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Impedance Method for Urban Waterworks:
Experimental Frequency Analysis for Leakage Detection

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Abstract – 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 pipeline 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 paper proposes an improvement of impedance method for zigzag pipeline by carrying out an experimental frequency analysis that has been compared with other methods based on frequency response. Hence, impedance method is generally used for simple 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.

I. Introduction

The problem of protecting natural resources has been becoming an important one because they are unlimited. In particular, water is one of the most important natural resources that is present in many locations all over the world as environmental component. Its rational and cleaver use is a matter of concerns 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 the 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 usages 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 more dense 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, leaks 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].

II. Impedance method and improvements

As recalled above, the impedance method is used for linear pipelines with less curves and bends. If we want to use a 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 to the following equations of continuity and motion:

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

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

where Q is the fluid discharge, H=z+p/ρg is the head, C is the pressure waves 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 impedance method [6].

II.1 Analysis of transients in pipelines

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

$$dQ \pm \frac{gA}{C}dH + gAJdt = 0, \; dx = \pm Cdt \qquad (3)$$

the + indicates the waves is 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. Eq.(3) determines the evolution of the head pressure and the discharge according to the time and the space. Its solutions constitutes the solutions to the original system of Eqs. (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 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 leak location .

II.2 Impedance method

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

$$Z(x) = \frac{h}{q} = \frac{i\gamma C^2}{\omega g A} \frac{C_1 e^{\gamma x} + C_2 e^{-\gamma x}}{C_1 e^{\gamma x} - C_2 e^{-\gamma x}} = -Z_c \frac{C_1 e^{\gamma x} + C_2 e^{-\gamma x}}{C_1 e^{\gamma x} - C_2 e^{-\gamma x}} \quad (4)$$

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

$$Z_c = \frac{\gamma C^2}{i\omega g A} = \frac{C^2}{\omega g A}(\beta - i\alpha) \quad (3)$$

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 Eq.(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:

$$|Z_{sx}| = Z_c \left\{ \frac{[1 + tg^2(\pi\omega_r l_r / 2]^2}{Z_c^2 / Z_L^2} + [tg(\pi\omega_r l_r / 2)]^2 \right\}^{1/2} \quad (4)$$

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 method has been applied to the hydraulic circuit of fig.1, 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 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. 1 Experimental pipeline system

The algorithm works as follows: calculating the characteristic impedance of all the pipeline (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, then it is possible to determine leak position l_r thanks to Eq. (4). 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.3 and fig.4.
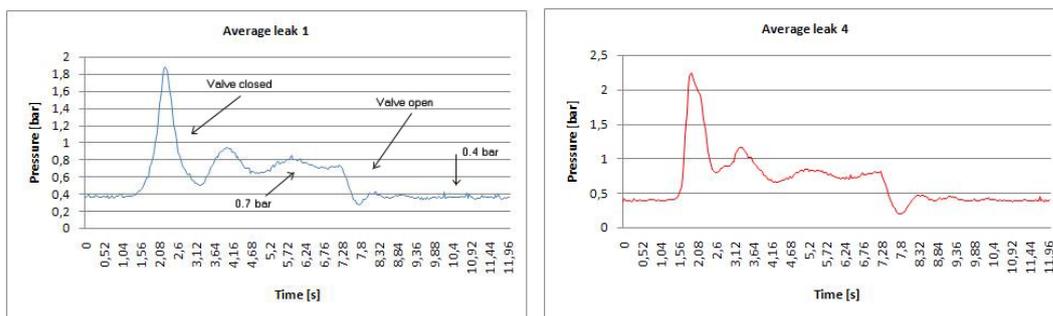
Fig.2 Time analysis for leak position 1 Fig.3 Time analysis for leak position 4
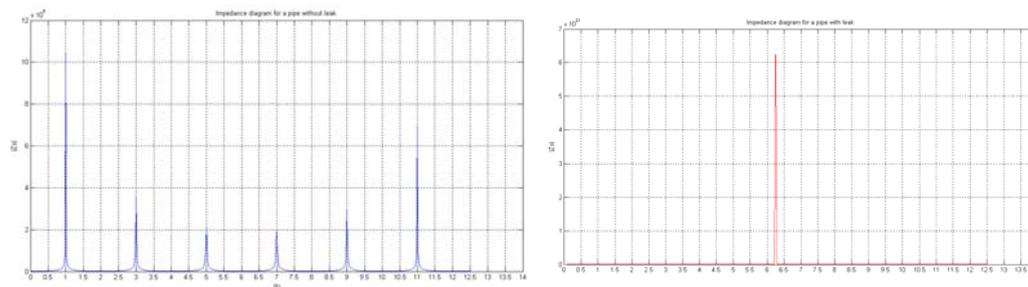

Fig.3 Time analysis for leak position 1 Fig.4 Time analysis for leak position 4

III. Result structuring and conclusions

The application of Eq. (4) for all leaks, with a good and precised frequency analysis has yielded to 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 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.

Table I Leak detection results

Input	Method	Regression	Uncertainty	Impedance M Zigzag pipe	Impedance M straight pipe
Opening and closing electrovalve periodically	STFT	Linear	$\pm 3.20\,m$	$\pm 3.60\,m$	$\pm 2.60\,m$
	STFT	Quadratic	$\pm 1.80\,m$	$\pm 2.10\,m$	$\pm 1.20\,m$
	FFT	Linear	$\pm 3.9\,m$	$\pm 4.05\,m$	$\pm 2.80\,m$
	FFT	Quadratic	$\pm 1.94\,m$	$\pm 2.10\,m$	$\pm 1.60\,m$

Square wave input and closed electrovalve	STFT	Linear	$\pm 6.00\,m$	$\pm 5.90\,m$	$\pm 4.30\,m$
	STFT	Quadratic	$\pm 8.50\,m$	$\pm 8.20\,m$	$\pm 6.50\,m$
	FFT	Linear	$\pm 7.90\,m$	$\pm 7.50\,m$	$\pm 5.80\,m$
	FFT	Quadratic	$\pm 9.68\,m$	$\pm 9.30\,m$	$\pm 6.40\,m$

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