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Water Supply Leak Detection Based on Audio Signal Processing

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Leak detection in water supply is a crucial challenge to ensure the efficiency and sustainability of water distribution networks, whose traditional process consists of listening to the sound of water flow through headphones, requiring special training for listening to sounds that correspond to water leakage. In this paper, various methods and recent advances in leak detection using audio signal processing are reviewed. The fundamental role of the Fast Fourier Transform (FFT) in extracting relevant features from the acoustic signals captured in the various sections of a pipeline network to locate problems in the water pipeline infrastructure is highlighted. A test scenario is set up, where the captured audio signal is sent to a laptop, tablet or smartphone where it is processed using the Fast Fourier Transform, to be visualised the frequency spectrum and observe the frequency amplitude values measured in W/Hertz and detect unseen water leaks and the section of the supply is marked. Practical applications demonstrating the feasibility and efficiency of these approaches in real conditions are discussed.

Keywords: FFT, digital filter, spectrum, water, simulink.

1. Introduction

Leak detection in water supply systems is a critical task in conserving water resources and reducing economic losses. In water distribution systems, leaks can cause structural damage, waste of potable water and increased operating costs. Therefore, the development of efficient methods for the early detection of leaks is essential to ensure the sustainability and efficiency of these systems, as well as the availability of water for human consumption, especially in regions where the resource is scarce. Water leaks in water supply networks represent a significant challenge for water management agencies. It is estimated that up to 30% of potable water may be lost due to leaks in old or poorly maintained distribution systems [1].

In many places, leak detection has been performed by manual methods such as visual inspections and the use of manual acoustic detection equipment. These methods, although effective in some cases, are laborious, time-consuming and labor-intensive [2]. In addition, they may not be efficient in detecting small leaks or in hard-to-reach locations. However, automatic leak detection can be performed by using acoustic signals and analyzing them using mathematical transforms such as the Fast Fourier Transform (FFT) [3]. The application of FFT in the analysis of pipeline acoustic signals has been shown to be effective in identifying patterns and frequencies associated with leaks [4].

Several studies have explored the use of DSP techniques and the FFT for leak detection. These studies have shown that FFT can detect variations in the frequencies of acoustic signals that are not perceptible to the naked eye [5]. Thus, in [6] the effectiveness of FFT in identifying leaks in water distribution systems by detecting changes in the dominant frequencies of acoustic signals is shown.

An unsupervised approach for leak detection and location in water distribution networks is shown in [7] using pipe network zoning and principal component analysis (PCA). Similarly, a statistical analysis for a water pipeline model is performed in [8], with the aim of obtaining reliable system data and leak detection.

The use of infrared thermography for water leak detection and location is proposed in [9] using thermal image processing. An associated challenge is the influence of external elements on the measurement. The paper presents the node concept of an acoustic-based system for leak detection and localization. Also, the use of a wireless sensor network (WSN) for leak detection and localization is proposed in [10], where WSN nodes communicate over the water in the pipe network using acoustic waves and alternatively in combined mode with radio waves.

FFT of hydraulic transient modelling and machine learning techniques have been combined in [11] to improve the accuracy of leak detection. Similarly, spectral clustering and support vector machine (SVM) classification are used to achieve better reliability between pressure and flow variations and leak location [12-14]. Also, a hydraulic model of the water network and a monitoring system are used in [15] to collect and record information about flow rates and pressures, which is used by a neural network-based module for water leak detection and location. Similarly, conditional convolutional adversarial generative networks (CDCGAN) on [16] images are used for the detection and localisation of leaks in water distribution networks

Despite advances, such as the integration of communication networks, Geographic Information System (GIS), cloud-based software, among others [17, 18]; there are challenges associated with the practical implementation of these techniques. The variability of acoustic signals due to different environmental and structural factors can complicate the accurate identification of leaks [19]. In this regard, algorithms for leak detection and localization for various transients and noise identification and filtering are developed in [20].

In this paper, for the detection of water leaks, the sounds coming from the pipes under review are captured and the signals are processed by means of the Fast Fourier Transform, using the Matlab environment for the execution of the FFT and the respective graphics. Likewise, a simulation of the digital signal processing system that allows the analysis of the water leak noise audio signal is performed using the Simulink environment.

The objective of this study is to develop and validate a method based on audio signal processing using FFT for leak detection in water supply systems. A systematic approach is proposed that includes the capture of acoustic signals, their transformation using FFT and the analysis of the frequency components to identify possible leaks.

This paper is organized as follows: Section I corresponds to the introduction where the water supply leak detection issues are described. The fundamentals on audio signal processing are shown in section II. Section III covers the procedure followed in the research, and Section IV shows the results obtained and analysis. Finally, the conclusion of the work carried out is indicated.

2. Background

Currently, water leak detection is performed by probes to either detect or confirm non-visible water leaks in the city's pipelines; this is done manually by listening for the sound of water leaks. Non-visible water leaks constitute a problem of loss of drinking water, a water resource that is becoming increasingly scarce. Therefore, it is necessary to detect them in a timely manner before more visible problems occur in the city. For example, in Peru, according to statistics from the Lima Drinking Water and Sewerage Service (SEDAPAL), about 85% of water leaks occur in line pipes (user).

The Audio Signal

It is the representation in electrical form of a sound signal, as an analog signal, whose frequency is between 20 Hz and 20KHz. As shown in Fig. 1, the sound signal is picked up by a microphone which converts it into electrical form and then amplified by an audio amplifier to be used or reproduced. The audio signal is converted into a sound signal by a speaker, which converts the audio signal into audible sound waves.

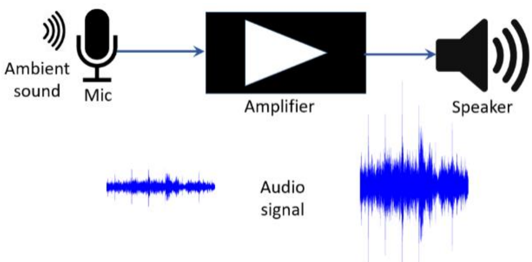

Figure 1. Audio signal process

Digital signal processing system

In the context of leak detection, acoustic signals generated by water flow and disturbances caused by leaks can be captured by sensors and then digitally processed [21]. FFT is a mathematical tool that decomposes a signal into its frequency components. This technique allows the identification of specific signal characteristics that may be indicative of a leak [22].

In order to be analysed in time, frequency and audibly, the audio signal must be captured, processed and reproduced. To perform the above processes, the signal must enter a digital signal processing system to analyse the audio signal. Fig. 2 shows a digital signal processing system consisting of the following: input filter, digital analogue conversion, signal processor, digital analogue conversion and output filter.

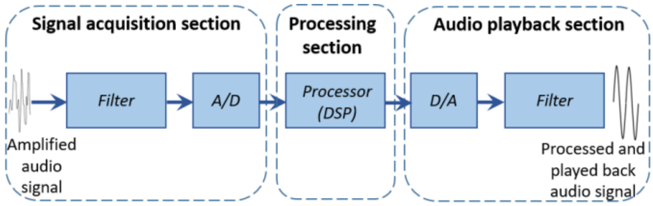

Figure 2. Digital signal processing system

Digital signal processing is a process of signal analysis or signal transformation depending on its application, in this case it is the analysis of the audio signal, for which digital audio signal processing hardware is required, the stages of which are described as follows:

- Input filter: It is a low-pass filter, whose cutoff frequency is half the sampling frequency (fs) of the analogue-to-digital converter of the next stage. This filter ensures that aliasing of the processed signal does not occur.

- Analogue-to-digital converter: This stage consists of an element whose function is to digitise the audio signal. That is to say, to convert the analogue signal into a digital signal, for which the processes of sampling, quantisation and coding are carried out. A quantization level is a voltage level that the converter assigns to each sample, the quantization levels are a function of the number of bits that each analogue-digital converter has. On the other hand, in encoding, each quantization level is assigned a binary value (bits per sample).

- Signal processor: This stage executes the program that allows to analyse or transform the digitised signal coming from the analogue-digital converter. This is usually a personal computer or a specialised card for signal processing. This program incorporates an algorithm such as the Fast Fourier Transform for the case of audio signal processing. The processed signal, represented by data (samples), is sent to the digital analogue conversion stage.

- Analogue Digital Converter: The processed signal as data stream is converted to an analogue signal at an amplitude level corresponding to each sample. This results in a stepped signal with the waveform pattern of the processed signal, so it must be taken to a subsequent filtering process.

- Output filter: This low-pass filter is responsible for smoothing the processed signal, removing the step effect. It removes harmonics from the frequency spectrum of the stepped signal. This process of removing these unwanted components is called smoothing.

Sections of the digital signal processing system

The system consists of the following sections:

- Signal acquisition section: Firstly, the audio signal coming from the microphone must be amplified in accordance with the dynamic range requirement of the analogue-digital converter. Also, its maximum frequency must be half the sampling frequency of 44.1KHz of the analogue-digital converter. This frequency is considered because it is compatible with the different audio systems. The pick-up stage consists of an anti-aliasing filter and a digital analogue converter with a sampling frequency of 44.1Khz. In this stage the audio signal is converted into samples.

- Processing section: The audio data is processed using a computer programme that implements the necessary algorithms for its analysis, graphing it in time and frequency using the Fast Fourier Transform (FFT), digital filters, audio compression, among others.

- Audio playback section: The signal leaving the converter has a settling time that is the same length as the sampling period, and features an internal zero-order sample-and-hold circuit that prevents glitch in the converter's output level change. Then, once the signal exits the converter, it enters a reconstructor filter that removes the harmonics that give the signal a stepped effect at the output of the analogue digital converter. Then, the signal is amplified to be sent to a loudspeaker.

The Fast Fourier Transform

This algorithm makes it possible to represent in frequency a digitised signal made up of a set of data representing the original signal. To plot the frequency spectrum of the noise signal, the modulus of the fast transform of the signal squared and divided by the number of samples of the processed signal, measured in Watts/Hertz, which is the unit of spectral power density, is calculated. An example of the application of the FFT for an N=4 signal is shown in Fig. 3 below.

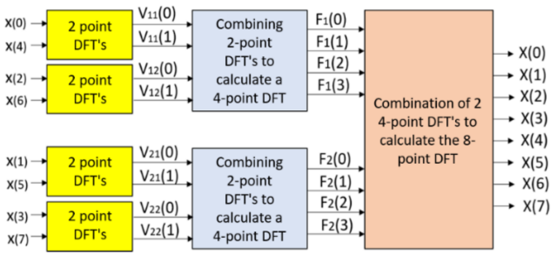

Figure 3. Schematic of the FFT for blocks of N=4

Table I. Reverse bits

Order of signal samples before reverse bit	Order of FFT inputs with reverse bit
00 (0)	00 (0)
01 (1)	10 (2)
10 (2)	01 (1)
11 (3)	11 (3)

Fig. 4 shows the entries obtained in Table I.

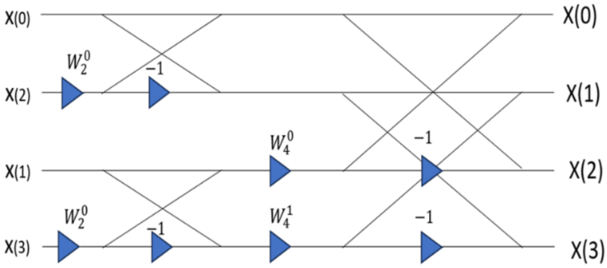

Figure 4. Butterfly diagram for N=4

Correspondingly, Fig. 5 presents the sample output of the Butterfly diagram.

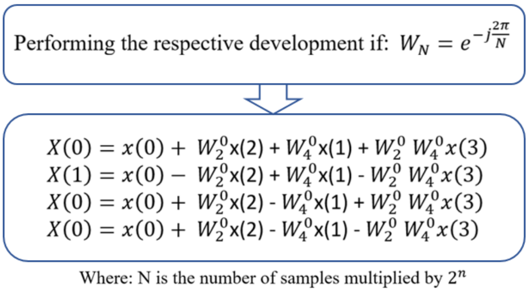

Figure 5. Obtaining the outputs of the Butterfly diagram

3. Methodology

It should be noted that measurements of water leakage noise levels are made on the water supply side corresponding to the water service provider's side as presented in Fig. 6. The utility side contains the box, user line and corporation. The box section contains the meter where water leaks are quickly detected and repaired. In the line section 85% of the water leaks occur; this section is 12m long and 2m deep and the PVC pipe is ½ inch. Then, the corporation section is made up of the water main from which a ½ inch pipe is derived for the house connection.

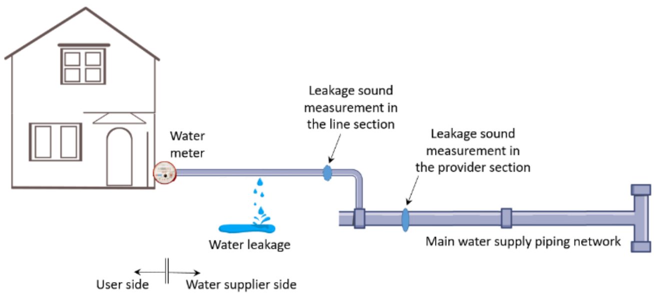

Figure 6. Measurement points of drinking water service sections

To obtain the audios analysed, probes containing a microphone are used, which are connected to the operator's headset, but instead of connecting it to the headset, it is connected to a smartphone that records at a frequency of 44.1Khz, which is the frequency considered for signal processing purposes. The recording of the signal can be done with a tablet, laptop or other mobile device with the application available to record the signal.

The Fast Fourier Transform (FFT) is used to analyse the frequency spectrum of the audio signal (noise from the water leak), analysing the amplitude levels it reaches in its frequency spectrum. The energy present in the signal does not have finite energy because it is characterised as a stationary random process. As indicated in equation 1, this signal has finite average power and is therefore characterised by its Power Spectral Density.

$$P\left(\frac{k}{L}\right) = \frac{1}{fsL}\left|\sum_{n=0}^{N-1} x(n)\, e^{-i2\pi nk/L}\right|^2 = \frac{1}{N}|X(f)|^2 \qquad (1)$$

The above formula is used to calculate the spectral power density and L=N to improve the resolution of the frequency representation. The units of spectral power density are Watts/Hertz.

The experiment is developed first by simulating the digital signal processing system for the process of capturing and processing the audio signal coming from the water leakage noises, this simulation is carried out using Simulink in Matlab. Then, Matlab programs are implemented in order to carry out the signal analysis process and subsequently a user interface is implemented with Matlab, in order to subsequently carry out the respective analyses to detect the water leakage.

4. Results and Discussions

Simulation of the acquisition and processing process

This simulation presents the digital signal processing system to capture and process the signals to analyse them by means of a device to observe the spectrum of the audio signal of the water leakage noise. The first block simulates the noise signal by reproducing the recorded noise signal which has been recorded at fs=44100Hz and 16-bit resolution.

The second block is the input filter which is a low-pass filter having an fc=fs/2, in this case fs=44100Hertz of eighth order elliptic type, representing the MAX293 IC with fc=22.05Khz, Rp=-0.15dB and Rs=-78dB with a transition ratio of 1.5 i.e. stop band frequency of 33.075Khz. The frequency response is shown in Fig. 7. Se observa un rizado de -0.15dB del rizado en la banda de paso del filtro pasabajo casi imperceptible y -78db en el rizado en la banda de supresión

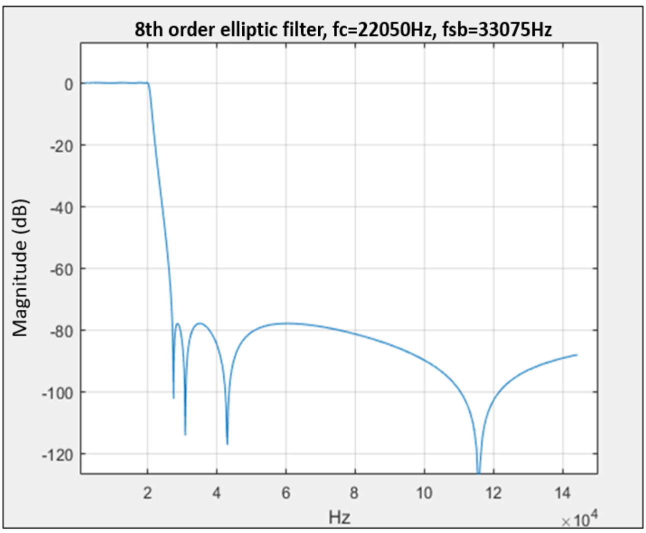

Figure 7. Representation of the frequency response of the input low-pass filter

The third, fourth and fifth blocks are part of the analogue converter stage which has an fs=44100Hz and 16-bit resolution; in this stage the sampling (sample time=1/44100), quantization (Quantization interval=2/2^16) and coding processes are carried out. The sixth and seventh blocks are part of the processing section, where the sixth block is called uniform decoder (peak=1 and Bits=16), the seventh block is a digital band pass IIR (Infinite Impulse Response) filter that filters the water leakage noise signal between 1000Hz and 5000Hz. The type of filter is Chebyshev type 2 with number of coefficients 13, ripple (rs=0.1), normalised frequencies (1000 / 22050, 5000 / 22050) generating the coefficients shown in Fig. 8.

B= [0.0121161086062078 -0.101461993193931 0.401993302731308 -1.009658435910870
1.8193655436139800 -2.522055941681730 2.799402836759840 -2.522055941681730
1.8193655436139800 -1.009658435910880 0.401993302731312 -0.101461993193932
0.0121161086062079]

A= [1.0000000000000000 -9.72988697302345 0 43.88438196474550 121.33481769298700
229.05859530977300 -311.056164690885 0 311.5713319533170 -231.94749063978300
127.37108638607800 -50.31998715289270 13.57735140031390 -2.2469270077359400
0.1725276520565270]

Figure 8. Resultant filter coefficients

In this filter block the numerator and denominator are only the values of A and B respectively. Then in the playback section, the eighth block which is gain2 (k=1e5) and finally the ninth block called Spectrum Analyzer whose parameters are shown in Fig 9.

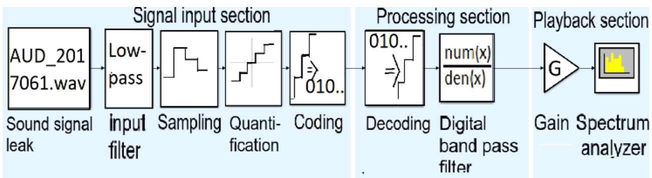

Figure 9. Simulation of the process of capturing the sound of water leakage for detection

Fig. 10 shows the noise signal spectrum on the analyser. It can be seen that the spectrum is limited between 1000Hz and 5000Hz, the spectral density exceeds 0.02W/Hz which is the threshold to indicate if there is noise due to water leakage. Also, the different parameters of the analyser are presented.

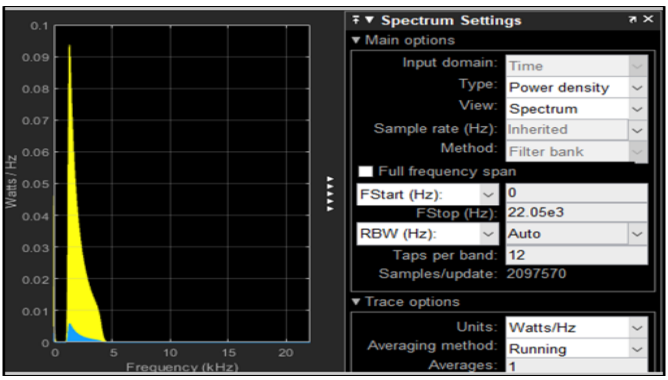

Figure 10. Spectrum and analyser parameters

Signal analysis process

The present study involves collecting the necessary information for the frequency representation of the water leakage sounds at the points of the water pipes with and without water leakage.

Using a program developed in Matlab, the audio signals obtained from the Line and Corporation sections are processed. The recorded sounds were captured with a sampling frequency of 44.1Khz and 16 bits of resolution by means of a probe. For the elaboration of the programme it has been considered that the signal has to be filtered by means of a digital IIR Chebyshev 2 filter to filter the signal by means of a band pass filter between 1000Hz and 5000Hz which is the frequency band where the water leakage sounds occur. Additional features of the filter have already been described in the previous section of the system simulation. Fig. 11 and Fig.12 show the graphs of the audio signals of the water leaks.

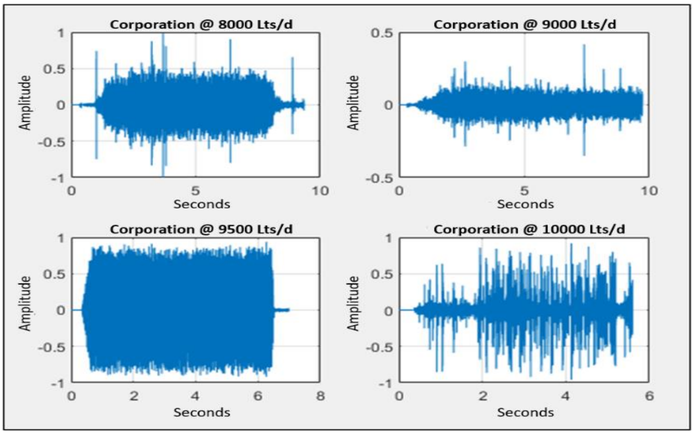

Figure 11. Audio signal in Corporation Section

The Fast Fourier Transform (FFT) function is then applied to the filtered signal, resulting in a plot of the signal's Spectral Power Density (w/Hz) versus frequency (Hertz). To detect the presence of noise, a threshold of 0.2W/Hz has been set in the frequency band between 1000Hz and 5000Hz.

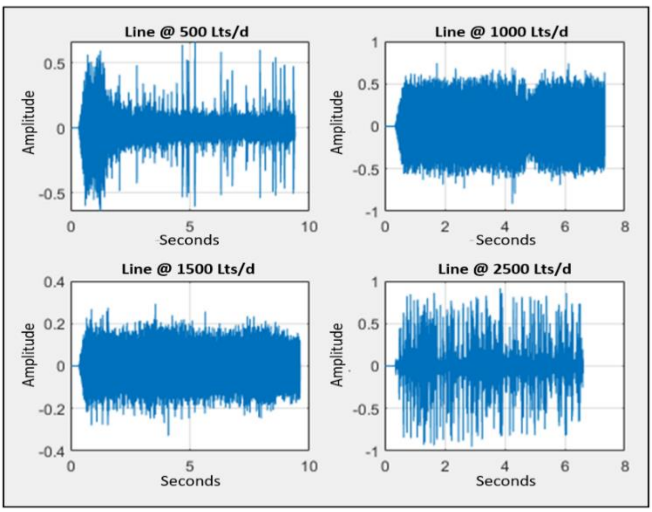

Figure 12. Audio signal in the Line Section

Fig. 13 shows the frequency spectra of the water leakage audio signals corresponding to the Corporation Section at different water flow rates from the acquisition point. It is observed that the power spectral density level of the water leakage noise varies and in all cases exceeds the threshold of 0.02W/Hertz.

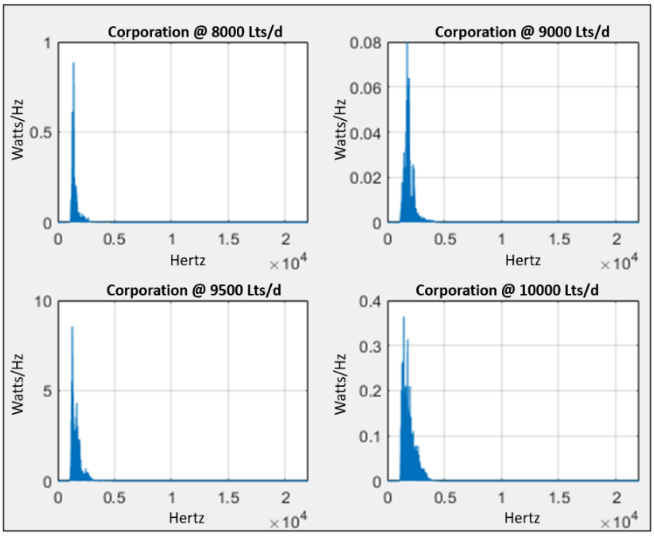

Figure 13. Frequency spectra of the Corporation Section

Fig.14 shows the frequency spectra of the water leakage audio signals from the Line Section at different water flow rates from the acquisition point. It is observed that as the flow rate increases, the power spectral density level varies and the noise has slight variations always within the band from 1000Hz to 5000Hz, as for the threshold of 0.02W/Hz, in all the graphs this value is exceeded.

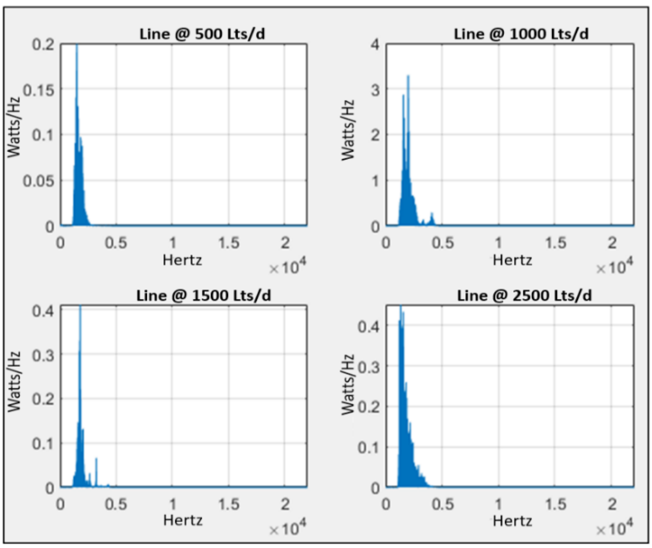

Figure 14. Frequency spectra of the Line Section

On the other hand, in the right graph in Fig. 15, we observe a water leakage audio signal from the corporation section before being repaired and we observe that the power spectral density level exceeds by far the threshold of 0.02 W/Hertz confirming the presence of water leakage. It should be noted that the 1000Hz and 5000Hz band corresponds to the water leakage audio signals.

The graph on the left of Fig. 15 shows the spectrum of the audio signal with noise after the water leakage in the corporate section was repaired, and it was found that there was no leakage in this section, whose spectral density does not reach the threshold of 0.02 W/Hertz.

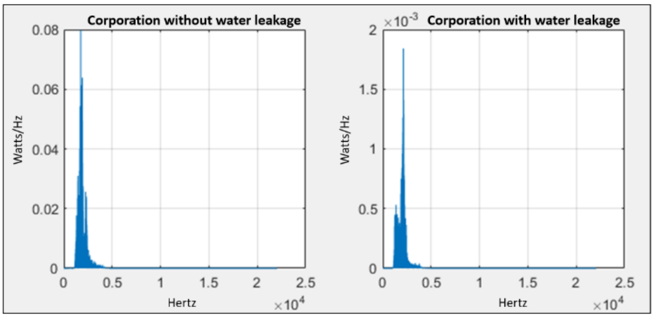

Figure 15. Frequency spectra without leakage and with leakage of water

A program was developed for the analysis of the water leakage audio signal, It has a user-friendly graphical interface (UI) as shown in Fig. 16.

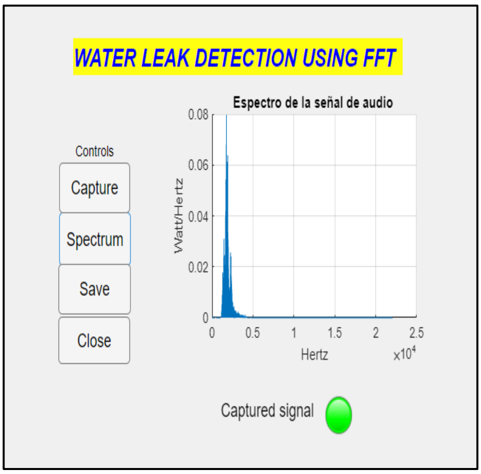

Figure 16. Project graphical interface

The UI interface is intended to make it easier for the user not to have to train the ear to detect a water leak, but simply to observe that the noise exceeds 0.02W/Hertz on the graph. Then, Fig. 17 shows the code base elaborated in Matlab language to plot the audio signal of water leakage and to analyse it.

```
clear all;
close all;
[x1,Fs1] =audioread('AUD 20170601 sin Fuga.wav');
r1=size(x1);
N=r1(1);
k=0:N-1;% Assignment of numbers to each sample
hertz=k*(Fs1/N);% Value of omega interval for each sample each sample
%=============================
% Use of the digital chebyshev type 2 band-pass filter
% To limit the audio signal between 1000Hz and 5000Hz
% 13 coefficients are generated =2x6+1
[B A]=cheby2(6,-20*log10(0.1),[1000/22050,5000/22050]);
y1=filter(B,A,x1);
%=============================
% The Spectral Power Density is calculated and the frequency spectrum is plotted
y=(abs(fft(y1)).^2)/N;% Calculation of power spectral density
plot(hertz(1:N/2),y(1:N/2));
title('Corporation without leakage');
xlabel('Hertz');
ylabel('Watts/Hertz');
grid;
```

Figure 17. Signal spectrum plot code

5. Conclusion

In this paper, a simulation of the digital audio signal processing system for water leak noise has been carried out. In addition, the signals from distribution water leakage pipes have been analysed. The results allow us to affirm that by using the FFT it is possible to detect water leaks, analysing the frequency spectrum of the sound produced by non-visible water leaks in the pipes of the drinking water distribution service, before the household flow measurement box. It should be noted that the sounds of water leaks vary with the water flow in the pipes and therefore the graphical interface is very useful to automate the detection process.

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