Characterization of In-Pipe Acoustic Wave for Water Leak Detection

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CHARACTERIZATION OF IN-PIPE ACOUSTIC WAVE FOR WATER LEAK DETECTION

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ABSTRACT

This paper presents experimental observations on the characteristics of the acoustic signal propagation and attenuation inside water-filled pipes. An acoustic source (exciter) is mounted on the internal pipe wall, at a fixed location, and produces a tonal sound to simulate a leak noise with controlled frequency and amplitude, under different flow conditions. A hydrophone is aligned with the pipe centerline and can be re-positioned to capture the acoustic signal at different locations. Results showed that the wave attenuation depends on the source frequency and the line pressure. High frequency signals get attenuated more with increasing distance from the source. The optimum location to place the hydrophone for capturing the acoustic signal is not at the vicinity of source location. The optimum location also depends on the frequency and line pressure. It was also observed that the attenuation of the acoustic waves is higher in more flexible pipes like PVC ones.

Keywords: leak detection, in-pipe measurements, acoustic signal attenuation and propagation.

INTRODUCTION

Effective and efficient transportation of water from utility to consumer is critical. Addressing water losses during distribution could limit the need to access new sources of freshwater; which are already diminishing. Various experimental techniques using field tests for leak detection have been reported (1 and 2). The most commonly used method for detecting leaks in water distribution systems involves using sonic leak-detection equipment, which identifies the sound of water escaping a pipe. Methods based on detecting and further processing acoustic signals inside and outside pipes are prevalent in leak detection. Slightly more sophisticated over direct sound measurements methods are acoustic correlation methods where two sensors are used. The leak should be located between the two sensors and the time lag between the acoustic signals detected by the two sensors is used to detect and locate the leak (3). The cross-correlation method works well in metal pipes; however, the effectiveness of the method is not so reliable with plastic pipes.

The acoustic leak detection technique based on external measurements is normally faced by some serious challenges (4 and 5). The leak signal has low frequency contents (<50 Hz) and is highly attenuated in plastic pipes, greater attenuation in large diameter pipes, attenuation caused by soft soils; e.g. clay or grass, pipes buried under a water table level, and pipes with pressure less than one bar. This means that distances between the sensors and the type and quality of sensor are of great importance. Attempts to characterize leaks in pipelines by utilizing internal measurements of the acoustic signal generated by the leak were conducted using either a tethered hydrophone (6) or a free swimming hydrophone (7).

The technique of in-pipe acoustic measurements relies mainly on the sound traveling through the water column inside the pipe. It is apparent that sound velocity in water pipes depends upon and is influenced by the pipe material or the elasticity modulus and the ratio between diameter and wall thickness (8). That is, larger diameters and more flexible pipes tend to attenuate higher frequencies. Accordingly, low-frequency signals will be more dominant. This effect makes leak signals susceptible to interference from low-frequency vibrations, e.g., from pumps and road traffic.

An experimental and theoretical investigation of the low-frequency acoustic propagation and attenuation characteristics of a submerged plastic water pipe was done by (9 and 10). Complex wave numbers were determined, which encompass both the wave speed and the wave attenuation. The wave speed for the in-vacuo pipe was found to be reduced substantially from the free-field value due to the pipe wall flexibility; when the pipe was submerged, this value was reduced yet further by the mass-loading of the pipe by the surrounding water. The measured attenuation was found to fluctuate but the average value compared well with the prediction. For the buried pipe, there was good agreement between the measured and predicted wave speeds, again, particularly at low frequencies. The surrounding soil markedly increases the wave attenuation compared with the in-vacuo case, which suggests an additional difficulty in that the signal to noise ratio will be substantially reduced.

An analytical model to predict the cross correlation function of leak signals in buried plastic water pipes, by combining the correlation technique with wave propagation theory in plastic pipes, was developed (11). The model is based on a theoretical formulation of wave propagation in a fluid-filled pipe in-vacuo and the assumption that the leak sound, at source, has a flat spectrum over the bandwidth of interest. This model has been applied to explain some of the main features of experimental data, including wave propagation and attenuation. It has been shown that in the noise-free case, good levels of correlation are only possible for ratios of sensor distances from the leak of less than about 10 and that an estimate of the signal-to-noise ratio at a measurement position can be simply determined from the ratio of the peak values of the experimental result of the correlation coefficient and its corresponding theoretical prediction.

Recently, a lot of research is being considered on the approach of in-pipe measurements for leak detection. Being inside the pipe provides good opportunities for leak detection like being close to the leak itself and being less dependent on the background noise, pipe material, soil type, and environmental effects. On the other hand, many challenges and questions arise when using this approach like what to measure or what type of sensor (acoustic, pressure,….etc.) to be used inside the pipe? What is the leak effect on the measured parameter? What is the effect of flow conditions (line pressure, flow rate, etc.) of leak signal? Where to place the sensor with respect to the leak? And so on.

The objective of the present work is to experimentally acquire the fundamental knowledge of how an acoustic wave emitted from a leak propagates and attenuates inside a plastic water-filled pipe under different pipeline conditions, using in-pipe acoustic measurements. The leak frequency and location of the leak are simulated by an acoustic source of known location, frequency, and amplitude. It is a fundamental study yet it is very important for designing a good in-pipe acoustic leak detection system.

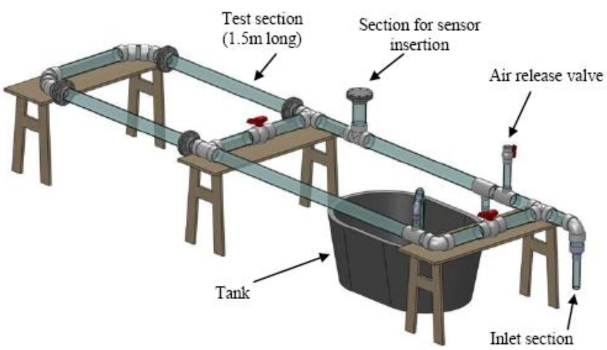
EXPERIMENTAL SETUP

Two Laboratory setups were used for testing the propagation and attenuation of an acoustic wave:

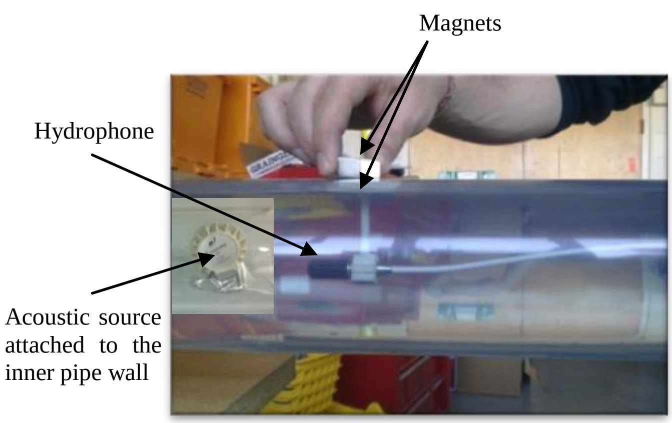
(1) A water closed loop, shown in Figure 1a, to simulate the water distribution network under different flow conditions. It consists of a 4-inch acrylic pipe loop with a total length of 14 m. The loop inlet can be connected to the municipality water supply by a hose or to a 10 hp centrifugal pump. Water is circulated using a large tank. The loop is fitted by flow control valves to operate at different conditions of pressures and flow rates. The setup also allows having stagnant water (no flow situation) at different pressures. It also allows different water flow rates/pressures when using the pump. A pressure gage is installed on the pipe for measuring the line pressure. An acoustic source (exciter connected to audio amplifier) is attached to the internal wall of a 4-inch pipe, at a fixed location, and produces a tonal sound to simulate the leak noise. The magnitude and frequency of the source was adjusted from a source generator/amplifier system. A hydrophone moves at the pipe centerline and captures the signal at different distances from the acoustic source. Data are collected at high rates and analyzed using an FFT algorithm.

(2) A simple straight PVC, SCH 80, pipe (6 m long) with a closed end. The acoustic source is attached to the closed end of the pipe and water is supplied from the open end. A hydrophone is used to receive the acoustic signal inside the pipe at different location. There is no water flow with this setup, only the water pressure and the frequency of the acoustic source can be controlled.

The hydrophone, B&K model 8103 with sensitivity 25.9 μV/Pa, is inserted into the pipe through a caped tee with sealant for the hydrophone cable. It is placed at the pipe centerline by a small plastic holder which is made mobile by magnets to move inside the pipe with respect to the acoustic source as shown in Figure 1b. A charge to voltage DeltaTron® converter is connected in series with the hydrophone and the sensor is powered from the DeltaTron® WB 1372 module. The output of the later module is then connected to a power amplifier and signal conditioner from Stanford Research Systems (Model number SR560). The unit has variable gain with low, high, and band-pass filter capabilities. The outputs of both hydrophone and pressure transducer are directed to a NI 9234 module on a cRIO-9113 reconfigurable chassis using a cRIO-9022 real-time controller. The sampling rate can be selected manually by the user and can go up to 51.2 KHz.



(a) A schematic of the test loop



(b) Hydrophone location with respect to the source is controlled by external magnet

Figure 1 Test loop and control of hydrophone location

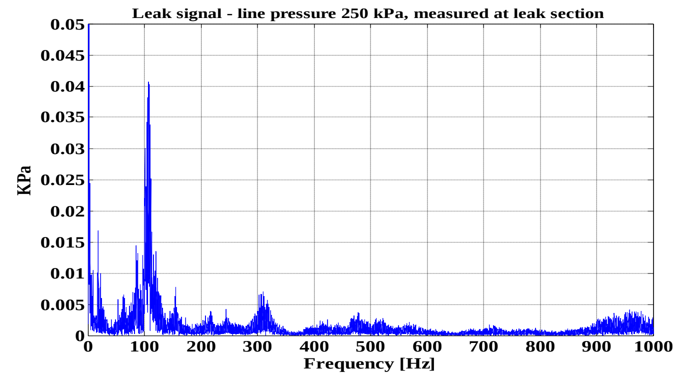


Figure 2 Actual leak signal measured by the hydrophone at leak section, line pressure is 250 kPa and no water flow.

The acoustic source used in experiments is an exciter, with audio amplifier, used to generate tonal noise at the required frequency with the help of tone generator software. The hydrophone location with respect to the acoustic source can be changed from outside the pipe. Data collected are analyzed using FFT algorithm. The FFT represents the signal strength at frequency range of interest and is a good tool when the signal is generated under the conditions of pipe flow. Figure 3 shows a sample of noise generated by the source at 50 Hz and measured 1 m from the source in water at no flow, no pressure situation. The same signal was recorded at 1 meter from the leak at both sides. The FFT magnitude (the peak value) of the generated signal at the specific frequency is used to assess the attenuation of the acoustic wave inside the pipe. One may observe the difference in the FFT magnitude between the actual leak signal and the generated signal, y-axis in figures 2 and 3. Controlling the wave amplitude is very helpful with real pipe flow.

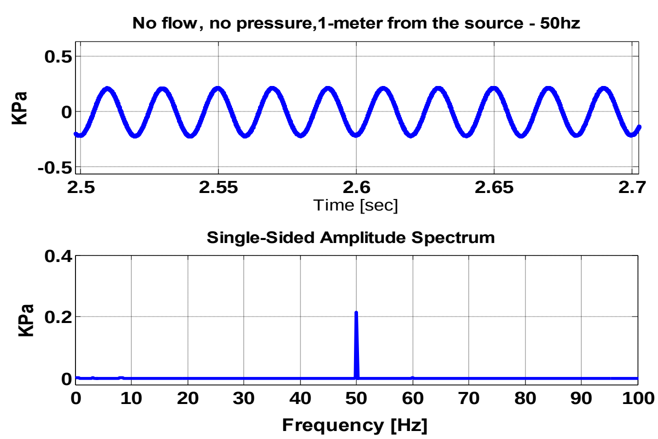


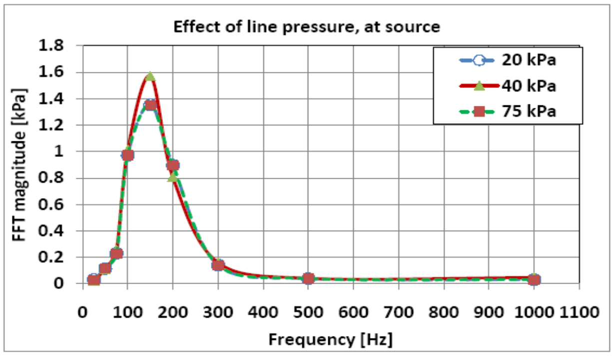
Figure 3 sample of noise generated by the source at 50 Hz measured 1-meter from the source in water, no flow-no pressure situation.

RESULTS AND DISCUSSION

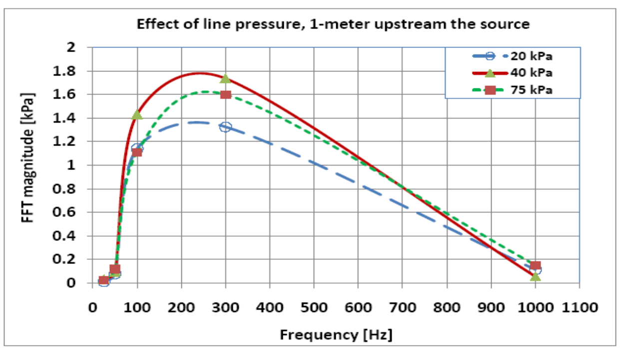
To give an idea about the acoustic signal of actual leak when measured from inside the pipe, stagnant water at a pressure of 250 kPa is allowed to leak from the 100 mm pipe to air from a hole of 6 mm in the pipe wall. The hydrophone is placed at the pipe centerline at the leak section (50 mm from the leak hole, pipe radius). Figure 2 shows the frequency spectrum of the hydrophone signal. A peak frequency is shown close to 105 Hz and few side bands appeared at different frequencies. Compared to the no leak signal (closed hole) which shows no peaks, these peaks represent the signature of the leak. However, it is not easy to follow the leak signal with real flow since the flow turbulence overcomes the leak wave. Thus simulating the leak using acoustic tonal source with controlled range of frequency and amplitude will hopefully provide more information about the acoustic wave propagation inside the water pipelines.

Acoustic waves with Flow: Acrylic tube water loop

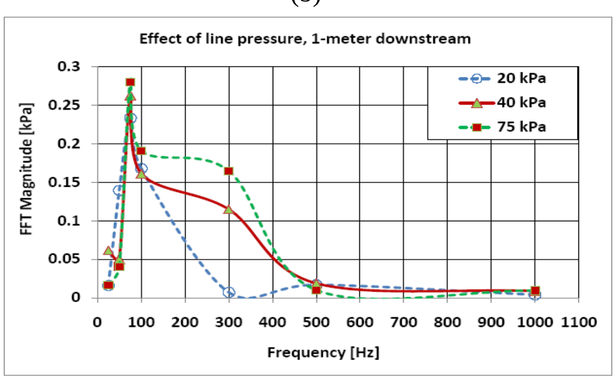
In this section, results are presented for the experiments carried out using the 4-inch acrylic tube water loop with the pump used to circulate the water. By controlling the pump speed, flow is created at different rates and pressures, namely, flow speeds of 0.5, 0.82, and 1.15 m/s are achieved corresponding to pressures of 20, 40, and 75 kPa; respectively. A set of acoustic waves having frequencies between 25 Hz and 1000 Hz is examined under these flow conditions. The receiver hydrophone is placed at different locations with respect to acoustic source. Figures 4 (a, b, and c) show the results of this experiment.



(a)



(b)



(c)

Figure 4 Effect of line pressure on signal attenuation at different frequencies and different locations from the source

Figure 4a, the hydrophone was located at the acoustic source section. In Figure 4b, the hydrophone is located 1-meter upstream the source. In Figure 4c, the hydrophone is located 1-meter downstream the source. For each generated signal, the peak value of the signal frequency in the spectrum is considered for comparison (values on the y-axis). The amplitude of the generated signals is kept constant. It should be mentioned here that other frequencies appear in the spectrum due to flow turbulence.

The figures reveal interesting observations. For the tested range of pressure, the strength of signals with frequencies approximately between 75 to 300 Hz is well captured by the hydrophone. Line pressure of 40 kPa corresponds to the best readings in this range of frequency. Results are showing that the strength of the signal measured 1-meter upstream is much higher than the same signal measured 1-meter downstream. It is even comparable (or better) to the signal measured at the source location. This observation proves that there is an interaction between the propagating wave and the flow direction in water-filled pipes; practically since similar signal were recorded previously at 1 meter upstream and downstream the leak in the case of no pipe flow. The authors believe that this point needs more analytical and experimental investigations in future.

To have more insights on the effect of signal frequency, the hydrophone was located 4-meters downstream the acoustic source. Frequencies from 25 to 1000 Hz were generated under line pressure of 75 kPa and results are shown in Figure 5. Two peaks were found at 75-100 Hz and 500 Hz. It appears that different frequencies propagate and attenuate differently with distance. Examining the FFT values on the y-axis for figures 4 and 5 reveals the fact that the wave is attenuated with distance downstream from the source. In general the attenuation is higher for high frequency signals.

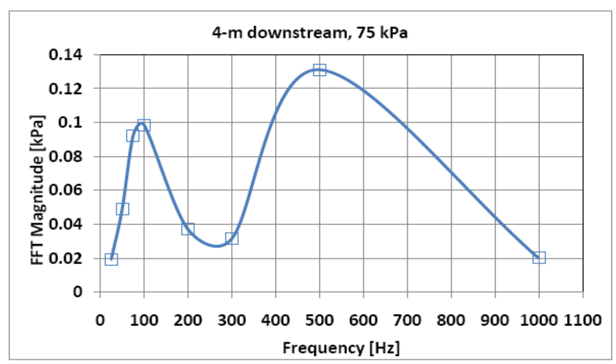
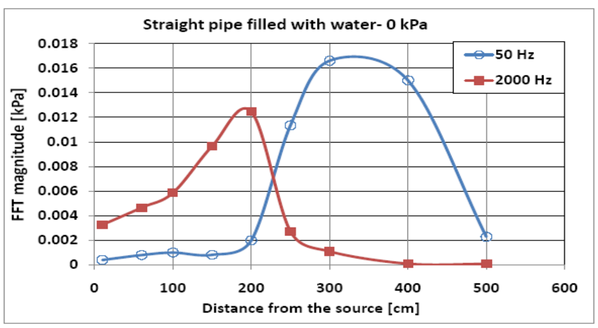


Figure 5measuring at 4 meters downstream the acoustic source

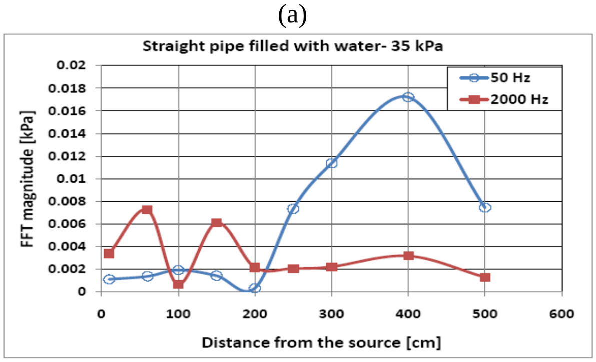
Acoustic waves without Flow: Straight PVC pipe

In this section, a 6-meter straight PVC pipe is used to pressurize the water under stagnation (no flow) conditions. One end is closed with a cap flange and the acoustic source is mounted on this end cap inside the pipe. Water is pressurized from the other end. The hydrophone is inserted from a capped tee close to the water supply end and moves along the pipe centerline to receive the acoustic signal at different location. The goal of this setup is to compare the signal attenuation in the PVC pipe with those previously measured using the acrylic tubes using the simple network geometry of straight pipe. Acrylic tubes are more rigid and fragile. Low and high frequency samples of 50 and 2000 Hz are shown in Figure 5 at different value of water pressure inside the PVC pipe.

The first important result from Figure 6 is that the peak value is not at the acoustic source. This simply means that placing the sensor at the source location (at leak location) may not be the optimum location to capture a good clean signal. For the case of 0 kPa, Figure 5a, the low and high frequencies peak at different distances from the source. High frequency signal attenuates very fast with increasing the pressure; while the low frequency signals still able to peak at a longer distance from the source.



(a)



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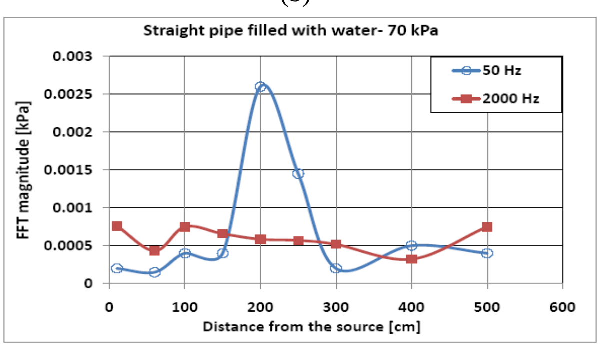

(c)

Figure 6 Effect of measuring distance and line pressure on acoustic wave propagation and attenuation

Even with the same frequency of 50 Hz, the location and magnitude of the peak depend on the line pressure.

Comparing the values of the FFT magnitudes in Figure 6 with those presented in Figure 4, one can realize that the big attenuation in the acoustic signal is due to the pipe material. The PVC pipe is more flexible and absorbs the energy of the propagating wave. Thus, detecting leaks in plastic PVC pipes is not an easy task.

CONCLUSION

Results showed that the low frequency acoustic signals behave differently from high frequency ones. High frequency signals get attenuated quickly with increasing distance from the source. Attenuation is less for low frequency components, practically from 100- 400 Hz at low pressures. The line pressure has a clear effect on the wave propagation at high frequency inside the pipe. Optimum location for the sensor to acquire good clean signal with respect to low frequency acoustic source is estimated to be 2 to 4 meters for the no flow situation. This distance depends on the source frequency and line pressure. Many reflections were measured when the sensor is located exactly at the leak section. Hydrophone directionality inside the pipe is a parameter to be considered. The attenuation of the acoustic waves is higher in more flexible pipes. In the case of real pipe flow, it was found that placing the sensor upstream is better in capturing the acoustic wave. This conclusion may help in designing a good system for detecting leaks in water pipe networks.

These results may be different for different experimental setup, and more experimental work using different configurations is needed. Nevertheless the presented findings give some interesting information on the wave propagation in water-filled pipe.

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REFERENCES

[1] Brones, H., and Schaffhaussen, H., 1972, "European Methods of Leak Detection and Location," Pipeline Industry, pp. 50-66.

[2] Hunaidi, O., and Chu, W. T., 1999,"Acoustical Characteristics of Leak Signals in Plastic Distribution Pipes," Applied Acoustics, Vol. 58, pp. 235-254.

[3] Fuchs, H.V., and Riehle, R., 1991,"Ten years of experience with leak detection by acoustic signal analysis, *Applied Acoustics,* 33, pp. 1–19.

[4] Bracken, M.; Hunaidi, O., 2005, "Practical aspects of acoustical leak location on plastic and large diameter

pipe", Leakage 2005 Conference Proceedings, Halifax, N.S., pp. 448-452.

[5] Hunaidi, O., Wang, A., and Guan, W., 2006, "A new system for locating leaks in urban water distribution pipes," Management of Environmental Quality: An International Journal, 17(4), pp. 450-466.

[6] Bond, A., Mergelas, B., and Jones, C., 2004, "Pinpointing Leaks in Water Transmission Mains," Pipelines 146, 91.

[7] Galleher, J., and W. Kurtz, D. W., 2008, "Evaluation of an Un-Tethered Free-Swimming Acoustic Leak Detection Technology," Journal of Water Resources Planning and Management, Vol 58.

[8] Thompson, M., Chapman, C.J., Howison, S.D., and Ockendon, J.R., 2001, "Noise generation by water pipe leaks," 40th European Study Group with Industry, Keele.

[9] Muggleton, J. M., and Brennan, M. J., "Leak noise propagation and attenuation in submerged plastic water pipes," Journal of Sound and Vibration, vol. 278, pp. 527-537, 2004.

[10] Muggleton, J. M., et al., "Axisymmetric wave propagation in fluid-filled pipes: wavenumber measurements in in vacuo and buried pipes," Journal of Sound and Vibration, vol. 270, pp. 171-190, 2004.

[11] Gao, Y., et al., "A model of the correlation function of leak noise in buried plastic pipes," Journal of Sound and Vibration, vol. 277, pp. 133-148, 2004.