from the changes in the power spectrum of the sensor signal, although there may be no obvious evidence of the flow distortion in the time series signal.

Pulsating flow has a major adverse effect on the performance of a turbine flowmeter. Modulation of the flow such as that caused by a pump, or a control valve, or oscillation of the pipeline itself, which causes discontinuity in the flow, also modulates the fundamental frequency and all harmonics with spurious frequencies that create distinct peaks around the main peaks in the frequency spectrum. This causes significant measurement error, especially at low frequencies

Swirling flow has strong effect on the performance of a turbine flowmeter, because it applies an additional rotational force that either increases or reduces the torque applied to the rotor, as a result of which the meter reading is either increased or reduced, leading to an inaccurate measurement. This effect cannot be distinguished from a change in flow rate, in either time or frequency domain, but it creates wide variations in the successive crossing time period signals which, in turn, can be identified by an increase in the rms value of the fluctuations.

The introduction of a *second gaseous phase* into a liquid flow has a major effect on the turbine flowmeter performance, due to gas bubbles being carried through the flowmeter and mixed by rotor blades. This strongly disturbs the rotational frequency and introduces significant measurement errors, which may be as high as $\pm 10\%$ even when the fraction of gaseous phase in the system is less than 1%.

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-inch and 2-inch loops can be configured in either a horizontal or a vertical plane, but the 100 mm loop only operates in the vertical plane. The flow loops themselves are built using PVC pipework, some of which is transparent so that, after seeding the flow with small air bubbles, the two-phase flow regimes can be studied. All the in-line components, including the various flowmeters, are fitted with screwed PVC unions, to facilitate reconfiguration of the loop.

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

In both the 1.5-inch and 2-inch 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 as close as possible to the start of the straight pipe test sections, to minimise distortion of the flow profile in the system.

An electromagnetic flowmeter and a multi-beam ultrasonic transit time flowmeter are employed as the reference flowmeters to monitor fluid flow rates for all measurements in 1.5-inch and 2-inch loop, respectively. The flow loop diagram is shown in Figure 1.

The air that is used as the second-phase fluid is taken from the system that provides compressed air throughout the building at a pressure of 8 bar (120 psi). A thermal mass flowmeter, a laminar gas

flowmeter, and a series of variable area gas flowmeters are installed in series to measure gas volumetric flow rate before injecting into the flow.

Two different sets of 1.5-inch turbine flowmeters were tested under pulsating flow and rotor fault conditions, whilst the swirling flow and two-phase flow conditions were studied using a five bladed turbine flowmeter in 2-inch line size.

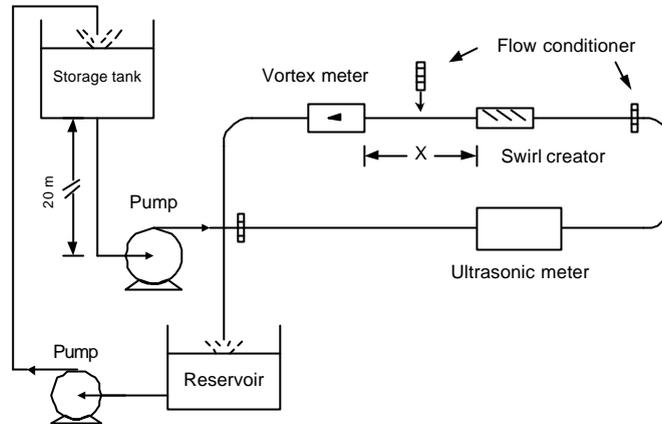


Figure 1. Flow loop diagram

4 Experimental results

4.1 Rotor erosion or damage

A six bladed, ball bearing turbine flowmeter of 1.5 inch line size was used to study the effect of a damaged rotor on turbine flowmeter signal. Four similar sets of rotor were tested - one rotor is kept in original condition and used as the reference (Rotor 1). For the second rotor, the sensor signal was recorded before any change was made. Then the radial length of one blade was reduced by 0.010 inches and the sensor signal was recorded again. Next the radial length of the same blade was reduced by a further 0.010 to 0.020 inches and the measurements repeated. Then the radial length of an adjacent blade was reduced by 0.010 inches and finally the radial length of the blade on the opposite side of the first blade was reduced by 0.009 inches. It is important to note that all these measurements were made on one rotor and therefore the only last test can be repeated. For the third rotor, two blades were chamfered on their leading edges (Rotor 3) and for the last rotor, three blades were chamfered shaped on their trailing edges (Rotor 4). The details of these modified rotors are shown in Figure 2.

A typical turbine sensor signal generated by a healthy rotor condition is shown in Figure 3 in both time series and frequency domains. In general, the waveform of the sensor signal of turbine flowmeter is nearly sinusoidal, but it is rich in harmonics. The amplitude and the width of each cycle are slightly different, depending on the circumferential spacing of the blades, and the pattern repeats itself every complete rotor revolution. It is noticeable that the number of rotor blades is identified by the principal harmonic and the number of its sub-harmonics.

The results from rotor No 2, on which the radial lengths of three rotor blades were reduced, show that there are the significant changes in the signal amplitudes, where the amplitudes of three signal cycles in every six complete cycles are shorter than the adjacent ones, as shown in Figure 3 to 7. From their frequency responses, the width of each peak is seen to be slightly broader than the corresponding peaks for healthy rotor condition, and the amplitude of the sub harmonics is also increased.

The three modified rotors were tested under a preset range of flow rates to determine the effects of each fault on the meter factor. During the test, the same series of flow rate was set from 177 l/min to 358 l/min. The time series and frequency response of other two defect rotors – chamfered leading edges and trailing edges – are shown in Figure 8 and 9.

The effects of the modified contact angles in both leading edges and trailing edges cannot be seen clearly in either the time series signal or frequency response. It is been known that if the trailing edge of rotor blades is modified, it will cause the K factor as well as the characteristic curve of the K factor change.

The K factors of three modified rotors are plotted against water flow rates as shown in Figure 11. It obviously shows that the K factors change dramatically from 98.86 pulse/l (healthy condition) to 100.85 pulse/l (two chamfered leading edges) and 103.04 pulse/l (three chamfered trailing edges) or from 406 Hz to 414.5 Hz and 423.5 Hz, respectively at 246.5 l/min constant water flow rate as shown in Figure 10. Surprisingly, the effect of three shortened radial blade lengths has only a small impact on the K factor, where it is about 0.5% different from a healthy rotor condition, compared with the other two modified rotors where their K factors are found to change by 2 to 5%. (Figure 12)

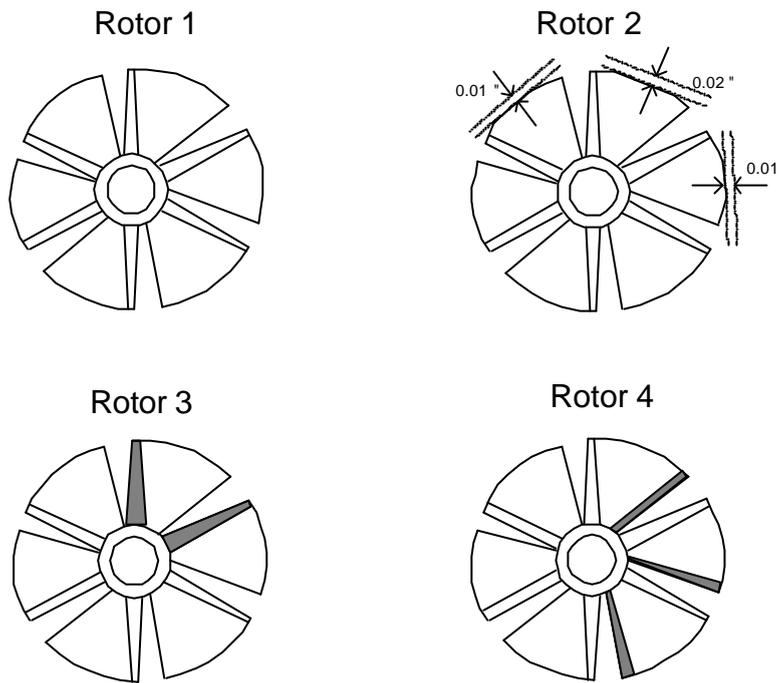


Figure 2. Turbine rotor conditions

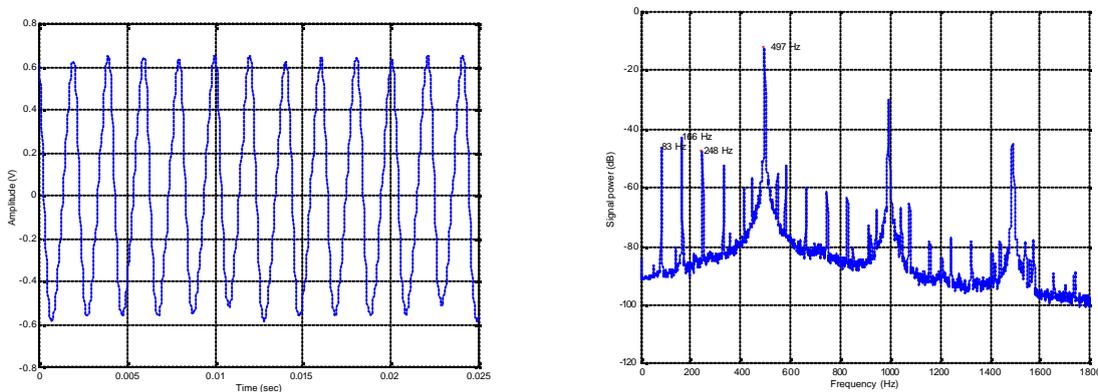


Figure 3. A typical turbine sensor signal with a healthy rotor condition (Rotor 2)

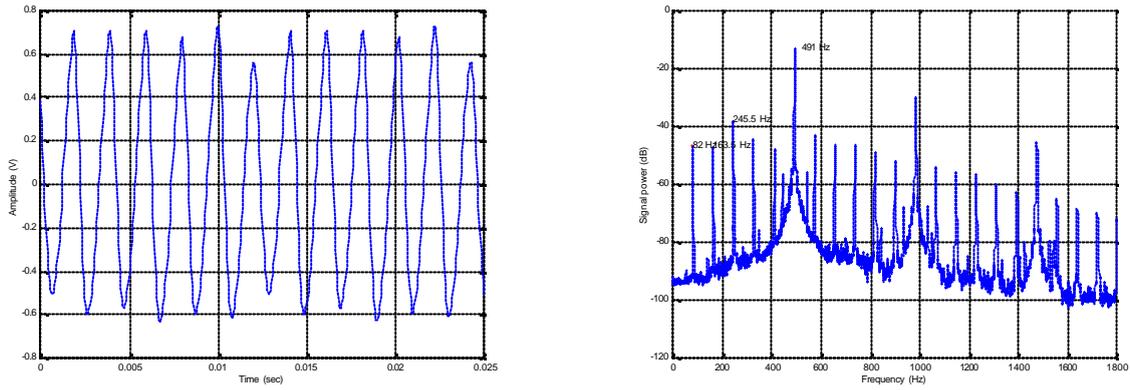


Figure 4. One blade was shortened by 0.010 inches (Rotor 2)

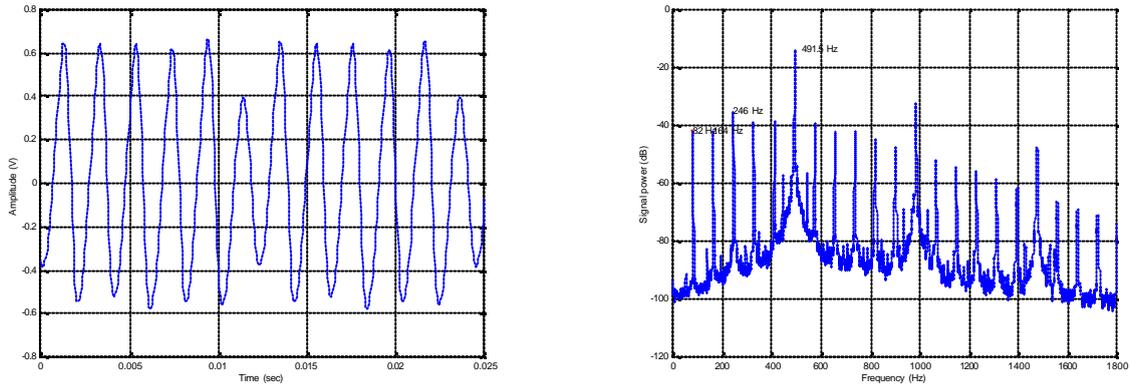


Figure 5. The same blade was shortened further by 0.020 inches (Rotor 2)

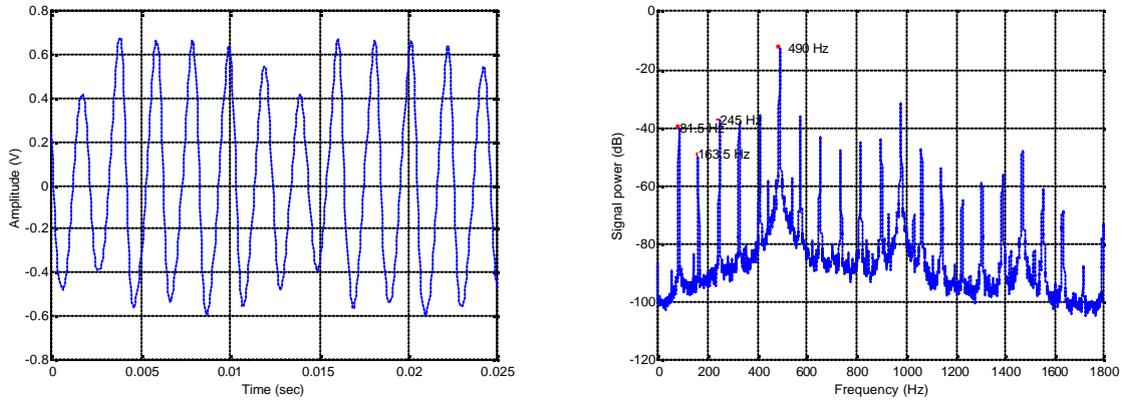


Figure 6. An adjacent blade was shortened by 0.010 inches (Rotor 2)

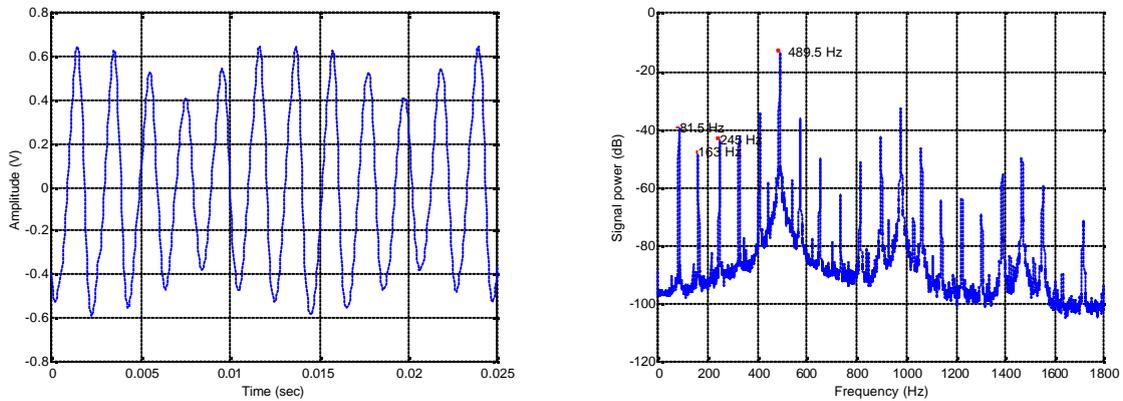


Figure 7. The opposite side of the first blade was shortened by 0.009 inch (Rotor 2)

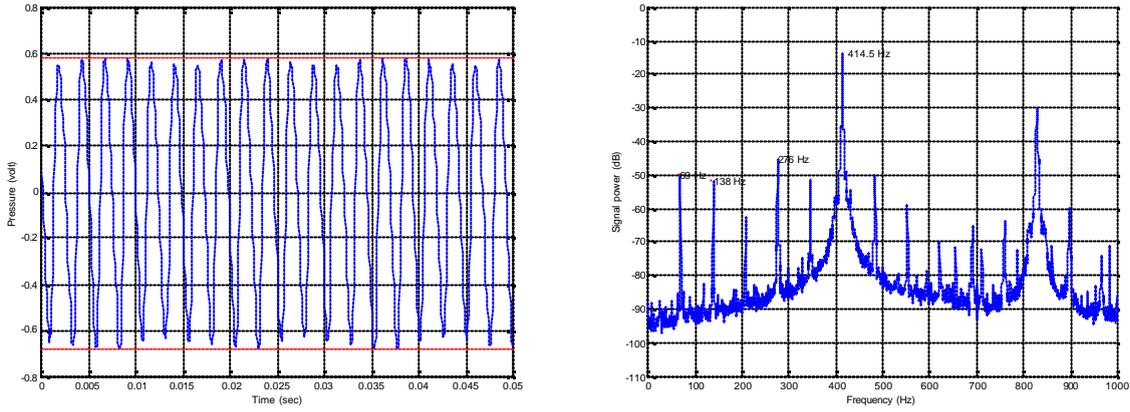


Figure 8. Turbine signal from rotor with two damaged leading edges (Rotor 3)

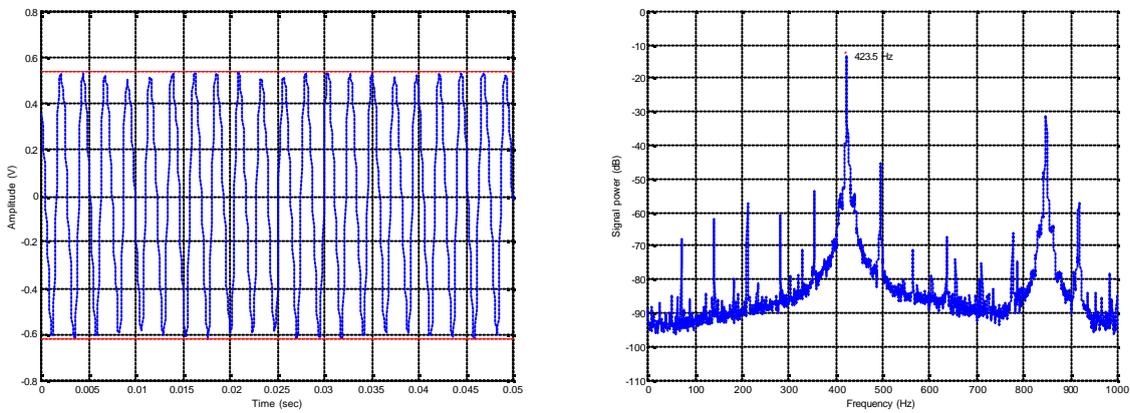


Figure 9. Turbine signal from rotor with three damaged trailing edges (Rotor 4)

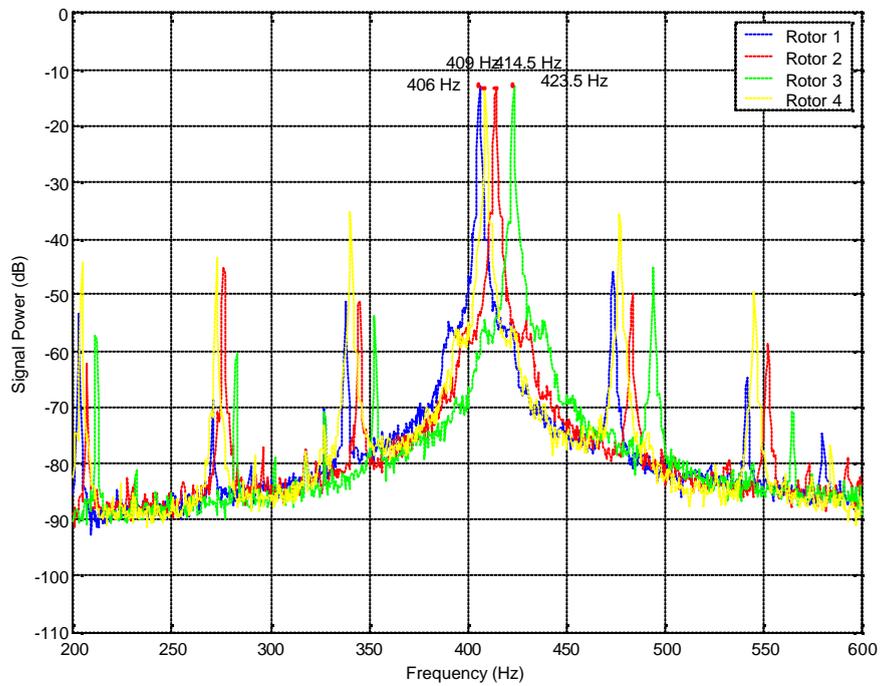


Figure 10. Frequency responses of turbine flowmeter with different rotor conditions

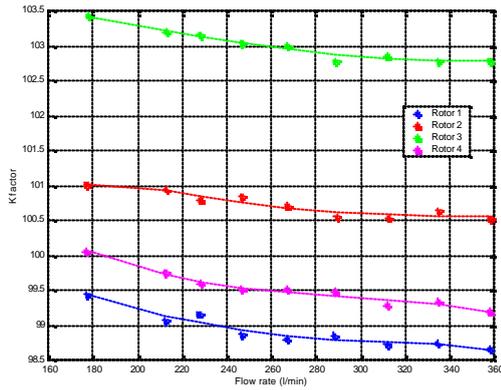


Figure 11. K factor for different rotor conditions

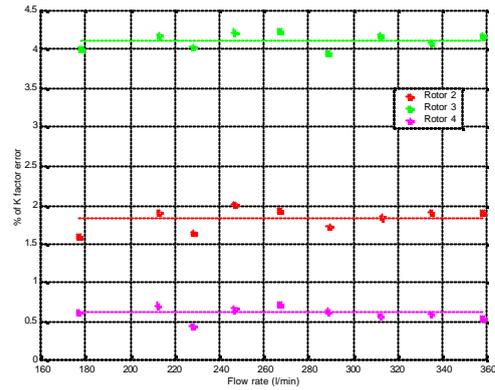


Figure 12. % of K factor deviation

4.2 Pulsating flow

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 flowmeter and the tested turbine flowmeter was installed downstream of an orifice plate flowmeter and separated by a 40 D straight pipe. The test diagram is shown in Figure 13.

A six-bladed 1.5 inch turbine flowmeter was used in these tests. The exciting frequencies were varied in discrete steps from 0 Hz to 140 Hz, whilst the water flow rate was held constant at 175 l/min. The results of pulsating flow on the turbine signal are shown in Figure 14 to 19.

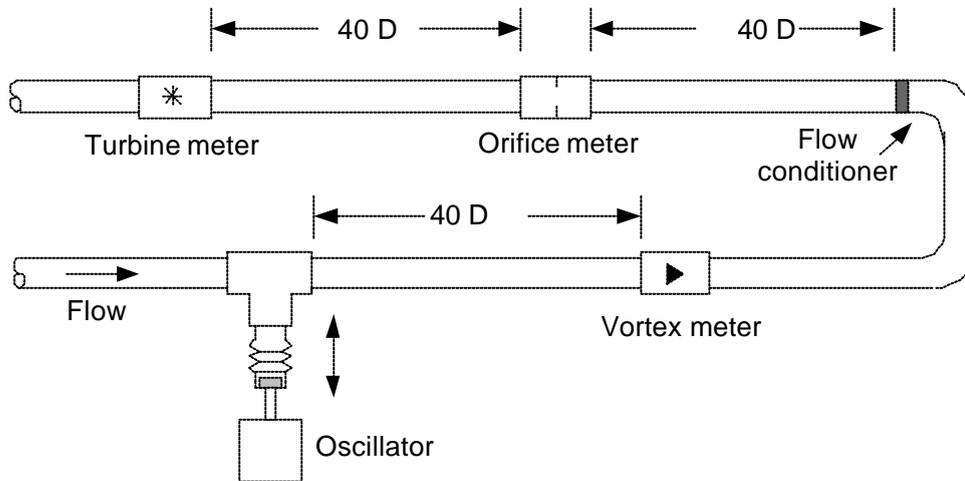


Figure 13. Flow pulsation test diagram

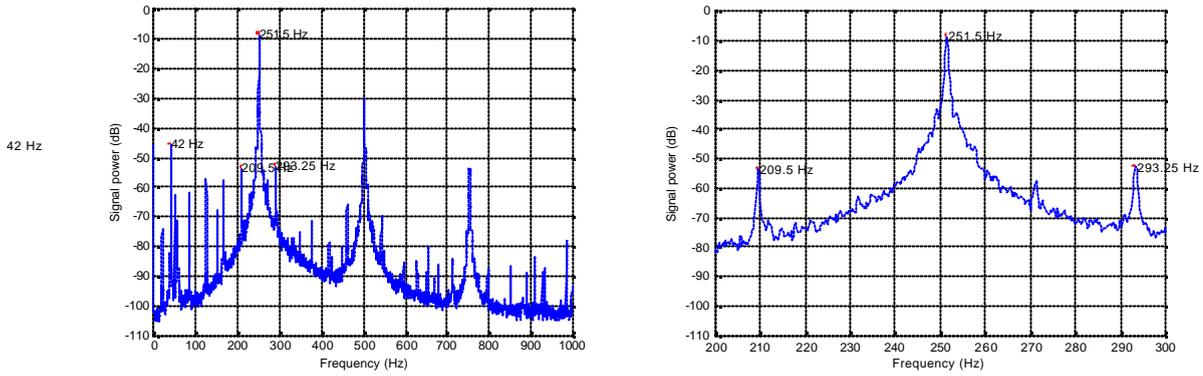


Figure 14. Time and frequency response of vortex signal under normal condition

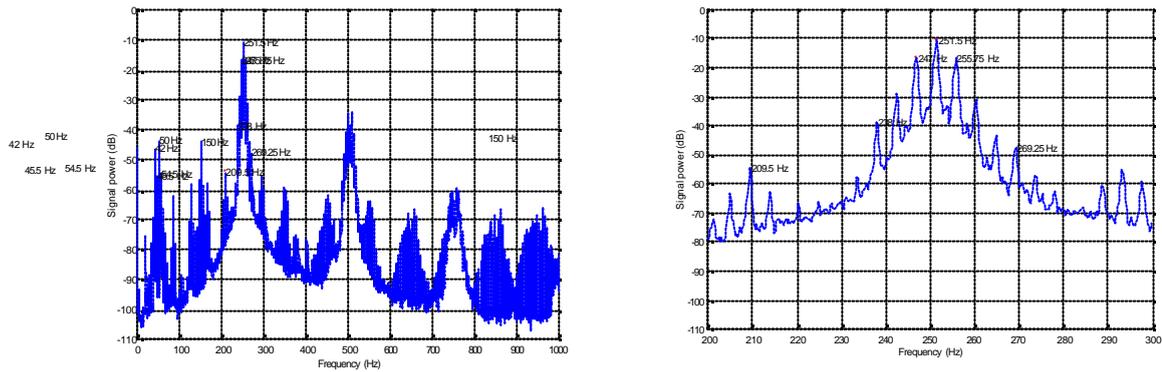


Figure 15. Time and frequency response of vortex signal at 4.5 Hz pulsation frequency

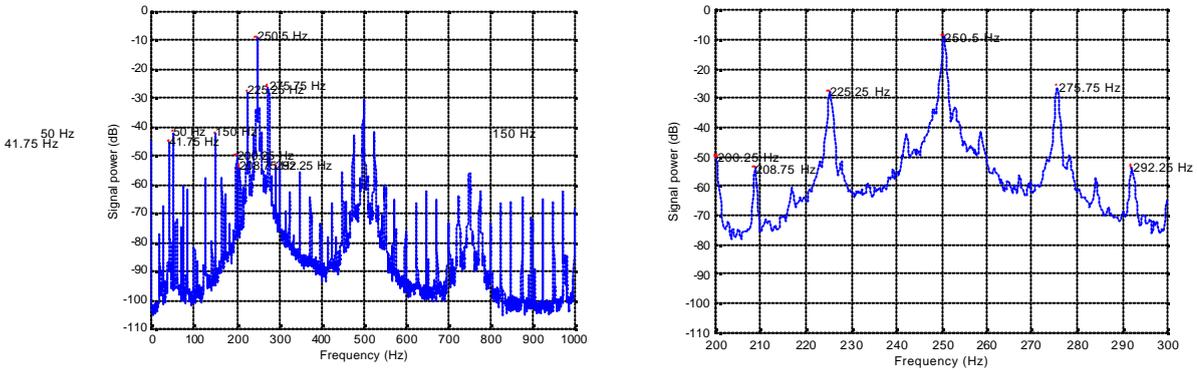


Figure 16. Time and frequency response of vortex signal at 25.25 Hz pulsation frequency

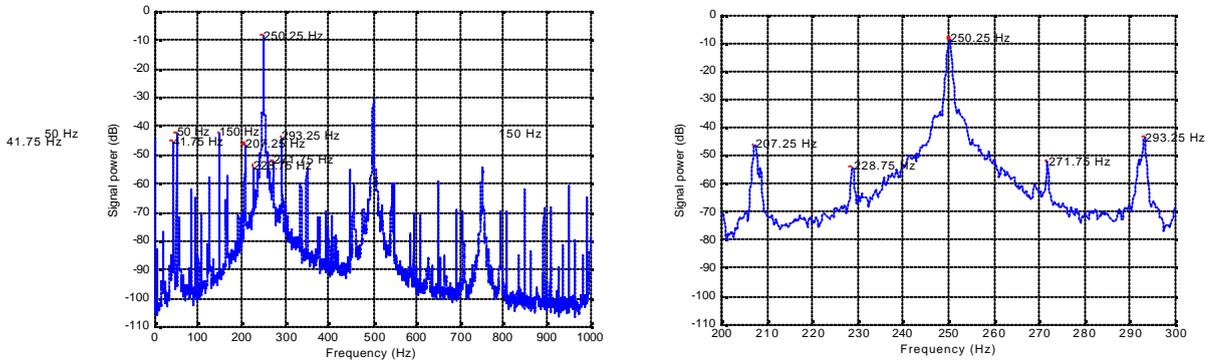


Figure 17. Time and frequency response of vortex signal at 43 Hz pulsation frequency

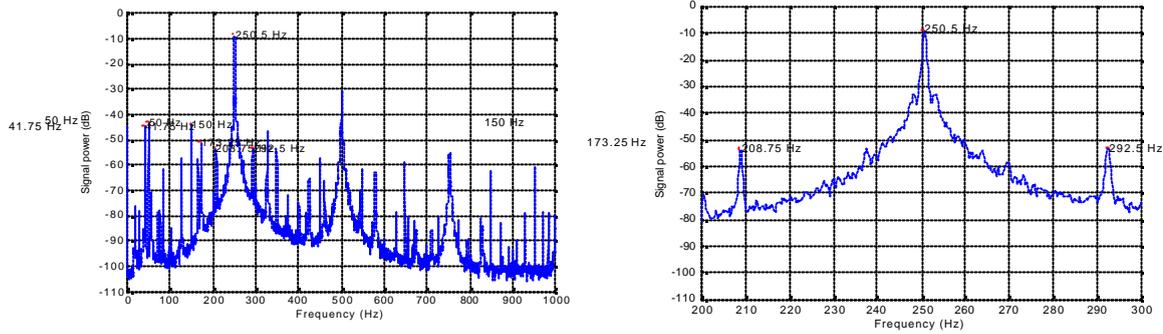


Figure 18. Time and frequency response of vortex signal at 77.25 Hz pulsation frequency

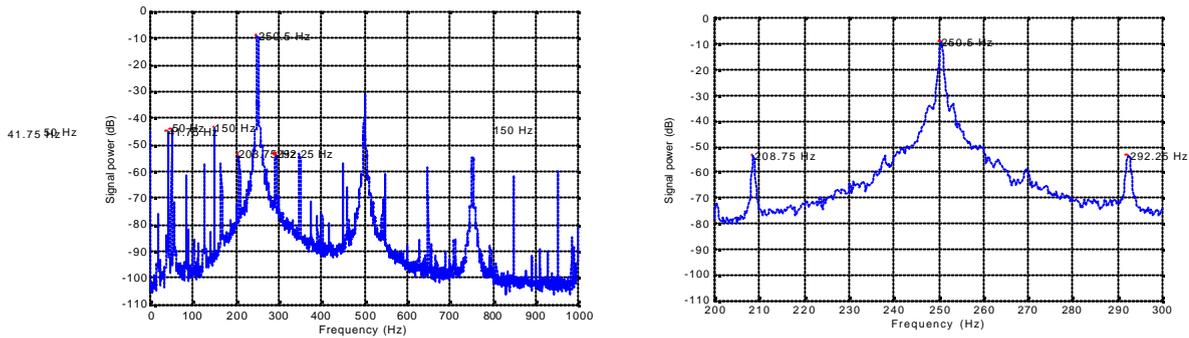


Figure 19. Time and frequency response of vortex signal at 140.25 Hz pulsation frequency

The results show that the basic turbine signal is modulated by oscillating flow, where the modulating frequency can be seen as side bands throughout the frequency response, but particularly around the main harmonics i.e. 1st, 2nd, 3rd ...etc. This clearly shows that low exciting frequencies have a very strong influence on the response of the turbine, where small peaks appear as side bands of the fundamental frequency, leading to an significant measurement error.

However, the presence of this external modulation of the flow can be seen clearly in the plot of the zero-crossing time intervals of turbine signal. As mention in section 4.1, the sensor signal from a turbine flowmeter is nearly sinusoidal, so that the periodicity of the signal can be defined as the difference of two successive zero crossing times. By plotting the successive zero crossing times for each cycle, the variation in the spacing of individual pairs of rotor blades can be identified, as shown in Figure 20 but the pattern repeats itself for every complete cycle of rotor. The tiny variation in the successive groups of zero crossing time intervals identifies the fluctuations in the flow sensed by turbine sensor. Figure 21 shows the plot of the time interval for each complete cycle of rotor i.e. one complete cycle comprising six single pulses for the six blades on the rotor. The time variation caused by flow pulsation is clearly evident.. These results show again that if a low frequency oscillation is impressed into the flow, it causes a very strong variation in the sensor signal as a result of which the measurement to become unstable.

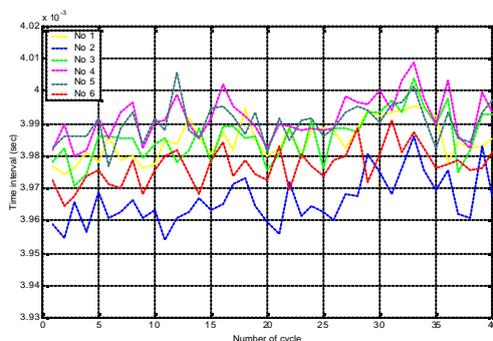


Figure 20. Successive zero crossing time interval from each rotor blade at standard flow condition

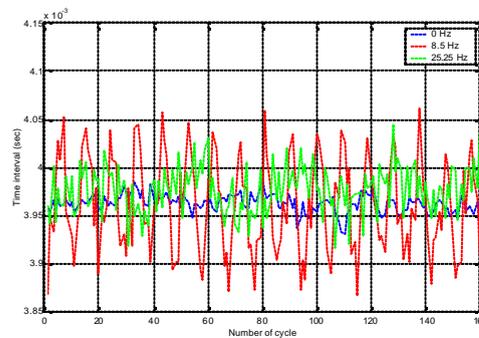


Figure 21. Successive zero crossing time interval of three different exciting frequencies on turbine signal.

4.3 Swirling flow

Swirling flow is another condition which seriously affects flowmeter performance, although the flowmeter itself generates a small amount of swirling flow downstream, as a result of the drag imposed on the rotor by the sensor. Swirling flow directly affects the angular velocity of the rotor and hence the signal frequency, because if the swirl is in the same direction as the rotation of the rotor, the additional torque increases the driving force on the rotor causing it to spin faster. But if the swirl is in the opposite direction, a counteracting force slows the angular velocity of the rotor. Two swirling flow generators were used in these tests. One had fixed blades to create right angle swirl and the other had similar blades but positioned for left hand swirl.

A 2-inch turbine flowmeter with five bladed rotor was studied under swirling flow condition. The two swirling flow regimes were set up where the swirl generators were installed close to and upstream of the flowmeter, as shown in Figure 22. The water flow rates were maintained constant during the tests and monitored upstream by the reference flowmeter. A Laws type flow conditioner was installed 5 D upstream of the turbine flowmeter to demonstrate its ability to greatly reduce the effect of swirl. The frequency responses due to the two different angles of swirling flow are compared with the response in standard condition shown in Figure 23 and the frequency responses of turbine flowmeter with the swirl generator and flow conditioner installed downstream are shown in Figure 24.

The results show that the right-handed swirling flow drives the rotor faster by 17.5 Hz whilst the left-handed direction slows the rotor speed down by 15.5 Hz. The effect of the swirl generators also raised the noise levels. The influence of the swirling flow can also be observed on the successive zero-crossing time period signals, which are shown in Figures 25 and 26.

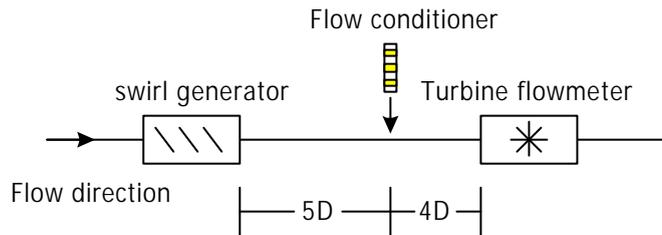


Figure 22. Swirling flow experiment configuration

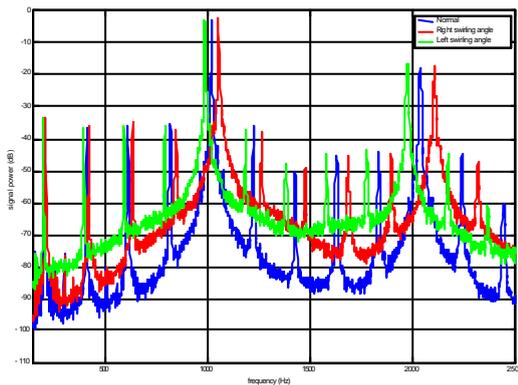


Figure 23. Swirling flow effects on turbine flowmeter

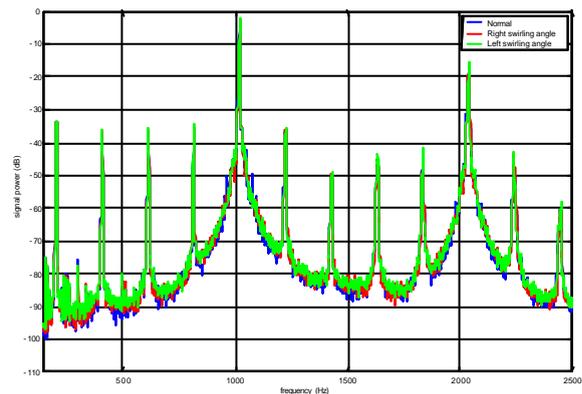


Figure 24. Swirling flows with flow conditioner installed upstream of turbine flowmeter at same water flow rate. The effect of swirling flow is eliminated.

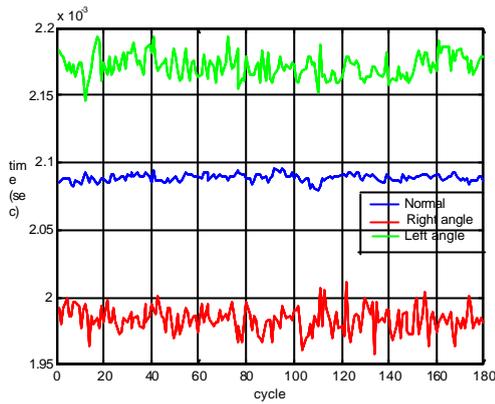


Figure 25. The successive crossing time period of turbine flowmeter under swirling flow condition

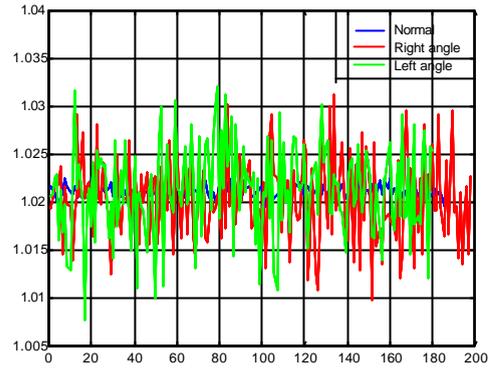


Figure 26. The normalisation of the signal in Figure 25

The plots in Figures 25 and 26 show that swirling flow in either direction causes greater variation in the successive zero-crossing time period signals than those that obtain for standard flow conditions. However, the inclusion of a Laws flow conditioner provides an effective method for reducing swirling flow and restoring a flow velocity profile close to fully developed.

4.4 Two-phase flow

A 1.5-inch turbine flowmeter with six bladed rotor was used to investigate the effect of a two-phase flow regime. To create two-phase flow, the compressed air was injected into the primary phase flow (water) at a point about 25 D downstream of the reference flowmeter and some 15 D upstream of a Laws flow conditioner, which served to mix the two phases. The flow rates of each phase were monitored separately before allowing them to mix. The schematic of the two-phase test system is shown in Figure 27. By the time the mixture reached the turbine flowmeter some 45 D further downstream, the bubbles of air had mostly risen up near to the top of pipe but the turbine rotor mixed them again and created small turbulence downstream of the flowmeter.

In the experiment, the primary flow rate was held constant while measurements were taken for seven different values of air flow rates from 0 to 30 l/min i.e. 0,5,10...30 l/min. Then the process was repeated for six different water flow rates.

From the results, the K factor of the turbine flowmeter was plotted against the primary phase flow rates shown in Figure 28. This clearly shows that, with no second phase present in the main flow, the K factor is likely to be stable over a wide range of flow rates, but when the second phase is introduced into the flow, the K factor progressive increases representing the higher velocity of the mixture flowing in the pipe. Also the main frequency of turbine flowmeter is increased almost in proportion to the increase of second phase in the system, as shown in Figure 29.

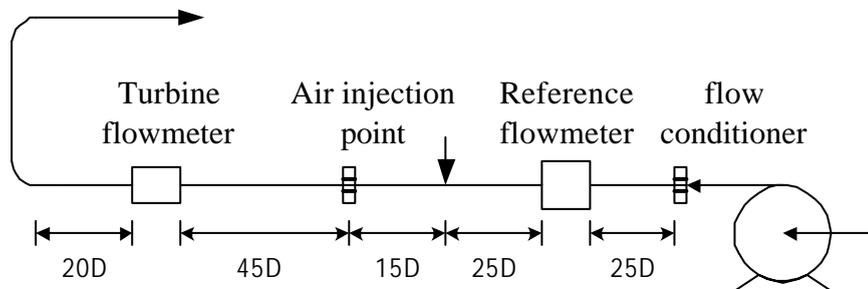


Figure 27. Schematic diagram of the two-phase test loop

The influence of the second phase on the periodicity of the turbine signal enables it to be detected from the increasing irregularity of successive zero-crossing time periods. The successive crossing time periods and the frequency responses are shown in Figure 30 and 31, respectively. The results show that the signal variations follow the increase of the second phase. In other words, higher fractions of second phase present in the flow cause higher fluctuations in the turbine frequency signal. The deviation of successive zero-crossing times can also be seen in the turbine frequency responses, where width of the fundamental frequency and its harmonics are broader and the noise levels rise.

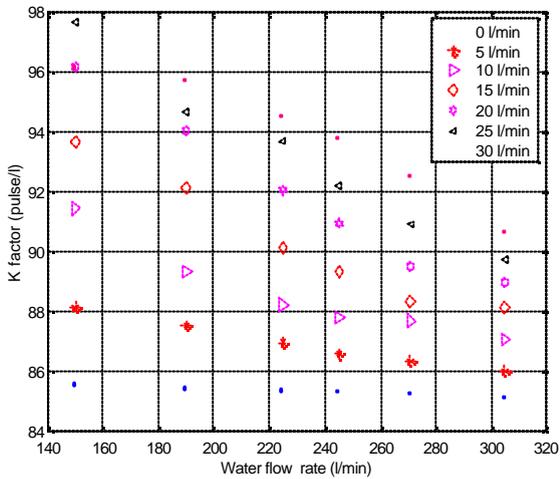


Figure 28. K factor of turbine flowmeter under two-phase flow conditions

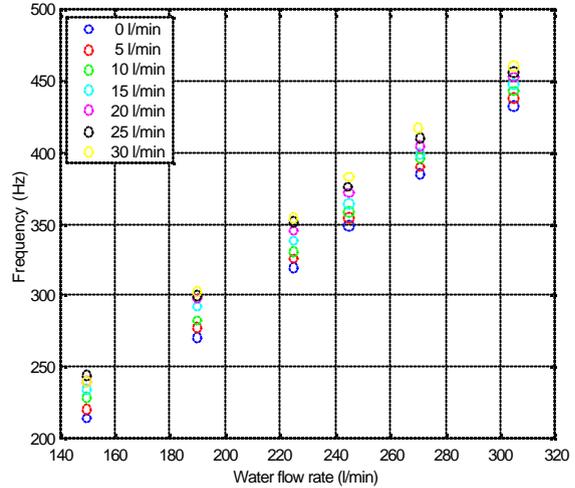


Figure 29. Principal frequency of the turbine flowmeter for different flow rates of the second phase

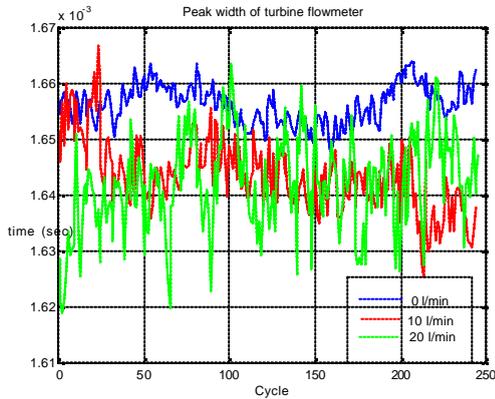


Figure 30. Successive crossing time signals at different flow rates of second phase

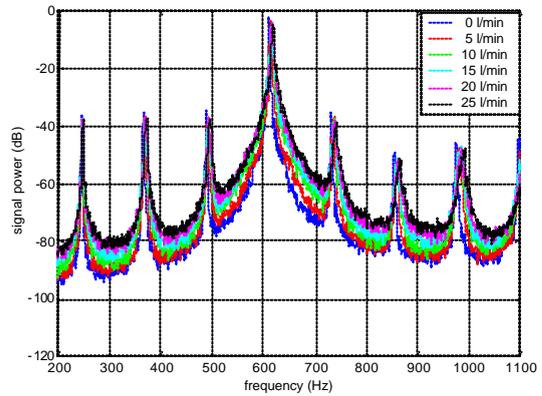


Figure 31. Frequency response of turbine signals with different flow rates of second phase

5 Conclusions

The experimental results show that four typical fault conditions present in the flow regime can cause a significant effect on flowmeter signal and its performance, leading to unreliable and erroneous measurement.

The erosion or damage on rotor blade has a very strong effect on the flowmeter accuracy especially when the trailing edge of the blade has been chamfered.. However these effects cannot be seen clearly in either the time series or frequency spectra. Conversely, the signal from the shortened radial blades is clearly visible in its time series signal but this defect has only a small influence on the meter factor.

Three different flow regimes have been studied, and results show clearly that the turbine sensor signal carries useful information regarding the flow regime in which the flowmeter is operating. All non-standard flow conditions such as swirl and flow pulsation influence its rotational frequency, causing higher fluctuations in successive zero-crossing signal times.

Pulsating flow has a very strong influence on the turbine signal by whereby the external frequency modulates the normal turbine signal, and small peaks appear around the fundamental frequency as well as its harmonics. This can cause a significant error in its measurement, especially at low frequencies, because it is customary in measurement to condition the raw sinusoidal signal into a square wave and then to measure the signal period by electronic counter.

Swirling flow causes the angular speed of the rotor to change, depending on the direction of swirl. This effect is difficult to identify in time series signal but it is clearly shown in the successive zero crossing time signal, where wider fluctuations can be seen.

Two-phase flow (gas-in-liquid) is another condition which degrades turbine flowmeter performance. When two-phase flow is present in the system, the flow velocity is increased causing higher rotational frequency from turbine flowmeter. However, the bubbles of the second phase cause turbulent flow within the rotor and this becomes apparent in the sensor signal. Higher fractions of the second phase in the flow, cause stronger fluctuations and the results suggest that the increase is proportional to the magnitude of the second phase.

6 Reference

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