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QUANTIFYING ACOUSTIC AND PRESSURE SENSING FOR IN-PIPE LEAK DETECTION

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ABSTRACT

Experiments were carried out to study the effectiveness of using inside-pipe measurements for leak detection in plastic pipes. Acoustic and pressure signals due to simulated leaks, opened to air, are measured and studied for designing a detection system to be deployed inside water networks of 100 mm (4 inch) pipe size. Results showed that leaks as small as 2 l/min can be detected using both hydrophone and dynamic pressure transducer under low pipe flow rates. The ratio between pipe flow rate and leak flow rate seems to be more important than the absolute value of leak flow. Increasing this ratio resulted in diminishing and low frequency leak signals. Sensor location and directionality, with respect to the leak, are important in acquiring clean signal.

Keywords: leak detection, in-pipe sensing, flow rate, sensor location

INTRODUCTION

While accessing and treating water are of paramount importance, effective and efficient transportation of water from utility to consumer is critical as well. Addressing water losses during distribution could limit the need to access new sources of freshwater; which are already diminishing. Water losses in different countries around the world typically range from 15 to 30 percent on average that represent a significant portion of the water supply (1, 2, and 3). Active leak detection program is crucial in identifying unreported water leakage and losses in the distribution system. Failure at joint connections, corrosive environments, soil movement, loading and vibration all can contribute to pipe deterioration over time and eventual leakage (4). Old or poorly constructed pipelines, inadequate corrosion protection, poorly maintained valves and mechanical damage are some of the factors contributing to leakage (5).

Various experimental techniques using field tests for leak detection have been reported (6, 7). The popular field tests are flow direction indicators, tracer gases, subsurface radar, earth sensitivity changes, infrared spectroscopy, microphones, and odorant and radioactive tracers. Most of these methods are limited, not easy, or so expensive to apply (8, 9). 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 sensors in-bracket the leak and the time lag between the acoustic signals detected by the two sensors detects and locates the leak (10). The cross-correlation method works well in metal pipes; however, the effectiveness of the method is doubtful with plastic pipes. The problems of using the present conventional correlation techniques with plastic pipes include the following (11, 12): (a) High damping; this means that distances between the sensors and the type and quality of sensor are of great importance. (b) Low frequency content; the frequency content of the leak noise is very low (<50 Hz) and therefore very difficult to distinguish as a leak. (c) The propagation of low frequency sound/vibration will be limited by the impedance of fittings.

A technique to detect pipeline features and leaks using signal processing of reflected pressure wave measurements is described in (13). Experimental observations of an inverse transient algorithm for leak detection in a laboratory pipeline detected, localized and measured both single and multiple leaks (14). The method detected leaks in laboratory conditions under high leak flow rates and its efficiency relied on several factors which are not easy to control (15). The applicability of the technique in practice depends on the ability of pressure sensors to detect small changes in pressure and the accuracy of modeling real pipe networks (16). The governing equations for transient flow in pressurized pipes are solved in the frequency domain by means of the impulse response method to detect the leak (17). The leak acts in the same sense of friction; reducing the values of peaks.

The acoustic leak technique based on external measurements is normally faced by some serious challenges, which include greater signal attenuation in plastic pipes, greater attenuation in large diameter pipes, attenuation caused by soft soils; e.g. clay or grass, pipes buried under the water table level, and pipes with pressure less than one bar. 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 (18) or a free-swimming hydrophone (19). The motivation for venturing into this technique stems from the following genuine considerations:

- Ability to survey long distance pipeline in a network.
- Surveying portions of the pipeline network, which may be logistically difficult to access by other techniques.
- The closeness of the sensor to the leak location.
- Leak detection and localization becomes more independent of pipe material, pipe depth, soil type, background noise, and environmental effects.

In this case, the technique relies mainly on the sound traveling through the water column inside the pipe. In order to show how the sound velocity in the pipe is directly influenced by pipe material and diameter, one may refer to the general expression for speed of sound in water-filled pipes, which was derived in (20) as;

$$V_p = \frac{V_0}{\sqrt{1+\frac{K.d}{E.t}}} \qquad (1)$$

Where V_p is the sound velocity in the pipe, V_o sound velocity in free-field water, K is the bulk modulus of elasticity in water, E is the modulus of elasticity of pipe material, d is the inner diameter of pipe, and t is the pipe wall thickness. 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. 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.

To explore the practical feasibility of acquiring a clean reliable signal emitted by a leak and measured from inside the pipe, experiments were conducted. The present experiments represent the first phase of an extended experimental program on developing a mobile leak detection system travelling inside the pipe. Available open literature on in-pipe sensing for leak detection do not give reliable information about the characteristics of leak signals. Thus, the objective of this experimental study is to provide the basic knowledge to characterize the leak signals in plastic pipes using acoustic and pressure measurements, by placing the sensor inside the pipe. The effects of leak flow rate and sensor location, within 2 ft upstream or downstream the leak, on the acquired leak signal are studied. Leak signals are captured with and without pipe flow to study the effect of superimposing the leak on pipe flow. In the case of pipe flow, the maximum flow rate is 22 l/min, limited by current setup, resulting in low speed flow inside the pipe.

EXPERIMENTAL SETUP

The setup used for experimentation is shown in Fig. 1. It consists of a 4 inch (100 mm ID) plastic pipe section (1.5 m long), with the municipality water supply being fed at one end, while the other end is fitted by a flow control valve. This setup allows pipe flow rates from 0 to 22 l/min, which are considered low compared to actual network flows, but it satisfies the current experimental objectives. A pressure gage is installed on the pipe for measuring the line pressure. A 1/8” valve is installed at the middle section of the pipe to simulate leaks with flow rates of interest. The flow rate is measured using an Omega low flow meter (Model FDP301) which can be used to measure flow rates as low as 0.3 l/min. A hydrophone is used to listen to leak noise and a dynamic pressure transducer (DPT) is used to pick-up the water pressure disturbance due to the leak. Both the hydrophone and the pressure transducer can move relative to the leak location; upstream or downstream, as shown in Fig. 2a. The simulated leaks are free to air. The dynamic pressure transducer, model 106B52 ICP® Piezotronics Inc, is mounted flush on pipe wall using special adapter. This pressure transducer has a built-in amplifier and produces ±5V for 1 psi pressure fluctuation. It is connected to a single-channel, line-powered, ICP® sensor signal conditioner model 482A21 which provides constant current excitation to the sensor. The hydrophone, B&K model 8103, with sensitivity 25.9 μV/Pa, is inserted into the pipe through a caped tee with sealant for data cable. It is placed at the pipe centerline by a small plastic holder made mobile by magnets, see Fig. 2b.

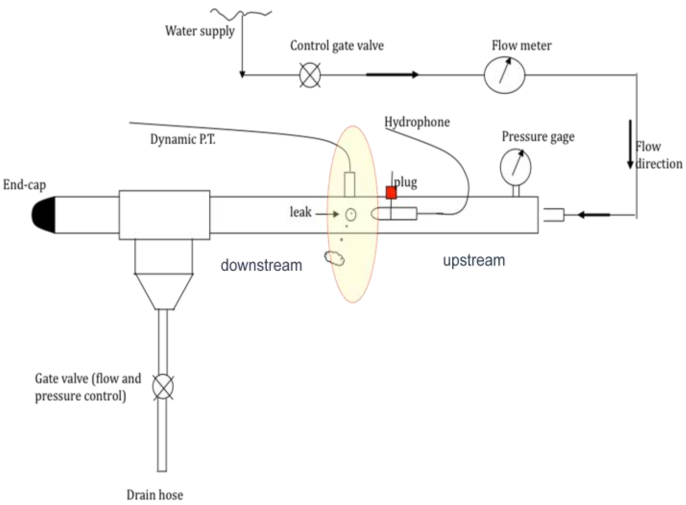
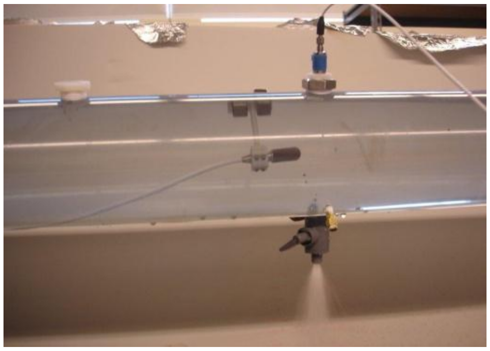
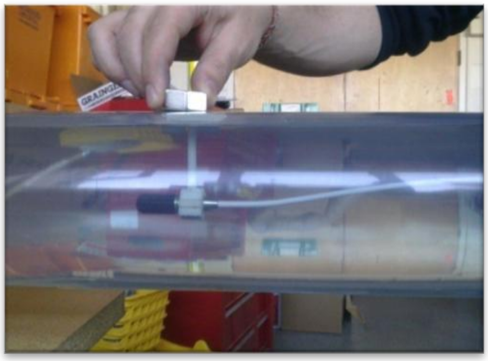


Figure 1: Schematic of the experimental setup



(a) Hydrophone and DPT during opened leak experiment



(b) Hydrophone location is controlled by external magnet

Figure 2: Photos for the test section and sensor location control

A charge to voltage DeltaTron® converter is connected in series with the hydrophone which is powered from the DeltaTron® WB 1372 module. The system also includes a power amplifier and signal conditioner from Stanford Research Systems (Model number SR560). 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. A 51.2 KHz sampling rate is used.

RESULTS AND DISCUSSION

The experiments were designed to explore the following:

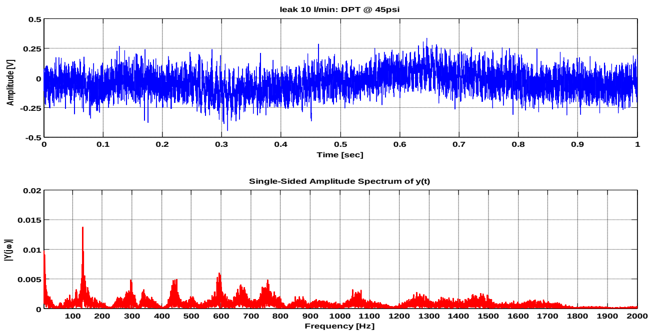
- Ability of using modern hydrophones and pressure transducers to acquire clean leak signals.
- Effect of leak flow rate on the acquired signals.
- Effect of pipe flow on the signals.
- Effect of sensor location: upstream and downstream in the proximity of the leak.

To satisfy this experimental matrix, both the dynamic pressure transducer and the hydrophone are used for signal capturing with controlled leaks to provide the basic knowledge on the previously mentioned objectives. Leaks are simulated using a 1/8” PVC valve and the valve opening is controlled based on the required leak flow rate. Experiments were carried out with no pipe flow (pipeline end valve is closed) and with low pipe flow to study the effect of having main pipe water flow on the leak signal. The pipe flow can be varied between 0 to 22 l/min. Location of the sensor, with respect to leak location, was studied for signal strength. The hydrophone can be moved inside the pipe within 2 ft upstream or downstream of the leak, using external magnets. The pressure transducer is mounted flush on the pipe wall but its location can be changed easily to previously designed set of locations upstream and downstream.

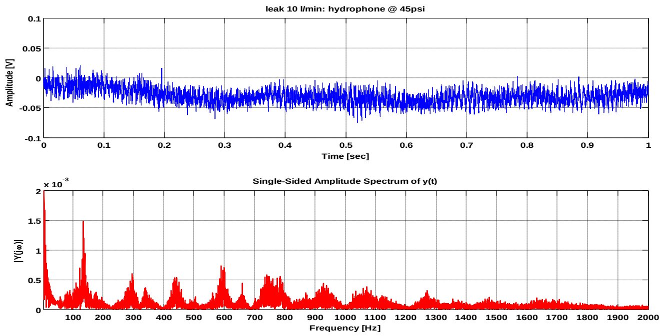
Results for the case of no pipe flow as well as the case of pipe flow showed that both the DPT and hydrophone are able to detect the leak; based on time and frequency plots when compared to the no leak situation. Figure 3 attests the fact that both sensors captured the same signal; for the case of no pipe flow and a leak of 10 l/min as an example. Note that the scales of Fig 3a and 3b are not the same due to the different output of each sensor; the hydrophone output is not amplified.

Despite the different characteristics of each sensor and the way it was placed inside the pipe, both sensors captured the same peak frequencies fairly well for all tests. They effectively sense the same pressure wave propagating in the pipe water and this reveals the facts that both sensors are mainly equivalent and can be used for leak detection. A wide range of frequencies appeared in the frequency spectrum as a results of induced turbulence due to partially opened leak. Based on this conclusion, the figures can be equivalently presented either for hydrophone or DPT for data measured at leak location.

The effect of leak flow rate on the frequency spectrum of leak signal is given in Fig. 4 for leaks of 0, 2, 6, 10, 14, 18.5 l/min, in the case of no pipe flow, using the DPT. Unwanted DC and low frequency (<20 Hz) components were filtered out in this figure for the sake of clarity.



(a) Dynamic pressure transducer



(b) Hydrophone

Figure 3: DPT and Hydrophone are capturing the same frequencies; no pipe flow

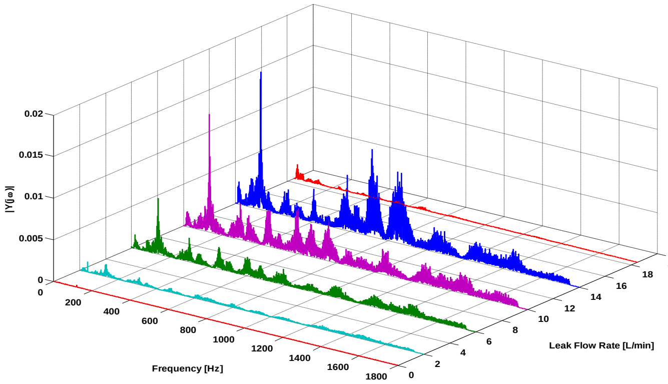
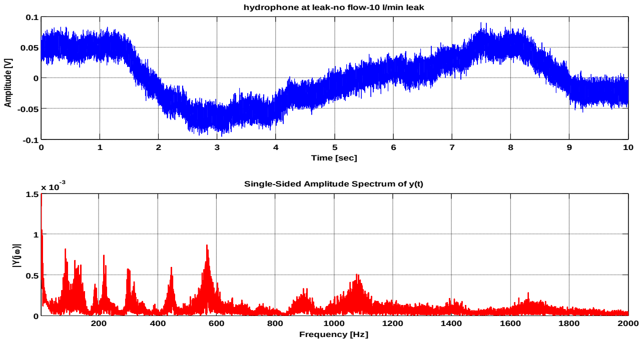


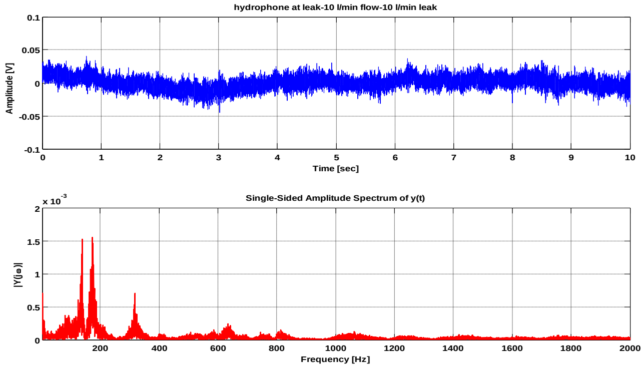
Figure 4: Effect of leak flow rate on frequency spectrum; DPT-no pipe flow

The figure alleviates that increasing the leak flow rate increases the magnitudes of peak frequencies and hence the signal energy content. Zero leak flow is almost flat with no peaks and is clearly distinguished from case of 2 l/min leak. Some frequencies are more affected by the leak flow rate than others and small shift in the frequencies of some peaks is noticed. The signal diminished sharply for fully opened leak valve at 18.5 l/min. This behavior is directly connected to the leak shape/type and the effect of having a partially or fully opened valve on the induced leak disturbances; which is out of the scope of this paper.

The case of no pipe flow represents a good test on sensors sensitivity and the effect of leak flow rate. However, a leak detection system inside a real pipe network will be exposed to the actual conditions of line pressure and flow. One may guess that it makes a big difference for the acquired leak signal. Figure 5 shows the effect of having pipe flow (10 l/min was selected for demonstration) on the frequency spectrum, using the hydrophone. This flow velocity is small for a 4 inch pipe; however, it has a great effect. The wide frequency spectrum for the no pipe flow case has turned to only few peaks at low frequency range (<400 Hz). A noticeable shift in peak frequencies between the two cases is also clear.



(a) No pipe flow, leak flow rate= 10 l/min



(b) Pipe flow 10 l/min, leak flow rate= 10 l/min

Figure 5: Effect of having pipe flow on frequency spectrum-hydrophone.

A more general picture for the effect of pipe flow rate at a given leak flow rate is presented in Fig. 6. The leak flow rate is kept at 8 l/min while the main pipe flow rate is changed from 2 to 14 l/min. As the ratio of pipe flow to leak flow increases; particularly when $Q_{pipe}/Q_{leak} > 1$; the leak signal is diminishing and only traces of low frequency components remain. Although the pressure was not kept the same for these cases due to setup limitations, this may be attributed to the tradeoff between acoustic power reflection and power transmission across the leak, as the amount of power transmission along the main pipe would be relatively larger at higher volume velocities. It should be mentioned here that the no leak signal for the same pipe flow condition is negligible.

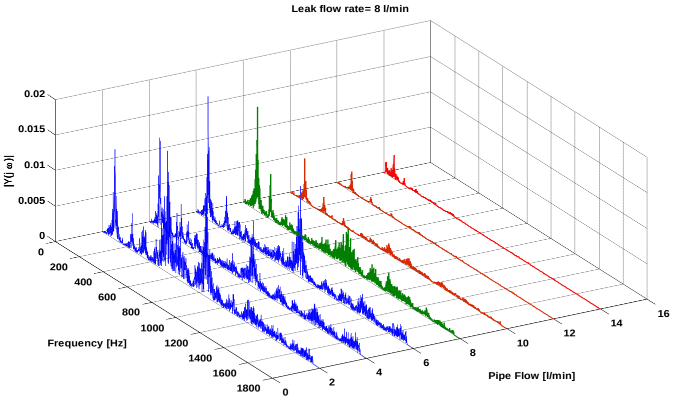


Figure 6: Effect of pipe flow rate on leak signal for constant leak flow rate of 8 l/min, DPT.

As complementary information, Fig. 7 presents the effect of leak flow rate on the frequency spectrum for the case of pipe flow of 8 l/min. Again, unwanted DC and low frequency (<20 Hz) components were filtered out in this figure for the sake of clarity. All tested leak flow rates had distinguished signatures on the frequency spectrum, compared to the no leak case, indicating the ability of the sensors to detect very small leaks under these conditions of pipe flow.

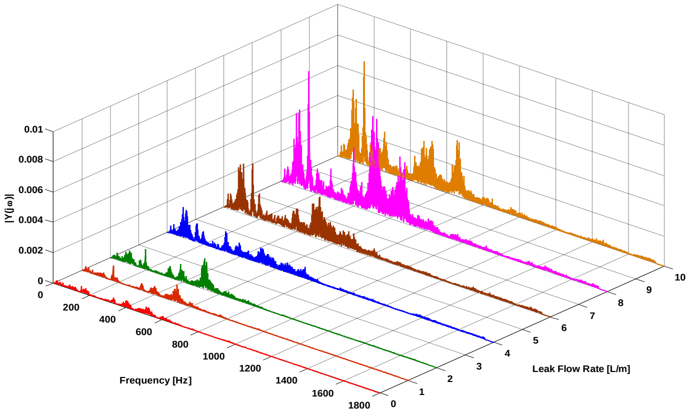


Figure 7: Effect of leak flow rate to the captured leak signal; with pipe flow 8 l/min

To signal a leak alarm, in general, one must have a reference signal profile of the healthy pipeline (no leak situation). In the case of in-pipe measurements, signaling an alarm, while avoiding false alarms would not be an easy task. For instance, the difference between a side branch and a leak port may become undistinguishable. Acoustic signals due to existing leaks (at steady-state) are very likely to be of low power transmission, and may be overshadowed by acoustic energy associated with small turbulence at pipe bends, surface irregularities at different locations. Larger leaks are anticipated to behave differently from smaller leaks, as large leak consumes an appreciable portion of the mainstream energy, to preserve the continuity of the volume velocity across the leak port, as mandated by conservation of mass. These points need further experimental investigation.

A criterion based on the power of the signal is presented for detecting the existence of leaks. Figure 8 shows the calculated power of the time signal for both cases with and without pipe flow, at different leak flow rates. The power of the signal is increasing for increasing leak flow rate (exception is the fully open valve case, which is not included in this figure). Similar trends using hydrophone and DPT were found. Flow rates above 2 l/min can be detected easily by calculating the signal power and compare it to the reference signal of no leak.

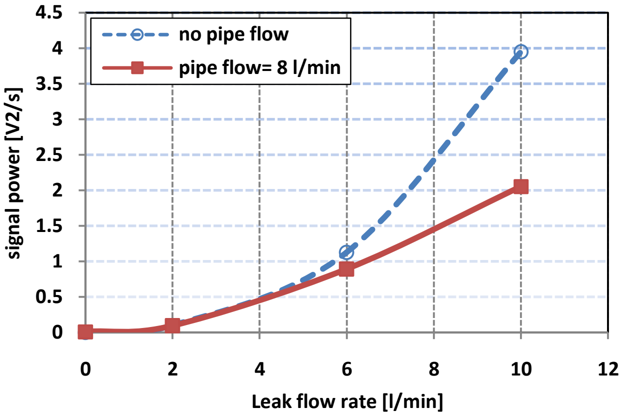


Figure 8:Calculated power of leak time signal with and without pipe flow-hydrophone

The location of the sensor may seem irrelevant since the sensor will pass by the leak anyway. However, results showed that the location of the sensor upstream or downstream the leak is important, particularly for small leaks and when the allowable detection time is small (e.g. high speed pipe flow). Figure 9 shows the leak signal captured by the hydrophone while moving with the flow direction from upstream to downstream the leak at pipe flow of 10 l/min with leak of 10 l/min. The leak signal becomes weak downstream within 2 ft from the leak while the signal is still clear and more informative upstream of the leak for the same distance. The directionality of the hydrophone may be the reason of this weak signal when the hydrophone is placed downstream the leak. These observations may be used to develop an algorithm for leak detection while the sensor passes the leak. On the other hand, signals captured by the DPT upstream and downstream were found to be good compared to the signal measured at the leak section. It has been concluded that the sensor characteristics, placing, and its directionality inside the pipe are important and need more investigation.

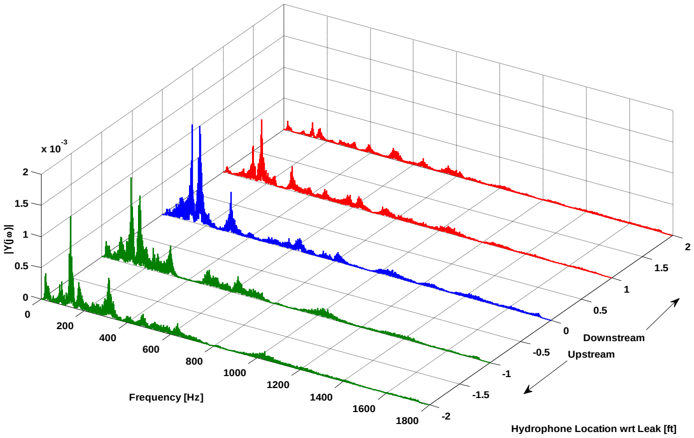


Figure 9: Effect of hydrophone location on leak signal with pipe flow of 10 l/min.

CONCLUSION

Noise generated by leak is generally a broadband noise spanning a wide range of frequencies. High frequency are attenuated by main flow and with distance; thus leaving a low-frequency band signature as the dominant frequency. The obtained signature is intrinsic to the experimental setup, and may be different for an actual pipeline system. However, the emphasis of this investigation is to characterize the acoustic signature of the leak using in-pipe measurements by comparing the leak-free pipe to the pipe with an induced leak. The hydrophone and the dynamic pressure transducer can be equivalently used for in-pipe leak detection, using the pressure waves induced by the leak. The signal power depends on the leak flow rate and shape, pipe flow conditions, and sensor location. With pipe main flow, the leak signals contain low energy and distinguished at low frequencies. Results gave a clue on the importance of sensor characteristics, position, and directionality inside the pipe with respect to the leak. Future experiments should be directed to study leak signal at velocities and pressures of real water distribution networks. Leak type/shape and pipe surrounding media are of great importance to study.

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