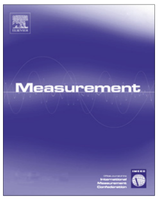
Measurement 50 (2014) 10–18

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement



Performance evaluation of piezoelectric and differential pressure sensor for vortex flowmeters

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ARTICLE INFO

Article history:
Received 7 August 2013
Received in revised form 5 December 2013
Accepted 12 December 2013
Available online 27 December 2013

Keywords:
Differential pressure sensor
Piezoelectric sensor
Bluff body
Strouhal number

ABSTRACT

Piezoelectric and transient differential pressure sensors are two among the most widely employed sensors for vortex flowmeter application. The present study evaluates the performance of these two techniques under fully developed and disturbed flow conditions. Firstly, the location of the transient differential pressure sensor is optimized to obtain high amplitude signals and good linearity in Strouhal number. Empirical mode decomposition method in combination with autocorrelation decay is successfully employed at high Reynolds numbers to identify the vortex shedding frequency in presence of hydrodynamic noise. The performance of the differential pressure sensor deteriorates significantly under disturbed flow conditions at low Reynolds number due to the presence of low frequency components. This deterioration in the signal quality limits the lower operating range of the flowmeter with differential pressure sensor. The output signals of the piezoelectric sensor and differential pressure sensor under no flow condition are compared to obtain the background noise due to piping vibrations and electrical interferences. These results will help a designer to suggest robust signal processing algorithms for vortex frequency detection.

1. Introduction

The literature concerning the design of vortex flowmeter focuses primarily on optimization of bluff body shape to obtain good quality signal. However, the sensor which detects the vortex shedding frequency is equally important as far as the overall performance of the flowmeter is concerned. The vortex shedding behind the bluff body gives rise to periodic changes in velocity and pressure (also temperature for non-isothermal flows). Any technology which can dynamically sense the above mentioned variables can potentially be used for vortex shedding frequency estimation. The early designs of vortex flowmeters were accomplished with mechanical movement of stutter ball in response to vortex shedding [1]. However, such devices are prone to wear and clog over a period of time. The commercially available sensors for vortex flowmeter use the differential pressure generated by the vortices to deflect a mechanical membrane. The mechanical deflection of the membrane (capacitance, strain, piezoresistive, inductive or piezoelectric) is converted in to an electrical signal for further processing. However, piezoelectric and dynamic differential pressure sensors are two of the most widely used sensors for measuring the vortex shedding frequency. A comprehensive summary of the design aspects pertinent to vortex flowmeters, including optimum bluff bodies, sensors and signal processing methods can be found in Venugopal et al. [2] and Pankanin [3].

One of the most widely used piezoelectric sensors makes use of a piezoelectric crystal embedded either inside the bluff body or inside a mechanical structure placed behind the vortex shedder [4,5]. Igarshi [6] performed experiments with a piezoelectric sensor embedded inside various vortex shedder bodies and found that cylinder with

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http://dx.doi.org/10.1016/j.measurement.2013.12.018

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_{av}	mean velocity (m/s)
PSD	power spectral density (W/Hz)
R_{xx}	normalized autocorrelation function
s	slit width (m)
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 $\left(\frac{\rho U_{av} D}{\mu}\right)$
$St_{average}$	average Strouhal number $\left(St = \frac{fd}{U_{av}}\right)$
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 flow conditions

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)

a slit is the optimum vortex shedder shape. Zheng et al. [7] conducted an experimental study with a piezoelectric sensor placed behind a trapezoidal bluff body in an open channel flow situation and found that the quality of the signal depends on the location of the sensor. Peng et al. [8,9] performed experiments in a circular pipe with a piezoelectric sensor placed behind dual triangulate bluff bodies. The optimum location of the sensor was qualitatively reported to be behind the separation point of the second bluff body. Venugopal et al. [10] suggested a distance of 0.85 times the width of the bluff body as the optimum location for the piezoelectric sensor behind the rear face of a trapezoidal bluff body. Another application of piezoelectric sensors is in energy harvesting from buff body wakes. Wang et al. [11] developed a prototype for harvesting energy from the wake of a trapezoidal bluff body using a piezoelectric membrane. A power output of 0.7 nW was obtained from a 0.3 kPa differential pressure of the shed vortices. Akaydin et al. [12] extracted a maximum power of 0.1 mW from the wake of a circular cylinder using a piezoelectric sensor; with an aero-electromechanical efficiency of 72%. These studies highlight the importance of optimization of the sensor location to achieve maximum output from the wake of bluff bodies.

Miau and Lu [13] first proposed the use of dynamic wall pressure measurement technique to obtain the vortex shedding frequency. The unsteady behaviour downstream the bluff body (ring shaped body in their case) can be picked up by a pressure sensor mounted on the pipe wall. Miau and Hus [14,15] further explored various shapes of the ring as vortex shedders for vortex flowmeter application, and suggested 2–3 times the width of the bluff body (ring) as the optimal location for the pressure sensor. Miau et al. [16] suggested drilling two taps on the face of the bluff body (T-shaped shedder) behind the separation point for dynamic differential pressure measurement, in order to enhance the signal quality. Zhang et al. [17] used a modified approach for measuring the vortex shedding frequency. Instead of using single pressure for obtaining the vortex shedding frequency, duct wall differential pressure with two pressure measurements, one on the upstream of the bluff body and the other downstream, was employed. The major advantage of this method was direct measurement of the mass flow rate. The magnitudes of the mean differential pressure and fluctuating pressure component were used together to obtain the mass flow rate directly in their case. Li and Sun [18] developed a mass flowmeter based on duct wall differential pressure method and demonstrated constancy in the meter factor for $Re_D > 5500$. A correction factor was suggested for the lower operating range where the uncertainty is ±5%. Sun et al. [19] conducted experiments to study the effect of sampling tube dimensions on the amplitude of the pressure signals. Short and small diameter tubes were recommended to obtain relatively strong signals. Venugopal et al. [20,21] further explored the duct wall differential pressure method with axisymmetric tap combination. Based on their detailed measurements, they found the optimal bluff body shape and location for the measurement of the wall pressures. Bluff body with trapezoidal shape was found out to be the most appropriate shape in terms of signal amplitude and deviation in Strouhal number with respect to Reynolds number. Sun [22] developed a vortex flowmeter with a converging–diverging structure to extend the lower operating range by 50% using an axisymmetric tap combination. Sun et al. [23] investigated the influence of shape of the bluff body on the irrecoverable pressure loss. An invariant trend was observed in the wall pressure distribution irrespective of the shape of the bluff body.

The utilization of ultrasound measurement principle is another potential technique used for the detection of the vortex shedding frequency. The convection velocity of the shed vortices can be used to modulate an ultrasonic beam diametrically traversing the pipe. Coulthard and Yan [24] used ultrasound transit time method to measure vortex shedding frequency from trapezoidal and T-shaped bluff