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FLOW EVALUATION FROM THE ENERGY OF PIPE WALL VIBRATIONS

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Abstract:

The leading idea of this work, is to propose a simpler and intuitive mean for evaluating the stationary flow rate in a pipe, through the measurements of vibrations transmitted by the flow to the pipe wall thanks to its turbulent regime. To achieve the target, the authors introduce the RMS value of the pipe oscillation modes, starting from the observation that the intensity of the pipe vibrations depends on the energy content of the signal, in its turn linked to the flow rate measurement. As this statistical parameter can be assumed as an energy level indicator of the whole signal acquired from the pipe vibration, it results linked to the flow rate responsible of that phenomenon. After verifying that the vibrational signal under investigation is a stationary stochastic process, the RMS value can easily and fast provide the value of the flow rate running in a pipe, without worrying too much about the noise associated to the measurement, once the pipe has been characterized.

Keywords: flow rate measurement, pipe vibration mode, signal RMS, non-intrusive measure technology.

1. INTRODUCTION

The water losses that occur in water network represent an important issue, not only from an economic point of view, but also because water resources are non-inexhaustible, especially underground ones. Furthermore, the presence of leaks in a water network also lowers the overall hydraulic efficiency and thus the overall reliability of the system.

The water losses are mostly due to a series of structural weaknesses, management inability and inadequate maintenance (ordinary and extraordinary) of water systems that give rise to significant losses [1]. The amount of water losses is typically between 20 to 30% of production. In Italy, for example, these losses represent almost 40% of the water resource; they have an effective and heavy impact on the environment. Losses of amounts of water already subjected to the required purification and sanification treatments and then, equipped with the hygienic requirements and organoleptic fit for the human consumption, could bring to social and economic issues especially in those regions characterized by poor rainfall.

The scientific literature provides so many examples about methods aiming to the identification and quantification of water losses occurring in water piping and networks, [2]-[7]. These techniques are based on the implementation of numerical algorithms directly on acquired signals related to certain physical parameters, which describe the operational condition of the pipe under analysis. Humidity sensors employed for water losses detection into the ground, pressure transducers used for pressure drops and changes along the pipe (and directly related to possible water losses), acoustic and/or vibrational measurements made on the pipe wall and aimed to detect possible vibrational status changes due to water flow rate changes, are among the most and viable choices to be considered.

In this paper, the authors provide a simple and intuitive way to easily evaluate the flow rate steadily running in a pipe based on post-processing of vibrational signals sensed on the pipe wall under analysis and due to the turbulent actions of the flow onto it, [9, 10]. Multiple sensing on the pipes (network) would also allow the immediate detection and quantification of possible water losses, so making more reliable and effective the monitoring and control of the water system, especially if all the operations are automatically managed via a wireless network of communication to a remote server.

2. PROPOSED METHOD

Previously [8]-[10], the authors developed an innovative water loss detection methodology based on the measure of vibration signals inducted from the fluid to the pipe wall, because of its turbulence. The method has been tested and proved by the authors for the measurement of flow rates in steady state conditions in reference [9], where the linear dependence existing between the fluid flow rate in a pipe (in turbulent regime) and the amplitude of the radial vibrational acceleration produced onto the pipe wall has been analysed and proved experimentally. This method implies the implementation of the FFT algorithm in order to get the vibrational signal spectrum, which reveals the most significant harmonics directly related to the natural frequencies of the investigated pipe.

Figure 1, from [10], is here proposed again as example to show the linear relationship between the signal spectrum amplitude and the inner flow rate in the pipe.

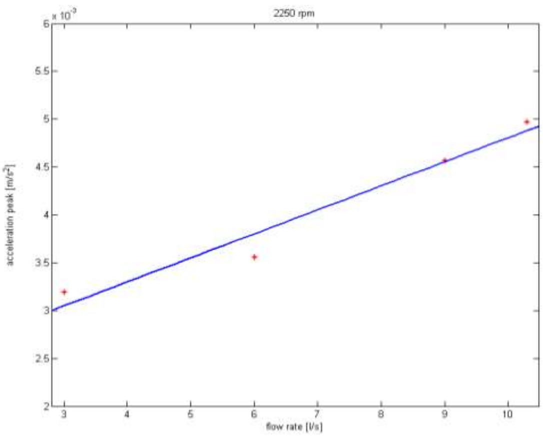

Figure 1– Acceleration peak of the most significant harmonic vs flow rate.

Once the linearity between vibration spectrum amplitude has been stated, any sudden water flow rate change could be easily detected and quantified. Unfortunately, this method could suffer from deficiencies whenever the vibrational signal under investigation is particularly noisy (in this case, the identification of the most prominent harmonic is hard).

Thus, the authors propose the use of the Root Mean Square (RMS) of the sensed signal as its energy depends on the flow rate, no matter noise is present or not.

2.1. Root Mean Square parameter

Any physical time-dependent signal representative of a periodical phenomenon can be, under opportune constraints, transformed into a time-series. Such a series can be interpreted as a succession of outputs of a stochastic process. Under specific conditions, it is always possible to identify significant parameters of the energetic content of the original signal. In the case of a stationary time-series, the RMS is the easiest parameter to be considered.

The root-mean-square level of a vector, X, is defined as,

$$X_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}|X_i|^2} \qquad (1)$$

with the summation performed along the specified dimension.

In the present case, the vibration induced by the flow onto the pipe wall can be seen as a stationary stochastic process with constant statistical properties (i.e. the root means square value and higher order statistics). In order to assess the stationarity of the random signal, several testing hypothesis could be taken into account.

Intuitively, a stochastic process is stationary if its probabilistic structure is invariant over time. In order to evaluate the stationarity of the signal, the autocorrelation function has been considered [11]. This function measures the correlation between values of the process at different times, as a function of two successive ones or of their time lag. The autocorrelation formula for k lag is,

$$r_k = c_k / c_0 \qquad (2)$$

where, being y_t a stocastic process:

$$c_k = \frac{1}{T}\sum_{t=1}^{T-k}(y_t - \bar{y})(y_{t+k} - \bar{y}) \qquad (3)$$

and c_0 is the sample variance of the time series.

The resulting value of r_k (correlation factor) ranges between -1 and +1.The stationarity of the signal, then, is verified when r_k is close to zero and checked by means of the correlogram of the pairs of values (k, r_k).

Once the stationarity test succeeds, the RMS value could be assumed as an energy level indicator of the whole signal.

2.2. Experimental set-up

The experiments have been carried out on a pipe belonging to water distribution network owned by Acquedotto Pugliese S.p.A. (AQP), a water utility company of Southern Italy.

The vibrational acceleration signals have been acquired by means of a single point Laser- Doppler Vibrometer (LDV) (Polytec PDV 100). Such an instrumentation cancels the insertion and loading effects instead occurring whenever a traditional technology is employed to measure the flow rate. The LDV output signals gives the acceleration of the vibrational motion of the pipe wall.

Figure 2 shows the experimental setup, while fig. 3 is a sketch of the instrumentation and the acquisition method.

The tests here reported have been carried out on a cast iron pipe of 300 mm nominal diameter, located in a public aqueduct substation of the AQP Company. Each test has been performed for an enough long period of time to assure the stationarity of the process, checked by means of an electro-magnetic flowmeter. Here, just one series of measured flow rates are reported as example: 25.0, 42.4 and 64.5 L/s.

The test procedure consisted in measuring the vibration signals (the velocity of vibrational oscillations) when a well-known water flow rate runs in the duct.

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Figure 2 – Experimental set-up and pipe section of the water distribution network

Figure 3–Test layout

3. RESULTS

To evaluate the RMS of the acquired signals, the properties of stationary has been assessed. In fig. 4 the autocorrelation functions, of each flow rate, are reported.

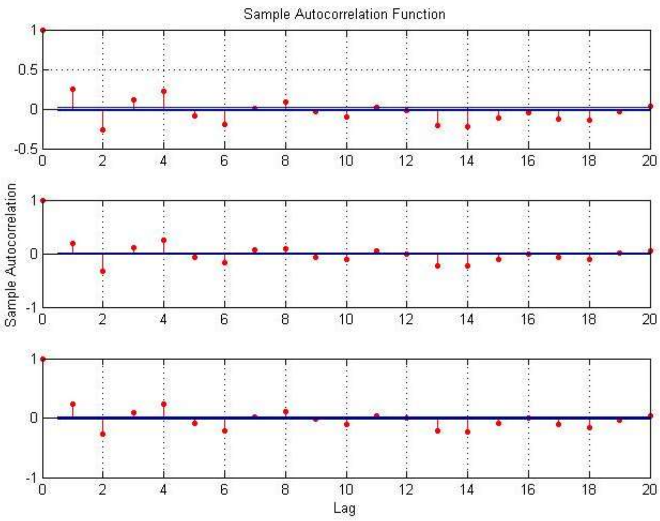

Figure 4– Correlograms of the first 20 lags of the sample autocorrelation function

The previous correlograms show the correlation of univariate stochastic time-series, being the autocorrelation the cross-correlation, by definition, of a signal with itself at different instants of time. The acquired signals under test result, therefore, stationary.

As the vibration modes of the pipe are always the same for different flow rates in it (only the energy content varies, and thus, the amplitudes of the signal harmonic components), the RMS of the signals for each flow rate can be evaluated and related to them. Figure 5, then, reports the linear fit between RMS values and the corresponding flow rates, so confirming the initial assertion.

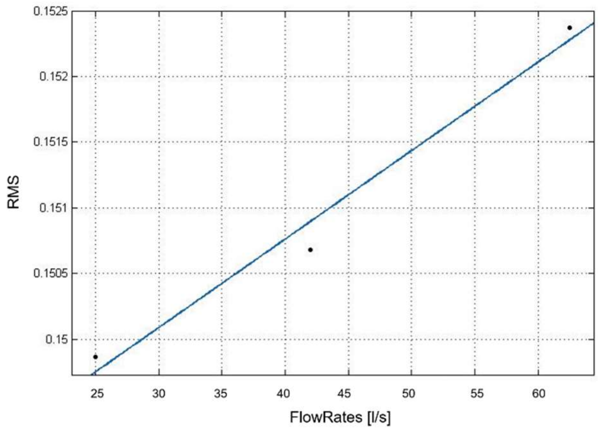

Figure 5 – The RMS vs flow rates. Goodness of fit: SSE: 6.705e-08, R-square: 0.9795, Adjusted R-square: 0.959, RMSE: 0.0002589.

4. CONCLUSIONS

The fundamental goal of this paper has been to propose a simpler and intuitive mean for evaluating the flow rate in a pipe, through the measurements of the vibrations transmitted by the flow to the pipe wall because of its turbulent regime. To achieve the target, the authors introduce the RMS value of the pipe oscillation mode so demonstrating that this statistical parameter can be assumed as an energy level indicator of the whole signal acquired from the pipe vibration, linearly linked to the flow rate responsible of that phenomenon.

After verifying that the signal under investigation is a stationary stochastic process, the RMS value, as vibration energy level indicator, can easily and fast provide the value of the flow rate running in it without worrying too much about the noise associated to the measurement, once the pipe have been characterized.

5. REFERENCES

[1] P. Jowitt, and C. Xu, "Predicting Pipe Failure Effects in Water Distribution Networks," Journal of Water Resources Planning and Management Volume 119, Issue 1, pp. 18-31, 1993.

[2] Ranko S. Pudar, and James A. Liggett. "Leaks in pipe networks." Journal of Hydraulic Engineering, Volume 118, Issue 7, pp. 1031-1046, 1992.

[3] James A. Liggett, and L. Chen, "Inverse Transient Analysis in Pipe Networks," ASCE Journal of Hydraulic Engineering, Volume 120, Issue 8, pp 934-955, 1994.

[4] S. Eyuboglu, H. Mahdi, H. Al-Shukri and L. Rock, "Detection of water leaks using ground penetrating radar." 3rd International Conference on Applied Geophysics, Orlando, Fla. 2003.

[5] M. Eiswirth, L.S. Burn, "New Methods for Defect Diagnosis of Water Pipelines" In: 4th International Conference on Water Pipeline Systems. March, York, UK, 2001.

[6] M. Bimpas, A. Amditis, and N.K. Uzunoglu. "Design and implementation of an integrated high resolution imaging ground penetrating radar for water pipeline rehabilitation." Water resources management, Volume 25, Issue 4, pp. 1239-1250, 2011.

[7] B. Brunone, "Transient test based technique for leak detection in outfall pipes." Journal of Water Resources Planning and Management, ASCE Volume 125, Issue 5, 302e306, 1999.

A. Lay-Ekuakille, and P. Vergallo, "Decimated signal diagonalization method for improved spectral leak detection in pipelines." Sensors Journal, IEEE 14 (6), pp. 1741-1748, 2014.

[8] M. M. Campagna, G. Dinardo, L. Fabbiano, G. Vacca, "Fluid flow measurements by means of vibration monitoring." Measurement Science and Technology, Volume 26, Issue 11, 115306, 2015.

[9] G. Dinardo, L. Fabbiano, and G. Vacca. "Fluid Flow Rate Estimation using Acceleration Sensors." 2013 Seventh International Conference on Sensing Technology (ICST), IEEE, pp 221-225, 3-5 December,2013, Wellington, New Zeland.

[10] G. Dinardo, L. Fabbiano, G. Vacca. "Proposal of Innovative Leak Sensing Systems for Water Distribution Networks." Ninth International Conference on Sensing Technology. NZL, pp 269-273, 2015.

[11] A. V. Oppenheim, R. W. Schafer, and J. R. Buck. *Discrete-time signal processing*. Englewood Cliffs, NJ: Prentice hall, 1989, 2nd ed. pp. 743.