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# STFT-BASED SPECTRAL ANALYSIS OF URBAN WATERWORKS LEAKAGE DETECTION

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**Abstract –** Water is an essential good for human being necessity. It must be protected against pollution and useless leakage. Urban waterworks is a strategic infrastructure to be managed with particular attention and care so that users must be satisfied. Different techniques are used to detect leaks from waterworks, specifically from pipelines carrying water. Among them, spectral analysis is very interesting to apply amid problems related to the pipeline section. This paper presents an application of STFT (short-term Fourier transform) technique for identifying urban waterworks leaks; STFT technique is usually used in processing speech. For the purposes of this research, a specific pipeline plant has been build in other to feature a real case. The pipeline section is almost one inch; the adopted section makes the research very interesting since spectral analysis, based essentially on FFT, is generally used for section greater than 20 cm.

**Keywords:** Waterworks, water pollution, spectral analysis technique, pipeline leakage, STFT, FFT.

## 1. INTRODUCTION

When a gas or liquid flows through any opening in a pressurized system, it creates vibrations which travel an indeterminate distance along the containment structure. These vibrations result from the transfer of pressurized energy to the molecules within the wall of the containment structure and are the basis for sonic leak detection. Using an electronic instrument that converts vibrations to sound, the leak detection operator listens to access points on the distribution system for telltale sounds created by a breach in pipes containing pressurized water. An access point is any component where direct contact can be made with the distribution system. Listed in order of preference, the five most commonly used access points are water mains, in-line valves, fire hydrant valves, fire hydrants, and service lines/meters. Since direct contact with a water main is often impossible because water mains are normally buried, valves and fire hydrants are most often used as access points. Service lines are only used as access points when other access points are not available, or when special conditions exist.

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]. Since freezing is not a problem in Florida, mains are usually buried to a depth of 36 to 48 inches and the surrounding soil is often loosely compacted. Due to its low cost and easy handling characteristics, PVC is used in most new installations. Unfortunately, if a leak cannot be heard or seen it goes undetected. Until leak detection technology improves, detecting leaks on plastic pipes will remain difficult.

## 2. LEAK DETECTION METHODS

For this study, leak detection technology has been classified as shown below. Hardware based methods are those that require special sensors while software based methods make use of routine pressure, temperature and flow rate information [4]. The hardware methods mainly include spectral response technique for signal processing,

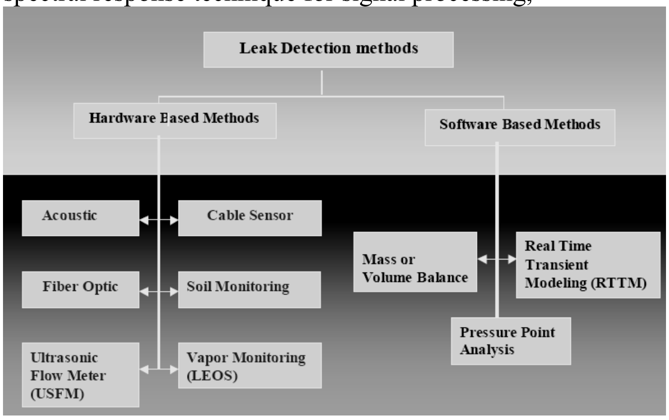


Fig. 1. Different detection methods

Non-invasive methods are based on the use of techniques as terrain analysis for detecting chemical substances or acoustic emissions. Among currently known techniques, it is possible to include those developed by different authors [5]-[6]-[7]-[8]-[9] who use transient analysis; that analysis requires a huge quantity of real-time data and hence, it has a high computational cost or, in some circumstances, it is difficult to be adopted. Other authors [10]-[11] have developed and experimented further methods based on spectral response analysis of water network. Beyond the above mentioned techniques, many others are included, that are: ultrasonic flow measurements, mass balancing, analysis of pressure points, fiber optic sensors and neural networks. Each technique offers advantages and disadvantages according to: operating conditions, accessibility, computational costs, economic costs, non-invasion, large data processing and accuracy. For example, acoustic technique is not suitable if a good insulation of noise, from external area, is not adopted. This limitation makes the approach quite impossible to be used. Terrain analysis technique is based on control of vapor to be analyzed looking for the presence of hydrocarbon concentration in the soil; the hydrocarbon is discharged by a chemical tracer utilized in the fluid flowing in the pipeline. Obviously, this technique is more expensive in case of buried and submerged pipelines.

## 3. PROPOSED TECHNIQUE AND LAB FACILITY

FFT is one of the important asset for spectral analysis in searching leaks in pipelines. But in some operating conditions in the water-distribution pipes, it could be easier to use short time algorithms like STFT.

Spectral representation is useful when it is necessary to get information from a spectral function $f(\hat{\Omega})$ of operator $\hat{\Omega}$ for which eigenvalues and eigenvectors are known:

$$f(\hat{\Omega}) = \sum_k f(\omega_k) \mid \omega_k)(\omega_k \mid \qquad (1)$$

The function $f(\hat{\Omega})$ is also an operator, with eigenvalues $f(\omega_k)$ and eigenvectors $\mid \omega_k)$. To show how the algorithm works, it is necessary to modify the FF algorithm by defining a complex one-dimensional signal in time domain $c_n = C(t_n)$, defined in a set of equidistant time intervals $t_n = n\tau,\ n = 0,1,...,N-1$ as a sum of damped sinusoids,

$$c_n = \sum_{k=1}^{K} d_k e^{-in\tau\omega_k} = \sum_{k=1}^{K} d_k e^{-2\pi i n\tau f_k - n\tau\gamma_k} \qquad (2)$$

with a total of $2K$ unknowns, that is, $K$ complex amplitudes $d_k$ and $K$ complex frequencies $\omega_k = 2\pi f_k - i\gamma_k$ that also include damping. Although Eq. (2) is nonlinear, its solution can be obtained from linear algebra. The proposed FFT associates an autocorrelation function, in an appropriate dynamic time system described by a complex Hamiltonian operator $\hat{\Omega}$ with complex eigenvalues $\{\omega_k\}$, to signal $c_n$ to be transformed in the form of Eq. (1):

$$c_n = \left(\Phi_0 \middle| e^{-in\tau\hat{\Omega}} \Phi_0\right) \qquad (3)$$

In this manner, the problem can be simplified as a diagonalization of the Hamiltonian operator $\hat{\Omega}$ or, similarly, evolution operator $\hat{U} = \exp(-i\tau\hat{\Omega})$.

The STFT represents a sort of compromise between the time- and frequency-based views of a signal. It provides some information about both when and at what frequencies a signal event occurs. However, you can only obtain this information with limited precision, and that precision is determined by the size of the window. As described in § 1, vibrations are created during leak and using an electronic instrument or an device it is possible to convert them in sounds or however in a sum of sinusoids [12]. So the spectral responses characterized by spectrograms that are produced by a procedure known as the *short-time Fourier transform (STFT)*. The STFT divides the entire signal into a series of successive short time segments, called *records* (or *frames*). Each record is used as the input to a DFT, generating a series of spectra (one for each record). Let $(X(t))_{t\in Z}$ be a digital signal. We review here the conditions for perfect reconstruction of the signal through STFT and inverse STFT [13]. Let $N$ be the window length, $R$ the window shift, $W$ the analysis window function and $S$ the synthesis window function. We suppose that $W$ and $S$ are zero outside the interval $0 \le t \le N$-1. We assume that the window length $N$ is an integer multiple of the shift $R$, and we note $Q = N/R$. The STFT at frame $m$ is defined as the discrete Fourier transform (DFT) of the windowed short-time signal $W(t - mR)\, X(t)$ (with the phase origin at the start of the frame, $t = mR$). The inverse STFT procedure consists in Fourier-inverting each frame of the STFT spectrogram, multiplying each obtained (periodic) short-time signal by a synthesis window and summing together all the windowed short-time signals. On a particular frame $mR \le t \le mR+N$-1, this leads to a reconstructed signal $Y(t)$ given by

$$
\begin{aligned}
Y(t) &= S(t-mR)\, W(t-mR)\, X(t) \\
&+ \sum_{q=1}^{Q-1} S(t-m(m-q)R)\, W(t-(m-q)R)\, X(t) \\
&+ \sum_{q=1}^{Q-1} S(t-m(m+q)R)\, W(t-(m+q)R)\, X(t)
\end{aligned}
\tag{4}
$$

where the three terms on the right-hand side are respectively the contribution of the inverse transforms of frame $m$, the overlapping frames on the left and the overlapping frames on the right. As the contributions of frames with an index difference larger than $Q$ do not overlap, by equating $Y(t) = X(t)$ for all $t$, we obtain as in [13] the following necessary condition for perfect reconstruction

$$
1 = \sum_{q=0}^{Q-1} W(t-qR) S(t-qR) \tag{5}
$$

Fig. 1 shows the experimental layout of the hydraulic circuit and fig. 2 depicts a partial view of the facility. Fig. 3 illustrates the zigzag pipeline (59 m) and acquisition platform, consisting of the following main units: a 4 channel-based Tektronix oscilloscope, a mm410 micromaster inverter, an Easy microdsPIC 30F2010 board, a HP33120A arbitrary waveform generator and a HP power pack. The microdsPIC allows the generation of a PWM signal at the dedicated port, which permits the control of the absorbed power of the pump by varying the duty cycle. The PWM signal is still digital and it has a maximum amplitude of 5V due to the limitation of the Easy microdsPIC developer kit. Hence, an amplifier circuit has been created. The shaped signal is considered to be analog input for port 7 of the inverter. Once the pump switching-on and timing system has been implemented, an analysis is performed of the signal coming from the pressure transducer.

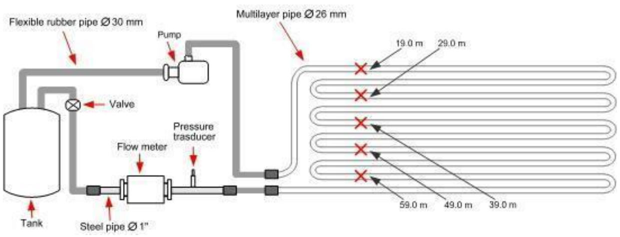


Fig.1 Experimental layout

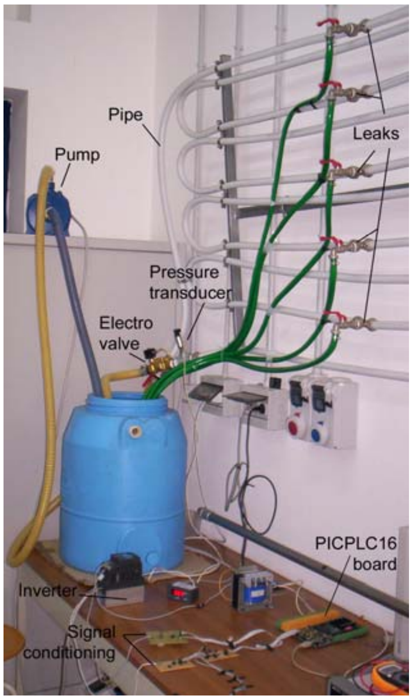


Fig.2 Partial view of facility

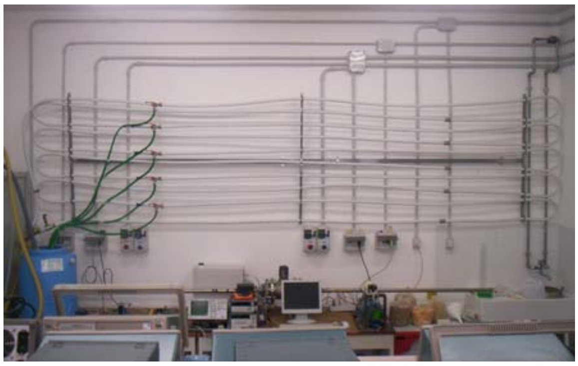

Fig.3 Acquisition platform near the plant

## 4. RESULTS AND FINAL COMMENTS

Data acquired from pressure transducer are processed according to the flowchart of fig.4 for FFT and for STFT by substituting FFT with STFT and by remembering Eq.(4) and Eq.(5). For both techniques, namely, FFT and STFT, the algorithms calculate a sum of successive sinusoids according to fig.5, fig.6 and fig.7. The leak is simulated by opening and closing one the 5 water taps and by varying the input: water flux. Obviously, the data recovered, in terms of amplitudes vs frequency, must be validated and corrected by using the regression: linear and quadratic. The type of regression is very important in order to recovery data in correct way. Table I shows the results of uncertainty in retrieving leak position according to the adopted technique: FFT and STFT. The STFT, by definition, displays a good uncertainty when the electrovalve is opened and closed for a short time: this behavior is good.

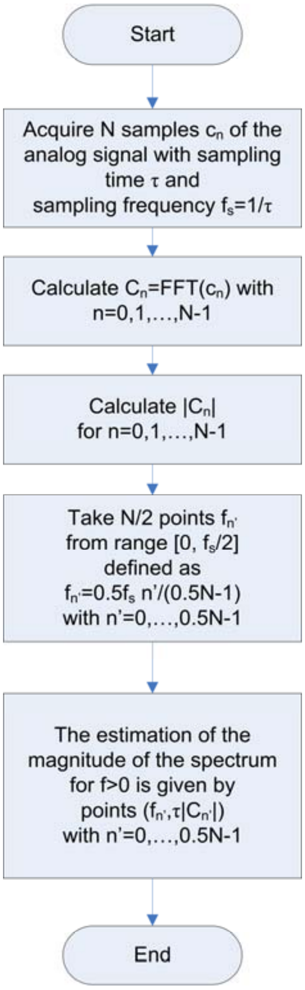


Fig.4 Developed FFT technique

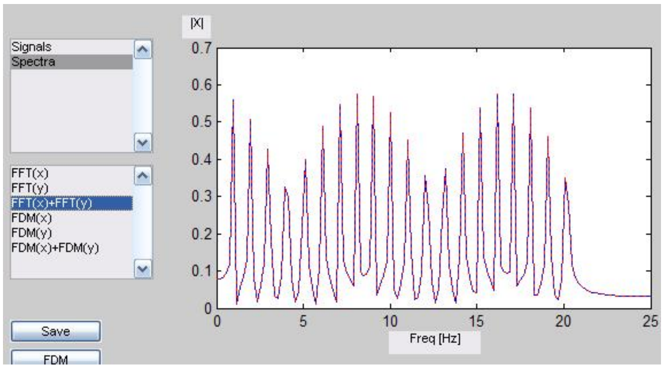


Fig.5 FFT recovered data based on Blackman window

After different acquisitions, the experiment has illustrated the kind of window is basically important to get acceptable values of accuracy. Other windows diverse from blackman and hamming deteriorate the signal quality, hence the spectral analysis. This paper has demonstrated the opportunity of using STFT as an appropriate technique of conducting spectral analysis capable of getting information of leak detection in water-distribution pipelines.

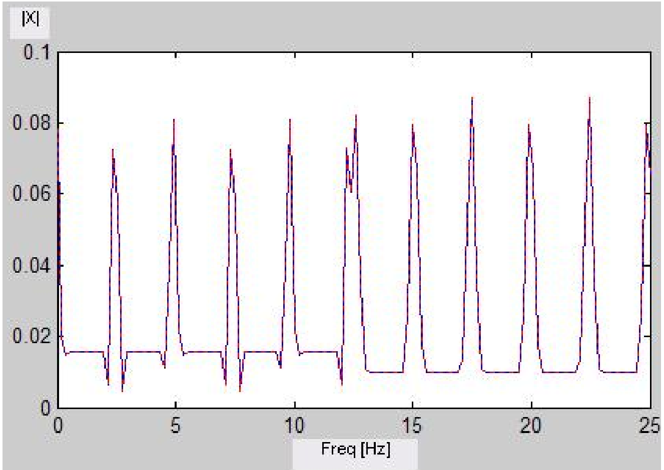


Fig.6 STFT recovered data based on Blackman window

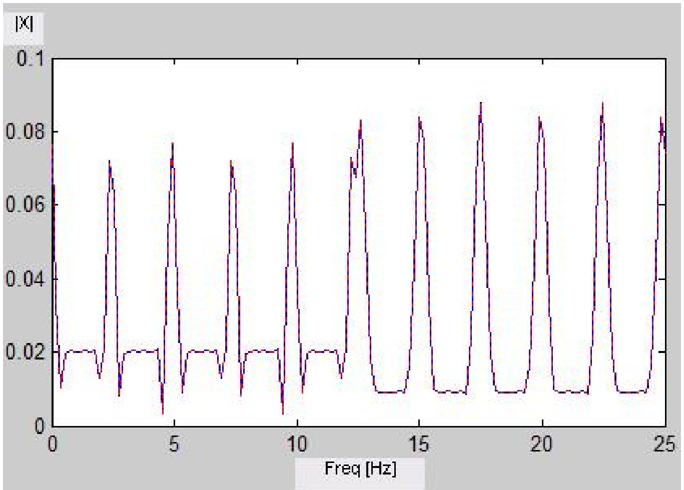


Fig.7 STFT recovered data based on Hamming window

Table I Leak detection results

| Input | Method | Regression | Uncertainty |
|---|---|---|---|
| Opening and closing electrovalve periodically | STFT | Linear | $\pm 3.20\,m$ |
| | STFT | Quadratic | $\pm 1.80\,m$ |
| | FFT | Linear | $\pm 3.9\,m$ |
| | FFT | Quadratic | $\pm 1.94\,m$ |
| Square wave input and closed electrovalve | STFT | Linear | $\pm 6.00\,m$ |
| | STFT | Quadratic | $\pm 8.50\,m$ |
| | FFT | Linear | $\pm 7.90\,m$ |
| | FFT | Quadratic | $\pm 9.68\,m$ |

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