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Vibrational signal processing for characterization of fluid flows in pipes

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ABSTRACT

The main idea of this paper is to assess a simpler and faster procedure leading to the evaluation of the fluid flow rate through a pipe. Currently, several methods are available and they involve *ad-hoc* instruments. All these methods are characterized by high accuracies and dynamic responses, but they are intended to be inserted within the pipe under investigation, bringing to well-known insertion effects, compromising the reliability of the measurements performed. The authors illustrate a newer methodology for the measurement of flow rates by means of the processing of the vibration signals of pipe walls, inferred by the flow turbulence. Previous studies of the same authors showed a linear dependence between the amplitude of the most prominent peak of the vibration spectra and the flow rate. In this work, the authors relate the power content of the processed signals (by introducing the signal Root Mean Square value) to the flow rate.

1. Introduction

The measurement of fluid flow rates in industrial and urban installations is of crucial importance. In industrial plants, for example, an accurate and precise fluid flow rate monitoring allows for the appropriate physical characterization of the process under analysis. In civil and urban infrastructures (i.e. aqueducts), an accurate water flow rate evaluation can allow for water leaks detection and quantification, with the resulting and certain reduction of water wastes [1–3]. In particular, such an accomplishment could lead to a solution to the scarcity of water, a perennial issue especially for those regions with poor rains.

The technological evolution in measurement instrumentation field, has led to the introduction of so many devices, characterized by very reliable performance both in static and dynamic conditions, with high precision and accuracy. The selection procedure of the most suitable device, must take into account several aspects. In first instance, the physical effect, which the instrument under choice is based on, is of crucial importance. By taking into account that, one can state its adequacy for a given application.

In addition, the user must take into account also the contingency of the process under monitoring. Indeed, the operating conditions (i.e. flow temperature, pressure, mean speed, turbulence and so forth), consistently influence the selection of the most appropriate fluid flow meter.

Nowadays, the most employed sensors are characterized by rather high overall performance. Despite such improvements, in some applications, non-intrusive flow meters are required. For example, in water distribution urban networks, the use of mobile flow monitoring device is desired, in order to perform a prompt and accurate detection, localization and quantification of possible water leaks [4,5].

Thus, the need for mobile flow monitoring installations makes the currently and widely employed flow meter devices, inadequate. The non-intrusive instruments, such as Coriolis and ultrasonic flow meters (which are among the most desired solutions) may poorly accomplish the purpose of water leak detection (for example), since they could suffer from inaccuracies due to wrong or inaccurate setting.

The authors of this paper, in Refs. [6,7], have developed a fluid flow rate monitoring system, which employs vibration measurement devices and exploits the acquired signals post-processing, in order to precisely and accurately evaluate the flow rate through a pipe under test. In [7], the same authors develop a methodology for the measurement of the fluid flow rate, by means of appropriate evaluations to be implemented on the vibrational signals in the frequency domain.

In [7], the authors show the linear relationship between the pipe inner flow rate and the radial acceleration affecting the pipe

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and due to the flow rate itself. By means of the acceleration signal frequency spectrum, the authors prove that any change of fluid flow rate causes a linear variation of the acceleration peak amplitude of the most prominent harmonics, which are proportionally influenced by the fluid flow rate itself.

By means of the development of such a relation, the authors set the aim of introducing an innovative, more reliable and relatively less expensive method for monitoring fluid flow rates through pipe, with the chance of exploiting its employment also for the detection of possible leaks affecting the urban networks for water distribution.

However, the vibration post-processing spectral approach could suffer from inaccuracies in case of acceleration signals corrupted by high noise level. Indeed, in such a case, the computed frequency spectrum exhibit peaks, whose amplitude could be affected by consistent errors.

In order to override such drawback, the authors introduce a new parameter as an indicator of the fluid flow rate through a pipe, that is, the *Root Mean Square*, RMS, value of the acceleration signal. This parameter, as discussed by the authors in Sections 2 and 3, takes into account the overall pipe vibration level, and, as showed in Sections 4 and 5, it is able to quantify the fluid flow rate, since its relationships with the flow rate is linear.

In this study, the authors perform a series of measurements with the purpose of confirming the RMS parameter goodness as a fluid flow rate meter and, at this aim, they compare the RMS vs. flow rate relation with the one between the acceleration peak amplitude (in the frequency domain) and the same flow rate.

2. Fluid flow rate and pipe vibrations relation theory

The authors have already developed a newer and innovative method for the evaluation of the fluid flow rate through a pipe by means of the exploitation of the relation existing between the flexural vibrations induced on a pipe and the flow rate itself [6,7].

According to those studies, there exists a linear relation between the fluid flow rate and the amplitude of the vibration acceleration in its frequency domain. Refs. [6,7] show that the pipe wall vibrations are consistently influenced by possible fluid flow rate changes, due to the consequent pressure waves propagating along the pipe.

In order to better understand how pressure fluctuations due to occurring fluid flow rate changes, influence the pipe vibrational status, it is worth to recall some interesting results found in the scientific literature. In [8,9], the relation between pressure fluctuations caused by sudden flow rate changes is developed (see Table 1):

$$\frac{\partial^2 r}{\partial^2 t} = -\frac{g}{A\gamma}\dot{p}(x) \tag{1}$$

In [10], Bird et al. state that it is the flow turbulence the responsible for the pipe walls flexural vibrations. In the same reference, the relation between fluid shear stresses at wall, τ_w, and the pressure gradients due to flow rate changes, $\dot{p}(x)$, is developed. In addition, the turbulent shear stresses are related to the time average of the product $u'v'$ (i.e. the flow velocity fluctuations along axial and transversal directions, respectively). Thus, a linear relation between the pressure fluctuations along the pipe direction and the time average of the product $u'v', \dot{p}(x) \propto \overline{u'v'}$ can be devised. In fully developed turbulent pipe flows (i.e. after sufficient development length), the turbulence intensity at a certain radial position across the pipe remains always constant when moving in stream-wise direction (if the mass flow and in turn, the Reynolds number, is kept constant). Then:

$$I = \frac{\sqrt{\overline{u'^2} + \overline{v'^2} + \overline{w'^2}}}{\overline{U}} \approx const \tag{2}$$

From Eq. (2), it is possible to state that $\overline{U} \propto u'$, for quasi 1-D flow [7,10,11].

By taking into account the previous results and exploiting the considerations made in [7], an experimental relation between the fluid flow rate through a pipe and the acceleration of the transversal motion of each section of the same pipe (along the *x*-direction) can be inferred:

$$\dot{Q} = A\overline{U} \propto u' \propto \frac{dp}{dx} \propto \tau_w \propto \frac{\partial^2 r_w}{\partial t^2} \tag{3}$$

In Eq. (3), the term $\partial^2 r_w/\partial t^2$ just stands for the transversal acceleration affecting each section of the pipe.

In Refs. [6,7], the authors experimentally proved the existence of the linear dependence between the pipe fluid flow rate (in fully-developed and turbulent regime) and the amplitude of the radial vibrational acceleration induced onto pipe walls. A careful inspection of the frequency spectrum of the acquired acceleration signals upon the pipe walls, reveals the linear proportionality between the amplitude of some significant spectral harmonics and the inner flow rate in pipe. As outlined in [6,7], in case of rather noisy vibrational signals, the evaluation should be performed on the most prominent harmonic, once the acceleration frequency spectrum has been computed by means of the Fast Fourier Transform (FFT) algorithm. The results shown in [6,7], exhibit an accurate, precise and predictable linear behavior between the identified acceleration peak amplitudes and the tested fluid flow rate through the pipe.

Once such a linearity has been assessed, any fluid flow rate change could be promptly detected and quantified.

However, for highly noisy signals, whenever the Fourier analysis outcome does not allow for a clear and unequivocal harmonic detection, a new method has to be introduced.

In this paper, the authors define a parameter, whose trend (as the flow rate changes) fulfills the linear behavior outlined in Eq. (3). Such a parameter (the signal Root Mean Square value, RMS), is a meter of the energy content carried by the signal under analysis and it is effectively related to the overall amplitude of the signal itself. In Section 3, the authors introduce an accurate definition of the RMS value, pointing out its statistical properties and the conditions to be fulfilled in order to make such parameter eligible for coherently representing the whole signal.

In order to evaluate the effectiveness of the introduced parameter and its trend as the tested fluid flow rate changes, the authors carried out several measurements performed on a test pipe belonging to the substation of a water distribution network run by the local public utility company AQP, in Apulia region (in southern Italy). Section 4 is devoted to the description of the whole experimental set-up and the performed measurements.

Table 1
Nomenclature of Section 2.

Symbol	Quantity
x	Direction along pipe axis
r	Pipe section displacement in radial direction
g	Gravitational acceleration
A	Pipe cross section area
γ	Specific weight of the duct wall material
$\dot{p}(x)$	pressure fluctuation in axial direction

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