XXI IMEKO World Congress “Measurement in Research and Industry”
August 30 – September 4, 2015, Prague, Czech Republic

NONINTRUSIVE METHOD FOR MEASURING WATER FLOW IN PIPES

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Abstract – This paper presents a method for measuring flow in pipelines based on the vibration caused by the flow of water, eliminating the need for interrupting the flow and opening the pipe for installation of traditional water flowmeters. Experimental measurements are presented and also a metrological validation in a laboratory accredited for calibration of flow meters.

Keywords: flow measurement, pipe vibration, piezoelectric accelerometer.

1. INTRODUCTION

The flow rate measurement of fluids is used in many applications for different purposes. Some of them include the supply of data for control of the system, analysis of processes, accounting for throughput and consumption [1].

The diversity of applications and, in general, the fact that the dynamic measurements demonstrate completely distinct properties, contribute to the existence of a very large variety of meters. This has become necessary to account for 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.

Generally, flow meters may be classified as invasive or non-invasive, and intrusive or non-intrusive, depending on the perturbation that the transducer element introduces into the measurement [2]. In this respect, it is known that there are many high quality flow sensors and several measurement techniques; however, it is observed in these meters that there are limitations that need to be overcome. Accordingly, research is necessary with the purpose of investigating new measurement techniques, preferably being 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 measuring water flow, the availability of a meter that is non-invasive, non-intrusive, of low cost and easy installation would bring financial and operational advantages for suppliers and consumers.

In this sense, this work proposes to evaluate a recently developed technique for the measurement of fluid flow rate, based on the vibrations measured by an accelerometer attached to the surface of a pipe [1]. For this, the objective is the metrological analysis of applying piezoelectric accelerometers to flow rate measurement.

In short, the technique consists of measuring the vibrations induced by the passage of fluid through the pipeline, a phenomenon known as Flow Induced Vibration (FIV), so that the flow rate is estimated from the standard deviation of this vibration [1].

The piezoelectric accelerometer is the acceleration transducer most used for the measurement of vibration [3], being pre-eminent due to certain important characteristics, such as an extensive range of frequencies, relative robustness and sufficient stability over time [4] being, therefore, the measurement device used in this work.

With the purpose of reaching the desired objective, an experimental study [5] was carried out to obtain and process data in an accredited flow meter calibration laboratory, estimating a flow rate for each vibration measured, accompanied by an uncertainty analysis.

2. BACKGROUND

Flow measurement based on FIV is a technology not regulated by codes or industrial standards. To a long extension, FIV is an operational problem, common in the nuclear industry, being viewed most frequently as a case that is somewhat mysterious by engineers or even something not completely understood [6].

Generally, in virtue of failures occasioned by components being very expensive in terms of repairs and loss of production, the vibrations induced in tubing are undesirable [7]. But recently, due to significant technological developments in electronic components, including computers, which enable simultaneous monitoring of several variables [8], FIV has been considered as a promising technique by researchers, in the sense of enabling the development of a sensor that displays characteristics which are highly interesting to the industry, such as being non-intrusive, non-invasive and of reduced cost.

Based on Newton’s laws of movement, Evans et al [9] considered that the mass of a fluid may be indirectly measured by means of the acceleration that it transmits to another body. Given this, these authors made a combination of analytical, numerical and experimental methods, and could thereby confirm the feasibility of the FIV technique by verifying that the standard deviation of the signal from the accelerometer that measures the vibration increases with the flow rate, being best fitted by a second degree polynomial. It is emphasized that this relationship depends on other parameters, such as geometry, position of the sensor [10] 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 tests herein presented, unlike most studies published on this topic, did not use test benches purposely built under the most ideal conditions possible, but were performed in a standard flow meter calibration line in an accredited laboratory from the Brazilian Calibration Network (RBC).

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

3. EXPERIMENTAL SETUP

Based on the specialized literature available, 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 m³/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 m³/h and resolution of 0.001 m³/h) – and by the accelerometers, with an acquisition time of 30 seconds.

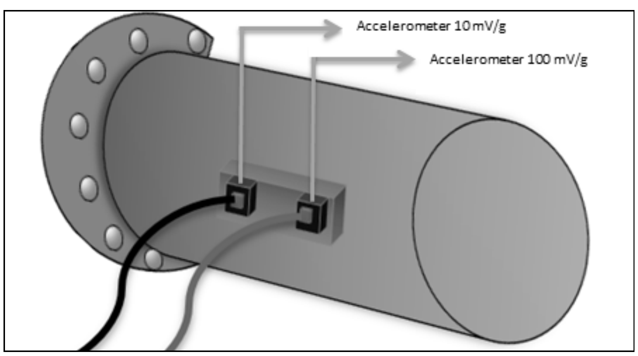


Fig. 1. Accelerometers installed on the steel pipe surface.

The tubing utilized is constituted of carbon steel with a four inch diameter (101.6 mm). The accelerometers utilized were models 752-10 and 752-100 from ENDEVCO with an operational range of ±500 g and ±50 g respectively, and frequency range of 50 kHz. The sample rate utilized was 19200 Hz which, according to the Nyquist theorem, enables the observation of phenomena with frequencies lower than 9600 Hz. This procedure was carried out three times for each flow condition, aiming at verifying its repeatability, as well as the influence of external factors.

4. SIGNAL PROCESSING

Initially, the data were transformed from the time domain to the frequency domain, as shown in Fig. 2, and, as expected, electromagnetic interference from the electricity network of 60 Hz and harmonics was detected. A consistent signal in the range of 17 to 20 Hz was also observed, which was considered to come from the vibration introduced by the pump. Therefore, it was necessary to utilize digital filters in the signals acquired, so as to remove the signals in these frequencies.

For the interference from the electricity network, it was 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 was employed with frequencies cut between 16 Hz and 22 Hz.

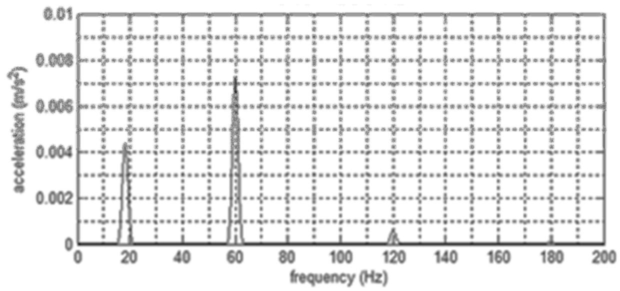
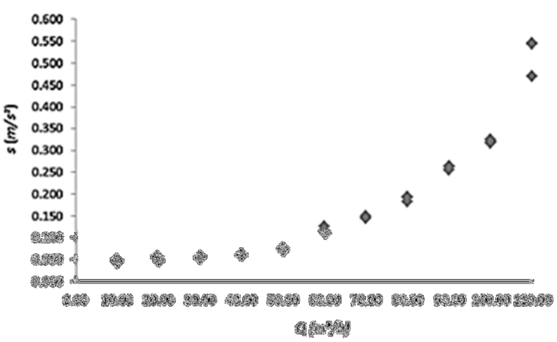


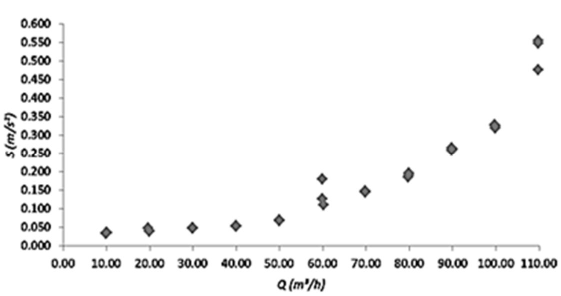
Fig. 2. Frequency spectrum of the raw acquired vibration signal.

5. ANALYSIS OF RESULTS

With the tests processed separately in the MATLAB® software, the standard deviation from the sample (*s*) may be extracted from the values of vibrations measured corresponding to each flow rate (*Q*) for the three measurements made with the two accelerometers A10 and A100, as indicated graphically in Fig. 3.



(a)

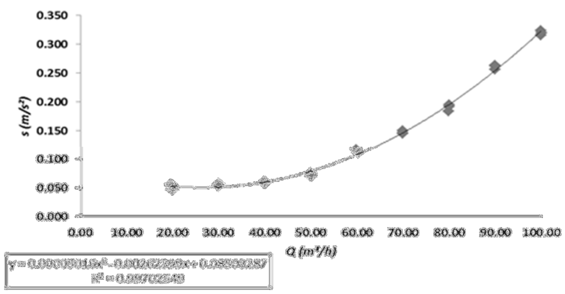


(b)

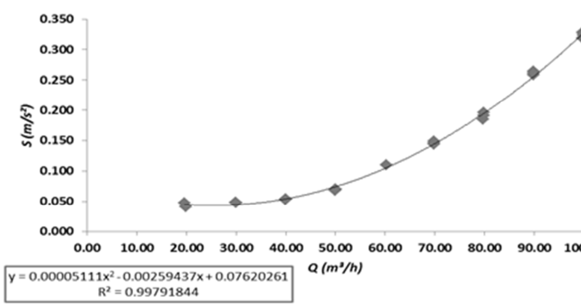
Fig. 3. Standard deviations corresponding to each flow rate for the 2 accelerometers A10 (a) and A100 (b).

With the standard deviations measured by the two accelerometers in hand, it was verified that part of the vibratory response was seen to be associated with secondary effects such as vibrations from the pump and the air compressor, as well as their own capacity limitations, and also the resonance frequency of the pipeline itself. Therefore, the first (10 m^3/h) and the last series of measurements (110 m^3/h) were discarded. Furthermore, the outliers were excluded in accordance with the Grubbs test.

With this, a chart of standard deviation versus flow was generated for both accelerometers (Fig. 4), being it possible to observe visually a quadratic relationship between the standard deviation of the vibration signal sample (s) and the flow rate (Q).



(a)



(b)

Fig. 4. Quadratic relationship between the standard deviation of the vibration and the flowrate, for the accelerometers A10 (a) and A100 (b).

Once obtained the direct relationship between flow and vibration, the next step of this work was estimating the flow rate from the measured vibration data.

6. ESTIMATION OF FLOW AND UNCERTAINTY ASSOCIATED WITH THE MEASUREMENT

With the purpose of enabling the vibration data to assist in the estimation of flow values, a metrological treatment of the data was carried out, such as the estimation of flow rate, percentage errors and an analysis of the uncertainty.

Initially the flow rate values were adjusted – by the method of quadratic fit [11] – where the values of the coefficients b_i may be calculated, resolving a unique 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 n^{th} order, being the matrix system represented by

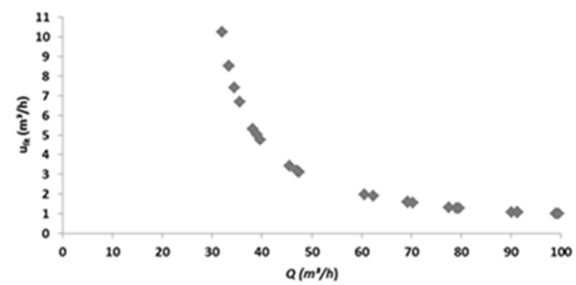
$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \cdots \\ y_i \end{bmatrix} \quad X = \begin{bmatrix} 1 & x_1 & x_1^2 \\ 1 & x_2 & x_2^2 \\ \cdots & \cdots & \cdots \\ 1 & x_i & x_i^2 \end{bmatrix} \quad b = \begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix}. \quad (1)$$

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

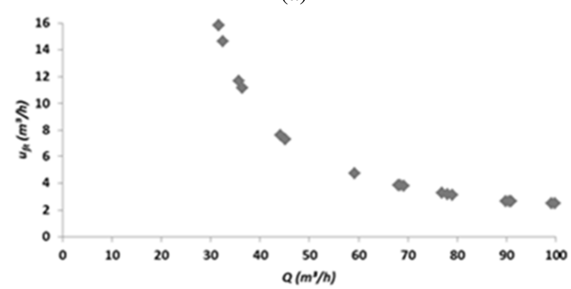
$$V(b) = \begin{bmatrix} V(b_0) & Cov(b_0, b_1) & Cov(b_0, b_2) \\ Cov(b_0, b_1) & V(b_1) & Cov(b_1, b_2) \\ Cov(b_0, b_2) & Cov(b_1, b_2) & V(b_2) \end{bmatrix}. \quad (2)$$

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, C_{ov}. The uncertainty associated with the quadratic least squares fitting is calculated by equation (3) and the results are indicated in Fig. 5.

$$u_{c(x)}^2 = \left(\frac{\partial x}{\partial \hat{y}} u_{\hat{y}}\right)^2 + \left(\frac{\partial x}{\partial b_0} u_{b_o}\right)^2 + \left(\frac{\partial x}{\partial b_1} u_{b_1}\right)^2 + \left(\frac{\partial x}{\partial b_2} u_{b_2}\right)^2$$
$$+ 2\left(\frac{\partial x}{\partial b_0} u_{b_o}\right)\left(\frac{\partial x}{\partial b_1} u_{b_1}\right) r_{b_0 b_1} + 2\left(\frac{\partial x}{\partial b_o} u_{b_o}\right)\left(\frac{\partial x}{\partial b_2} u_{b_2}\right) r_{b_0 b_2} \quad (3)$$
$$+ 2\left(\frac{\partial x}{\partial b_1} u_{b_1}\right)\left(\frac{\partial x}{\partial b_2} u_{b_2}\right) r_{b_1 b_2}$$



(a)



(b)

Fig. 5. Quadratic fit and uncertainty of the fitting for the accelerometers A10 (a) and A100 (b)

For the uncertainty analysis, there are as components, in addition to the uncertainty of the fit (u_{fit}), the uncertainty of the standard Coriolis mass meter (u_{sta}), declared on the calibration certificate as 0.3 m^3/h and the uncertainty of the instrument (accelerometer) which already forms part of the coefficients of regression, with its resolution (R = 0.0001 m/s^2) not included by virtue of having such a low value (far below the smallest point fitted: 0.048 m/s^2) considering the fitting of the curve, so that it becomes negligible.

Thus, the combined standard uncertainty may be calculated as follows:

$$u_c = \sqrt{u_{sta}^2 + u_{fit}^2} \tag{4}$$

Based on (4), the combined standard uncertainty was estimated. For the calculation of expanded uncertainty (5), the sources of uncertainty must be identified because, when one component of uncertainty of "Type A" is evaluated using a reduced number of observations ($n < 30$), it becomes more appropriate to attribute the distribution of the data to a distribution of t-Student probability.

$$U = t_s \times u_c \tag{5}$$

Therefore, the expanded uncertainty was estimated (Fig. 6), based on a t-Student distribution (t_s) with (n-3) degrees of liberty for a given level of confidence (1-α).

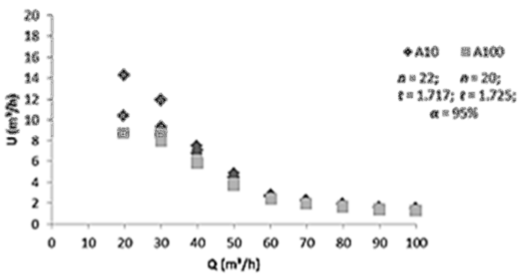


Fig. 6. Estimate of the expanded uncertainty of accelerometers A10 and A100.

It is appropriate to mention that, starting from a certain value of flow indicated (around 60 m³/h) the behaviour of the flow rate fit tends to improve considerably, both for A10 and for A100, suggesting that below this the tube may not be completely filled, which implies greater vibration and discrepancy in the information set.

7. REGRESSION BY PARTS

Considering the observation mentioned above, a regression by parts [12] was applied, dividing the range of flows in two regions (the first from 0 to 60 m³/h and the second from 60 m³/h to 100 m³/h), in order to reduce the fitting error of the flow estimates.

The first range was subjected to a 3rd degree polynomial regression, as shown in Fig. 7 and Fig. 8.

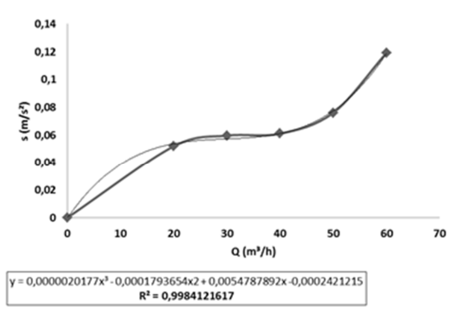


Fig. 7. 3rd order regression for accelerometer A10.

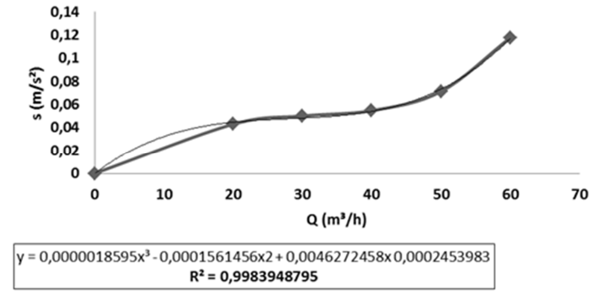


Fig. 8. 3rd order regression for accelerometer A100

The second range of flows remained fitted using a quadratic regression, but it was observed that the R^2 values referring to this range increased in comparison with the previous regression, as shown in Fig. 9 and Fig. 10.

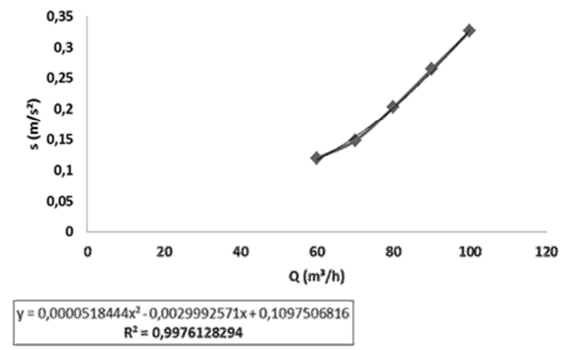


Fig. 9. 2nd order regression for accelerometer A10

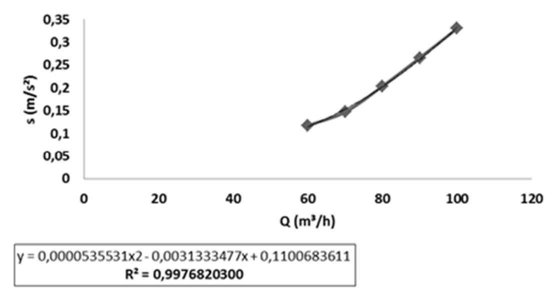


Fig. 10. 2nd order regression for accelerometer A100

From the new regression functions a new analysis was performed of the flow obtained from the standard deviations. Curves correlating the new flow with the standard flow values were generated (Fig. 11 and Fig. 12), and from these data the errors corresponding to each accelerometer were calculated.

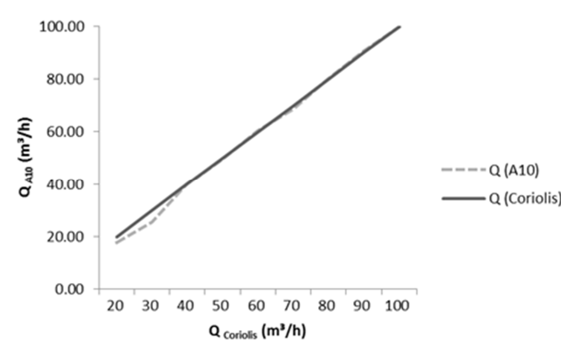


Fig. 11. Estimated flow vs. standard flow for A10.

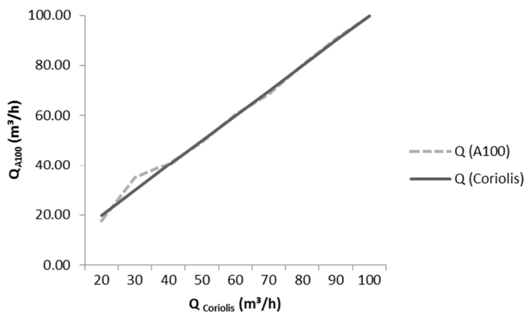


Fig.12. Estimated flow vs. standard flow for A100.

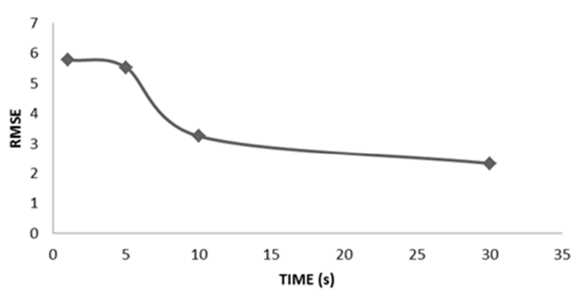
According to the results, it was found that the errors decreased in relation to the previous quadratic regression using the full range from 20 to 100 m³/ h. The initial RMSE error for A10 was 3.25 m³/ h and reduced to 1.65 m³/h, while for A100 it was 2.42 m³/h and reduced to 1.87 m³/ h. These results indicate that the regression by parts seems to be more suitable, considering that the system does not show a sinple quadratic behavior in the entire measuring range.

8. MEASUREMENT TIME OPTIMIZATION

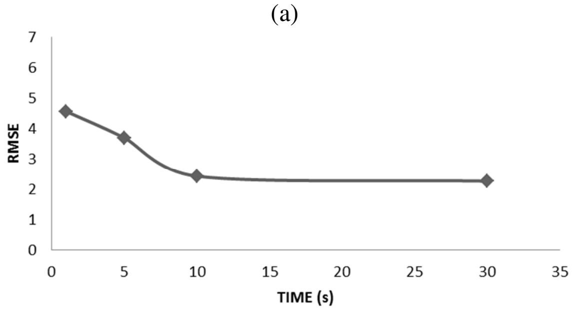
Proceeding with the data analysis, it was investigated the effect of the measurement time in the estimation error. Acquisition periods of 30 s, 10 s, 5 s and 1 s for the vibration signals measured by accelerometers have been tested, in order to define the minimum time required for an accurate estimation of the flow, based on the RMSE,

$$RMSE = \sqrt{\frac{\sum(Q_{Coriolis} - Q_{Accelerometer})^2}{n}}. \qquad (6)$$

The RMSE errors obtained show that the difference between the original period time (30 s) and 10 s is very low (Fig. 13), which allows the definition of 10 s as the optimum period to estimate the flow rate.



(a)



(b)

Fig. 13. Mean Squared Error vs. Optimization time of the accelerometers A10 (a) and A100 (b).

ACKNOWLEDGMENTS

We thank the Brazilian funding agencies FINEP, CAPES, CNPq and FAPERJ, for their financial support, and LC Controls for offering their calibration laboratory and their support in the experimental work.

8. CONCLUSIONS

The estimate of the uncertainty associated with the measurement of the flow rate using the FIV technique and the propagation of the flow measurement uncertainty from the FIV technique enabled to conclude that, based on the experimental results extracted from a flow meter calibration line with accelerometers fixed to a carbon-steel pipeline, the FIV method is feasible for application in the measurement of water flow, since the uncertainty for the estimated flow rate is near the range required for calibration of water flowmeters for which, according to Ordinance nº 246 (2000) of INMETRO [13], the relative variation of flow during each test shall not exceed the range of values ±2.5% for flows between the minimum flow (Q_{min}) and the transitional flow (Q_t), and ±5.0% for flows between Q_t and the maximum flow rate (Q_{max}).

In addition, this application for accelerometers via FIV technique has the potential to be able to meet the existing demand for a system to measure the flow variation (fluctuation) during calibration, given that this aspect is not yet well defined within the normative documents.

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