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Detecting & Locating Leaks in Water Distribution Polyethylene Pipes

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Abstract— **This paper focuses on the problem of detecting and locating the position of water leaks in water distribution Medium Density Polyethylene (MDPE) pipes using passive acoustic detection methods. A leaking water pipe generates noise which depends primarily on water pressure, pipe characteristics and the leak size and shape. This leak noise comprises vibration and acoustic signals, which can be detected using non-invasive accelerometers and invasive hydrophone sensors respectively. In current practise, a correlation technique is typically employed to detect, position and characterise these water leaks using the leak noise produced. This is proved to be very efficient for metallic pipes; however, the same is not true for plastic MDPE pipes where the attenuation rate with distance of the leak/source signal is very high, and the generated leak signals are of low frequency and narrow bandwidth.**

In order to locate leak with good accuracy in MDPE pipes, correlation process relies on estimation of the speed of sound in water/pipe and the time delay between leak signals measured at two locations across the pipes. The speed of sound can be calculated with good accuracy. However, the estimation of time delay depends upon the type, positioning of sensor and the processing of signals obtained; which is very difficult to do for MDPE pipes. Therefore in this paper, MDPE pipes are experimentally evaluated and it has been found that most of the leak signals for tested MDPE pipes lie in the frequency band of 20Hz to 250Hz, with the upper frequency limit changes with flow rate and leak characteristics. With these results, it is possible to achieve better performance of existing correlators by means of using appropriate filters and amplification.

Index Terms— **Correlators, Leakage, Leak detection, Leak Location, Medium Density Polyethylene Pipes and Water Shortage.**

I. Leaks and their Importance

Worldwide the shortage of drinking water is a subject of increasing concern. This is because of the increasing demand for water and decrease in water supplies. A partial solution to this problem can be obtained by controlling the amount of water loss in distribution networks. Water loss mainly occurs due to leakage in distribution networks. The volume of leaking water may constitute a significant portion of the water fed into the networks. For example in 1991, International Water Supply Association (IWSA) reported a water loss in between 20 to 30% of production, with leakage being the main component [1]. Leaks not only cause water loss but also pose a risk to public health; economical losses due to the high cost of energy wasted on the treatment and pumping action of leaking water [2], and risks to infrastructure such as building foundations and roads. Thus, water leakage reduction from distribution networks is a vital strategy in the improvement of sustainable use of water, the most fundamental of our natural resources.

Leak noise correlator (LNC) is the only credible option for detecting and locating leaks in these pipes. The advantages of LNC's over other leak detection methods have been appreciated and accepted within the UK water industry [3] and many other countries worldwide. In practice, LNC's are proved to be very efficient for metallic pipes. However, the same is not true for MDPE pipes where the attenuation rate with distance of the leak signal is very high and the generated leak signals are of low frequency and narrow bandwidth. Also in recent years, MDPE pipes are increasingly being used in water industries because of their inherent advantages such as long life, ease of handling and low cost over metallic pipes. Therefore, this paper primarily focuses on understanding the characteristics of leak signals in MDPE pipes, which are used to optimize the variables of leak noise correlators to aid leak detection and location in MDPE pipes.

II. Leak Detection and Location in MDPE pipes

A leaking water pipe generates noise (sound and vibration) which is transmitted for long distances both inside the pipe and in the soil close to the leak [4, 5]. The term "noise" in this paper refers to a combination of leak signals and ambient noise due to various sources. Acoustical devices such as hydrophones and mechanical vibrations measuring devices such as accelerometers are the most typical transducers used for measuring this noise. The signals from these transducers are normally analyzed using LNCs [4].

LNC equipment is based on the principle of cross-correlation of leak signals (Figure 1), obtained from the transducers/sensors connected to two known access points (such as fire hydrants) on either side of a leak and shows a distinct peak if a leak exists. To compute the leak location using correlation process, it will be assumed that the signals measured at the sensor positions 1 and 2 be $x_1(t)$ and $x_2(t)$ respectively. If the time taken by these leak signals to travel from leak position to sensor positions 1 and 2 be t_1 and t_2

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respectively, then the time delay (τ_{delay}) between two measured signals ($x_1(t)$ and $x_2(t)$) is related to location (L_1) of the leak from sensor 1 by

$$L_1 = (D - c\tau_{delay})/2 \tag{1}$$

where c is the propagation speed of sound in water pipe, L_2 is the corresponding leak position from sensor 2 and D is the total distance (L_1 + L_2) between two sensors. Propagation speed (c) depends upon pipe characteristics; however it can be estimated with good accuracy using various theoretical and practical methods. Time delay (τ_{delay}) is estimated using cross-correlation of measured leak signals. The quality of this estimate depends upon the type, positioning of sensors and the processing of signals obtained. Cross-correlation of two measured leak signals $x_1(t)$ and $x_2(t)$ is usually done in the frequency domain [6] for ease of calculations, by taking the inverse Fourier transform (Figure 2) of the product of complex conjugate of Fourier transform of measured leak signal $x_1(t)$ with the Fourier transform of leak signal $x_2(t)$ as

$$\hat{R}_{x_1x_2}(\tau) = \frac{1}{T}\int_{-\infty}^{\infty} X_1^*(f)X_2(f)e^{j2\pi f\tau}df \tag{2}$$

where * denotes the complex conjugate. In practise, due to the noise and attenuation of leak signals, the measured signals and their correlation function fluctuates. These fluctuations can sometimes be very large, making it difficult to identify the correlation peak responsible for leak signals. Therefore, the cross-correlation function ($\rho_{x_1x_2}(\tau)$) is expressed in normalized (dimensionless) form i.e. on the scale of -1 to 1, as:

$$\rho_{x_1x_2}(\tau) = \frac{\hat{R}_{x_1x_2}(\tau)}{\sqrt{\hat{R}_{x_1x_1}(0)\hat{R}_{x_2x_2}(0)}} \tag{3}$$

where $\hat{R}_{x_1x_1}(0)$ and $\hat{R}_{x_2x_2}(0)$ are the values of auto-correlation functions $\hat{R}_{x_1x_1}(\tau)$ and $\hat{R}_{x_2x_2}(\tau)$ at τ=0. In equation 2, the correlation function depends upon the frequency of input signals; thus an inappropriate filter range may lead to an error or false peaks. Therefore in current paper, the frequency and phase characteristics of leak signals in MDPE pipes are evaluated using experimental studies; which help to achieve better performance of existing LNC's in MDPE pipes by means of using appropriate filters and amplification.

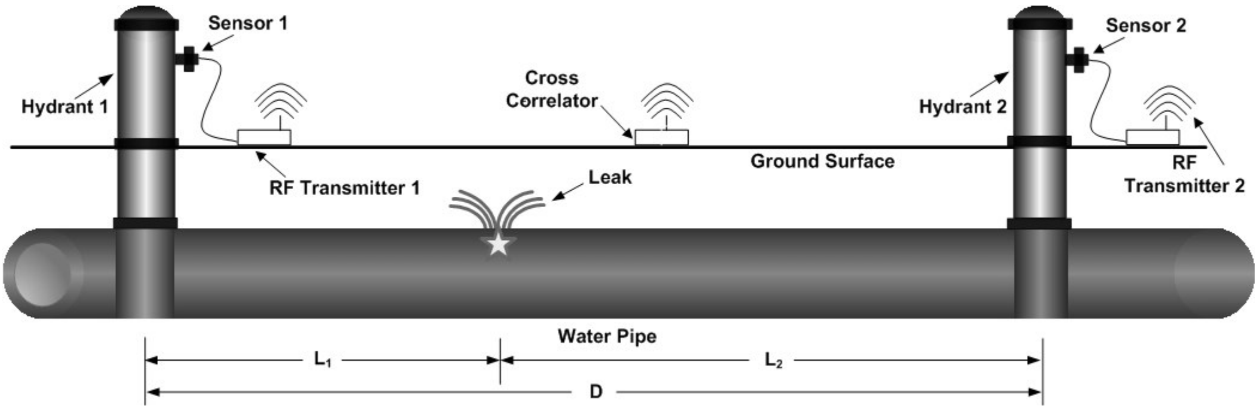

Figure1: Basic principle of cross-correlation for leak detection.

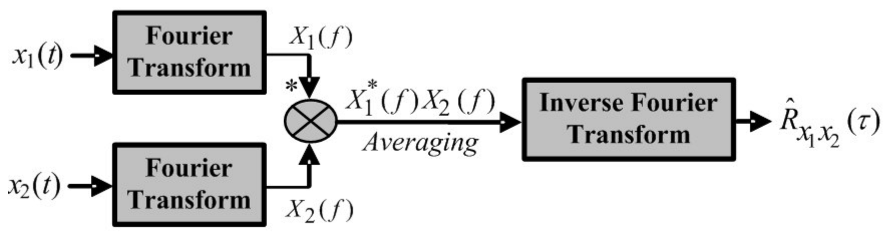

Figure 2: Schematic diagram of implementing cross-correlation of leak signals in frequency domain.

III. Experimental Studies

A. Test Set Up

The pilot study measurements were initially carried out on MDPE pipes in air under controlled laboratory conditions and are detailed by Pal et al. in [6]. This decision was made on the basis of studies done by Muggleton et al. [7], in which the effect of surrounding medium in buried plastic pipes on wavespeed was found to be relatively small. However in practise, the water pipes are buried; thus, to determine the effectiveness of the proposed cross-correlation method, a series of tests were conducted on buried MDPE pipe network at Severn Trent (ST) Lake House test site located in Anstey, Leicestershire, UK. The layout of the buried pipe network at Lake House is shown in Figure 3. The 90mm diameter MDPE main pipe (Figure 3) was 110.1m long with FH2 Type

Underground Fire Hydrant (DN80, PN16 Pressure Rating and BS 750 Type 2) connected at each end using flange fittings and a rubber gasket in between. Three 25mm diameter MDPE service pipes (SP1, SP2 and SP3) were connected to the main pipe at 23.4m, 51.8m and 90.5m respectively from the hydrant 1 position using electro-fused fittings and a boundary box. The other end of these service pipes were closed with a stop cap. A chamber measuring 1.2m long and 0.8m wide was made along the length of main pipe and a distance of 31.1m from hydrant 1 position; to simulate leaks in a section of 90mm diameter MDPE pipe measuring approximately 1.0m in length. This smaller section of pipe can be connected to the main pipe using couplers and/or flange plate couplings (BS404). This MDPE pipe section was used to make different types of defects and thus simulate different types of leaks in the 90mm diameter MDPE main pipe. The pipe network was connected to a water pump, which can provide water pressure up to 100kPa (10 bars).

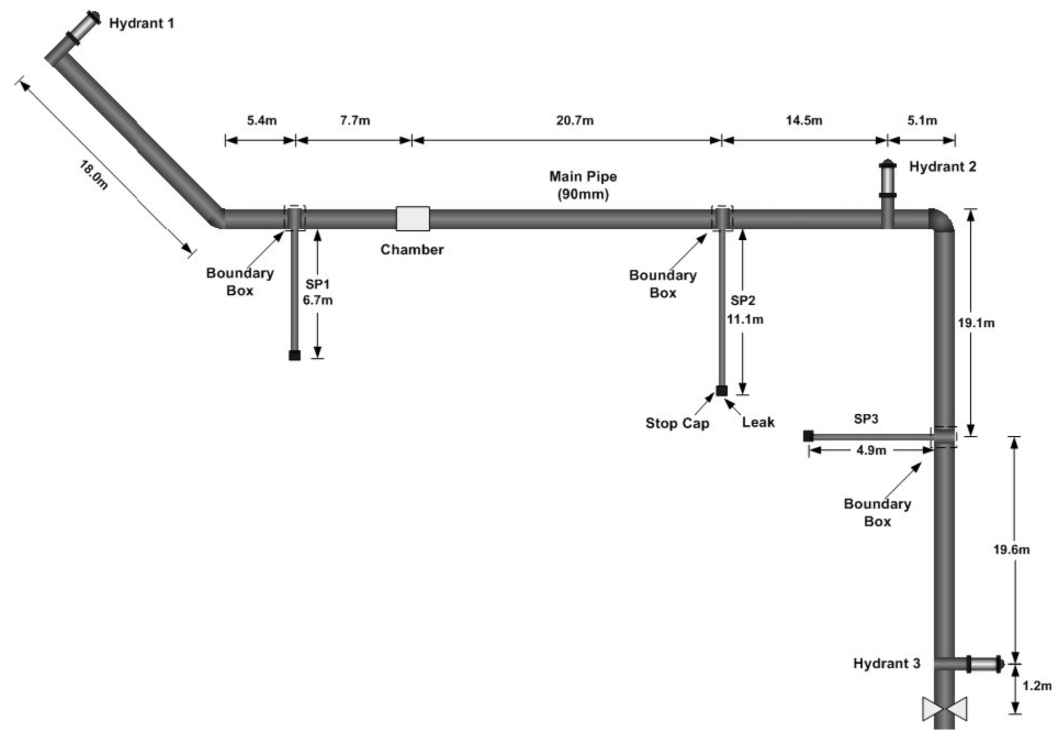

Figure 3: Schematic diagram of a test rig made up of 90mm diameter MDPE main pipe and 25mm diameter MDPE service pipe at Severn Trent Lake House, Anstey.

B. *Test Procedure*

Leaks with various shapes and sizes were simulated in the 90mm diameter pipe section fitted in the chamber; however, the results obtained from a typical leak shown in Figure 4 are discussed in this paper. The water pressure inside the pipe network was initially set to 300kPa. Signals were measured simultaneously from hydrants 1 & 2. Practically, the hydrophones are very difficult to deploy in water distribution pipes in UK; therefore, the tests were carried out with only accelerometers. A piezoelectric accelerometer having sensitivity 10V/g and frequency response 0.1Hz to 5 kHz was used to measure vibrations produced by leaks. A magnetic mounting was used to secure accelerometer firmly to hydrant (The frost valve of hydrant was closed with a plug, to avoid an additional source of leak). The output of accelerometers was amplified using pre-amplifiers with gain set to 28dB for this leak. The pre-amplifier features a transformer-balanced input and output to produce low-noise and low-distortion adjustable gain. These amplified leak signals were transmitted to the processing unit using a wireless transreceiver system, where these were digitised using a 12 bit analog to digital converter (NI DAQ-9221). The transreceiver system has the frequency response of 5 Hz to 18 kHz with signal-to-noise ratio >110 dB and a HDX compander to reduce the noise interference. These digital signals were recorded on the hard disk of a personal computer using NI data acquisition software (Labview Signal Express). The sampling rate was set to 2.5 kHz and the dynamic range to ±3V; in order to have a good resolution of signal. These digital signals were filtered using 7th order Bessel digital filter and spectral analysis was then performed on these filtered signals using 1024 points FFT, RMS averaging and a Hanning window for better frequency resolution. Bessel filter is a type of linear filter with a maximally flat group delay and linear phase response. It preserves the wave shape of filtered signals in the passband, so it is used for leak signal analysis.

IV. Results and Observations

A. *Frequency Response*

The leak signal spectrum obtained at hydrant 1 & 2 is shown in Figures 4(b) & 4(c) respectively and is divided into three sub-bands with leak signals mostly dominated by low frequencies in the band 20Hz to 250Hz. The main findings and observations are summarised in Table 1 and explained

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below:

- The frequency spectrum of most of the leak signals were found below 250Hz, with the high amplitude leak signals mostly concentrated in the narrow frequency range of 60Hz to 150Hz.
- The frequency range up to 20Hz corresponds to the longitudinal resonance frequency of the pipe as it was also seen in case of no leaks in pipe.

The results obtained are very much reproducible, i.e. when the sensors are removed and reconnected again, the frequency content is very much similar. It may be slightly different in some instances because of the variations in leak flow pattern, water flowing in the pipe, ambient noise as the signals are measured in audio range. However, performing averaging over time for say 10 to 15 window signals; results almost the same frequency spectrum.

TABLE 1: LEAK SIGNAL CHARACTERISTICS IN MDPE PIPES.

Frequency Band	**Signal Source/Comments**
DC to 20Hz	Longitudinal resonance frequency of pipe and ambient noise.
20Hz to 250Hz	Leak signals. Up to 100Hz is highly affected by ambient noise.
250Hz and above	Can have leak signals in this range depending upon characteristics of pipe and leak. Ambient noise due to the vehicular motions and running machinery.

The effect of various parameters on frequency spectrum of leak signals is discussed below:

1) **Effect of leak type:** Two leaks of different shapes & sizes were simulated in Figures 5 & 6. It can be noticed that variation in leak size and shape effect the frequency range of leak signals. The signals below approximately 20Hz are almost not affected, as these are dominated by the ambient noise and longitudinal resonance frequency of the test pipe. However, the second frequency band 20Hz to 250Hz, comprising actual leak signals, was found to be fluctuating by approximately $\pm$20Hz with variation in leak characteristics. The noise seen in the frequency spectra of signals could be attributed to several sources including longitudinal resonance of the water pipe and ambient noise. Therefore, the most significant frequency range is 20Hz to 270Hz and the frequency of leak signals fluctuates in this range for any variation in leaks studied in MDPE pipes.

2) **Effect of leak flow rate:** In Figure 5, the flow rate of leak was increased by increasing the size of leak. The flow meter was not installed on the test rig, so the accurate measurement of increase in flow rate is not known. For same pressure, it can be found that increase in flow rate increases the amplitude of leak signals; particularly the higher frequency content (between 60Hz to 120Hz in this case). This is because increase in flow rate increases the speed/energy with which the water exits the leak; which produces signals of comparatively higher amplitude. A little effect was noticed on signals below 20Hz, which are mostly dominated by resonance noise of pipe. However, this may not be true for very large size leaks, where the energy spreads over large area.

3) **Effect of pipe pressure:** In Figure 6, the pressure was increased to 820kPa. The high pressure leads to clearly audible and distinguishable leak signals; however, their frequency spectrum is similar to those at 300kPa and exists up to 250Hz. It is also noticed that increase in pressure has more effect on the amplitude of the higher frequencies (>=50Hz) of leak signals. This is because, for a fixed dimensional leak in a buried pipe, increasing the pressure causes the water exiting the leak at higher speed (higher flow rate), thus producing high amplitude leak signals.

B. *Phase of leak signals*

From the theoretical analysis of leak signals propagation in pipes done by Pal [8], the phase (ϕ) of leak signals varies linearly with angular frequency (ω) as

$$\phi = -\frac{\omega x}{c} \tag{4}$$

Where c is the speed of leak signals and x is the position of sensor relative to leak location. The phase-frequency relationship of leak signals generated by leak in Figure 4 is shown in Figure 7 and explained below:

- The phase is found to be varying nearly linear with the frequency. The small variation is due to the fact that all the measured signals may not be the leak signals but some is background noise.
- A slightly non-linear response is observed for signals below 20Hz. A similar irregular behaviour was also observed in their frequency spectrum, possibly due to the dominant low frequency pipe resonance and ambient noise.
- An approximately linear phase-frequency relationship was obtained for signals with frequency range 20Hz to 250Hz. The same is true with the frequency spectrum, where most of the leak signals were found in this range.
- In some cases, the line does not pass through the origin, possibly due to the dominant low frequency ambient and pipe noise.

In general, it can be concluded that for leak signals measured at Lake House, most significant phase information is concentrated between 20Hz to 250Hz.

C. *Cross-correlation of leak signals*

To perform the cross-correlation, the measured signals are filtered in the frequency range (20Hz to 270Hz) using the 7th order Bessel filter. The results obtained are shown in Figure 8, with which the performance of system is evaluated as follows:

1) **Leak detection:** In correlation method, a leak is detected if the cross-correlation function shows a distinct peak. In Figure 8, a distinct peak is obtained in the correlation function, which indicates that the system is capable of detecting single leak in MDPE pipes with up to 75m sensor spacings.

2) **Leak location:** The time delay between the signals measured at hydrants 1 & 2, calculated from Figure 9 is 0.0158sec. For the standard velocity (used by most commercial correlators in water industry) of leak signals in 90mm diameter MDPE pipe as 325m/s and the total distance

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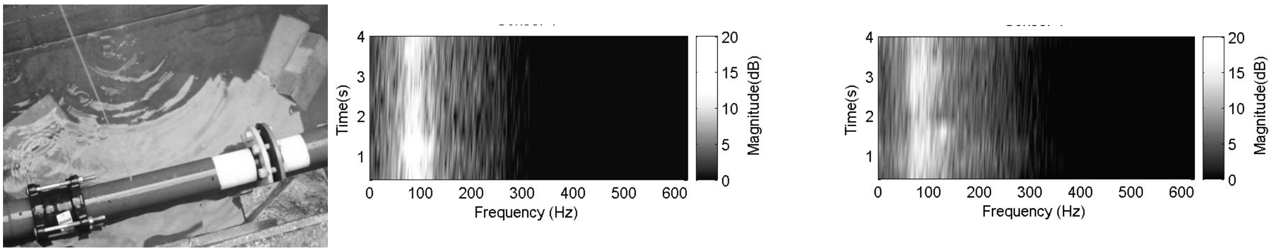
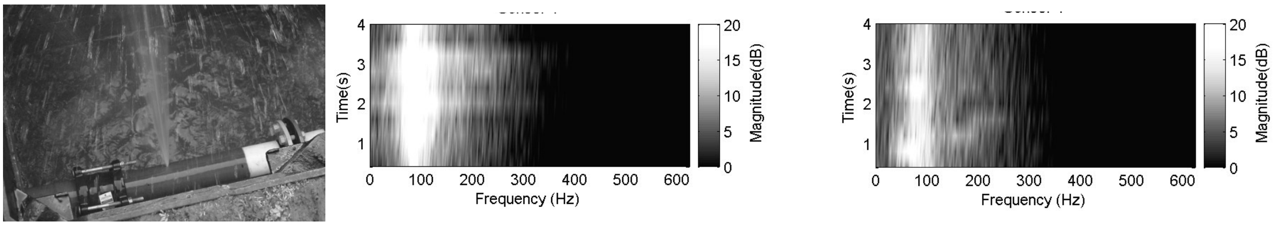
between the hydrant 1 & 2 as 66.3m, the position of leak relative to hydrant 1 calculated using the cross-correlation method is 30.58m. Practically, the leak was approximately 30.8m from the hydrant 1, which gives an error between the true distance and the calculated value of 0.22m. This error is practically acceptable in the water industry, thus the specified system is capable of locating leaks in MDPE pipes.



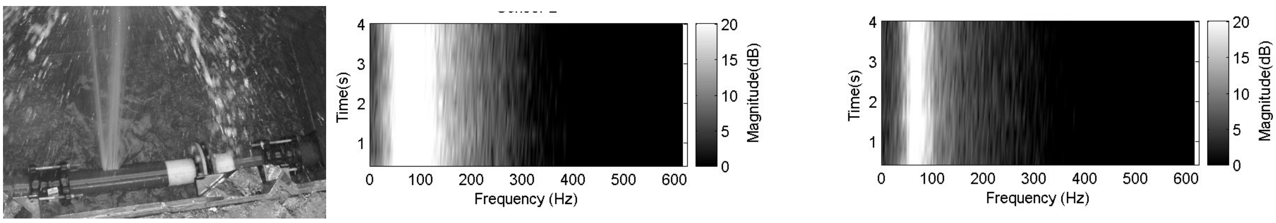
(a) 1mm hole in pipe (b) Frequency Spectrum (Hydrant 1) (c) Frequency Spectrum (Hydrant 2)

Figure 5: (a) A typical simulated leak in 90mm diameter pipe section; Frequency spectrum of signals measured at (b) hydrant 1 and (c) hydrant 2.



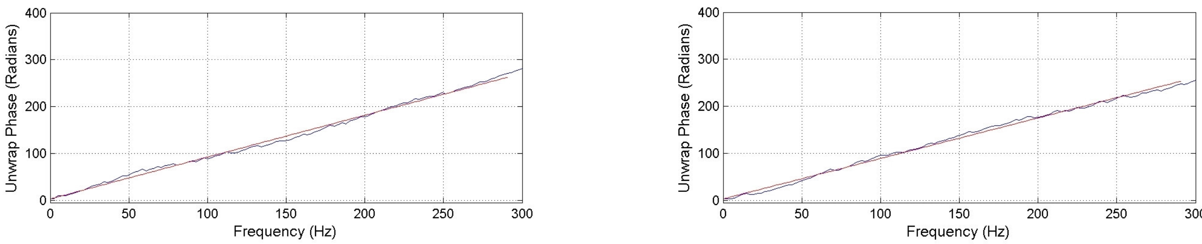
(a) Increase in flow rate (b) Frequency Spectrum (Hydrant 1) © Frequency Spectrum (Hydrant 2)

Figure 6: (a) The flow rate is increased by increasing the size of leak; Frequency spectrum of signals measured at (b) hydrant 1 and (c) hydrant 2.



(a) Increase in pressure and size of leak (b) Frequency Spectrum (Hydrant 1) (c) Frequency Spectrum (Hydrant 2)

Figure 7: (a) The size of leak is increased in longitudinal direction and the pressure is increased to 820kPa; Frequency spectrum of signals measured at (b) hydrant 1 and (c) hydrant 2.



(a) Phase-frequency relationship (Hydrant 1) (b) Phase-frequency relationship (Hydrant 2)

Figure 8: Phase-frequency relationship of leak signals generated by leak in Figure 5 and measured from (a) hydrant 1 and (b) hydrant 2.

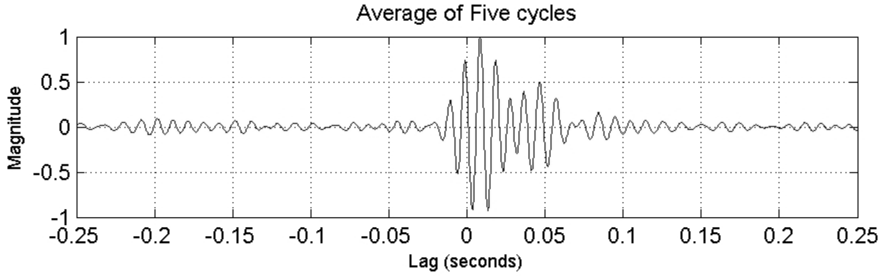


Figure 9: Cross-correlation of leak signals generated by leak in Figure 5 and measured from hydrant 1 & 2.

V. CONCLUSION

In this paper, the characteristics of leak signals in MDPE pipes are discussed. It has been found from the experimental results that most of the leak signals in buried MDPE pipes exist in the frequency range 20Hz to 250Hz, which drifts with changing flow rate and leak characteristics such as shape & size. For this frequency range, the phase of leak signals was found to be nearly linearly varying with frequency. Therefore, when using LNC in leak detection mode on MDPE pipes, a filter range of 40Hz to 250Hz and a long time averaging is recommended to reduce the effect of ambient noise. In survey mode, filters range of 20Hz to 450Hz are advisable as this may help in providing information on leak flow rate. The effectiveness of the proposed method is assessed for the MDPE pipes at ST Lake House. The simulated leak signals were found to be highly attenuated at hydrant 1 and 2. Even in these circumstances the proposed method enables the determination of leak location using leak signals in water-filled MDPE pipes within the frequency range 20Hz to 250Hz. Further studies are in progress to investigate factors influencing generated signals in MDPE pipes.

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