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Technical Note

The design and instrumentation of an experimental rig to investigate acoustic methods for the detection and location of underground piping systems

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Abstract

A major UK initiative, entitled 'Mapping the Underworld', is seeking to improve our capability of locating buried utility service infrastructure without resorting to extensive excavations. One of the four projects aims to develop and prove the efficacy of a multi-sensor device for remote buried utility service detection, location and, where possible, identification. An essential technology to be combined into the device is low-frequency acoustics, and suitable techniques for detecting buried infrastructure, in particular buried plastic water pipes, have been proposed. In order to develop and test these techniques, an experimental rig has been built. It is the design and instrumentation of this rig along with the rationale for the chosen design which is the main focus of this paper. Preliminary measurements have been made on the rig, to determine the most appropriate acoustic excitation method and to confirm that the rig is behaving as anticipated. The results of these investigations are also reported.

Keywords: Buried pipes; Fluid-filled; Measurements; Location; Axisymmetric wave

1. Introduction

The problems associated with inaccurate location of buried pipes and cables have been serious for many years and are getting worse as a result of increasing traffic congestion in the UK's major urban areas. The problems primarily derive from the fact that the vast majority of the buried utility infrastructure exists beneath roads and therefore any excavation is likely to disrupt the traffic. The social costs of this type of congestion in the UK, for example, are estimated to be between £2 and £4 billion per annum.

The location techniques that are currently commercially available are either simple (yet strictly limited in their ability to detect the wide variety of utilities) and carried out immediately prior to excavation by site operatives or are more sophisticated and carried out by specialist contractors. Controlled trials carried out by UK Water Industry Research have shown that, even when sophisticated detection techniques are employed, detection rates are often very poor [1] and, as a result, far more excavations are carried out than would otherwise be necessary for maintenance and repair. While a variety of techniques using different technologies are available, all suffer from the same essential drawback that, when deployed alone, they will not provide an adequate solution to the problem; moreover, all have their own specific limitations.

In response to this, a large multi-centre programme, Mapping the Underworld [2], is being undertaken in the UK to assess the feasibility of a range of potential technologies that can be combined into a single device to accurately locate buried pipes and cables. The potential technologies include ground penetrating radar, low-frequency

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quasi-static electromagnetic fields and acoustics. As part of the acoustics package, enhancements to the existing techniques for locating buried piping systems have been proposed and an experimental programme has been planned. To carry out this part of the programme, a dedicated experimental rig has been designed and built so that appropriate measurements can be made. It is the design and instrumentation of this rig which is the main focus of this paper. A number of preliminary measurements have been made on the rig, to establish the most appropriate excitation method, and to ensure that the intended wavetype is excited preferentially.

The structure of this paper is organized as follows: first, a short review of the state of the art in acoustic detection is given, and the main limitations highlighted; second the proposed improvements are briefly described and a detailed description of the design and instrumentation of the experimental rig is presented, along with the rationale for the choices made; finally, the results from the preliminary measurements, confirming the expected pipe behaviour, are shown.

Fig. 1. Listening rod with audio output.

2. State of the art in acoustic detection

The state of the art in acoustic detection of buried infrastructure is limited and not well advanced. As metallic structures can be relatively easily located using other technologies, the focus for acoustic detection has been on plastic pipes, in particular plastic water pipes. A full review of the current possibilities using any of the proposed technologies is given in [3]; here, the focus is on acoustics.

The current acoustics approach has its origins in water leak detection, and is set very much in the same empirical tradition, in which the understanding of the underlying physics is, at best, often limited. Historically, water leaks have been detected using a listening rod in contact with the ground in the vicinity of the leak; the leak noise propagates through the soil to the ground surface where it can be picked up by the human ear at the end of the listening rod. Currently available acoustic pipe location systems operate on this same principle that acoustic signals in the pipe will propagate to the ground surface where they can be detected and the location of the pipe inferred. In this case, however, the acoustic signal is not a leak, but is injected into the pipe deliberately by some means at a known location, for example, using a ‘chatter’ valve [4] or a single frequency tone [5]; the excitation frequency is sometimes tuned to exploit possible resonant behaviour in the pipe, and again this is determined empirically. The signal is detected at the ground surface using an electronic ‘listening rod’, consisting of a single transducer at the end of a rod (see Fig. 1) in which the acoustic signal can be heard via headphones, and seen on a simple amplitude meter. The listening rod is gradually moved away from the sound source, following local maxima in signal strength; it is assumed that the run of the pipe lies directly below this path.

2.1. Performance and limitations

Reports on the performance of the systems described above vary, but a few themes tend to recur.

The type of soil in which the pipework is buried significantly affects the performance of the systems. Whether the soil is wet, dry, sandy or clay, affects the propagation of the acoustic signal to the ground surface. Pipes laid under hard surfaces (e.g., concrete) tend to be particularly difficult to locate. This is in accordance with the results from modelling work undertaken by the authors of this paper [6] which concluded that in some soils, although the energy propagates well within the piping system itself, it does not radiate effectively into the surrounding ground. Furthermore, if the soil type changes, problems have also been reported as the signals at the ground surface tend to disappear. In this case, as the pipe and surrounding medium are likely to be well coupled, discontinuities in the soil will result in the waves in the pipe being reflected back towards the vibration source [7], thus permitting less energy to propagate further along the pipe.

The presence of tree roots, rocks and other pipes in the vicinity have also been found to cause difficulties, as these present alternative, well coupled, paths along which the sound can travel. Bends in the pipework also can pose a problem for pipe location.

Under ideal conditions (no road traffic noise, pipe depth <0.5 m, straight pipe) it may be possible to follow a pipe for up to 100 m, but a more typical range would be around 10 m, and possibly even less. When the authors of this paper used one of the above systems in a blindfold test, they found it possible to locate the source of the sound using the listening rod, but not to follow the run of the pipe at all.

2.2. Potential advances

Whilst little can be done to alter the way in which acoustic energy propagates along pipework (both in the water within the pipe and in the pipe structure), into to the surrounding soil, and up to the ground surface, as this depends on the basic physics of the pipe/soil system, there is much which can be done to enhance the basic system described above.

Attention to the type of excitation (both in terms of mechanics and signal content) will allow the maximum energy to be transmitted into the pipe system in the first place. Knowledge of the dominant mode of propagation for any particular form of excitation is crucial in this selection process. Moreover, the appropriate frequency or frequency band can be chosen to permit good propagation along the pipework.

Current detection systems employ only one ground vibration sensor, and only the amplitude information is taken into account. It is likely that much more information can be gleaned both by using an array of sensors and, at the very least, taking account of the phase information in the measured signals. Moreover, signal processing techniques offer the possibility of extracting useful information from potentially noisy and contaminated data.

3. Experimental rig design and installation

To test the feasibility of the two approaches, an experimental rig was designed and installed at Southampton University. The rig consists of an ~18 m length of MDPE water pipe (180 mm OD) buried to a depth of ~1–1.25 m (the standard burial depth for mains water pipes in the UK). A right-angled bend brings the pipe up to the ground surface at one end, and a man-hole provides access at the other. This allows direct access to the pipe at either end of the rig, and hence the possibility of excitation at each end. Flanged pipe ends enable each end to either be sealed with a blanking plate as required, or used as the excitation site.

At low frequencies, well below the pipe ring frequency (in this case for frequencies up to at least 1 kHz), four wavetypes will, in general, be responsible for most of the energy transfer along the pipe [8,9]: three axisymmetric waves ($n = 0$) and the $n = 1$ wave related to beam bending. Of the $n = 0$ waves, the first, termed $s = 1$, is a predominantly fluid-borne wave; the second, $s = 2$ is a predominantly compressional wave in the pipe wall; the third wave, $s = 0$, is a torsional wave uncoupled from the fluid. For axisymmetric excitation, for a system in which the pipe wall and the contained fluid are well coupled (as is the case here), whether it is the pipe wall that is excited or whether it is directly the fluid, the $n = 0$, $s = 1$, predominantly fluid-borne wave will dominate, and carry most of the energy [8]. Even for non-axisymmetric excitation, in the case of a water leak in a plastic water pipe, for example, much of the leak noise is carried by this wave.

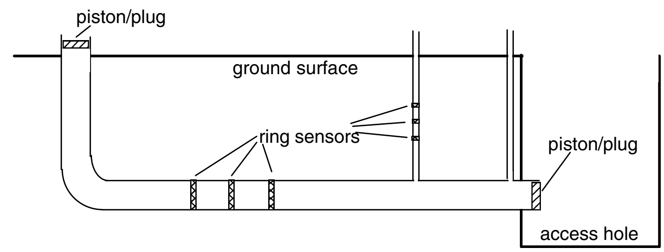

Fig. 2. Pipe rig layout (only one set of ring sensors shown here on the main pipe).

As well as being transmitted along the pipe, under most conditions, the axisymmetric, $n = 0$, $s = 1$, predominantly fluid-borne wave will be well-coupled to the surrounding soil and radiate effectively towards the ground surface [6,10,11], so this is the ideal wavetype to deliberately excite for detection at the ground surface. Accordingly, the pipe was instrumented with this particular wavetype in mind.

The main pipe was instrumented with two sets of three PVDF ring sensors [8]; these allow the wavespeed and attenuation, as well as the wave amplitudes, $n = 0$, $s = 1$ wave in the pipe to be determined, even in the presence of other wavetypes [10]. Connected to the main pipe were also two smaller diameter pipes rising to the surface. One of these was to allow bleeding of trapped air in the pipe; the other was instrumented with three pvdf ring sensors [8] to monitor the acoustic pressure in the main pipe using a recently developed sidebranch acoustic sensor technique [12].

The general layout of the rig is shown in Fig. 2.

Particular attention was paid to waterproofing the ring sensors, protecting them against mechanical damage, and decoupling them from the surrounding soil; the wires were waterproofed with a layer of silicon and then encased in polyethylene pipe insulation, as shown in Fig. 3a and b.

As well as responding to internal pressures in the pipe via the circumferential strain of the pipe wall, the ring sensors are also sensitive to changes in external pressure; it was hoped that the pipe insulation would isolate the sensors from the soil sufficiently so that the signals obtained would not be contaminated by the effects of waves in the soil. Further protective layers of waterproof tape were then applied on the outside of the pipe insulation.

Fig. 4a and b show the actual assembled rig just before and just after burial in the ground.

4. Preliminary measurements

Preliminary measurements were carried out on the pipe rig in order to determine the most suitable way to excite the axisymmetric fluid-dominated wave, and to confirm that this wave is indeed being excited, as expected. As stated earlier, in plastic pipes, for this wavetype, energy in the fluid is well coupled to energy in the pipe wall, so it is possible to excite the wave using either fluid or structural excitation. Both kinds of excitation were tested, and evaluated

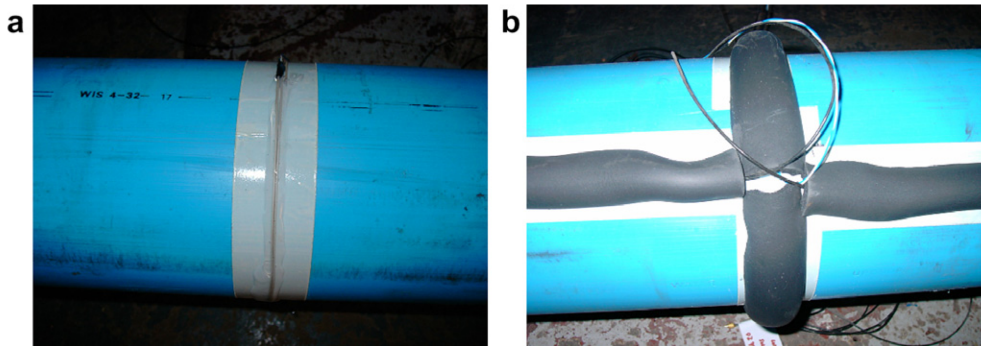

Fig. 3. PVDF ring sensor (a) waterproofed with silicon and (b) protection with polyethylene pipe insulation.

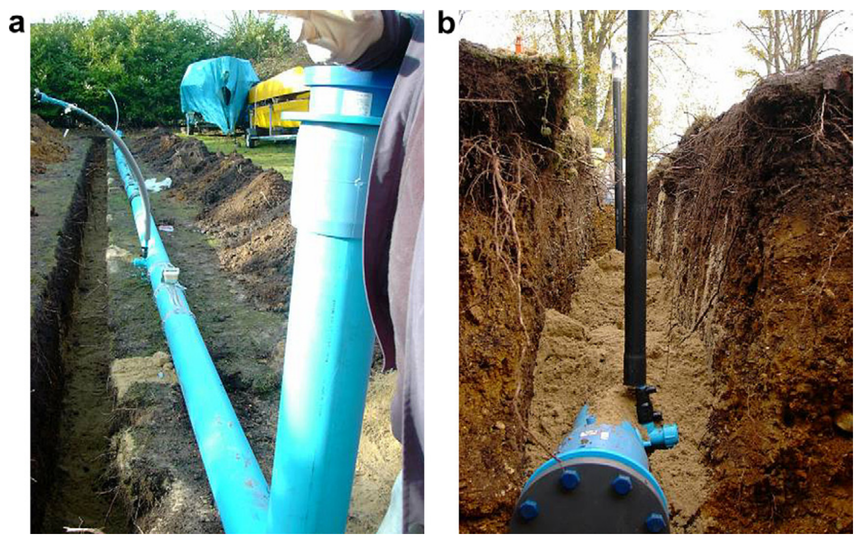

Fig. 4. Assembled pipe rig (a) just prior to burial; (b) just after burial, with a layer of sand around the pipe; the side branches and associated instrumentation are housed in a polypropylene pipe for protection.

both in terms of transferring energy effectively into the wave and practical implementation. The end of the pipe rising to the ground surface was excited for these tests.

4.1. Excitation methods

Three different configurations were tested, all using a Wilcoxon F4 inertial (reaction mass) shaker. In two of these configurations, structural excitation was of the pipe wall via excitation of an end-plate bolted to the flanged end of the pipe (Fig. 5a and b); both a plastic and a steel end-plate were evaluated. It should be noted that, for these tests, the water level did not reach the top of the pipe, and hence was not in contact with the end-plate. For these configurations, even though some bending waves will be excited as a result of the L-shaped geometry of the pipe, it was anticipated that, because of the strong fluid-structural coupling, the preferred wave would predominate.

In the third configuration, both the fluid and the pipe wall were excited. Here, excitation was via a drain tester plug, consisting of a rubber ring clamped between two end-plates, inserted into the pipe until the lower end plate was slightly below the water surface (Fig. 6a and b). The wing nut on the plug could be tightened, thus closing the gap between the two end-plates and expanding the rubber ring, to ensure a good seal between the rubber ring and the pipe wall. The whole assembly then acted as a piston (the lower end-plate) which could excite the water directly, mounted on the pipe wall via a stiffness (the rubber ring). Even though the pipe was not pressurized, the partial immersion of the plug in the water ensured that good contact was maintained between the tester plug and the water at all times, and that linear acoustic behaviour was assured.

For each test, the shaker was driven with a swept sine input from 10 Hz to 400 Hz, and the output from a number of the ring sensors along the pipe recorded. Fig. 7 shows the output from the nearest sensor to the excitation point ($\sim$4 m along the pipe), relative to the input force. This was calculated as the ratio of two cross spectra: that of the ring sensor output and the voltage applied to the shaker, and that of the force delivered by the shaker and the voltage applied to it.

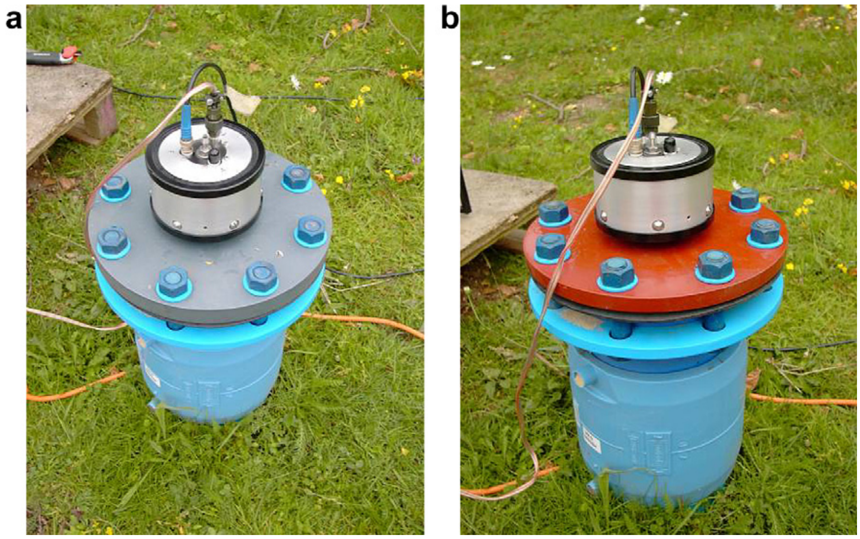

Fig. 5. Shaker mounted on end-plates (a) plastic and (b) steel.

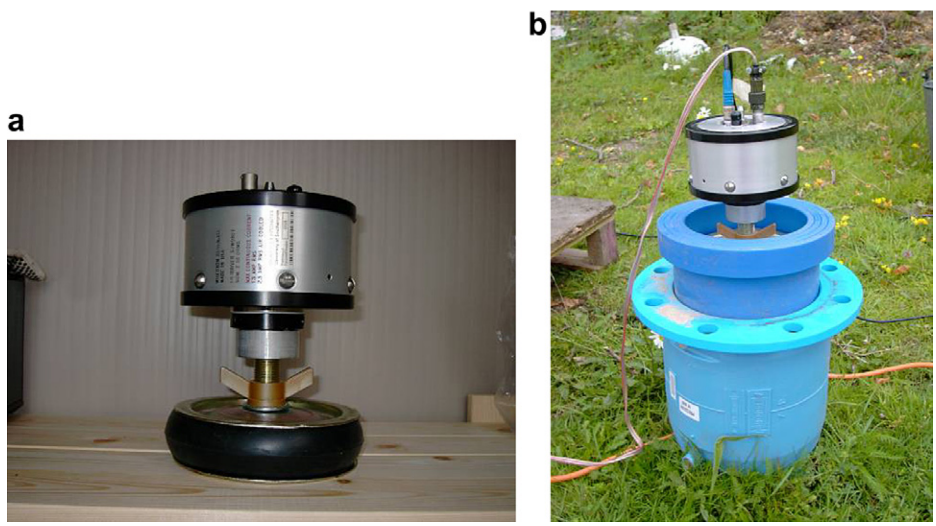

Fig. 6. Shaker mounted on drain-tester plug (a) shaker/plug assembly and (b) assembly inside pipe.

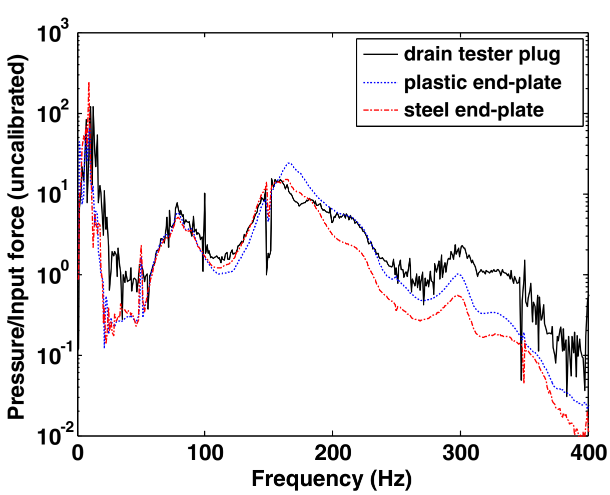

Fig. 7. Pressure measured in pipe relative to input force.

$$\text{Ring sensor output/input force} = \frac{G_{SV}}{G_{FV}} \tag{1}$$

where the subscripts S, F and V refer to the ring sensor output, the force delivered by the shaker and the input voltage, respectively.

It can be seen that, for all the excitation configurations and for the same input force delivered by the shaker, the pressure transmitted into the water is very similar, with the results for the drain tester plug being slightly noisier than for the end-plate configurations. It would therefore appear, at first sight, that all the configurations are equally effective at exciting the fluid. However, examination of the transmitted pressures relative to the input voltage to the shaker, for each excitation configuration, (calculated as the ratio of the cross spectrum between the ring sensor output and the voltage applied to the shaker, and the power spectrum of the voltage applied to the shaker –

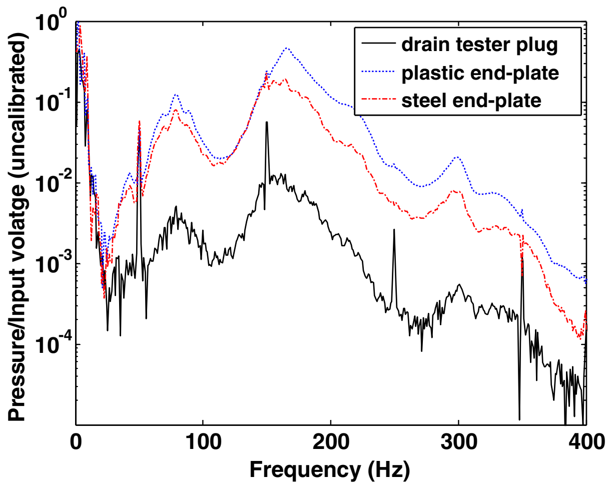

Fig. 8. Pressure measured in pipe relative to input voltage.

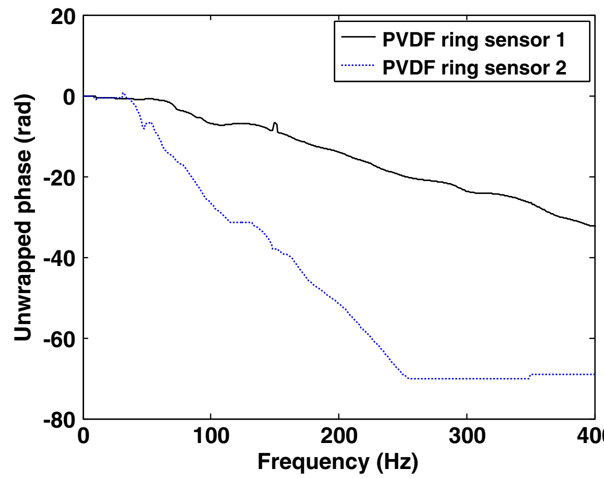

Fig. 9. Unwrapped phase of pressure measured in pipe relative to input force.

Ring sensor output/Inputvoltage $= \frac{G_{SV}}{G_{VV}}$ – Fig. 8) shows this is not the case. Here it can be seen that, for the same input voltage to the shaker, the end-plate configurations are much more effective at transmitting pressure into the water than the drain-plug configuration, with the plastic end-cap being most effective. Again, the data for the drain plug are slightly noisier. Clearly a lower force is being delivered to the drain tester plug compared to the plastic and steel end plates, most probably because the drain tester plug has a lower impedance, and therefore is more mobile, than the end plates.

4.2. Wave propagation in the pipe

To confirm that the desired wave (the axisymmetric, fluid-dominated) had been excited by each of the above configurations and measured by the PVDF ring sensors, the speed of the waves in the fluid was determined by examining the relative phase of the measured pressure at two locations along the pipe. (When end-reflections are significant, three equispaced locations are required in order to determine the wavespeed [10]; however, it was found that, in this case, the pipe was sufficiently long for the reflections to be minimal at frequencies above 30 Hz, so two measurement locations were sufficient.) This was then compared with that expected for the fluid-dominated wave.

Fig. 9 shows the unwrapped phase of the measured pressure from the each of the selected PDVF ring sensors relative to the input force, $\frac{G_{SF}}{G_{FF}}$. For the first ring sensor, the nearer of the two to the excitation point, the phase unwraps linearly, as expected, at frequencies above 30 Hz. For the second ring sensor (12 m downstream from the first), phase unwrapping ceases at frequencies higher than 250 Hz; the wave attenuation increases with frequency and here, the signal to noise ratio is too low for the phase unwrapping to be successful.

Fig. 10 shows the relative unwrapped phase of the pressure measured by the two sensors, $\frac{G_{S_2F}}{G_{S_1F}}$. Performing a least squares straight-line fit on the data between 30 Hz and 250 Hz shows that the slope of the line corresponds to a phase speed of ~365 m/s. This is as expected for the fluid-dominated wave, as the bulging of the pipe wall as the wave travels along will slow the wave down, in this instance, from the free field value of 1500 m/s to a value between one fifth and one quarter of this [10,11].

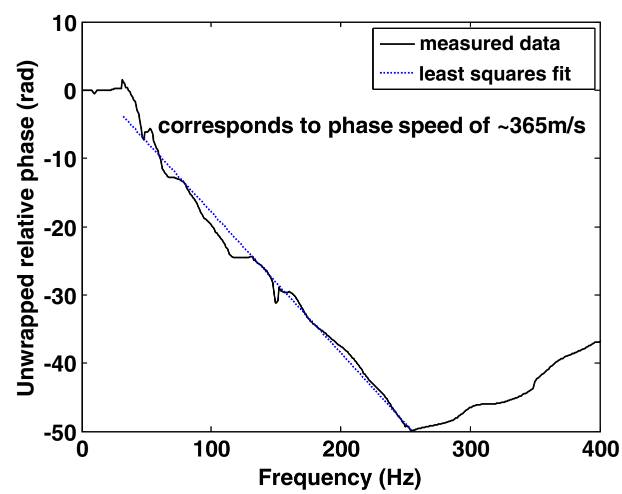

Fig. 10. Relative unwrapped phase of pressure measured in pipe at two locations, 12 m separation.

5. Conclusions

In this paper, the design and instrumentation of a buried pipe rig for the acoustic detection of underground piping systems has been described. It represents part of the initial phase of the acoustics element of the 'Mapping the Underworld' programme, a UK programme which aims to develop and prove the efficacy of a multi-sensor device for remote buried utility service detection, location and identification.

Current acoustic detection systems operate on the principle that vibrational energy injected at a known location on the pipework will propagate along the pipe and hence to the ground surface where it may be detected. The run of the pipe is then inferred from the position of local maxima in the detected signal. The performance of these systems is often poor; at present the systems are limited in that they employ only rather crude means to excite the pipe, use only a single transducer for measurement of the ground vibration, and make inferences from the magnitude of the measured signals alone. However, a number of enhancements to this system are possible.

The experimental rig has been designed specifically in order to investigate these possibilities. In particular, the rig was designed with the excitation and propagation of one particular wavetype in the pipe in mind: the axisymmetric, fluid-dominated mode. For plastic pipes, this mode is well coupled to the pipe wall and also the surrounding ground; furthermore, it is often the main carrier of energy at low frequencies. Measurements have been undertaken on the rig, in order to determine the best way to excite this wavetype, and to confirm that it was, indeed, being excited as expected. The results of those experiments have also been presented here. Of the methods tested, it was found that the intended wavetype could be most effectively excited with an inertial shaker mounted on a plastic end-plate bolted to the flanged end of the pipe as it comes up to the ground surface; no direct contact with the water inside the pipe was required.

The next phase of the work is to undertake ground vibration measurements in order to relate the measured response at the ground surface to the wave propagation inside the pipe. The results from these measurements will be reported at a future date.

Acknowledgement

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