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Optimization of flow rate measurement using piezoelectric accelerometers: Application in water industry

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ABSTRACT

This paper presents a method for measuring flow rates in pipelines based on the flow induced vibration principle using water as fluid, eliminating the need for interrupting the flow and opening of the pipeline for installation of traditional water flow meters. Experimental measurements are carried out in an accredited laboratory for calibration of rate flow meters and a metrological validation, followed by an uncertainty evaluation, are presented. Data analysis is accompanied by a method of optimization that minimizes adjustment errors of measurement using regression by parts and by the selection of the optimum period to estimate more accurately the flow rate. The results meet the specifications of Brazilian Metrology Institute.

1. Introduction

At collect data for system control, process analysis, accounting income and consumption, the flow rate measurement of fluids is used in many applications for different purposes [1].

The diversity of applications and, in general, the fact that the dynamic measurements demonstrate completely distinct properties, contributes to the existence of a very large variety of flow meters. This has become necessary to take into account the types and physical conditions of the fluid, in addition to aspects such as accuracy, operating range, cost, complexity, readability, lifetime, and principally the measurement principles utilized.

However, it is observed in these flow meters that there are limitations that need to be overcome. Accordingly, more research is necessary with the purpose of investigating new measurement techniques, preferably non-invasive, non-intrusive and with low cost, which permit the development of a flow sensor that overcomes the existing technical difficulties.

Notably, in the case of measurement of water flow rate, the availability of a non-intrusive, non-invasive, low cost and easy installation meter would clear financial and operational advantages for suppliers and end consumers.

In this sense, this study judges the worth and quality of a recently developed technique for the measurement of fluid flow rate, based on the vibrations captured by an accelerometer attached to the surface of a pipe [1]. In this case, the aim of this work is the metrological analysis of applying piezoelectric accelerometers to flow rate measurement, specifically in water industry.

In short, this technique uses the measurements of the vibrations induced by the transit of the fluid through the pipeline. This phenomenon is known as Flow Induced Vibration (FIV) and basic principle is to estimate the flow rate data from the standard deviation of its vibration signals [1].

The piezoelectric accelerometer is one of the most utilized transducer for the measurement of vibration [2], being pre-eminent for displaying certain important characteristics, such as an extensive range of frequency, being relatively robust and sufficiently stable over time [3] being, therefore, the measurement device used in this work.

To attend this goal, an experimental study [4] is carried out in an accredited flowmeter calibration laboratory. Water flow rates are estimated for each vibration measurement, followed by an uncertainty analysis. Moreover, adjustment errors in flow

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estimates are minimized through an optimization, using regression by parts.

2. Background

Flow measurement based on FIV is a technology not regulated by international guidelines and standards. FIV is an operational technique, widely used in the nuclear industry, however still considered as somewhat mysterious by some researchers [5].

Due to failures occasioned by very expensive components in terms of repairs and loss of production, the vibrations induced in tubing are undesirable [6]. Recent significant technological developments in electronic components, including computers, which allow simultaneous monitoring of several parameters [7], FIV has been regarded as a technique in expansion, once the development of a sensor that displays characteristics which are highly interesting to water industry: non-intrusive, non-invasive and of reduced cost.

Mass of a fluid may be indirectly estimated by means of the acceleration that it transmits to another body [8], based on the laws of movement of Newton. Evans et al. [8] have combined analytical, numerical and experimental methods, in order to confirm the feasibility of the FIV technique by verifying that the standard deviation of the signal from the accelerometer. Initially, a second-degree polynomial represents the best relation between the vibration and the flow rate. Physically, this relationship depends on other parameters, such as geometry, position of the sensor [9] and pipeline material.

Thus, this manuscript seeks to estimate indirectly the flow values through vibration data collected by piezoelectric accelerometers attached to the pipe. The presented tests, unlike most studies published on this topic, do not use bench tests purposely built under the ideal conditions possible, but are performed using a standard flow meter calibration line in accredited Brazilian laboratory.

Assuming that the direct correlation between the vibration of the pipe and the flow rate can be determined as previously explained, the purpose of this article encompasses the acquisition and metrological validation of such correlation, including estimation of measurement uncertainty.

3. Experimental setup

Accelerometers of different sensitivities – one with 10 mV/g (A10) and the other with 100 mV/g (A100), being *g* the acceleration of gravity – were installed in a straight stretch of a flow meter calibration line, as shown in Fig. 1. The water injection pump systematically released a flow from 10 m^3/h up to 110 m^3/h, in steps of 10 m^3/h. The flow was measured simultaneously by a standard meter – a Coriolis mass flowmeter (manufacturer Yokogawa, 4″ nominal diameter, nominal flow range from 0 to 150 m^3/h and resolution of 0.001 m^3/h) – and by the accelerometers, with an acquisition time of 30 s.

The tubing used is constituted of carbon steel with a four-inch diameter (101.6 mm). The models of the accelerometers used are 752–10 and 752–100 from ENDEVCO with an operational range of ±500 g and ±50 g respectively, and frequency range of 50 kHz. Based on the Nyquist theorem, relation of observation of phenomena with frequencies lower than 9600 Hertz, this study uses sample rate of 19,200 Hertz.

This procedure is carried out three times for each flow rate condition, aiming at verifying its repeatability, as well as the influence of external factors.

4. Signal processing

The processing begins with the transformation of data the time domain to the frequency domain, in the MATLAB® software, as shown in Fig. 2 and, as expected, electromagnetic interference from the electricity network of 60 Hertz and harmonics is detected. A consistent signal from 17 Hz to 20 Hz is also noticed, derived from the vibration introduced by the pump. Hence, it is necessary to use digital filters in the signals acquired, to exclude the signals in these frequency ranges.

For the interference from the electricity network, it is opted to use a 'notch comb' digital filter, which removes the multiples of 60 Hz up to half the sampling frequency on a timely basis. For the mechanical interference, a Butterworth 8th order band-stop filter is employed with cuts of frequencies between 16 Hz and 22 Hz.

5. Analysis of the results

Starting the values of the vibration measured, the sample standard deviation (s) may be extracted and associated with its corresponding flow rate (Q), Fig. 3.

Then, it is verified that part of the vibratory response is associated to secondary effects such as vibrations from the pump and the air compressor, as well as their own capacity limitations, and the resonance frequency of the pipeline itself. Therefore, the first series (10 m^3/h) and the last series of measurements (110 m^3/h) are discarded. Data are tested for normality and the outliers are treated in accordance to the Grubbs test.

Standard deviations versus flow rate are generated for both accelerometers (Fig. 4). Here, it is clear to observe visually a quadratic relationship between the standard deviation of the vibration signal sample (s) and the flow rate (Q).

Since experimental data confirm the theory, i.e., flow rate can be estimated by vibration data, a metrological treatment of the data is carried out.

6. Metrological treatment of the data

Initially the flow rate values were adjusted – by the method of quadratic fit [10] – where the values of the coefficients b_i may be calculated by resolving a single matrix equation: $b = (X^t X)^{-1} X^t Y$, in which the matrix $(X^t X)$ is not singular. For a second order model, $y_i = b_0 + b_1 x_i + b^2 x_i^2$, where x_i represents the independent variable in the ith level, being the matrix system represented by:

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \cdots \\ y_i \end{bmatrix} X = \begin{bmatrix} 1 & x_1 & x_1^2 \\ 1 & x_2 & x_2^2 \\ \cdots & \cdots & \cdots \\ 1 & x_i & x_i^2 \end{bmatrix} b = \begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} \tag{1}$$

These matrices are used to express the calculation of uncertainties in the estimation of the parameters b_0, b_1 and b_2, from the covariance matrix:

$$V(b) = \begin{bmatrix} V(b_0) & Cov(b_0, b_1) & Cov(b_0, b_2) \\ Cov(b_0, b_1) & V(b_1) & Cov(b_1, b_2) \\ Cov(b_{0,} b_2) & Cov(b_1, b_2) & V(b_2) \end{bmatrix} \tag{2}$$

Given this, the calculation of the square root of the elements of the principal diagonal is carried out, from whence it becomes possible to obtain the standard uncertainties of coefficients b_0, b_1 and b_2 and its covariance, *Cov*. The uncertainty associated with the quadratic least squares fit is calculated by Eq. (3) and the results are indicated in Fig. 5.