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Towards an in-situ measurement of wave velocity in buried plastic water distribution pipes for the purposes of leak location

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ABSTRACT

Water companies are under constant pressure to ensure that water leakage is kept to a minimum. Leak noise correlators are often used to help find and locate leaks. These devices correlate acoustic or vibration signals from sensors which are placed either side the location of a suspected leak. The peak in the cross-correlation function of the measured signals gives the time difference between the arrival times of the leak noise at the sensors. To convert the time delay into a distance, the speed at which the leak noise propagates along the pipe (wave-speed) needs to be known. Often, this is estimated from historical wave-speed data measured on other pipes obtained at various times and under various conditions, or it is estimated from tables which are calculated using simple formula. Usually, the wave-speed is not measured directly at the time of the correlation measurement and is therefore potentially a source of significant error in the localisation of the leak. In this paper, a new method of measuring the wave-speed in-situ in the presence of a leak, that is robust and simple, is explored. Experiments were conducted on a bespoke large scale buried pipe test-rig, in which a leak was also induced in the pipe between the measurement positions to simulate a condition that is likely to occur in practice. It is shown that even in conditions where the signal to noise ratio is very poor, the wave-speed estimate calculated using the new method is less than 5% different from the best estimate of 387 m s^{-1}.

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1. Introduction

Buried water distribution systems are susceptible to leakage through defective joints, or split pipes because of ground movement due to seasonal changes. To repair these pipes, holes have to be dug which is both costly [1] and inconvenient. It is estimated that 40–50% of drinking water is wasted through leakage in developing countries, and less than 10% is wasted in countries where the utilities are well-kept, such as Japan [2,3]. Globally, water companies have been investigating ways to reduce this level of wastage.

To determine if a leak is present in a specific region of the network, pressure measurements together with flow measurements are used [4]. To determine the exact location of a leak, at least to within a certain tolerance, leak noise correlators are in common use, and have been used for more than 30 years [5]. These devices calculate cross-correlation functions between two leak noise signals (acceleration, pressure or velocity) acquired at two different positions (generally hydrants) on the pipe, which are then used to detect and locate a leak based on the peak in the correlation function. Although correlators work well for metallic pipes [6,7], their performance on plastic pipes is more limited. The two main factors that affect correlator performance in this case, are the relatively high rates of attenuation experienced by waves propagating along the pipes due to damping in the pipe-wall, and the variability in the speed at which they propagate along the pipe. The wave-speed is heavily influenced by the pipe properties, such as the pipe radius and wall thickness, and Young's modulus of the pipe wall material [8,9]. The accuracy with which the leak can be located is therefore directly linked to the accuracy with which the wave-speed is known. For maximum accuracy, the wave-speed should be measured in-situ on the section of pipe in which there is a leak, at the same time as the correlation measurement is made. In nearly all cases, however, the wave-speed is estimated from a historical database determined from calculations made using assumed material properties and pipe geometry. Wavespeeds are rarely measured at the time of the correlation measurement because of practical difficulties and the time needed to make the measurement.

In buried plastic water pipes the leak propagates generally at low frequencies, mainly below 200 Hz, because of the high levels of damping in the pipe-wall, and the radial motion of the pipe-wall due to the high degree of coupling between the fluid and the pipe [10]. Hence only low-frequency waves located well below the ring frequency propagate for long distances in the pipe. The ring frequency, which occurs when the quasi-longitudinal wavelength in the pipe-wall equals the circumference of the pipe, separates two frequency regions. Below this frequency the dominant stiffness mechanism is associated with membrane stiffness of the pipe, and hence the wave is non-dispersive in this frequency region. Above the ring frequency the dominant stiffness mechansim is associated with the bending stiffness of the pipe-wall and hence the wave is dispersive in this frequency region [11]. Thus the wave responsible for leak noise propagation in plastic pipes is non-dispersive. As this wave is a combined structural-acoustic wave, then either hydrophones can be used to sense the wave in the water, or structural sensors (geophones or accelerometers) can be used [12,13]. Moreover, because of the strong coupling between the water and the pipe-wall the wave can be excited by a structural actuator attached to a pipe fitting, such as a fire hydrant.

This paper presents a robust and simple method of estimating the wave-speed in a buried plastic pipe, that can be implemented in the presence of a leak. The measurement method is illustrated by its application to measurements made on a full-scale buried pipe rig. The work presented here should be seen as the basis for the development of a practical system rather than the description of a tailor made system that could be implemented immediately. In this work, electro-dynamic shakers are used to excite the pipe, but other types of excitation methods may be more appropriate in a practical system, such as an impacting system, that can work without a power amplifier. The pipe response at a number of junctions is measured using accelerometers. Based on the work of Gao et al. [14], an analytical model of the cross-correlation function is used to investigate numerically the new method of wave-speed estimation, which is subsequently applied to experimental data. Data were collected under a wide-range of conditions such as differing shaker strengths and with a leak of varying severity located between the measurement positions.

2. An overview of leak detection using acoustic correlation

A typical situation where noise from a leak is used to detect and locate its position is shown in Fig. 1. Acoustic or vibration sensors are attached to access points, which are typically hydrants or valves, on either side of the suspected leak position. The actuators shown in the figure are not normally used in the field for leak detection, but are used in this work to measure the speed of the wave responsible for leak noise propagation. Further details about the test-rig are given in Section 4.

In Fig. 1, the leak position d_1 from the left-hand sensor is given by [14]

$$d_1 = \frac{d - cT_0}{2}, \tag{1}$$

where c is the speed of propagation of the leak noise, $d = d_1 + d_2$ is the total distance between the sensors, and $T_0 = (d_1 - d_2)/c$ is the difference in arrival times of the leak noise at the sensor positions (time delay). It has been found in practice that the wave which carries the leak noise in plastic pipes is predominantly a fluid-wave that is strongly coupled to the radial motion of the pipe-wall [10,15]. Because the flow speed of the water in the pipe is much less than the speed of the leak noise, it has a negligible effect [16], so the wave-speed in one direction should, in principle, be similar to the wave-speed in the other direction.

The most widely used technique to determine the time delay between signals uses the correlation function $R_{12}(\tau)$ between the two measured signals $x_1(t)$ and $x_2(t)$ as shown in Fig. 1 [7]. The presence of a leak appears as a distinct peak in