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Experimental investigation into vibro-acoustic emission signal processing techniques to quantify leak flow rate in plastic water distribution pipes

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ABSTRACT

Leakage from water distribution pipes is a problem worldwide, and are commonly detected using the Vibro-Acoustic Emission (VAE) produced by the leak. The ability to quantify leak flow rate using VAE would have economic and operational benefits. However the complex interaction between variables and the leak's VAE signal make classification of leak flow rate difficult and therefore there has been a lack of research in this area. The aim of this study is to use VAE monitoring to investigate signal processing techniques that quantify leak flow rate. A number of alternative signal processing techniques are deployed and evaluated, including VAE counts, signal Root Mean Square (RMS), peak in magnitude of the power spectral density and octave banding. A strong correlation between the leak flow rate and signal RMS was found which allowed for the development of a flow prediction model. The flow prediction model was also applied to two other media types representing buried water pipes and it was found that the surrounding media had a strong influence on the VAE signal which reduced the accuracy of flow classification. A further model was developed for buried pipes, and was found to yield good leak flow quantification using VAE. This paper therefore presents a useful method for water companies to prioritise maintenance and repair of leaks on water distribution pipes.

1. Introduction

1.1. Leaks in water distribution systems

Leakage from water distribution systems (WDS) leads to a substantial loss of water, which can have high negative environmental and economic effects [1]. Typically, 20–30% of water pumped into the pipe network is lost through leakage, and can be as high as 50% in developing countries and older distribution networks [2,3]. This loss of water represents a substantial amount of energy loss, as pumping and treating water has been reported to use between 2 and 3% of the worlds energy consumption [4]. In the UK, leakage alone has been estimated to cost the government £7bn annually in street works, as well as further social and damage costs [5]. Typically, hydrophones or accelerometers are placed at some distance either side of a leak (Fig. 1) and the leak's location is found using Eq. (1):

$$L_1 = \frac{d - c\tau_{delay}}{2} \quad (1)$$

where d describes the distance between two accelerometers or hydrophones and c is the wavespeed of the leak noise on the pipe wall. τ_{delay} is the difference in signal arrival time between accelerometer 1 and 2, which is calculated from the peak in the cross correlation function.

The two accelerometers receive two inputs in the form of vibration, $x_1(t)$ and $x_2(t)$. It is possible to model the leak signal (S) and the background noise ($n_1(t)$ and $n_2(t)$) for accelerometer 1 (x_1) and accelerometer 2 (x_2) as:

$$x_1(t) = S(t - \tau_1) + n_1(t), \; x_2(t) = S(t - \tau_2) + n_2(t). \quad (2)$$

where τ_1 and τ_2 describe the travel time of the leak signal arriving at both accelerometers. The majority of leak acoustic modelling studies represent background noise as Gaussian and uncorrelated between sensors (see Gao et al. [6] for example) therefore the peak

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Nomenclature

τ_{delay}	difference in signal arrival time between accelerometer 1 & 2 (s)	q	leak flow rate (l/min)
$x_1(t), x_2(t)$	VAE signals at accelerometer 1 & 2	C_d	discharge coefficient
d	distance between accelerometer 1 & 2 (m)	g	acceleration due to gravity (m/s^2)
c	wavespeed of propagating acoustic signal (m/s)	h	head (m)
L_1, L_2	distance between leak and accelerometers (m)	α	exponent due to discharge
$R_{x_1x_2}$	cross correlation between leak signals	$X[k]$	discrete Fourier Transform
$E[\cdot]$	expectation operator	C	leakage coefficient

in the cross correlation represents the leak. The cross correlation of the signals is described by:

$$R_{x_1x_2} = E[x_1(t)x_2(t + \tau_{delay})], \tag{3}$$

where $E[\cdot]$ is the expectation operator and τ_{delay} describes the lag in time between both received signals. τ_{delay} is given as:

$$\tau_{delay} = \tau_2 - \tau_1. \tag{4}$$

where τ_1 and τ_2 describes the arrival time at accelerometer 1 and 2 respectively.

A number of variables have been reported to influence the leak's VAE signal received by the accelerometers, including pressure [7], flow rate [7,8], surrounding media [9], pipe material and pipe diameter [10]. Leak signals do not propagate long distances along plastic compared to metallic pipe. This is due to the viscoelastic nature of the material causing damping in the pipe wall [3], and higher frequencies tend to be attenuated or filtered as the plastic pipe acts as a low pass filter [11]. The propagation of waves in plastic pipes has been discussed elsewhere, for example Pinnington and Briscoe [12].

VAE still remains the most common method of leak detection in the UK and despite the ongoing research in improving the accuracy and capability of leak detection systems, the ability to classify a leak's flow rate accurately using VAE is still not yet possible. The lack of research into the quantification of leak flow rate on WDS is likely due to the complex nature of variables influencing the leak signal; yet the accurate quantification of leak flow rate using VAE would provide an excellent tool allowing water suppliers to prioritise maintenance thereby saving water and costs. The overall aim of this research therefore is to investigate signal processing methods to classify leak flow rate on plastic water distribution pipes using VAE.

1.2. Relationship between acoustic emission and leak flow rate

Increasing WDS pressure has been demonstrated to increase leak flow rate [13], and this in turn has shown to increase the amplitude of the VAE leak signal [7,8] as well as providing a more defined peak in the cross correlation [14]. This agrees with theory that for fixed sized leaks, higher pressure results in a higher leak signal amplitude due to increased leak flow rate [15]. Similarly, Papastefanou [16] and Pal et al. [8] demonstrated increasing signal amplitude with increasing pressure due to the strong influence of leak flow rate. Pal et al. [8] also found leak flow rate increased leak VAE frequency. Papastefanou [16] established an empirical relationship between leak size, amplitude and leak flow rate and continued to comment that it is easier to detect leaks of a higher flow rate compared to those at lower flow rates. A study by Humphrey [14] investigated the influence of leak flow rate on correlation performance, finding that leaks with flow rates of 0.5 m^3/h at a distance of 186 m from the leak had a low success rate in detection, whereas leaks at higher flow rates of 1 m^3/h at the same distance were detected more successfully. However, increasing the leak flow rate to 1.5 m^3/h and increasing the measurement distance to 316 m did not produce any successful correlations [14]. The information from the literature indicates that increasing the leak's flow rate is likely to result in an increase in leak amplitude, and it therefore seems logical to use signal parameters that will describe leak energy in order to quantify leak flow rate.

Traditionally, leak flow rate (q) has been shown to be sensitive to pressure through the orifice equation [17]:

$$q = C_d A\sqrt{2gh} \tag{5}$$

where g is acceleration due to gravity, C_d is the discharge coefficient, hole area (A), pressure head (h) and q is the flow rate through the leak. The equation can be simplified for the application of water distribution pipes and can be written as [17]:

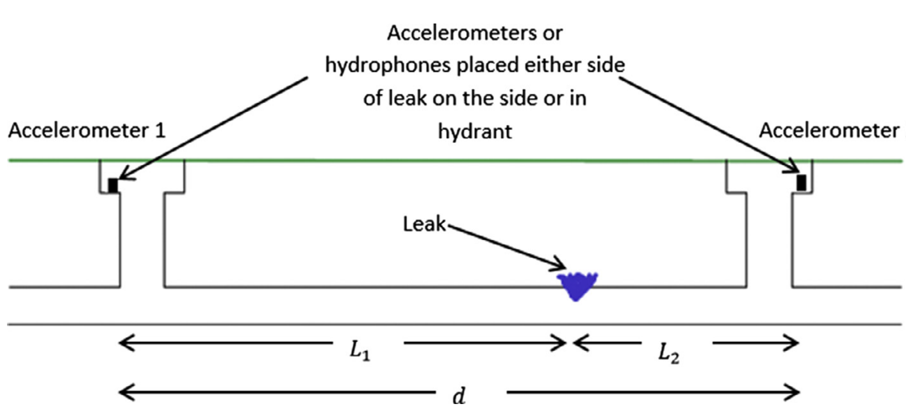

Fig. 1. Leak location schematic.