Fluid Flow Rate Estimation using Acceleration Sensors

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Abstract — **The present paper describes a procedure improving the measurement of fluid flow rates in pipes through the measurement of vibrations. The authors show, via experimental tests for water system, that for a given pipe in terms of width, diameter and material, the first harmonic amplitude of the vibration signal transmitted from the flow to the pipe walls is linearly proportional to the flow rate at a given revolution of the pump. Then, accelerometer mini/micro-transducers can be used for non-intrusive, low-cost and reliable flow rate measurements without load errors.**

Keywords-vibrations measurement; flow rate measurement in pipes; accelerometer, LDV.

I. Introduction

Flow measurements are very common and widely used in civil as in industrial framework, and accurate flow rate measurements are an important issue [1]. Many flowmeters exist of different type depending on fluid, technology, application, environment, cost, etc., each one with suitable characteristics, strengths and weaknesses. Despite the existence of high performances and sometime sophisticated sensors for special applications (some examples are in [2] and [3]), there is any case the need of having a more general device, possibly non-intrusive, reliable and low-cost, for more common wide spectrum applications. Such kind of devices can be well represented by mini/micro accelerometers transducers, once it is accepted the principle that there exists a correlation between pipe transverse vibrations and fluid flow rates, as shown in [4] - [6], as much strong as much turbulent the flow is. Evans demonstrated, [4], that such vibration components arise from the transfer of the fluid momentum variation due to the fluctuations of its velocity because of the turbulence. Depending on the elasticity properties of the pipe inside which the fluid runs, the vibrations can be more or less amplified, [7], [8].

In this paper a functional relationship is searched that could simply link the accelerations inducted by the flowing fluid onto the pipe walls to its flow rates so giving, if it exists, an easy and reliable method to measure them.

As the flow rate of a fluid depend on its density, velocity and pipe cross sectional area, a first series of tests has been performed on an existing water plant slaved to a test bench for small hydraulic turbine by controlling the flow rate of the fluid and the speed revolution of the motor-pump powering the plant itself. According to the characteristics of the pump, five different speed revolutions have been considered and few possible flow rates for each of them controlled by a manual valve and measured through a high accurate magnetic flowmeter. A LDV equipment has been used to measure the searched pipe vibrations.

II. Theoretical Background

Evans et al., [4], well describe and theoretically prove how flow rates in pipe could be linearly related to the transverse vibrations of it, by considering the differential equation of motion for transverse vibration of a beam as given by Seto [9] and the relation between pressure fluctuations and the rate of change of the momentum along the length of the beam (from structural mechanics), [10], as:

$$\frac{\partial^2 r}{\partial t^2} = -\frac{g}{A\gamma} EI \frac{\partial^4 r}{\partial x^4} = -\frac{g}{A\gamma} p'(x) \quad (1)$$

where:
x = axial direction;
r = radial direction;
g = gravity;
A = cross sectional area of the beam;
γ = specific weight of the beam;
EI = flexural rigidity.

Further, Blake [11] stated the correlation between vibrations of pipes and flow rates of fluid flowing in it; Bird et al. [12] clarified that the turbulence of the flow is the responsible of the transverse vibrations inducted onto the pipe walls. Then, by introducing the intensity of turbulence, it has been easy to show the linear proportionality between the averaged flow velocity and the velocity oscillating component, as Evan himself indicated in his already cited work. Just the velocity oscillating component is responsible of the pressure oscillation in the flow and then of the transverse acceleration of the pipe, because of the momentum transfer.

III. Measure Methodology and Experimental Tests

The flow rate measurements through vibration detections have been carried out by using laser doppler vibrometer (LDV) to sense the accelerations inducted by the flow to the pipe

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walls. The pipe under test is a part of a hydraulic system powered by a turbo-pump with variable revolution. The choice of using the LDV to investigate the pipe vibrations due to internal flow has been suggested by accuracy considerations, so obtaining more precise information about the proposed technique, and by the experience of the authors in managing such technology, [13].

A. Hydraulic System

The hydraulic system (the schema of the hydraulic circuit is reported in Fig.1) consists of a turbo-pump with variable revolution (nominal flow rate $36\,m^3/h$ at $2950\,rpm$); two hydraulic valves, the first is the pump starting valve, the second is a manual control valve used to control the flow rate; a discharge tank in which it drives the water discharge; and the test section. The water discharge through a recirculation circuit returns back to the pump. The turbo pump is driven by a three-phase motor ($22\,kW$ at $3000\,rpm$) powered by an inverter (FC302 – Danfoss).

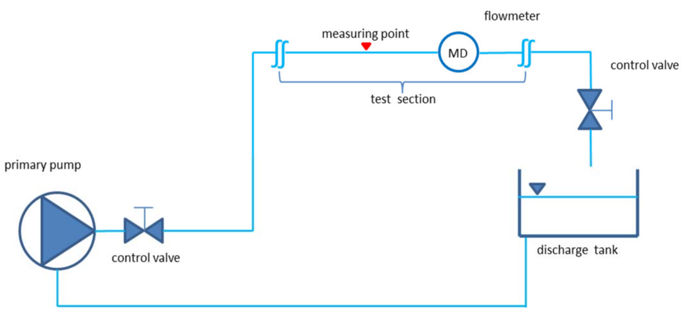

Figure 1. Hydraulic system schema

The flow test section is an horizontal stainless steel pipe of circular cross section having a length equal to $5.5\,m$, nominal diameter of $89\,mm$ and thickness of $2\,mm$. An electromagnetic flowmeter is flanged to the pipe in the test section, but far enough from the test point, to give the nominal value of the flow rate controlled through the manual valve located at the end of the pipe. The LDV is positioned under the pipe in order to measure the transverse vibration signal transmitted from the flow to the pipe wall. The test-point has been chosen in such a way that it can be considered free of oscillating in the transversal out-plane as far enough from the constraints. The inverter powering the pump is operated by a software control panel on which is also reported the value of flow rate acquired by the electromagnetic flowmeter, as shown in Fig. 2.

B. Measurement Transducer and Data Acquisition System

The instrumentation consist of:

- The Polytec Portable Digital Vibrometer, PDV100, non-contact velocity measurement from 0 to 22 kHz;
- The electromagnetic flowmeter - *Mag3100 – Danfoss,* 0,5% L of accuracy

The vibration signals, measured by the LDV, are recorded on a data acquisition system. Data from LDV are acquired in LabVIEW environment by using SignalExpress software and processed in Matlab®.

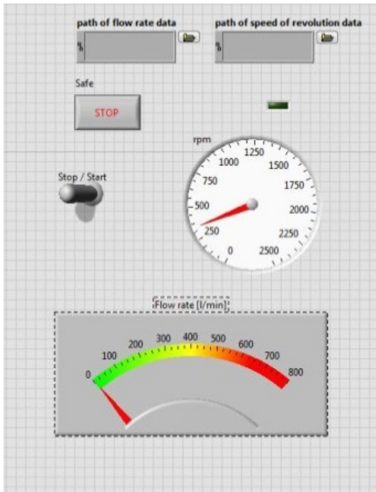

Figure 2. Software control panel of the hydraulic system.

C. Test Procedure

After few runs of the system to suitably choose the acquisition parameters, the sample rate has been set at $1kHz$ for an acquisition time of 10 s. Five different rpm of the pump have been tested, for each of one different flow rates have been measured starting from the maximum value for fully opened control valve, as reported in Table I.

Table 1 – test runs

Test ID	rpm	Flow rate span[*l/s*]
Test 1	1250	1.5 - 3 – 4.5
Test 2	1500	3 – 4.5 - 6 – 7.1
Test 3	1750	1.5 - 4.5 - 6 – 7.1 – 8.2
Test 4	2000	3 – 4.5 - 6 – 7.5 – 9.2
Test 5	2250	3 - 6 - 9 – 10.3

Ten acquisitions have been performed for each value of flow rate to verify the repeatability. The relative errors have resulted negligible for all the measurements.

Appropriate precautions have been taken to avoid or minimize external undesirable vibrations to the structural support (tripod) for the LDV. Furthermore, preliminary tests have been carried out, for any set of measure, to evaluated the noise signals attributable to the pump operation and inducted onto the test section. At this aim, the pump has operated at no load conditions so inducing vibrational solicitations onto the pipe, with the flow at rest in, due to its revolution only: the measurements acquired represent the noise affecting the pipe system.

The time series data-noise, Fig.3, have been analysed in the frequency domain to better recognized the noise frequencies during the measuring test. The signal presents a perfectly null average value, as it has to be. As example of transversal vibration spectrum obtainable from the acquisitions, the case at 1750 rpm is considered in Fig. 4, where the first 3 harmonics are well discernible, while the peaks at the lower frequencies than the fundamental one are alias of the highest harmonics representative of the noise, included that one induced by the pump operation.

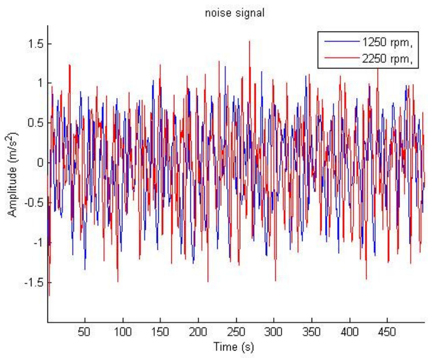

Figure 3. Examples of noise signal in physical domain for minimum and maximum values of rpm tested.

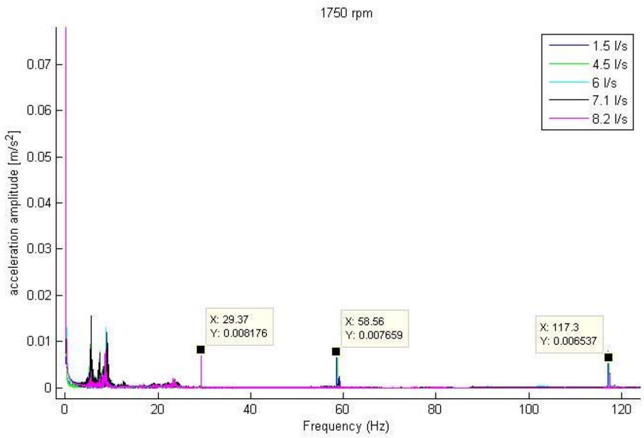

Figure 4. Transverse vibrations spectrum at 1750 rpm

IV. RESULTS AND COMMENTS

The focus of this research has been to find a functional relation between flow rates and transverse vibrations inducted by them onto pipe walls. Via experimental results, the first harmonic amplitudes of the vibrational signals acquired have been resulted linearly proportional to the flow rates for a given revolution of the pump, so corroborating the idea of using simple acceleration transducers positioned on the pipe wall to measure the flow rate. The results here presented are valid for a given diameter and material of the pipe.

In Figs. 5-9 the first harmonic of the signal spectra are reported for the different speeds of revolution inspected.

Results show that:

- the amplitude of the first harmonic increases as the flow rate grows;
- the first harmonic frequency increases as the rpm raises, as expected;
- same behaviour have the successive harmonics, but lower amplitudes, as expected.

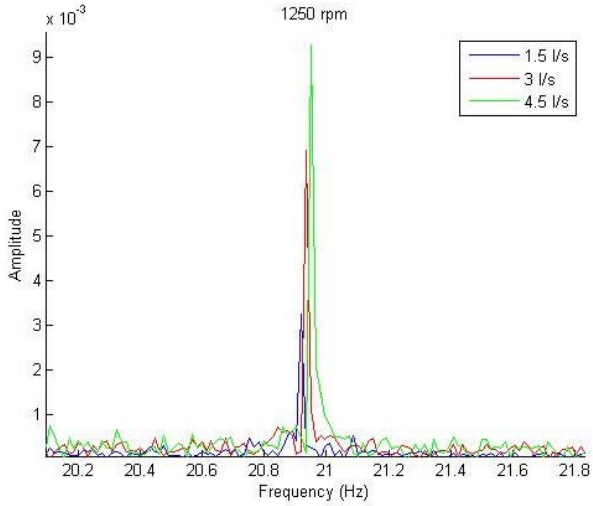

Figure 5. First harmonic of the vibrational spectrum plotted for 3 different flow rates at 1250 rpm.

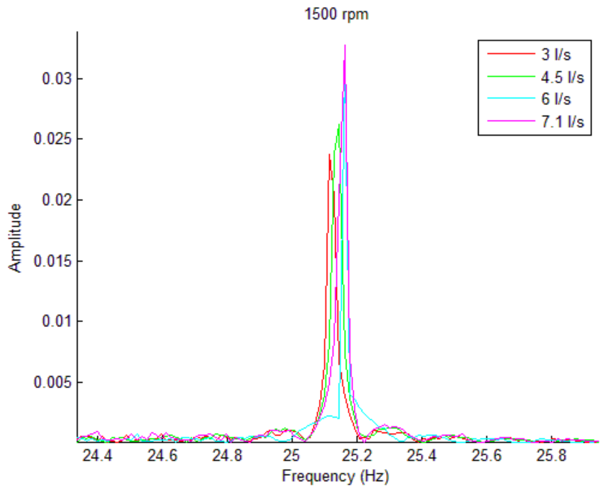

Figure 6. First harmonic of the vibrational spectrum plotted for 4 different flow rates at 1500 rpm.

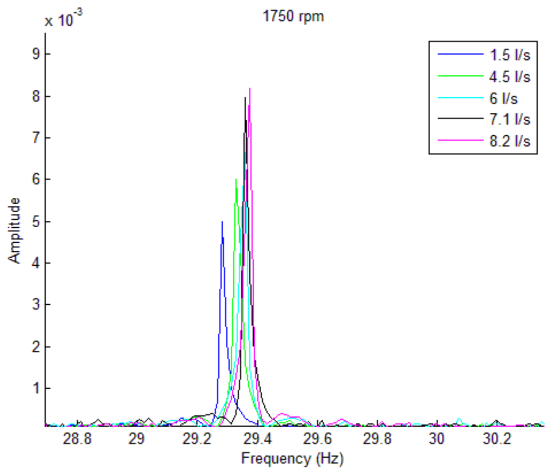

Figure 7. First harmonic of the vibrational spectrum plotted for 5 different flow rates at 1750 rpm.

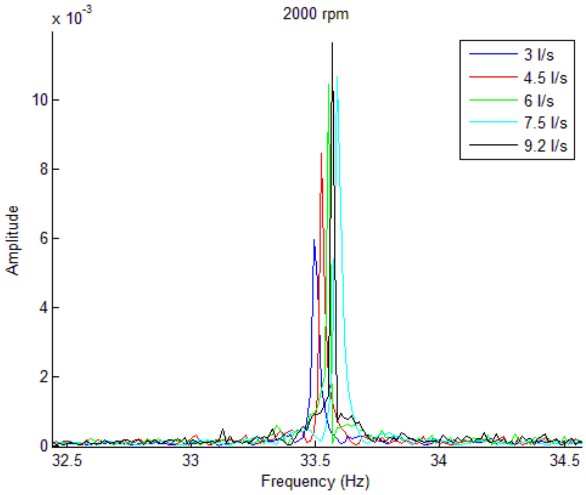

Figure 8. First harmonic of the vibrational spectrum plotted for 5 different flow rates at 2000 rpm.

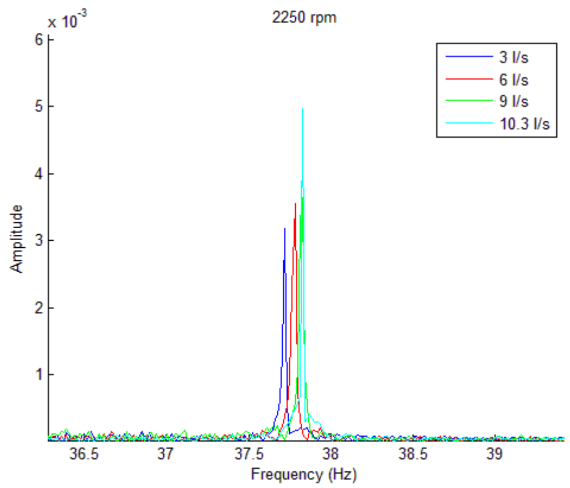

Figure 9. First harmonic of the vibrational spectrum plotted for 4 different flow rates at 2250 rpm.

From these main observations, graphs have been produced relating 1st harmonic amplitude of the inducted acceleration to flow rate at constant speed of revolution, as presented in Figs. 10-14, which verify the linear dependence between the two quantities, as the theory assures.

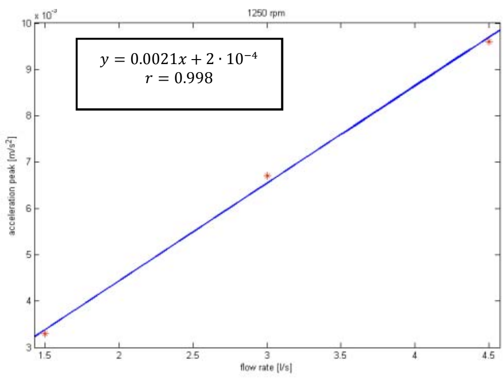

Figure 10. Acceleration peak (m/s^2) vs flowrate (l/s) at 1250 rpm

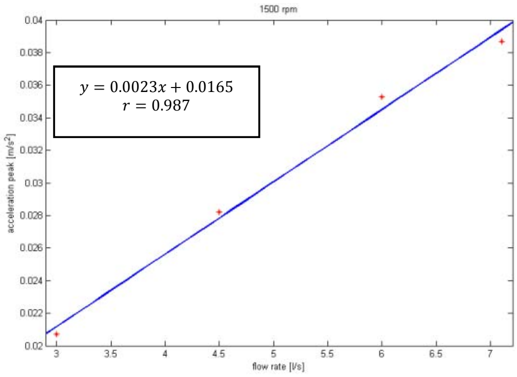

Figure 11. Acceleration peak (m/s^2) vs flowrate (l/s) at 1500 rpm

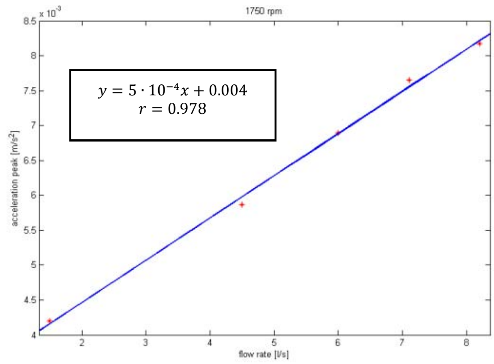

Figure 12. Acceleration peak (m/s^2) vs flowrate (l/s) at 1750 rpm

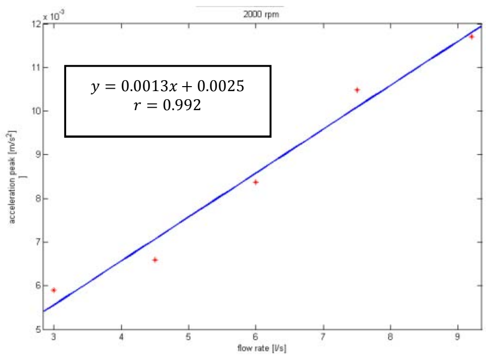

Figure 13. Acceleration peak (m/s^2) vs flowrate (l/s) at 2000 rpm

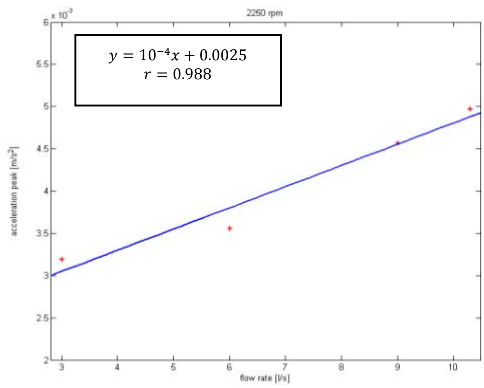

Figure 14. Acceleration peak (m/s^2) vs flowrate (l/s) at 2250 rpm

V. CONCLUSION

The results shown in Figs. 5-14 provide the important assessment that it is possible to find an exposed point on a pipe where to sense the transverse acceleration signal inducted onto its walls because of the flow turbulence and strongly correlated to the flow rate of the fluid running in it, regardless of shape, layout and pipe mounting methods. The procedure of measure it has resulted highly repeatable, showing negligible errors indeed. The relation between the 1^{st} harmonic amplitude of the transverse acceleration and the flow rate flowing inside the pipe is linear. Here, it has been experimentally verified that it is possible to easily measure water flow rates in pipes by simply and reliably measuring vibrations so promoting the use of non-intrusive and low-cost sensors like the acceleration mini/micro-transducers, which allow acquisitions with no load effects. The calibration of the procedure is fast and easy, because of the linearity of the transfer function. Further tests are going to be planned to better investigate the influence of the pipe flexural rigidity on the limits of the procedure applicability.

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