Two-phase flow measurement based on the analysis of the sensor signal from a conventional vortex flowmeter

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1   Introduction

This paper presents a new technique for measuring the volumetric flow rates of each phase in a two-phase gas-in-liquid flow regime, by analysis of the sensor signal from a conventional vortex flowmeter. The vortex flowmeter has become established throughout the process industry for the measurement of both liquid and gas flows, principally because of its wide rangeability, coupled with a nearly linear relationship between the vortex shedding frequency and volumetric flow rate, plus the fact that it has no moving parts which are liable to deteriorate in service.

In recent years, the measurement of multiphase flow has become increasingly important in the management of oil wells, and there are also many instances in the process industries where it would be helpful to have on-line measurements of this type. It has therefore been the subject of extensive research because virtually all available flowmeters are suitable for measuring only single phase flows, and when a second phase is introduced their performance is seriously impaired and in some instances they may cease to function.

It has been known for some time that the presence of a second phase increases the 'noise' embedded in the sensor signal from the primary transducer of a conventional flowmeters. Hitherto, this has attracted little attention, but recent studies [6, 7] have shown that the introduction of a second phase into the flow increases the range and amplitude of the high frequency components that are embedded in the sensor signal. These high frequency signals carry useful information not only regarding the flow regime in which the flowmeter is operating but also regarding the status of the flowmeter itself, both of which can be recovered by applying well-established analysis techniques to the sensor signal. To be really effective, it is essential to ensure that all the information that is available at the interface between the flowing fluid and the primary sensor is gathered, and that the primary sensor has the widest possible frequency response.

The object of the study is to provide a method of metering two-phase fluid flow using a vortex flowmeter to yield the volumetric (or mass) flow rates of each component. The presence of a secondary phase within a primary phase changes the features of the flow sensor signal. In the case of air being introduced into water flowing at a constant rate, this produces changes in the features of the sensor signal from which the relative magnitude of the two phases in the gas-in-liquid flow regime can be determined.

2   Background

The vortices are generated by the presence of a non stream-line object, known as a "bluff body", placed centrally across the confining conduit in which the fluid flows. As the fluid flows around the bluff body, two distinct wakes are formed known as a Karman Vortex Street which create an oscillatory pressure differences between two sides of bluff body. It has been shown that the vortex shedding frequency is determined by the Strouhal Number, $St = fD/U$, which for a cylindrical bluff body is given

by fD/U = 0.198(1-19.7/Re). f is the vortex shedding frequency, D is the diameter of cylinder, U is the mean flow velocity, and Re is the Reynolds number.

The nature of the Strouhal Number shows clearly that the frequency of vortex shedding is primarily a function of the velocity of the flowing fluid, and is essentially independent of its physical properties such as temperature, pressure, density, viscosity, conductivity etc., provided that the presence of vortices can be sensed reliably. In practice, this depends on the Reynolds Number being greater than about 10,000. The most widely used method of detecting the shedding of the vortices involves sensing the differential pressure at a fixed point downstream but close to the vortex shedding body.

However, it has not been generally recognised that 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 its behaviour is that the differential pressure developed across it varies in accordance with Bernoulli's theorem:

$$P/ \rho g + v^2/2g + z = \text{constant.} \tag{1}$$

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. The volumetric flow rate Q can be determined by $Q = K \times (\Delta P/\rho)^{1/2}$, where ΔP is the differential pressure developed across bluff body, ρ is the density of the flowing fluid and K is a constant.

In a steady flow regime and when a differential pressure sensor is used to detect the vortices, the sensor signal from the flowmeter is characterised by variations in periodicity of as much as ±10% and even wider fluctions in amplitude. It is customary, therefore, to condition the sensor so that these fluctuations are eliminated. For a typical vortex flowmeter operating in a single-phase fluid, the frequency of the vortex shedding is proportional to the volumetric flow rate Q, and the average amplitude A_0 of the vortex sensor signal increases as the square of the volumetric flow rate i.e. $A_0 = \alpha Q^2$, where α is a constant.

Laboratory tests on a flowmeter of this type, positioned so that the fluid flow is either vertical or horizontal, have revealed that the amplitude of the vortex-shedding signal is strongly dependent on the fraction of the second phase present in the flow. Before the flowmeter can be used to measure the flow rates in these regimes, it has to be calibrated for a series of flow rates throughout the operating range of the primary phase flow, and at each of these flow rates, a further set of calibration points must be obtained to identify the influence of the secondary phase flow.

Such a calibration, carried out for gas-in-liquid flow regimes, yields graphical data on the measured signal features from which the presence of single or two-phase flow can be identified, and the magnitude of the volumetric flow rate of the primary phase flow in single component flow, or the volumetric flows of both components in two-phase flow determined.

3   Flow rig and flow facilities

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 a horizontal or a vertical plane, but the 100 mm loop is only available in the vertical plane. The flow bops are built using PVC pipework, some of which is transparent so that after seed the flow with small air bubbles two-phase flow regimes can be studied. All the components including the various flowmeters are interconnected using screwed PVC unions. The main water supply is drawn from the very large water storage tanks on the roof of the building about 20 meters above the laboratory floor providing the static head pressure of 1.20 bar (gauge). Under normal operation, 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. However, the flow in the 1.5" and 2" loops can also be accelerated in each flow loop by pumps which are driven by the 2 pole motors, rated at 5.5 kW and 7.5 kW respectively and controlled by individual variable speed drives. The 100 mm loop is installed in a separate vertical framework, 3 meters high, with the various types of flowmeters located centrally within the framework and interconnected by sections of transparent acrylic pipework using flanged connections. The water is supplied to this loop via either the 1.5" or the 2" loop.

Laws type flow conditioners [2] are used to minimise flow profile distortion in the system. They are normally installed as close as possible to the start of the straight pipe test sections. A horizontal loop diagram is shown in Figure 1. An electromagnetic flowmeter (4) is employed as the reference flowmeter to monitor the liquid flow rate for all measurements. The main reasons for using this type of flowmeter is that it has (i) a linear characteristic (ii) wide rangeability and (iii) does not disturb the flow regime.

The air that is used as the second-phase fluid is taken from the system that provides compressed air throughout the building at pressure about 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 injection into the flow. The diagram of the air supply system is shown in Figure 2.

The air injection point (5) is located at a distance of about 20 D further downstream of the EM flowmeter (4), to minimise any disturbance to the reference flowmeter. A straight pipe section of about 45 D is provided between the air injection point and the flowmeter under investigation (6) to allow the flow profile of the mixture to develop before it flows through the flowmeter. In this system, an additional flowmeter can be tested simultaneously if it is installed in the upper section of the loop.
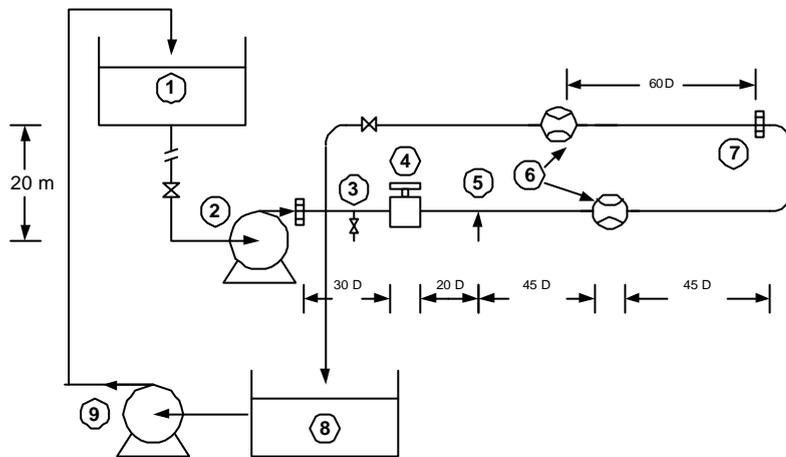
1. Storage tank
2. Accelerate Pump
3. Draining point
4. EM flowmeter (Reference flowmeter)
5. Air injection point
6. Tested flowmeter
7. Flow conditioner
8. Reservoir
9. Return Pump

Figure 1.   Flow rig diagram
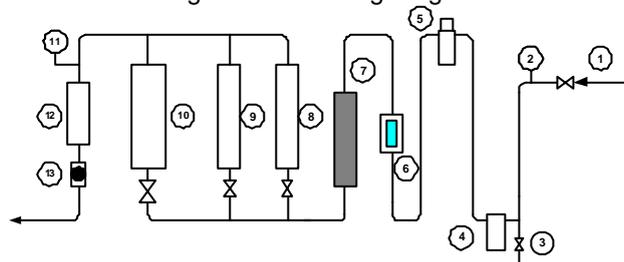
1. Input pressure
2. Pressure gauge
3. Draining valve
4. Pneumatic water drain
5. Filter and regulator
6. Mass flow meter
7. Laminar flow meter
8. Variable area air flow meter 5 L/min max
9. Variable area air flow meter 25 L/min max
10. Variable area air flow meter 200 L/min max
11. Pressure gauge
12. Transparent pipe
13. Non return valve

Figure 2.   Air supply system

4   Experimental results

A typical vortex sensor signal and its frequency response are shown in Figure 3 and 4, respectively. The first experiment was to test vortex flowmeter response under a single phase (water) fluid flow. A 1.5 inch vortex flowmeter with differential pressure sensor was installed in series with an electromagnetic flowmeter acting as the reference flowmeter. Water flow rates were varied from the maximum flow rate of 343.6 l/min down to 8.10 l/min. The shedding frequency of the vortex signal is determined by the maximum peak of its power spectrum. The frequency responses of the vortex signal at different water flow rates are shown in Figure 5.
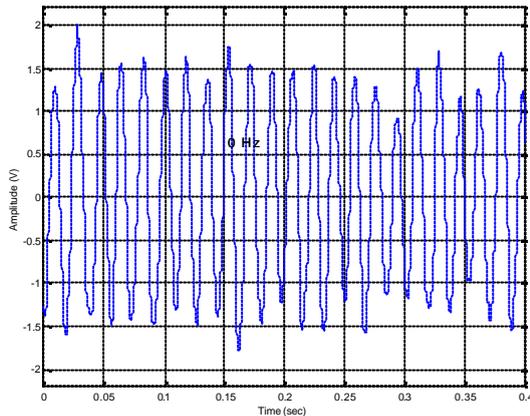
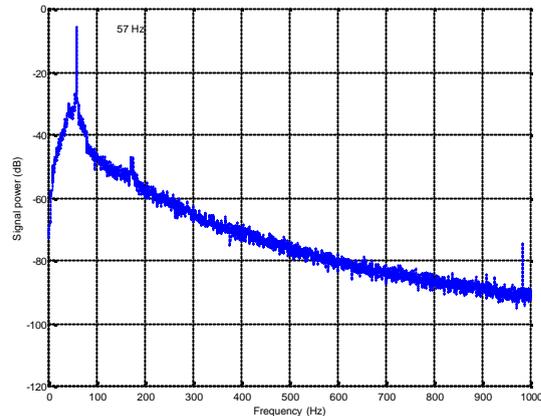Figure 3.   A typical vortex shedding signal   Figure 4.   Frequency response of vortex
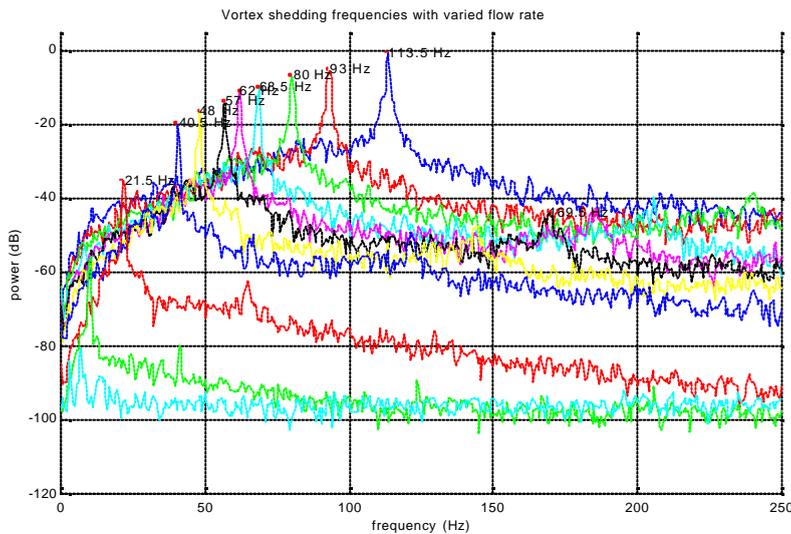
Figure 5.   Variation with liquid flow rate of the power spectrum of a vortex flowmeter

The amplitude of the vortex signal, which represents the oscillating differential pressure across the bluff body caused by the shedding of vortices, exhibits a square law relation with volumetric flow rate. Bernoulli's law implies that the differential pressure across the bluff body of the vortex flowmeter is equivalent to the differential pressure across the orifice plate/differential pressure at the same beta ratio. However, the vortex flowmeter is a fluidic oscillator and vortex shedding is strongly influenced by the flow regime in which it is operating. Even with a steady flow, the amplitude and periodicity of the sensor signal is not constant but varies irregularly. This fluctuation makes the signal amplitude less reliable for calibration than shedding frequency. The average amplitude of vortex signal can be calculated by $A_0 = \alpha Q^2$. However, it is highly dependent on the physical properties of working fluid and sensor characteristic. Alternatively, the rms amplitude can be calculated directly from the sampled data, where the rms amplitude is defined as

$$x_{rms} = \sqrt{\frac{\sum\limits_{n=1}^{N}\left(x(n) - \overline{x}\right)^2}{N}} \tag{2}$$

where N is the number of sampled $x(n)$. and $\overline{x}$ is mean of $x(n)$

From Bernoulli's theorem, the mass flow rate (W) of the working fluid can be calculated by

$$W = k_1 \times (\Delta P \times \rho)^{1/2} \tag{3}$$

The volumetric flow rate measured by the vortex flowmeter is

$$Q = k_2 \times f \tag{4}$$

and the mass flow rate is $\qquad Q = k_2 \times f$

$$W = Q \times \rho = (k_2 \times f) \times \rho \tag{5}$$

Substituting for W from Equation (5) to Equation (3) yields

$$W = k_3 \times (\Delta P / f) \tag{6}$$

where k_1, k_2 and k_3 are constants.

Equations (3) and (6) show that fluid mass flow rate can be calculated either by the square root of the differential pressure multiplied by the liquid density or by dividing the differential pressure by the shedding frequency of the vortex flowmeter.

Figures 6 and 7 demonstrate results from Equations (3) and (6), respectively. The vertical scales differ due to the different calibration constants k_1, k_2 and k_3.
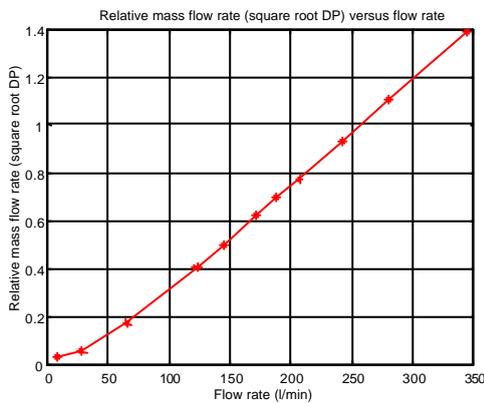

Figure 6. Relative mass flow rate $[(\Delta P \times \rho)^{1/2}]$ versus single phase fluid flow rate
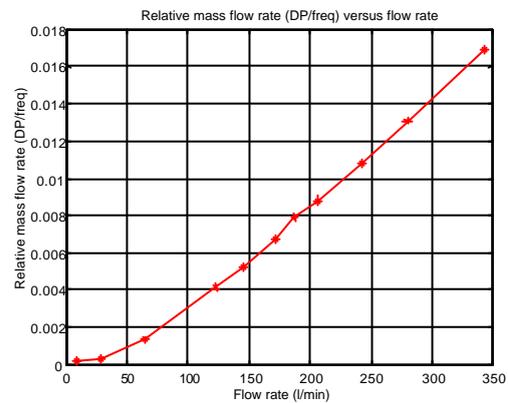
Figure 7. Relative mass flow rate $[(\Delta P / f)]$ versus single phase fluid flow rate

The next experiment was to determine the response of the vortex flowmeter under two-phase flow. To create two-phase flow, compressed air was used as the second phase component and was injected into the primary phase (water) at about 60 D upstream. A Laws flow conditioner is installed close to the air injection point downstream 15 D for mixing purposes. The flow loop diagram is shown in Figure 8. The flow rates of each phase were monitored separately by the reference flowmeters before mixing. The air flow rate was adjusted in steps from 0 to 25 l/min while the water flow rate was held constant. The measurements were then repeated with same set of air flow rates but with the four different water flow rates. Vortex signals were collected over 16 seconds with 8 kHz sampling frequency for each two-phase flow condition. The *K* factors at different phase fractions are plotted against liquid flow rate in Figure 9.
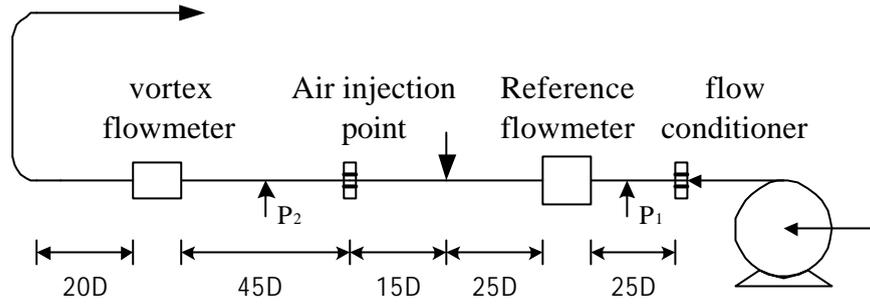
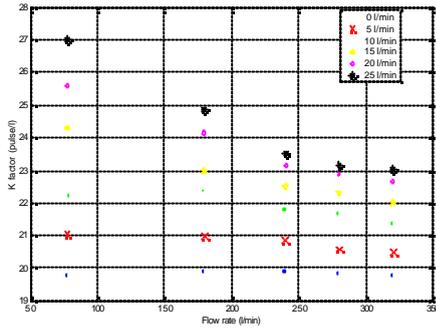Figure 8. System configuration for vortex flowmeter experiments

Figure 9. *K* factor of vortex flowmeter under two-phase conditions
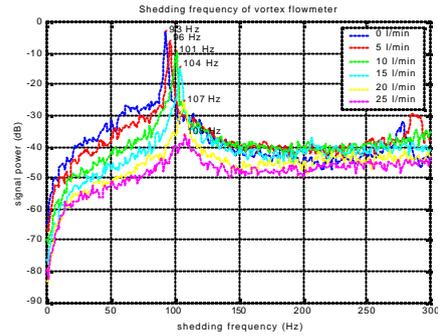

Figure 10. Change in the amplitude and frequency of the vortex sensor signal resulting from the introduction of a second fluid phase (air)
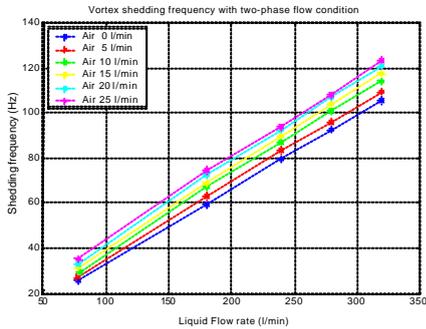

Figure 11. Change in vortex shedding frequency with flow rate of the primary phase (water) resulting from the introduction of the second phase (air)
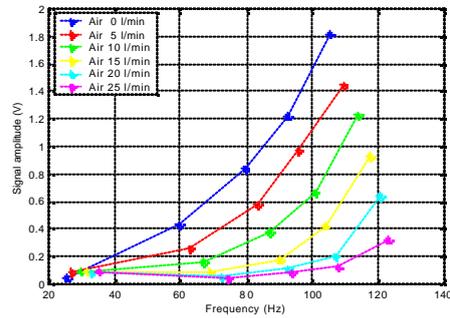

Figure 12. Change in amplitude of the vortex sensor signal with flow rate of the primary phase (water) and the introduction of a second phase (air)
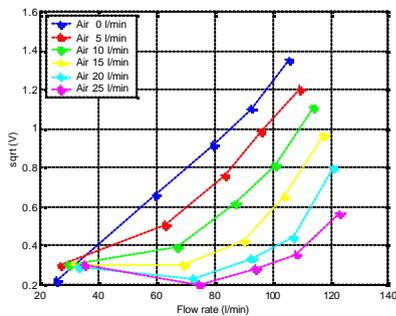

Figure 13. Change in square root of amplitude of the vortex sensor signal with flow rate of the primary phase (water) and the introduction of a second phase (air)
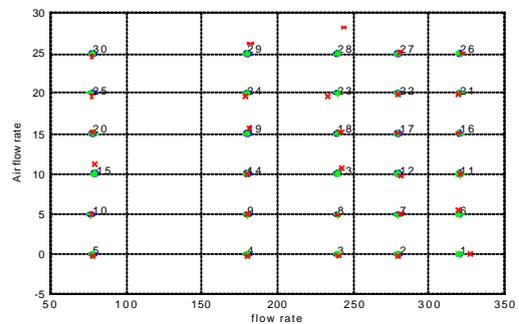

Figure 14. The output from neural network
O --- training targets
* --- Neural outputs after training
x --- tested outputs of the network

The results show that introducing a second phase into the primary phase has a strong influence on the vortex shedding signal. The introduction of a second phase causes the velocity of the mixture to increase. As a result, the shedding frequency increases, but conversely the vortex signal amplitude decreases significantly with increasing fraction of the second phase; whereas its amplitude in the case of a single phase fluid flow would increase according to the higher shedding frequency. By plotting four features i.e. vortex shedding frequency, signal power, rms signal amplitude and square root of rms signal amplitude as shown in Figure 10 to 13, respectively the flow rate of each individual phase can be measured by manipulating those features by graphical methods, or by an intelligent system such as neural network or fuzzy logic.

Two separately sets of vortex sensor signal are collected under the same conditions. One set of data is used to train the neural network, while the second set is used to test the system. Four input data values from the vortex flowmeter as mentioned earlier are used as inputs to the network. The network is trained to generate two output values, the primary phase (water) flow rate and the secondary phase (air) flow rate from the four input values. The outputs of the neural network after training and testing are shown in Figure 14. As a results, the neural network is seen to be capable of predicting and estimating the percentage of air in water, the water flow rate and air flow rate in the system. The advantage of this technique is that it uses information already available from the sensor in the vortex flowmeter to determine the percentage of the second phase in the system without needing changes in the construction of the instrument or sensors

5   Conclusion

The experimental results show that vortex flowmeter has the capability to measure two-phase flow. The influence of the second phase strongly affects its shedding signal amplitude and frequency. In a single-phase fluid flow the signal amplitude increases according to the square of the fluid flow rate, (or equivalently, the shedding frequency). But when the second phase is introduced into the primary phase flow, vortex shedding signal amplitude decreases progressively with an increase of the second phase.

The signal amplitude and shedding frequency vary non-linearly with individual phase flow rates. A multi-layer neural network is capable of fitting complex non-linear data, and therefore provides a method for handling the observable data to produce a system which can yield good measured values for both the primary and the secondary phase flow rates.

Calibration data from a commercially available vortex flowmeter has been used to train a neural network which, thereafter, has been used successfully on a continuous basis, to determine the flow rates and volumetric fractions of each phase in a two-phase flow. The only input signals required for input to the network are the vortex shedding frequency and several features derived from the amplitude of the vortex sensor signal. The volumetric flow rates of each phase can be determined with accuracy better than $\pm$ 5% for gas fraction up to 30% in a gas-in-liquid flow regime.

6   References

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