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Acoustic Detection of Leaks in Water Pipelines Using Measurements inside Pipe

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Abstract: Acoustic leak-detection techniques are proven to be effective and have been widely used in water-distribution systems for several decades. Most of the existing acoustic leak-detection techniques rely on external measurements of sound emitted from the turbulent jet of water escaping the pipe. Direct acoustic measurements through hydrophones, which travel inside the pipe with the flow, have been recently addressed as an efficient complementary leak-detection technique. This paper presents an experimental investigation that addresses the feasibility and potential of in-pipe acoustic measurements for leak detection. An experimental test rig was constructed to simulate a water transmission pipeline and permits different leak sizes, flow rates, and pressures. The acquired acoustic signals were analyzed; the feasibility and limitations of invoking in-pipe measurements for leak detection were addressed. **DOI:** 10.1061/(ASCE)PS.1949-1204.0000089.

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Introduction

The traditional acoustic leak-detection schemes relied on devices, such as listening rods, aqua phones, and ground microphones. The operations of these devices are usually straightforward, but their effectiveness depends on the experience of the user. The concept of utilizing acoustic measurements to locate leaks in pipelines was introduced in the 1930s, e.g., Richardson (1935) and Larson (1939). Nearly 20 years later, further interest in the problem was revived (McElwee and Scott 1957). The record of progress in developing an operational system is reported by Reid and Michel (1961), wherein the first systematic attempt to develop an improved means of leak detection combining both active and passive approaches was described. The American Gas Association (AGA) supported such early effort with the technical work being carried out at the Institute of Gas Technology (IGT). An interesting historical review of the development of acoustic leak-detection techniques was reported by Loth et al. (2003).

Brodetsky and Savic (1980) developed an approach to identify the noise of leaking gas in a pipeline and isolate this signal from the other background noise sources. Their acoustic model adopted an electric transmission line formulation instead of the standard acoustic wave equation. This model was developed into a leak pattern-recognition system in terms of an autoregressive-moving average scheme (ARMA).

Rocha (1989) introduced one of the early leak-detection techniques on the basis of acoustic measurements, wherein two pressure sensors were used for recording the leak-induced pressure waves while applying noise cancellation to eliminate the background noise. Low-frequency waves were capable of traveling the large distances between pipeline shut-off valves, without excessive damping. The change in pipeline velocity associated with the sudden appearance of a leak causes an acoustic pressure wave signal, which could be detected for small leaks, when noise cancelation was employed.

Raijtar et al. (1994) addressed the problem of passively monitoring pressurized oil pipelines for evidence of leaks. They conducted a lab experiment using a 10-ft-long pipe with leak simulated by a metering valve. Acoustic emission signals were investigated as functions of the pipe pressure, leak rate, and distance from the leak. The spectrum of the leak was significantly different from the background signal even with relatively low pipe pressure and the leak rate, while the attenuation along the pipe was not significant in the lab scale pipe. A field experiment was performed to investigate signal attenuation along a pipeline. Even at low pressure, leaks can be detected from a distance of 200 ft in surface pipelines; however, in buried pipelines, the acoustic emission signals were strongly attenuated. Another acoustic emission technique to detect pipeline leaks was developed by Lee and Lee (2000). They addressed two different methods for determining source location, in terms of the reduction in signal amplitude with increasing distance from the source (attenuation based), and the increase in signal transit time with increasing distance from the source (time of flight based), respectively. The leak in pipeline generates acoustic waves, which propagate along the pipe wall. They carried out experiments on a 6-m-long, 19-mm-diameter pipe with nitrogen gas. The attenuation-based method was found to be more effective to detect leaks.

As for water leak detection, acoustic techniques are proven to be effective and are widely used in water-distribution systems (Hunaidi 1998). Acoustic leak-detection equipment identifies the

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sound or vibration induced by water escaping from pipes under pressure. When pressurized water leaks from a pipe, it creates a sound that can travel through the pipe wall, the water column, or to the surface. In general, leak in a pipe creates a turbulent jet. As the jet interacts with the wall of the pipe, it results in significant turbulent pressure fluctuations, thus generating sound. Moreover, as water passes through the leak hole, its velocity increases. If the velocity is high enough, the pressure at the leak point can drop below the vapor pressure of the liquid and form vapor bubbles. When a bubble implodes, minute shock waves are created. These shock waves, by impacting on the solid pipe wall, result in sound. The sound-generation mechanism of leak signal could be either at low frequencies because of unsteady flow separation at the leak point, or at high frequencies because of cavitations (Thompson et al. 2001). Acoustic leak detection using noise correlators has been employed in water-distribution systems for several years. In this case, either accelerometers or microphones were used as sensors, which are placed either directly on the outer surface of the pipe or on the surface above buried pipeline. Accelerometers are used as surface-mounted sensors that measure the vibration induced into the pipe wall by the leak noise (Fig. 1). By measuring the vibration at two or more locations, the source of vibration can be identified. Vibration sensors or accelerometers are typically attached to fire hydrants, valves, or other contact points with the pipe (Hunaidi et al. 2004). Other correlation techniques employed a multiple-model state-estimation scheme, which utilizes the nonmeasurable state variables, to detect and locate single leaks in water pipeline systems (Khulief and Shabaik 2006). Yang et al. (2008) utilized the overlap-save and cross-correlation fitting technique in blind system identification to estimate the acoustic channels and locate leaks in water-distribution systems.

In contrast, hydrophones may be used as sensors for in-pipe measurements (Fig. 1). Hydrophones are underwater microphones that are placed in contact with the water column and detect the acoustic noise transmitted through the water column, as shown in Fig. 1. Hence, the hydrophones must be inserted into the water through openings on fire hydrants or other outlets along the pipeline. The methodology underlying this technique invokes direct acoustic measurements through hydrophones, which travel with the flow inside the pipe. In this context, it is needed to highlight the nature of the leak-generated acoustic wave propagating inside the pipeline, which, in general, is manifested by a perturbation of velocity and pressure (Barabanov and Glikman 2009). Accordingly, one must anticipate the challenging task of distinguishing the leak-induced perturbation from other turbulence-induced perturbations. It is well known that turbulences of various strengths are normally generated at the bends and other internal surface irregularities of the pipe.

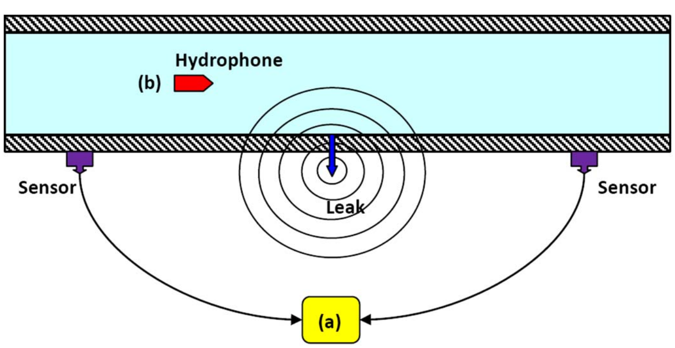

Fig. 1. Leak sound source: (a) external correlation technique; (b) in-pipe measurement technique

Although the in-pipe measurement of the acoustic signature of leaks has recently captured the interest of investigators in this area, no data or benchmark studies were reported in the available literature. The objective of this investigation was to bridge this gap in literature by conducting an experimental study to characterize the acoustic signature of leak in water-distribution systems through in-pipe measurements, examine its feasibility, and outline the associated challenges.

In-Pipe Measurements

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 or a free-swimming hydrophone. The idea of free-swimming acoustic leak-detection systems has been addressed very recently and briefly by some leak-detection manufacturers (Kurtz 2006); however, the technique is at its infancy and no commercial product was developed yet. The motivation for venturing into this technique stems from the following genuine considerations:

- Ability to survey long distance of the pipeline network;
- Surveying portions of the pipeline network, which may be logistically difficult to access by other techniques; and
- Closeness of the sensor to the leak location.

In this case, the technique relies primarily on the sound traveling through the water column inside the pipe. In this context, one can state the basic differences between outside and in-pipe measurements. First, the leak orifice acts as high-pass filter, i.e., it passes high-frequency sound power through the leak orifice to the outside environment. In this case, the low-frequency sound energy is not radiated out of the leak, but is reflected back toward the source, which indicates that high frequency is transmitted outside the pipe. Second, the high-frequency sound energy is attenuated inside the pipe, leaving the low-frequency signal as the primary signal for leak diagnostics. The latter can be explained by the succeeding analysis.

Acoustic waves attenuate inside the pipeline because of material intrinsic absorption. In general, absorption losses are a result of internal friction attributable to work done at material interfaces (Prek 2007). Larger diameters and more flexible pipes tend to attenuate higher frequencies. Accordingly, lower frequencies remain as the most dominant frequencies. 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 (Thompson et al. 2001), which was derived as

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

where V_p = sound velocity in the pipe; V_o = sound velocity in free-field water; K = bulk modulus of elasticity in water; E = modulus of elasticity of pipe material; d = inner diameter of pipe; t = pipe wall thickness.

It is apparent that sound velocity in water pipes depends on 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.

In addition, further attenuation of sound energy transmitted past the leak may be considered. To access this correlation, it may be assumed that the condition of low-frequency plane wave traveling

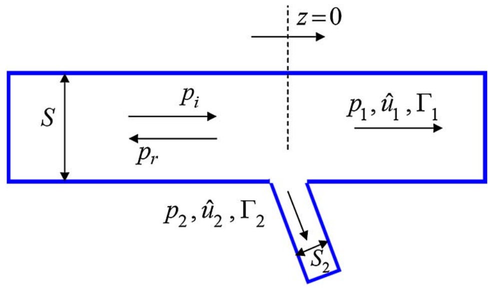

Fig. 2. Conditions in the vicinity of branched leak

in the pipe filled with water as consistent with the acoustic characteristics of a leak. To this end, the leak port may be viewed as a branched pipe connection, as shown in Fig. 2. The acoustic impedance Γ at any cross section S of a pipe can be simply expressed in terms of the characteristic impendence $\rho_o c$ of water, as

$$\Gamma = \frac{\rho_o c}{S} \tag{1}$$

The boundary conditions must comply with both the continuity of pressure p, and the continuity of the volume velocity $\hat{u}$, which is mandated by conservation of mass. Now, the incident and reflected waves can be represented by

$$p_i = P_i e^{j(wt-kz)}$$

$$p_r = P_r e^{j(wt+kz)} \tag{2}$$

The acoustic impedance for $z < 0$ is

$$\Gamma = A + jB = \frac{p_i + p_r}{\hat{u}_i + \hat{u}_r} = \frac{\rho_0 c}{S} \frac{P_i e^{-jkz} + P_r e^{jkz}}{P_i e^{-jkz} - P_r e^{jkz}} \tag{3}$$

Let the acoustic impedance at a point $z = 0$ along the pipe changes because of the branched leak port, from Γ to Γ_o. In general, the flow near the leak will be complicated, however, in the limit for long wavelengths; the acoustic impedance in the vicinity of $z = 0$ can be approximated by evaluating Eq. (3) at $z = 0$ (Kinsler et al. 1982). This can be written as

$$\Gamma_o = \frac{\rho_0 c}{S} \frac{P_i + P_r}{P_i - P_r} = A_o + jB_o \tag{4}$$

Now, solving for the pressure reflection coefficient (P_r/P_i), one obtains the power reflection coefficient $\mu_r = |P_r/P_i|$ as

$$\mu_r = \frac{(A_o - \rho_o c/S)^2 + B_o^2}{(A_o + \rho_o c/S)^2 + B_o^2} \tag{5}$$

and the power transmission coefficient $\mu_t = 1 - \mu_r$ is written as

$$\mu_t = \frac{4 A_o \rho_o c/S}{(A_o + \rho_o c/S)^2 + B_o^2} \tag{6}$$

For the pipe with leak port junction at $z = 0$, as shown in Fig. 1, it may be considered that the postleak continuation of the pipe and the leak port as two branches of the preleak or the upstream portion of the pipe. Assuming that the wavelength is much greater than the pipe diameter, while the leak port has an arbitrary acoustic impedance $\Gamma_2 = A_2 + jB_2$ to be connected at $z = 0$ to an infinitely long pipe, one can rewrite both the reflection and transmission coefficients, and by simple manipulation obtain the ratio of the power transmitted into the leak port to that in the incident wave as

$$\mu_R = \frac{(\rho_o c/S) A_2}{(A_2 + \rho_o c/S)^2 + B_2^2} \tag{7}$$

If A_2 is greater than zero, but not infinite, some acoustic energy is dissipated in the leak port and some is transmitted beyond the junction. At the extreme case when either A_2 or B_2 becomes very large compared with $(\rho_o c/S)$, almost all the incident power is transmitted beyond the junction (Kinsler et al. 1982). Accordingly, one concludes that the size of the leak is relevant to dissipating the acoustic energy. Yet, small leaks have negligible effect on attenuating the acoustic energy transmitted past the junction.

Although techniques for leak detection using in-pipe acoustic measurements are being investigated, the available literature appears to be short of any pertinent experimental data. Now, to explore the practical feasibility of acquiring a clean, reliable acoustic signal emitted by a leak using in-pipe measurements, a laboratory experiment was conducted.

Experimental Setup

A schematic diagram for the setup is shown in Fig. 3. A 10-hp centrifugal pump (Goulds $21/2 \times 3$-in.) is used to circulate the water and to build the required line pressure. The loop is controlled by a set of valves and fittings. The pipes are carried on a strong steel structure. A 1-m^3 plastic tank is used as water reservoir and recirculation tank. The flow rate is measured by a standard 10.15-cm (4-in.) stainless steel orifice meter connected to a mercury U-tube manometer. The line pressure is measured using a pressure gauge mounted on the pipeline. Pump discharge has been equipped with a control gate valve and a flexible connector to minimize pump vibrations transmitted to the test loop. Most of the length of the loop pipeline is clear acrylic plastic pipes to facilitate flow and sensor visualization. For the tethered hydrophone to be placed inside the pipe, tee fittings are distributed close to test section and special sealing for the sensor cable was made in the tee cape. The sensor is carried on a thin plastic spider to position it at the pipe centerline, as shown in Fig. 4. A test section of the loop simulates a large leak by a 2.5-cm (1-in.) service house connection, whereas the small leak is simulated by 0.635-cm (1/4-in.) valve at the middle of the test section so that the leak flow rate is controllable. Acoustic measurements were continuously monitored to demonstrate the variation in the signal strength as the sensor traverses the leak location.

Fig. 3. Instrumented test rig

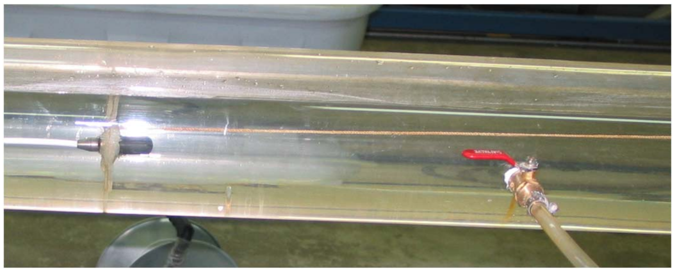

Fig. 4. Tethered hydrophone

Hydrophone Selection

Brüel & Kjær hydrophone type 8103 is suitable for laboratory and industrial use. The transducer is individually calibrated waterborne-sound transducer, which has a flat frequency response and is omnidirectional over a wide frequency range. This is a small-size, high-sensitivity transducer for making absolute sound measurements over the frequency range 0.1 Hz to 180 kHz with a receiving sensitivity of -211 dB re 1 $\mathrm{V}/\mu\mathrm{Pa}$. It has a high sensitivity relative to its size and good all-round characteristics, which make it generally applicable to laboratory, industrial, and educational use.

Data Acquisition and Analyzer Hardware

The compact five-channel data acquisition system B&K PULSE type 3560-B was used. B&K PULSE is a versatile, task-oriented sound and vibration multianalyzer system. It provides the platform for a range of PC-based measurement solutions. The unit handles communication with the PC, acquires measurement input, and provides a sample clock. It provides automatic calibration sequencing and registration of calibration history, in addition to a level meter for monitoring of conditioned signals for optimal data quality. The PULSE software type 7707 is the base software for simultaneous fast Fourier transform (FFT) and $1/n$ octave analysis of the same data with simultaneous measurement of exponential, linear, impulse, and peak levels. Spectral units of RMS, power, power spectral density, and RMS spectral density are available. Acoustic postweighting includes A-, B-, C-, D-, and L-weighting. The analyzer was set at 3,200 lines for calculating FFT spectrum for the time record, at all measurements. The averaging can be either continuous through cyclic buffer averaging or over a period of time at a minimum linear averaging time of 0.1 s The maximum bandwidth frequency span is 25.6 kHz per channel.

Experimental Measurements and Analysis of Data

The main objective of this experimental investigation was to verify the practicality of using in-pipe measurements for identifying leaks. To sort out the challenges involved in realizing this technique, some key issues need to be investigated. These include the effect of the leak size on the measured signal, the effect of hydrophone location with respect to the leak port, the effect of pipe pressure on the delectability of the acoustic signal, and the effect of the background noise.

Characteristics of the Leak Sound Source

To correctly interpret the in-pipe acoustic measurements, some pertinent considerations are outlined. In this context, the following are some important characteristics of the anticipated sound emitted from a leak in a pipe conveying water:

- The leak as a noise source can be approximated by a point source, for relatively small leaks, which emits spherical waves measured in half space. For all pipe diameters used in water-distribution systems, measurements are most likely done in the near field. This can be verified by recalling that the speed of sound in water is more than four times that in air, measured at the same temperature. For instance, a sound emitted in air at 1,000 Hz has a wavelength of approximately 0.34 m, which corresponds to a wavelength of more than 1.35 m for the same sound generated in water. Accordingly, it is anticipated that the leak acoustic measurements are dominated by the near-field characteristics, with some influence of the reverberant field attributable to reflections on the pipe's hard walls. In this region, the sound field will not follow the inverse square law with regard to sound intensity, i.e., doubling of distance as the sensor moves away from the source will not show the expected 6 dB decrease in sound-pressure level.
- An acoustic wave in a pipeline represents a perturbation of velocity and pressure that propagates as a plane wave. Noise generated by the leak is generally a broadband noise spanning a wide range of frequencies (turbulence induced); however, high-frequencies are known to attenuate faster, thus leaving low frequencies as the dominant ones. Previous acoustic studies have shown that although the acoustic signals of a pressurized fluid escaping through a leak may include a wide range of frequencies, only the relatively low frequencies are useful for practical leak-detection methods because of the significant attenuation of the higher-frequency components.
- Sound measurements in water are normally perceived differently from that in air with regard to loudness. Accordingly, one needs to be careful in interpreting the strength of the acoustic signal measured in water. Comparing decibel measurements in air and water involves two different measurement corrections; one is purely a numerical shift, whereas the other is more complicated, involving both mathematical and physical considerations (Cato 1997). In water, where the human hearing system is inefficient (because the eardrum does not respond well to the added pressure), it does not make sense to count decibel in relation to human audibility threshold (20 μPa), so it is instead measured from an arbitrary level of 1 μPa. Recalling the logarithmic relationship between micropascals and decibels, a simple calculation shows that a sound of a given intensity will be measured as being 26-dB higher in water than in air. The second adjustment is attributable to water being much denser than air; thus, water has higher impedance. Accordingly, sounds of equal measured pressure will be measured at approximately 36-dB higher in water (Potter and Chitre 1999). It is generally accepted in ocean acoustics that sounds of equal pressure (in the respective reference units) can be considered 62-dB higher in water than in air. This indicates that when a sound is reported as 162-dB in water, it will correspond to a sound measuring 100-dB in air. Underwater noise measurements typically do not have frequency weighting applied. In addition, underwater noise levels are reported only for limited frequency bands.

In these measurements, no acoustic weighting is used, which is normally adopted in acoustic measurements in water. The hydrophone was positioned along the centerline of the pipe using a thin four-legged plastic spider. The leak port was simulated using a valve. Measurements were taken at three stations: at $5D$ (51 cm or 20 in.) upstream of the leak port, at the leak port, and at $5D$ downstream of the leak port, respectively, where D is the inner diameter of the test pipe. The water flow speed in the main pipe was rated at 2 m/s, whereas the pipe pressure was varied up to 300-kPa (3-bar). The small-leak flow rate was metered at 0.082 L/s at 100-kPa, 0.192 L/s at 200-kPa, and 0.266 L/s at

300-kPa, whereas the large leak was metered at 4.54 L/s at 100-kPa, and 10.74 L/s at 200-kPa. The unweighted sound level and the acoustic spectrum were measured. When characterizing a sound-pressure spectrum for a waveform, the unit of amplitude is normally the RMS pressure, which is measured over a defined frequency bandwidth. Fig. 5 shows the sound-level spectrum for a small leak at line pressure of 200-kPa. Although in the presence of the leak, one may observe that the sound level attains higher amplitudes in the vicinity of a low-frequency band centered nearly approximately 35-Hz frequency; the sound-level variation was relatively low. The sound-level peak at 57.5 Hz refers to the synchronous pump speed of 3,450-rpm. As the variation in sound level was relatively low, the RMS spectral density was found to give a better measure of the sound power. Figs. 6–8 show the RMS sound spectral density ($Pa/\sqrt{Hz}$) of the acoustic signal at three values of line pressures.

In a virtual piping system in which all the components are perfectly quiet, there would still be a base noise level associated with fully developed turbulent flow in the pipe. All flow disturbances, whether pipe fittings, valves, pumps, or leaks, add to the intensity of the turbulence and, therefore, increase the noise levels above the base. Yet, the acoustic signature shown in such figures is intrinsic to the experimental piping system and may vary from one pipe network to another. It may very well vary from one pipe segment to another of the same pipe network. The focus, however, is directed to identifying the effect of the leak with respect to the existing leak-free pipe signature. Fig. 6 shows that the effect of the leak is minor at the upstream station, and may not be distinguishable. Yet, as the hydrophone traverses the leak port, the sound spectral density increases noticeably close to a frequency of approximately 35 Hz, as shown in Fig. 7. The same trend is clearly noticeable in Fig. 8 at the downstream station. Accordingly, the following observations can be made: (1) the leak can be identified using in-pipe acoustic measurements, (2) the leak acoustic signature is more observable at the leak port and downstream of the leak port, (3) the leak-signature strength increases as the line pressure increases, and (4) the leak signal is hardly noticeable for pressures close to 100-kPa. The last observation is consistent with the reported experimental finding by Hunaidi et al. (2004), in which they observed that it is difficult to detect leaks in pipes having pressures less than 100-kPa (15 psi).

Figs. 9 and 10 show a comparison of the small-leak sound spectral density at the three measurement stations for line pressures of 2 and 3 bar, respectively. However, Fig. 11 shows the same comparison for the 1-in. pipe connection (large leak) at line pressure of 2 bar. The leak signature occurred at a frequency band centered

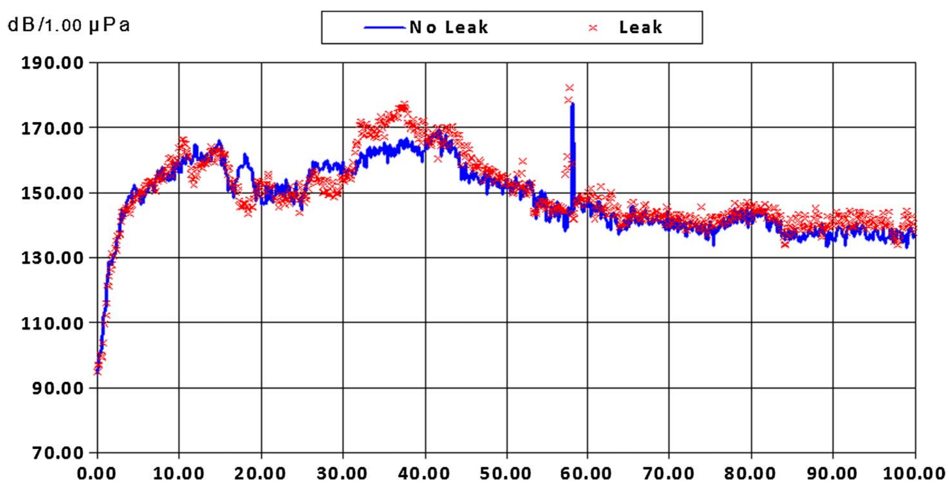

Fig. 5. RMS acoustic spectrum of the sound level at 2 bar (small leak)

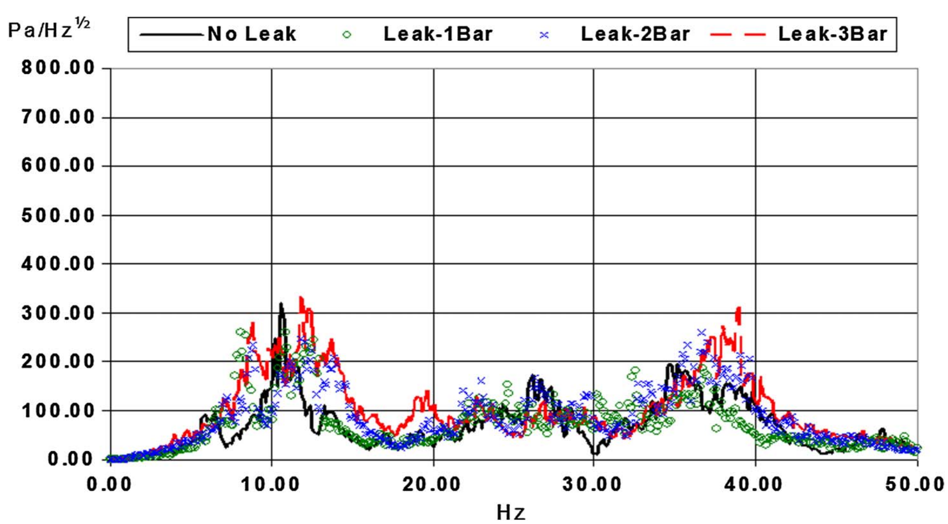

Fig. 6. RMS sound spectral density at upstream station (small leak)

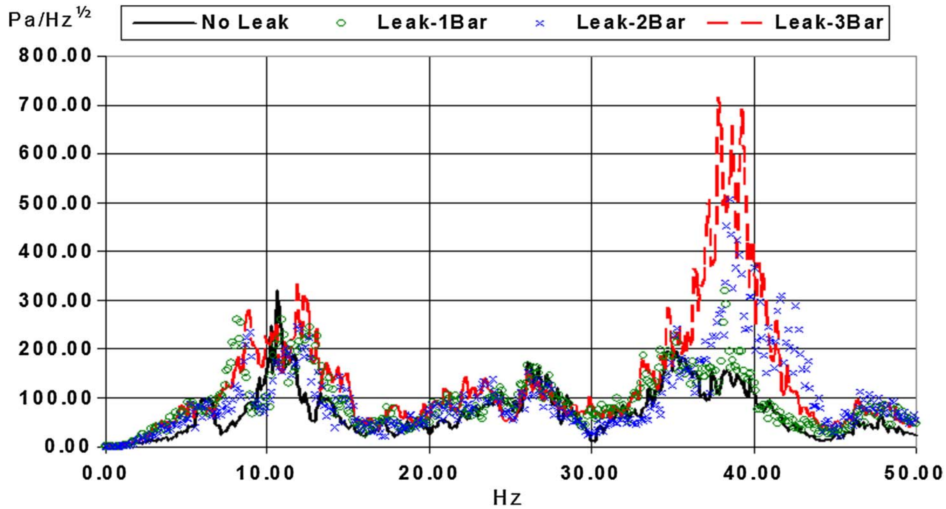

Fig. 7. RMS sound spectral density at the leak port (small leak)

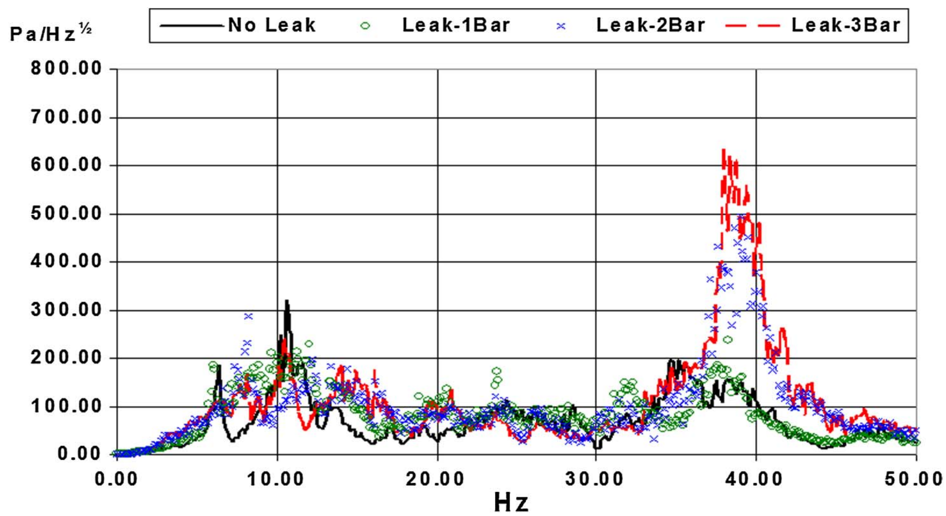

Fig. 8. RMS sound spectral density at downstream station (small leak)

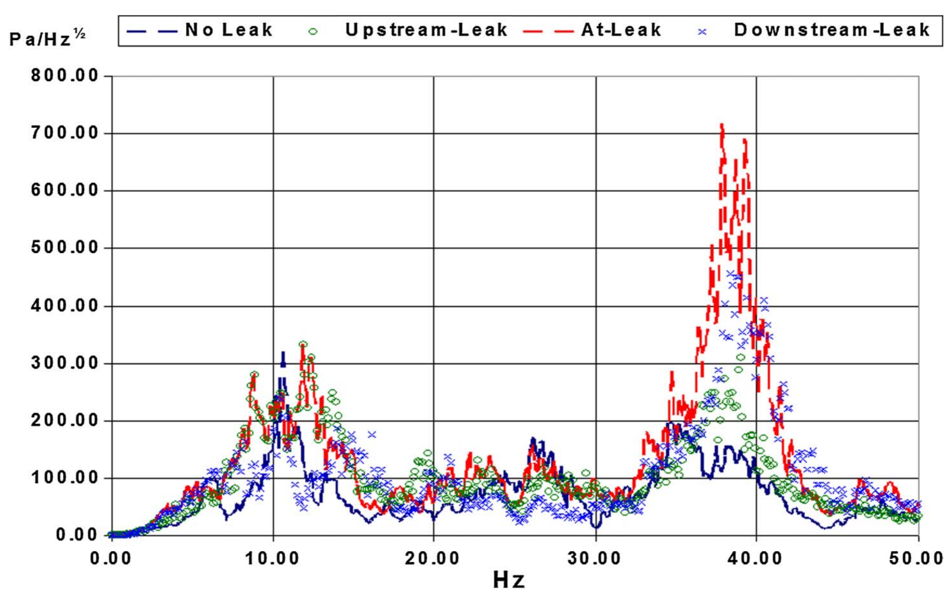

Fig. 9. Acoustic-power spectral density at 2 bar (small leak)

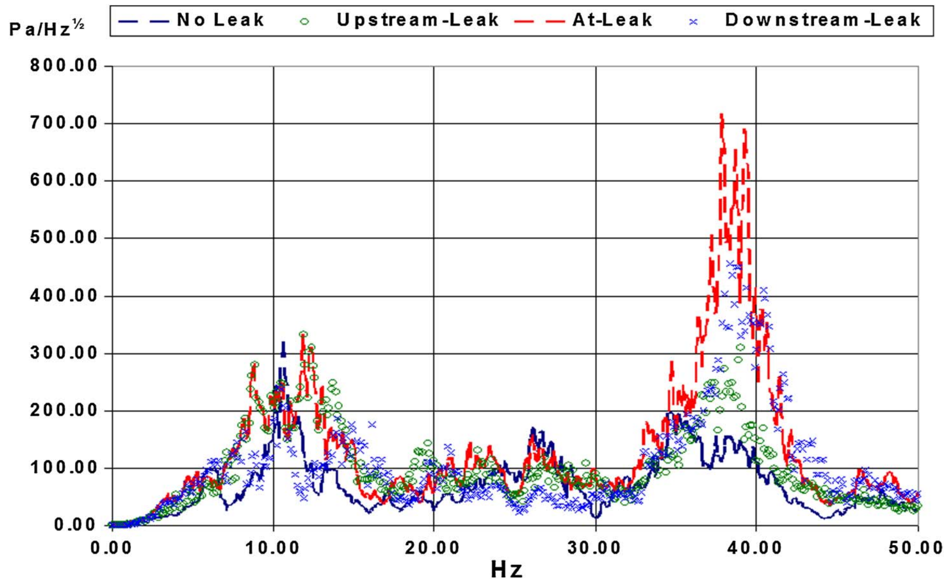

Fig. 10. Acoustic-power spectral density at 3 bar (small leak)

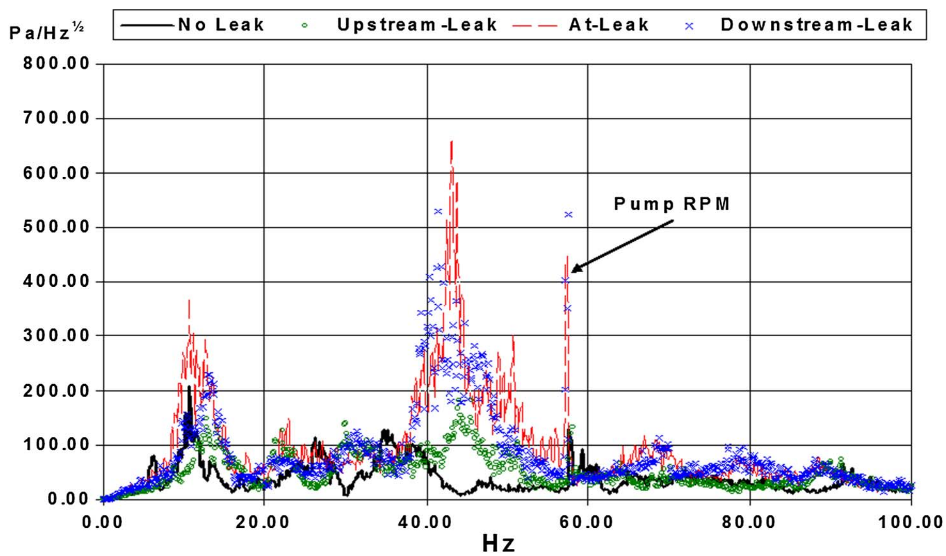

Fig. 11. Acoustic-power spectral density at 2 bar (house connection)

nearly approximately 45 Hz. In this regard, Fig. 11 reveals two important observations: (1) the frequency band of the leak acoustic signature may vary for the same pipe setup depending on the leak size, and (2) the acoustic energy of the leak signal at the leak port drops to a lower value in the downstream side of the port. The second observation agrees well with the branched connection hypothesis as presented previously, leading to the ratio of the power transmitted into the leak port to that in the incident wave, as given by Eq. (7). Accordingly, one concludes that the size of the leak is relevant to dissipating the acoustic energy. Yet, small leaks have a negligible effect on attenuating the acoustic energy transmitted past the leak port, as shown in Figs. 9 and 10.

As for acoustic signal attenuation attributable to pipe material and dimensions, it could not be observed in this experimental lab scale piping system with a limited length of few meters. This phenomenon is expected to be measurable in appreciably longer pipe systems, i.e., several hundred meters long (Barabanov and Glikman 2009).

Implementation and Challenges

The leak-detection scheme, which is based on in-pipe measurements, is not meant to replace existing leak-detection technologies, but instead to compliment the existing technologies. The method of implementation may take the following steps; a similar procedure was adopted in testing a prototype sensor by Kurtz (2006):

1. The hydrophones are to be inserted into the water through openings in fire hydrants or other outlets along the pipeline.
2. The hydrophone-sensor floating assembly is then propelled by the water flow over long distances of the pipeline and makes a continuous recording of the acoustic signature inside the pipeline.
3. The movement of the sensor assembly is tracked by a set of transponders, which are placed along the pipeline at convenient surface access locations. In addition, a miniature transponder can be placed inside the sensor assembly to communicate with a global positioning system (GPS)-based logger on the surface.

4. Once the sensor has traversed the desired pipeline length, it is retrieved to analyze the acoustic data, thus determining whether any leaks exist and pinpointing their locations.

The previously discussed leak identification process is based on a comparison between the acoustic spectrum of the leak-free pipeline and that of the same pipeline with an induced leak. To carry out the in-pipe measurement technique in field applications, one needs to set a reference spectrum for depicting the effect of leak on the acoustic energy transmitted inside the pipe. This may prove to be a challenging task, which either requires a reference acoustic spectrum for the leak-free segment of the pipeline, or using two spaced microphones for establishing a correlation. Other challenges, which warrant further investigations, include the need to invoke noise-cancellation techniques to offset background noise for better detection and avoidance of false alarms, finding a spatial reference for the moving hydrophone for logging the leak location, and devising a procedure for deployment and retrieval of the free-swimming sensor. In addition, a swimming sensor requires some special design considerations pertinent to the capability of negotiating valves, sharp bends, and motion against gravity; the pipe-diameter limitations; and battery-life limitations.

Conclusions

Although the in-pipe measurement of the acoustic signature of leaks has recently captured the interest of investigators in this area, no data or benchmark studies were reported in the available literature. This investigation is an attempt to bridge this gap in literature by conducting an experimental study to characterize the acoustic signature of leak in water-distribution systems through in-pipe measurements, examine its feasibility, and outline the associated challenges. In this context, the reported experimental results provided more insight into this process by revealing the following important findings:

1. The leak can be acoustically identified through in-pipe acoustic measurements using a swimming hydrophone.
2. An acoustic wave in a pipeline represents a perturbation of velocity and pressure that propagates as a plane wave. Noise generated by the leak is generally a broadband noise spanning a wide range of frequencies (turbulence induced). However, the relatively low frequencies associated with the unsteady flow separation at the leak point are useful for practical leak-detection methods because of the significant attenuation of the higher-frequency components.
3. The acoustic spectrum reported in this paper is intrinsic to the experimental pipe setup attributable to minor turbulences at various surface irregularities inside the pipe, and is expected to vary for other pipeline systems.
4. The leak acoustic signature is more observable at the leak port and downstream of the leak port.
5. The leak-signature strength increases as the line pressure increases.
6. The acoustic signal of the leak signal becomes noticeable for line pressures above 1 bar.
7. The frequency band of the leak acoustic signature may vary for the same pipe setup depending on the leak size.
8. For larger leak sizes, the acoustic energy of the leak signal at the leak port drops to a lower value in the downstream side of the leak port.

The challenges and other technical considerations for implementing the in-pipe acoustic measurements into a reliable leak-detection scheme were also addressed.

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