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Theoretical and experimental investigation into structural and fluid motions at low frequencies in water distribution pipes

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ABSTRACT

Vibrational energy is transmitted in buried fluid-filled pipes in a variety of wave types. Axisymmetric ($n = 0$) waves are of practical interest in the application of acoustic techniques for the detection of leaks in underground pipelines. At low frequencies $n = 0$ waves propagate longitudinally as fluid-dominated ($s = 1$) and shell-dominated ($s = 2$) waves. Whilst sensors such as hydrophones and accelerometers are commonly used to detect leaks in water distribution pipes, the mechanism governing the structural and fluid motions is not well documented. In this paper, the low-frequency behaviour of the pipe wall and the contained fluid is investigated. For most practical pipework systems, these two waves are strongly coupled; in this circumstance the ratios of the radial pipe wall displacements along with the internal pressures associated with these two wave types are obtained.

Numerical examples show the relative insensitivity of the structural and fluid motions to the $s = 2$ wave for both metallic and plastic pipes buried in two typical soils. It is also demonstrated that although both acoustic and vibration sensors at the same location provide the identical phase information of the transmitted signals, pressure responses have significantly higher levels than acceleration responses, and thus hydrophones are better suited in a low signal-to-noise ratio (SNR) environment. This is supported by experimental work carried out at a leak detection facility. Additional pressure measurements involved excitation of the fluid and the pipe fitting (hydrant) on a dedicated water pipe. This work demonstrates that the $s = 1$ wave is mainly responsible for the structural and fluid motions at low frequencies in water distribution pipes as a result of water leakage and direct pipe excitation.

1. Introduction

Pipelines are the most economic and safest mode of transportation for fluid and gases in a wide range of practical engineering environments. Whilst they are designed and constructed to fulfill high demands of safety and reliability, it is difficult to avoid the occurrence of leakage resulting from sudden changes in pressure, corrosion, cracks, material defects, ground movement due to seasonal changes, or even poor workmanship. Pipeline leakage has been a major concern due to the

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significant environmental damage and economic losses. For example, every day, huge amount of clean, treated water is lost through leakage from water supply networks [1,2]; explosions caused by leaking oil and gases from underground piping systems have frequently made headlines in recent years. A variety of techniques have been developed for the detection and location of pipeline leakage in recent years [3–7]. Up to date, there is not yet an approach that can efficiently detect leaks in any of these pipe systems.

Acoustic techniques have proven to be effective and are widely used to locate leaks in water distribution pipes in many years [8–11]. It is believed that leak noise is concentrated at low frequencies, in particular in plastic water distribution pipes [12–16], although acoustic emission sensors have been attempted to acquire high-frequency leak signals up to 100–300 kHz [17,18]. In general, the upper frequency limit of measured leak noise is found to be 1 kHz for metal pipes and only 200 Hz for plastic pipes. Other non-acoustic techniques, such as hydraulic methods [19], ground-penetrating radar, tracer gas and magnetic fields [20] have also been investigated for the application of water leak detection.

For acoustic leak detection techniques, most of the methods and equipments proposed are based on the vibro-acoustic measurements in water distribution pipes. Water escaping from pressurised pipes generates leak noise that travels by two roots, including through the soil to the ground surface, and in the pipe wall and the water. Correspondingly, practice leak detection surveys are commonly performed by utilizing equipments based on vibro-acoustic sensors, such as listening devices above ground, namely geophones and listening rods, and hydrophones or accelerometers at two access points such as hydrants and valves. With the latter, leak signals are then transmitted to the leak noise correlator to pinpoint a suspected leak. Acoustic methods based on cross-correlation provide a powerful solution for locating leaks, even where there is substantial background noise or only the quietest of leak noise is present.

Leak noise travels in both directions away from the leak through the pipe wall (as minute vibrations) and through the water column (as a pressure wave). In the "classic" correlation process, two accelerometers are attached magnetically to access points on pipe fittings (i.e., "dry" connection) bridging the suspected leak on the water main. In difficult situations such as for the pipe being plastic, with large diameter and large burial depth, "wet" connection may be adopted (optionally) using hydrophones connected to hydrants. For these methods to be effective, the propagation wavespeed need to be know *a priori*. Plastic pipes have proven to be problematic due to the uncertainty in the propagation wavespeed and large wave attenuation. Previous work by Gao et al. [12–14] has shown that the cross-correlation methods are most successfully conducted on low frequency leak signals resulting from an approximately non-dispersive propagating wave.

The way in which vibration and waves propagate in fluid-filled pipes *in vacuo* has been discussed previously [21–23]. Fuller and Fahy [21] derived the wavenumbers for fluid-filled pipes defined as "hard" and "soft" shells. Fuller [22] further investigated theoretically the energy distribution among various wave types for a radial wall input force and for internal pressure pulsations. Pinnington and Briscoe [23] introduced an external circumferential piezoelectric transducer to detect the radial wall motion of a fluid-filled pipe. It has been shown for a multiple jointed pipe system with fluid and pipe wall excitations, two axisymmetric ($n = 0$) wave types are excited, including a predominantly fluid-dominated ($s = 1$) wave and a predominantly shell-dominated ($s = 2$) wave. These two waves are primarily longitudinal involving both structural and fluid motions, and the strength of coupling between these motions is governed by the pipe's dimensions and physical properties. The $s = 1$ wave is predominantly fluid-based with some radial shell motion associated with the shell compliance, and the $s = 2$ wave is predominantly a compressional wave in the shell with some associated radial wall motion influenced by Poisson's ratio and fluid loading. Since the $s = 1, 2$ waves are strongly coupled, even pure pressure or pipe wall excitations will lead to both structure and fluid motions.

Substantial research [23–26] has involved modelling of the $s = 1, 2$ wavenumbers, together with experimental investigations of the $s = 1$ wave that propagates in a fluid-filled pipe. Pinnington and Briscoe [23] first derived the analytical solutions to the wavenumbers for a fluid-filled pipe *in vacuo* and calculated the relative sizes of the two wave types for various boundary conditions in soft and hard-walled pipes. Muggleton *et al.* [24] derived the wavenumber expressions for a buried fluid-filled pipe under lubricated contact, in which the frictional stress is presumed to be zero at the pipe-soil interface. For leak detection in buried pipes, however, the relative motion of the pipe and soil is unlikely to occur. Therefore, the pipe is more appropriate to be assumed to be in perfect contact with the surrounding soil, for which displacement continuity conditions are fully satisfied. Gao *et al.* [25] have recently developed an analytical method for investigating the coupled equations of $n = 0$ motion in a buried fluid-filled pipe. Furthermore, an expression for the $s = 1$ wavenumber has been found and validated by some wavenumber measurements made on a buried MDPE water pipe [26].

Although it is believed that the $s = 1$ wave carries most of the acoustic energy at low frequencies in water distribution pipes, the contributions associated with the two wave types have not been well documented. A comprehensive analysis of the fully coupled system would be extremely complex and beyond the scope of the present paper. An approximate method is now adopted to quantify the contributions of the $s = 1, 2$ waves to the internal pressure and the radial pipe wall displacement, which is a similar approach to that taken by Pinnington and Briscoe [23]. This enables better understanding of the transducer sensitivities to these two waves. It builds on the coupled equations of motion given recently by the authors [25], which are solved for $s = 1, 2$ wavenumbers. Here, the results for the $s = 1$ wave are reproduced briefly for completeness. Ratios of the pipe wall displacements along with the internal pressures associated with these two waves are subsequently derived. Numerical analysis is then performed for both a metal and plastic water pipes. To support the theoretical analysis, measurements made from two buried water pipe systems are presented.