10.2478/v10048-010-0036-0

Impedance Method for Leak Detection in Zigzag Pipelines

A. Lay-Ekuakille[1], P. Vergallo[1], A. Trotta[2]

[1]Dipartimento d'Ingegneria dell'innovazione, University of Salento, Via Monteroni, 73100 Lecce, Italy, aime.lay.ekuakille@unisalento.it
[2]Dipartimento di Elettrotecnica ed Elettronica, Polytechnic of Bari, Via Orabona, 70100 Bari, Italy

Transportation of liquids is a primary aspect of human life. The most important infrastructure used accordingly is the pipeline. It serves as an asset for transporting different liquids and strategic goods. The latter are for example: chemical substances, oil, gas and water. Thus, it is necessary to monitor such infrastructures by means of specific tools. Leakage detection methods are used to reveal liquid leaks in pipelines for many applications, namely, waterworks, oil pipelines, industry heat exchangers, etc.. The configuration of pipelines is a key issue because it impacts on the effectiveness of the method to be used and, consequently, on the results to be counterchecked. This research illustrated an improvement of the impedance method for zigzag pipeline by carrying out an experimental frequency analysis that has been compared with other methods based on frequency response. Hence, the impedance method is generally used for simple (straight) pipeline configurations because complicated pipelines with many curves introduce difficulties and major uncertainties in the calculation of characteristic impedance and in the statement of boundary conditions. The paper illustrates the case of a water pipeline where the leakage is acquired thanks to pressure transducers.

Keywords: Pipeline leak detection, magnetic sensors, impedance method, transient analysis, pressure transducers

1. INTRODUCTION

THE BUILDING of strategic infrastructures as pipelines is a matter of interest because it is a multidisciplinary field that involves financial resources as much as human ones**.** The problem of protecting natural resources has become important because resources are limited. In particular, water is one of the most important natural resources that is present in many locations all over the world as an environmental component. Its rational and clever use is a matter of concern for thousand of millions of people all over the world. Since sweet water is not unlimited, its use in locations where it is not present authorizes its transportation towards areas where it must be used, thanks to pipelines and artificial reservoirs and natural basins. For the above reasons, the control and the detection of leakages in pipelines for water usage is basically an interesting topic for research.

Leak Detection is accomplished in two phases. During the first phase, the entire system is surveyed for "leak sounds." When a sound is heard, the location is noted as a potential leak site. Actually, any condition which interferes with the normal flow of water can produce vibrations similar to the vibrations caused by leaks. During the second phase, each location is further investigated. If necessary, a computerized leak correlator that works on sonic transmission (speed of sound) principles is used to pinpoint the exact location of the leak. The correlator eliminates the need for extensive hit-or-miss excavation, and the unnecessary destruction of expensive pavement. Without the correlator, finding many leaks would be like searching for the proverbial needle in a haystack [1]. Since current leak detection techniques rely on vibrations that travel from molecule to molecule along the wall of the pipe, the most important factor affecting leak detection is the pipe material itself. The denser the wall of the pipe, the greater the distance leak sounds will travel. Density is a function of molecular proximity. Cast iron, ductile iron, galvanized steel, and copper pipes are all extremely dense and exhibit excellent transmission qualities. Asbestos-concrete pipe (AC), or transite as it is often called, is not as dense and dampens vibrations much quicker than metallic pipes. Due to their lack of density, PVC and poly-pipe absorb, or attenuate, vibrations rather quickly. As a result, leak sounds do not travel great distances on these plastics. To compensate for transmission shortcomings, the leak detection operator will, if at all possible, choose access point intervals appropriate for the pipe material [2]. Pipe diameter also affects sound transmission characteristics. Large diameter pipes tend to attenuate vibrations. Thus, a six-inch iron main will transmit leak sounds farther than a 12-inch iron main. In addition, the degree of soil compaction around a pipe often alters its transmission characteristics. When the soil around a pipe is firmly compacted, the pipe wall loses some of its elasticity, and sound transmission is improved. Generally, the degree of compaction is a function of pipe depth [3]. Fig.1 illustrates an overview of leak detection methods currently used.

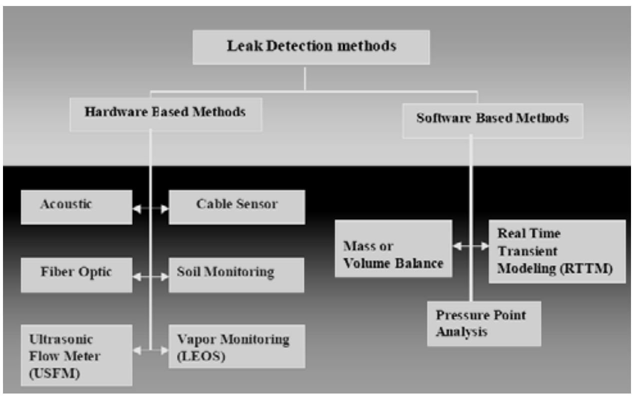

Fig.1. Leak detection method overview.

2. IMPEDANCE METHOD

The impedance method is generally used for linear pipelines with less curves and bends, that is, straight pipelines. If we want to use an analytical model, we have to point out the motion equations which describe transient one-dimensional flow in a cylindrical pipe according to the Hooke law that can be modified from the model implemented by some authors [4]. Applying the conservation laws of mass and momentum yields the following equations of continuity and motion:

$$\frac{\partial Q}{\partial x}+\frac{gA}{c^2}\frac{\partial H}{\partial t}=0 \tag{1}$$

$$\frac{\partial H}{\partial x}+\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{\lambda Q|Q|}{2gDA}=0 \tag{2}$$

where Q is the fluid discharge, H=z+p/ρg is the head, C is the pressure wave celerity, ρ is the fluid density, λ is the coefficient of friction, A is the cross section area of the pipe, D is the circle pipe diameter, t is the time and x is the distance along the pipe. The integration of Eqs. (1) and (2), utilizing the method of characteristics [5], permits to describe the pressure time-history at each computational point as originated by the propagation of positive and negative pressure waves. Following this approach, first of all, we can briefly describe two methods: leak analysis using transients and the impedance method [6].

2.1 Analysis of transients in pipelines

The method of characteristics is used to transform the system of partial differential (1) and (2) into a system of ordinary differential equations that can be integrated numerically without difficulty. Hence,

$$dQ\pm\frac{gA}{C}dH+gAJdt=0, dx=\pm Cdt \tag{3}$$

the + indicates the waves are coming from the upstream while the - stands for the waves coming from downstream. $J=(\lambda/D)Q|Q|/(2gA)$ is the linear head loss by unit of the length of the pipe. Equation (3) determines the evolution of the head pressure and the discharge according to the time and the space. Its solutions constitute the solutions to the original system of (1) and (2). In an experimental pipeline, when the valve is suddenly closed, an abrupt increase in pressure wave is then reflected back by the leak provoking a partial reduction of the incoming pressure wave [7]. Then, the wave is reflected bringing on a negative wave, if for instance a reservoir is connected to the pipe. Analogously, discontinuities in the pipe flow conditions such as leaks, provoke partial reflection of the incoming pressure wave. Thus, through correctly interpreting these head and leak discharge-time histories at the valve section, it is possible to extract information on the leak location.

2.2 Impedance method

The instantaneous hydraulic impedance line elevation H and the discharge Q are divided into two parts, the average magnitudes and $\overline{Q}$ and the oscillatory $H=\overline{H}+h$ and $Q=\overline{Q}+q$ [8]. The hydraulic impedance $Z(x)$ is defined as the ratio of the head fluctuation h to the discharge q. Hence

$$Z(x)=\frac{h}{q}=\frac{i\gamma C^2}{\omega gA}\frac{C_1e^{\gamma x}+C_2e^{-\gamma x}}{C_1e^{\gamma x}-C_2e^{-\gamma x}}=-Z_c\frac{C_1e^{\gamma x}+C_2e^{-\gamma x}}{C_1e^{\gamma x}-C_2e^{-\gamma x}} \tag{4}$$

having assumed the following:
$h=H(x)e^{j\omega t}$ and $q=Q(x)e^{j\omega t}$, where ω is the angular frequency;
$\gamma=\alpha+i\beta$ is generally referred to as the propagation constant;
C_1 and C_2 are the integration constants from h and q.
The characteristic impedance Z_c is defined by

$$Z_c=\frac{\gamma C^2}{i\omega gA}=\frac{C^2}{\omega gA}(\beta-i\alpha) \tag{5}$$

Particular boundary conditions of the pipeline must be envisaged in order to assess the integration constants C_1 and C_2. The terms used in (3) are the following: C as water speed, g stands for acceleration of free fall and A is the pipe section. If the pipe friction is neglected, the final formulation of the pipe impedance with a leak could be:

$$|Z_{sx}|=Z_c\left\{\frac{\left[1+\tan^2(\pi\omega_r l_r/2)\right]^2}{Z_c^2/Z_L^2}+\left[\tan(\pi\omega_r l_r/2)\right]^2\right\}^{1/2} \tag{6}$$

The leak position l_r is calculated from the above relationship by calculating Z_L for each point where a leak could be detected. The system equation without leaks is given by the following:

$$|Z_{s2}|=\left\{Z_c\Bigg/\left(\begin{array}{l}\left[1+\tan^2(\pi\omega_r l_r/2)\right]^2+\\ \frac{Z_c^2}{Z_L^2}\left[\tan(\pi\omega_r l_r/2)-\tan(\pi\omega_r/2)\right]^2\end{array}\right)\right\}*$$
$$\left\{\left[-\frac{Z_c}{Z_L}\left[1+\tan^2(\pi\omega_r l_r/2)\right]\left[\tan(\pi\omega_r/2)-\tan(\pi\omega_r l_r/2)\right]^2\right]^2+\right.$$
$$\left.\left[\begin{array}{l}\frac{Z_c^2}{Z_L^2}\tan(\pi\omega_r l_r/2)\left[\tan(\pi\omega_r l_r/2)-\tan(\pi\omega_r/2)\right]^2\\ +\tan(\pi\omega_r l_r/2)\left[1+\tan^2(\pi\omega_r l_r/2)\right]^2\end{array}\right]^2\right\}^{1/2} \tag{7}$$

3. EXPERIMENTAL FACILITY DESCRIPTION

The method has been applied to the hydraulic circuit of Fig.2, used in previous work [9] in order to make a comparison. The length of the circuit is 59 m while the section is 1 inch. The inner part of the pipe is in copper with a plastic sheath. 5 water taps are used to simulate leaks and a series of pressure transducers is located on the zigzag pipeline.

Fig.3 illustrates the signal transmission as a loop departing from the computer across different aforementioned devices and apparatuses and arriving to the same computer. The MATLAB-based interface is connected to the hardware thanks to a RS-232 connection the user utilizes.

The experimental setup includes, as depicted in Fig.4: tank (100 liters); flexible rubber pipe (1 inch); electric pump (Ebara CMA 1.00T, 0.75kW, 3000 rpm, impeller diameter 160 mm); multilayer pipe in copper, coated with a plastic-based sheath, having 11 valves; Gems sensors 2200A pressure transducer (output 4-20 mA 2 wires, supply voltage sensitivity 0.01% FS/Volt, supply voltage 1.5 VDC above span to 35 VDC @ 6mA); and various other items such as electronic control.

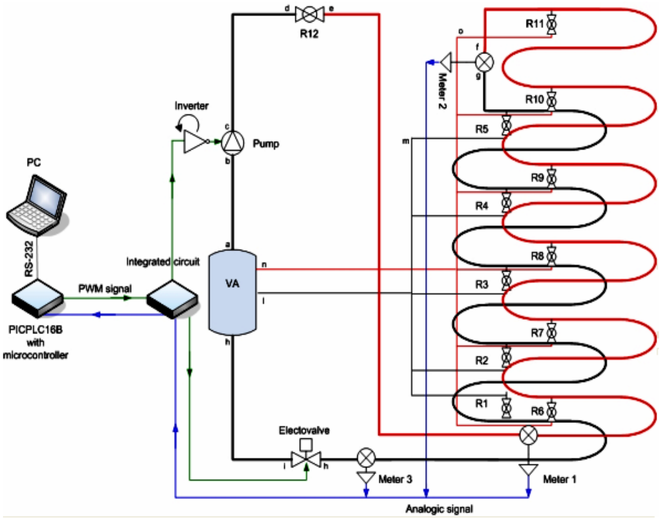

Fig.2. Experimental plant layout.

The electronic card PICPLC16 with the microcontroller has analog inputs, PWM (Pulse Width Modulation) outputs and a RS-232 connection. The successive active lowpass circuit transforms PWM signal into a signal proportional to the duty cycle of PWM.

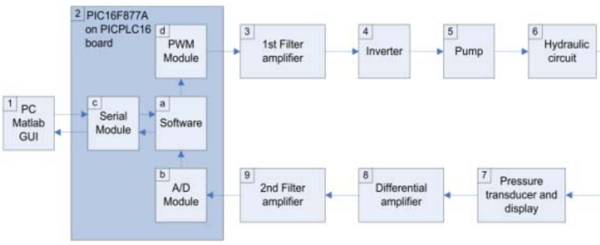

Fig.3. Experimental plant data architecture.

The water flow variation is accomplished by acting on the pump voltage thanks to micromaster 410 inverter (0.55kW); afterwards, on the above described pressure transducer. The successive differential amplifier allows the transformation of differential voltage coming from the pressure transducer into one amplified signal referred to the system potential GND, where GND stands for ground. The last block illustrates a lowpass circuit with an appropriate gain to remove noise at high frequencies related to analog input of the microcontroller of the PICPLC16 card. The entire wall mounted pipeline is illustrated in Fig.4.

Fig.4. System mounted on the wall.

4. DISCUSSION

The algorithm works as follows: calculating the characteristic impedance of all the pipelines (on 59 m), analyzing the suitable frequency for each location of the water tap, calculating Z_L and Z_{sx} for each water tap position, it is possible to determine leak position l_r thanks to (4). Further explanations are derived from Fig.5. The frequencies are experimentally recovered from plots of Fig. 2 and Fig.3 for each position of presumed leaks by transforming the time domain in frequency one versus pressure. Only the time (then the frequency) that corresponds to a high peak is considered for the impedance method. The procedure is performed by calculating the impedance at the presumed leak as indicated in Fig.6 and Fig.7.

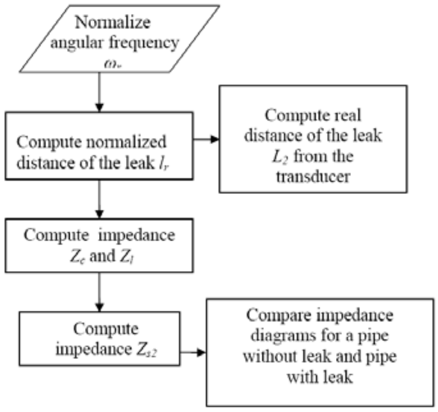

Fig.5. Impedance method procedure.

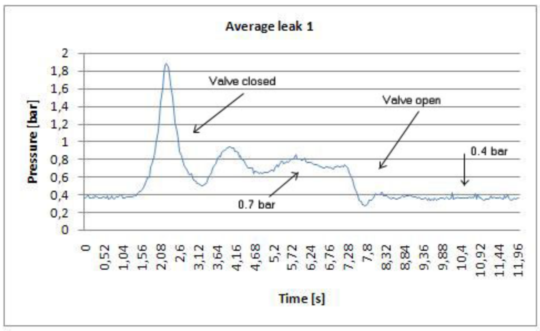

Fig.6. Opening and closing trend for leak1.

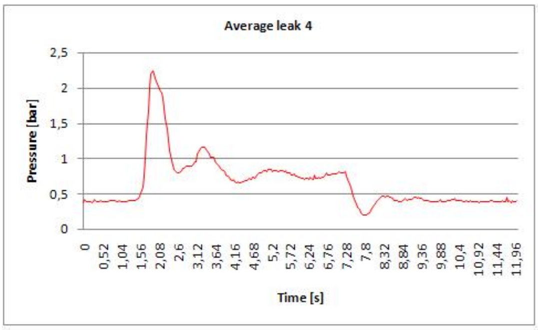

Fig.7. Opening and closing trend for leak 4.

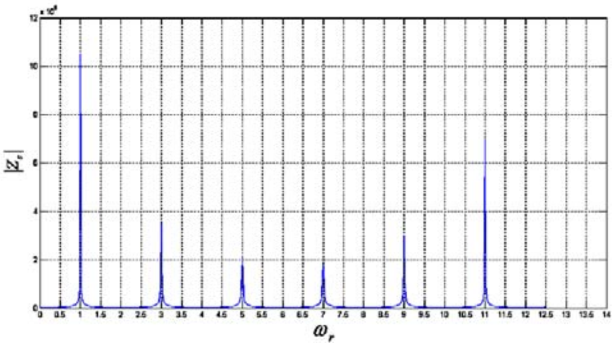

Fig.8. Trend without leaks.

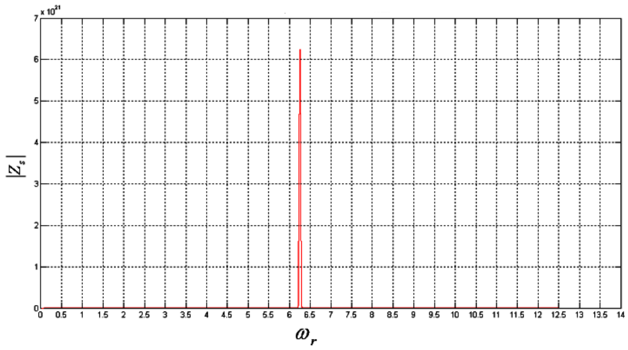

Fig.9. Time analysis for leak 1.

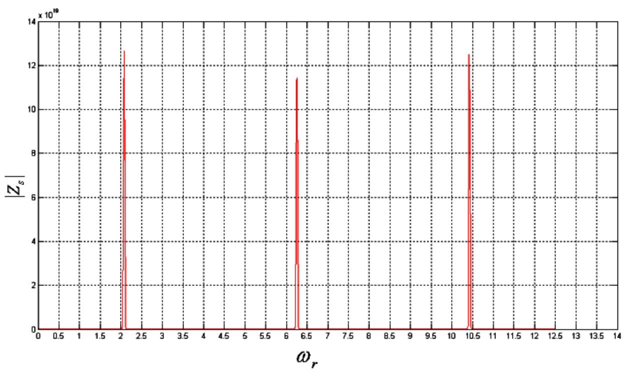

Fig.10. Time analysis for leak 3.

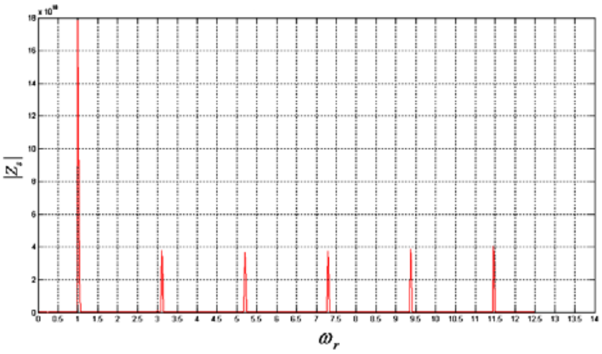

Fig.11. Time analysis for leak 6.

The results of the aforementioned algorithm are illustrated in Fig.8 - Fig.11 for each leak of the experimental pipelines. In absence of leaks, the system displays the plot of Fig.8 in accord with the relationship (7), while the other plots show the detection of leaks accordingly. Simultaneously, during the acquisition of data for the application of the impedance method, FFT and STFT algorithms were applied for a comparison, as depicted in Fig.12. Tab.1 illustrates the final results with appropriate comparisons among the different methods.

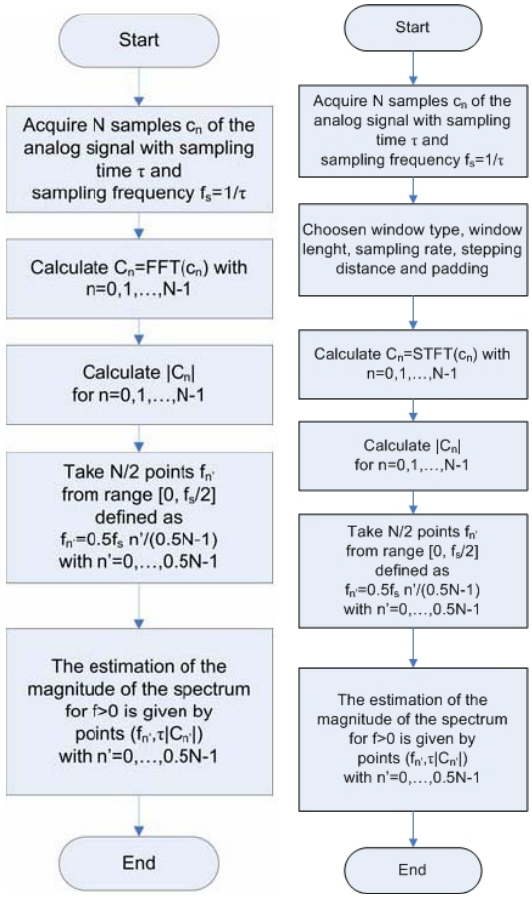

Fig.12. FFT and STFT algorithms.

Tab.1 also illustrates the difference between zigzag pipe and a straight pipe. Hence, the modified impedance method demonstrates the possibility of a good application for a double zigzag pipeline. The experimental hydraulic circuit has a counter-current flow in a vertical direction after the 6^{th} leak. So, the condition of the application of the proposed method is very conservative with unexpected difficulties with respect to common plants encountered in reality.

Table 1 Experimental results.

Input	Method	Regression	Uncertainty	Impedance M. Zigzag pipe
Opening and closing electrovalve periodically	STFT	Linear	± 3.20 m	±3.60 m
	STFT	Quadratic	± 1.80 m	± 2.10 m
	FFT	Linear	± 3.90 m	± 4.05 m
	FFT	Quadratic	± 1.94 m	± 2.10 m
Square wave input and closed electrovalve	STFT	Linear	± 6.00 m	± 5.90 m
	STFT	Quadratic	± 8.50 m	± 8.20 m
	FFT	Linear	± 7.90 m	± 7.50 m
	FFT	Quadratic	± 9.68 m	± 9.30 m

5. CONCLUSIONS

As we have already mentioned in the introduction, water is becoming one of the most precious natural resources. Human activities require huge amounts of water and thousands of cubic meters of water are wasted during its transportation with pipelines and distribution by means of urban waterworks. Implementing water leak detection is a challenging task for many researchers. Impedance method is one of them.

The application of (4) for all leaks, with a good and precised frequency analysis has yielded the results depicted in Tab.1. In that table a comparison is carried out between the impedance method and the STFT (Short-time Fourier Transform) and FFT (Fast Fourier Transform). The procedure that leads to STFT and FFT has been explained in [10]. In the same table, a simulation has been executed by considering the pipeline as a straight one. Thus, the results are, of course, better than for the zigzag pipe. This last performance is due to the nature of the impedance method for straight pipeline. However, the frequency analysis procedure used in this paper has shown good and comparable results with respect to STFT and FFT. That is the desired improvement found in this research.

REFERENCES

[1] Water & Waste Pipe Testing Inc. (1999). *A Report for Conducting a Water Leak Detection Survey on the Entire Water Distribution System for the Town of Ipswich.* Wakefield, MA, USA.

[2] Georgia Enviromental Protection Division. (2007). *Water Leak Detection and Repair Program.* Atlanta, USA: Georgia EPD.

[3] New Mexico Environmental Finance Center. (2006). *Analysis of Fluid Conservation System's Leak Detection Technology*. Albuquerque, NM, USA.

[4] Wylie, E.B., Streeter, V.L., Suo, L. (1993). *Fluid Transients in Systems.* Prentice Hall.

[5] Fox, J.A. (1977). *Hydraulic Analysis of Unsteady Flow in Pipe Networks.* Halsted Press.

[6] Al-Khomairi, A.M. (2005). Use of the steady state orifice equation in the computation of transient flow pipe leaks. *The Arabian Journal for Science and Engineering*, 30 (1B), 33-45.

[7] Mpesha, W., Chaudry, M., Grassman, S.L. (2001). Leak detection in pipes by frequency response method using a step excitation. *Journal of Hydraulic Research*, 40 (1), 55-62.

[8] Lee, P., Vítkovský, J. (2006). Discussion of 'Detection of partial blockage in single pipelines by P.K. Mohapatra, M.H. Chaudhry, A.A. Kassem, J. Moloo'. *Journal of Hydraulic Engineering*, 132 (2), 200-206.

[9] Brunone, B., Ferrante, M. (1999). On leak detection in single pipes using unsteady-state tests. In Hamza, M.H. (ed.) *IASTED International Conference on Modeling and Simulation*, May 5-8, 1999. Anaheim, CA: Acta Press, 268-272.

[10] Lay-Ekuakille, A., Vendramin, G., Trotta, A., Vanderbemden, P. (2009). STFT-based spectral analysis of urban waterworks leakage detection. In Girao, P.S., Ramos, P.M. (eds.) *IMEKO XIX World Congress: Fundamental and Applied Metrology*, September 6-11, 2009. Lisbon. Portugal.

Received November 17, 2010.
Accepted December 30, 2010.