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Frequency detection in vortex flowmeter for low Reynolds number using piezoelectric sensor and installation effects

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ABSTRACT

Piezoelectric sensors are one of the most widely used sensors for vortex flowmeter application due to their low cost. Various researchers have employed piezoelectric sensor for this application. However, the location of the sensor and the performance of vortex flowmeter under disturbed conditions are seldom reported. In the present study, experimental investigations are conducted with water as the working medium in a circular pipe of diameter 52.5 mm. The optimum position of the piezoelectric sensor behind the trapezoidal bluff body is found out be 0.85 times the width of the bluff body. A new algorithm based on empirical mode decomposition and autocorrelation decay rate is suggested to identify the vortex shedding frequency under low Reynolds numbers flow condition. The performance of the flowmeter is also evaluated under different disturbed flow conditions to quantify the sensitivity of the flowmeter. The disturbances studied are single 90° bend, gate valve, globe valve, and two 90° out of plane bends. The overall uncertainty in the Strouhal number is within ±1.71%.

1. Introduction

Vortex flowmeters are one of the most widely used flowmeters in various flow measurement sectors. Compared to differential pressure devices, they offer large turndown ratio (minimum flow rate/maximum flow rate) 1:20 and better accuracy (±0.5–1% of the reading) [1,2]. Vortex flowmeters are cheaper than Coriolis and multi-path ultrasonic flowmeters. Piezoelectric sensors are one of the most widely used sensors for vortex flowmeter application because of their relatively low cost and ease in fabrication [3]. The sensor uses piezoelectric elements to detect strain in some mechanical arrangement having sufficient area exposed to the differential pressure of the vortices. These sensors detect time-varying forces (lift) to measure the vortex shedding frequency. Most of the commercially available vortex flowmeters use a piezoelectric crystal embedded inside a mechanical structure placed behind the vortex shedder. Piping vibration, flow pulsations and electrical interferences are inevitably present in real life applications. Under these extreme harsh conditions, the output signal from the piezoelectric sensor of the vortex flowmeter is a complex signal consisting of many undesirable frequency components along with the main vortex shedding signal. Hence, signal processing of the complex raw signal is one of the most important and difficult tasks in designing vortex flowmeters with piezoelectric sensor. The sensitivity of a piezoelectric sensor under low flow rate conditions and in the presence of external disturbances is not satisfactorily addressed, and forms the subject of our investigation.

Venugopal et al. [4] comprehensively summarized the key issues pertinent to the design of vortex flowmeter. Igarashi [5] performed experiments with piezoelectric sensors embedded inside various vortex shedder bodies. However, details of the type of the piezoelectric sensor employed and the location of the sensor with reference to the bluff body were not provided. Hence, it is difficult to reproduce and extend their findings. Zheng et al. [6] conducted an experimental study with a piezoelectric probe placed behind a trapezoidal bluff body. The optimum location of the sensor behind the bluff body was reported to be half the wavelength of the vortex street. However, these studies were restricted to open channel flows which do not include the influence of blockage. The optimum location of the piezoelectric sensor placed behind the bluff body is seldom reported in the literature.

Venugopal et al. [7,8] explored duct wall differential pressure method in detail covering optimum bluff body shapes, location of the wall pressure sensor and installation effects. Various two dimensional bluff bodies (cylinder, triangle and trapezoid) and axisymmetric bluff bodies (rings and cones) were investigated. The bluff body with trapezoidal shape was found to be most appropriate shape in terms of signal amplitude and deviation in Strouhal number.

In the early stage, vortex signal processing methods were based on power spectrum analysis. Ghaoud and Clarke [9] analytically simulated the vortex flowmeter signal and compared with experimental results. Pre-filtering along with zero-crossing algorithm was explored to extend the lower operating range of the

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Nomenclature

A	cross sectional area of the pipe (m^2)
D	diameter of the pipe (m)
d	width of the bluff body (m)
f	vortex shedding frequency (Hz)
U_m	mean velocity (m/s)
P_0	power of the vortex shedding frequency component (W)
P_i	power of the other component contained in the interval i (W)
P_t	total energy of the spectrum (J)
$P(w)$	energy content in frequency component (J)
ΔP	differential pressure (Pa)
PSD	power spectral density (W/Hz)
R_{xx}	normalized autocorrelation function
U_{st}	total uncertainty in St
U_1	repeatability
U_2	repeatability
U_3	uncertainty in the frequency resolution
U_4	uncertainty in the flow calibration system
x	streamwise coordinate (m)

Non-dimensional numbers

Re_D	Reynolds number $\left(\frac{\rho U_m D}{\mu}\right)$
$St_{average}$	average Strouhal number $\left(St = \frac{fd}{U_m}\right)$
St_{max}	maximum Strouhal number
St_{min}	minimum Strouhal number
St_{mean}	$\left(\frac{St_{max}+St_{min}}{2}\right)$
St_{fd}	Strouhal number under fully developed conditions
SNR	signal to noise ratio

Greek symbols

ρ	fluid density (kg/m^3)
μ	dynamic viscosity (Pa s)
δ	deviation (in percentage)
ζ	deviation from fully developed conditions (in percentage)

flowmeter. However, the signal output from a piezoelectric sensor consists of hydrodynamic noise, piping vibration and other interferences. Hence, power spectrum based signal processing methods sometimes fail to differentiate the vortex shedding signal from other frequencies. In the recent past, Hilbert transform, which is a time-frequency domain analysis, is widely used for vortex shedding frequency estimation. Empirical mode decomposition is the key step in the application of Hilbert–Huang transform proposed in detail with theoretical basis by Huang et al. [10]. Sun et al. [11] proposed using Hilbert–Huang transform to estimate the vortex shedding frequency. The complex raw signal was first decomposed into intrinsic mode functions (IMF) with the help of empirical mode decomposition (EMD). The percentage error in the meter factor obtained by this method was four times lower as compared to the Fourier transform based method at low flow rates. Zheng et al. [12] proposed an algorithm based on Hilbert transform and empirical mode decomposition for weak vortex signal. The residue after every intrinsic mode decomposition was subjected to probability density function estimate. A probability density of 5% was selected as the termination criteria for the shifting process. The last residual component corresponds to the vortex shedding frequency. The minimum Reynolds number covered with this method was Re_D = 6500. Sun and Zhang [13] proposed an energy ratio based method for diagnosing the vortex flowmeter performance based on the empirical mode decomposition method. The vortex energy ratio greater than 80% was dictated as the normal operating condition. However, the sturdiness of these methods under real applications where the amplitude of vibration signals are comparable to the vortex signal needs to be demonstrated [14].

Like other flowmeters, vortex flowmeter is sensitive to upstream disturbances. The flow field investigation downstream of the disturbance and its impact on the performance of the vortex flowmeter are studied by Miau et al. [15] and Laneville et al. [16] using cobra probe and hotwire anemometer to study the axial flow distribution and swirl intensity at various upstream distance to the flowmeter. Yang et al. [17] studied the effect of a perforated plate upstream to the vortex flowmeter as a source of flow disturbance. They compared the performance of a vortex flowmeter with a piezoelectric sensor downstream of the bluff body and a commercial vortex flowmeter (Yokogawa YF105). The study revealed that the piezoelectric sensor placed downstream of the bluff body was more sensitive to turbulence intensities due to upstream disturbance as compared to the commercial flowmeter. However, there is no information available on the sensitivity of a vortex flowmeter downstream to a gate valve/globe valve/out of plane bends, which are the major flow profile distortion elements in industrial applications. Therefore, the objectives of the present study are:

1. Optimization of the location of piezoelectric sensor placed behind a trapezoidal bluff body,
2. Explore signal processing methods for the detection of vortex shedding frequency at different Reynolds numbers,
3. Evaluate the sensitivity of the performance of vortex flowmeter under various disturbed flow conditions.

2. Experimental setup

A closed loop water circuit is built to conduct the experiments in a circular pipe of diameter 52.5 mm. Appropriate test sections are designed and fabricated for conducting experimental investigations with a piezoelectric sensor. A high accuracy water flow dynamic calibration facility utilizing dynamic weighing is employed in the present study. The system is capable of handling flow rate in the range of 0–550 m^3/h. The accuracy of the present facility depends on the diameter of the pipe and mass flow rate range. The collecting tank is equipped with an electronic platform scale load cell at the base. The collecting tank capacity is 4000 kg. The system can respond to a time change of 0.1 s with 1 kg resolution. The uncertainty in the velocity estimation for the minimum Reynolds number covered in the present system is 0.34%. The details of the experimental setup and calibration facility are shown in Fig. 1. A mixed flow type of pump (capacity 78 m and 114 m^3/h) is used for circulating water through the system from an underground sump. The flow rate is controlled with the help of gate valves as shown in Fig. 1.

The load cell is interfaced to a personal computer through an RS232 port. Two butterfly valves (150 mm) are provided downstream of the collecting tank in order to drain or collect water in the tank. Water from the tank is recirculated back to the sump. The experiments are conducted in a circular pipe of diameter 52.5 mm. The test section is provided with an upstream pipe length of 35D to achieve fully developed inlet velocity profile. Flexible bellows are mounted at the inlet to the upstream pipe and outlet to the downstream pipe to dampen the pipe vibrations. A clamp on type ultrasonic flowmeter is installed 10D downstream of the test section for coarse adjustment of the mass flow rate. The output from the sensor is logged to a personal computer with the help of a Picoscope 2203. The bluff body employed in the present study is trapezoidal in shape with a 72.5° included angle and a blockage