An evaluation of acoustic reflectometry for leakage and blockage detection

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Abstract: Acoustic reflectometry has been shown to be an effective technique for detecting defects, such as holes and blockages, in relatively short, single lengths of pipe. This paper discusses briefly the physical basis of the technique and then describes the results of a series of experiments that were designed to evaluate the suitability of using this approach for monitoring the health of natural gas pipelines. Such pipelines will typically be many kilometres long, have diameters of up to 1 m and may form part of a complex network of pipelines. Previous studies have demonstrated that acoustic reflectometry techniques can be used to detect pipeline defects in relatively small bore pipelines with lengths of several hundred meters. The results reported in this paper indicate that even when using fairly crude equipment, the technique can be successfully applied to detect defects in single pipelines and pipeline networks with large diameters and lengths exceeding 5 km. Although the results presented in this paper are not conclusive, they do provide the necessary justification for a second phase of experiments to be conducted to extend the scope of the technique further.

Keywords: leakage detection, blockage detection, acoustic reflectometry

1 INTRODUCTION

Pipeline systems are an essential and ubiquitous feature of modern society, being employed for the delivery of utilities such as drinking water, petrochemicals, and other fluid substances. Monitoring the health of a pipeline or, more particularly, detecting leakage, blockage, and corrosion has never been of greater importance because of the economic and environmental consequences that can occur as a result of damaged pipelines. The work described in this paper was completed as part of an investigation into the detection of leakage and blockage in long lengths of natural gas pipeline.

Detection of leakage and blockage in pipelines has been an active area of research for many years and several methods have been proposed. These include, but are not limited to, volume balance, pressure drop analysis, inverse transient analysis, acoustic detection methods, thermographic, radar, and tracer gas techniques [**1**, **2**]. For the detection of leakage and blockage in pipelines transporting natural gas from the field, differential pressures measured between the inlet and outlet of the pipeline can be used together with real-time modelling of the pipeline. In such a system, abnormally large pressure differentials would indicate a possible blockage in the pipeline. Unfortunately, natural gas pipelines can be tens or even hundreds of kilometres long and the lack of instrumentation along the length of the pipeline means that it is difficult to locate any blockage with any degree of accuracy. This is compounded in subsea locations, where there is little readily available access to the pipeline.

More recently, acoustic devices have been used as a method for detecting leakage and blockage within pipelines. The principal acoustic techniques are referred to as listening devices and noise correlators. Such devices have been shown to provide substantial benefits in the detection of leakage in water distribution systems [**3**]. For relatively short lengths of pipeline, guided wave techniques have

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been developed [**4**] and shown to be capable of accurately detecting areas of corrosion in pipelines. Unfortunately, both noise correlators and guided wave approaches are unsuitable for application to very long lengths of pipeline, where there may be no access to the pipeline for several kilometres.

An alternative acoustic technique that can be used to detect both blockage and leakage in fluid-filled pipelines was proposed by the Central Electricity Generating Board (CEGB) in the late 1970s [**5**, **6**]. The CEGB developed an instrument they named the Acoustic Ranger, which was applied successfully to detect damage to the pipe wall and blockage in relatively short-lengths of gas filled pipes. Morgan [**6**] revealed that, although the majority of the tests were conducted on small bore pipe, with inside diameters <0.05 m, the device had been successfully applied to a pipeline with an inside diameter of 1 m and to a pipeline with a length of 300 m. There is little detail published with regard to these tests and hence, there are still many unanswered questions regarding the use of the instrument. The instrument operated by injecting a small acoustic signal into the fluid within the pipeline. This signal is partially reflected wherever there is a change in the acoustic impedance within the pipeline, such as that occuring at a flange, T-piece, orifice plate, valve, a deposition of wax, or where there is damage, such as a hole in the pipeline wall. The reflected signal, which is measured using a microphone, should remain approximately constant whenever a similar acoustic signal is transmitted through the pipe. However, if a defect, such as wall damage or a blockage is introduced into the pipeline then this will create new reflections. Therefore, comparison of the signals recorded before and after the defect is introduced provides a simple and accurate method for detecting such features in pipelines.

Despite the claimed success of this technique, Morgan and Crosse [**6**], for example, suggest that the acoustic ranger had saved companies many millions of dollars, academic interest in it did not materialize until relatively recently when the approach was revisited by several research groups in the UK. Sharp and Campbell [**7**], for example, used the technique to detect the position and size of leakage in musical instruments. Horoshenkov *et al.* [**8**] conducted a series of in-depth theoretical and practical programmes that have explored the use of acoustic reflectometry for detecting damage in sewage pipelines. Furthermore, Gao *et al.* [**9**] investigated the related acoustic methods for detecting the leakage in water distribution pipes.

This paper provides details of the results that have been obtained in a series of experiments that have been designed to determine the applicability of using the acoustic technique proposed by Morgan [**5**] to detect defects in natural gas pipelines. In particular, the experiments have addressed the following issues.

1. What is the maximum length of pipe that the technique can be applied to?
2. Can the technique be used in pipelines with a large internal diameter?
3. What effect does the pipeline material have on the technique?
4. What is the sensitivity and accuracy of the technique?
5. Is the approach capable of detecting defects in a pipeline network?

Section 2 of this paper provides a brief description of the physics of the technique and a basic overview of how the acoustic reflectometry technique can be applied in practice. This is followed in section 3 with a series of results obtained using a variety of pipeline systems, which reveal the ability of the technique to identify defects in pipelines of varying length, configuration, and material. Finally, section 4 provides some conclusions from the experiments and suggests future work.

2 THEORY

2.1 Background

The basis for the leakage detection method described in this paper is the observation that the propagation of acoustic waves in a fluid medium is very sensitive to any discontinuity in the properties of the fluid.

To illustrate this, Fig. 1 shows an expansion in the diameter of a pipeline containing a stagnant fluid. If an acoustic wave is injected from the left into the pipe, then it will be partially reflected at the interface, producing reflected and transmitted acoustic components. For weak plane waves of the type considered here, the waves propagate at the local speed of sound, which will vary depending upon the local conditions of the fluid. Reflective waves will occur wherever there is a change in the cross-sectional area of the pipe [**7**]. In industrial pipeline systems, this will occur wherever there is a valve, ‘T’-piece or blockage, for example. Further to this, any leakage within a pipe will act like a change in the cross-sectional area and hence, a fraction of the incident acoustic energy would be reflected. This was demonstrated, to a limited extent,

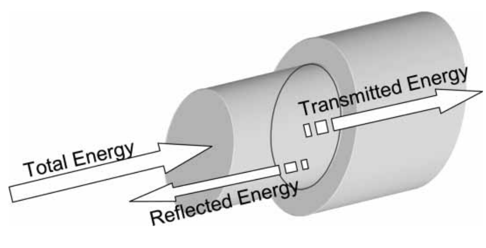

Fig. 1 Acoustic transmission at pipe joint

in reference [7] by using reflected signals to identify small leaks in a musical wind instrument.

3 EXPERIMENTAL RESULTS

In the experimental results presented in this paper, the acoustic signal was transmitted into the fluid in the pipe via a loudspeaker, which was driven by an acoustic pulse generator. A microphone was then used to measure the transmission and the reflection of this wave as it propagated along the pipe. Prior to there being any defect in the pipe, the acoustic wave will be reflected from every discontinuity in the pipeline, for example, where there is a valve or orifice plate. If similar acoustic waves are transmitted into the pipe, then the measurement made by the microphone should remain unchanged. If, however, the signal recorded by the microphone differs significantly, then this will indicate that there is a new discontinuity in the pipe, which may have been caused by a hole or blockage.

The ideal frequency content of the acoustic signal injected into the pipe is the subject of current research. However, in this work a short period square pulse, with a width of ~0.002 s, has been used. This pulse is translated through the speaker and microphone such that the signal recorded by the microphone is similar to that shown in Fig. 2.

3.1 Detection of holes in the pipeline wall

The results reported by Morgan and Crosse [6] illustrated the application of the technique to straight lengths of pipe. For the delivery of natural gas, the pipelines are likely to contain internal features such as bends, T-pieces, and valves. To evaluate the ability of the acoustic technique to detect defects in such pipelines, the system illustrated in Fig. 3 was employed. In this example, the pipe was constructed from PVCu, with an internal diameter of 150 mm, and contained stagnant air.

In this pipeline system, a loudspeaker is connected to one end of a single, open-ended pipe of length 39.84 m. A microphone mounted in a tapping in the pipe wall was located 6.11 m from the loudspeaker.

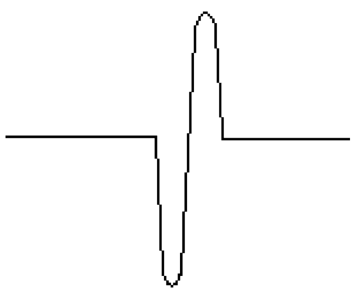

Fig. 2 Acoustic signal recorded in the pipe

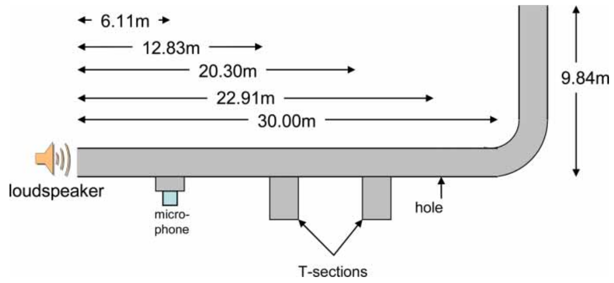

Fig. 3 Experimental configuration

An acoustic wave was injected from the loudspeaker and the reflection response of the pipe was measured using the microphone. The measurement from the microphone is recorded for a sufficient length of time for the acoustic wave reflected at the end of the pipe to return to the microphone. The microphone was sampled at a rate of 50 kHz. This measurement made by the microphone is referred to as the reference signature of the pipeline. A circular hole, of diameter 25 mm and located 22.91 m from the loud speaker, was then introduced into the pipeline. With the hole present, a second acoustic wave with the same amplitude and frequency content used earlier was injected into the pipeline. The measurement made by the microphone with the hole present, referred to as the test signature, was then recorded and compared with the original reference signature. In each of the experiments conducted in this work, it was found that improved accuracy was obtained by averaging the results from several (10 to be specific) tests. This had the effect of filtering out background noise. In other words, the reference signature is actually the average of the signals recorded from ten tests. Figure 4 shows a time trace of the averaged reference and test signatures measured by the microphone.

The acoustic signal was transmitted into the pipeline at time 0 s and as Fig. 4 shows the two traces are very similar. The first peak, which occurs in the traces at ~0.018 s, represents the passage of

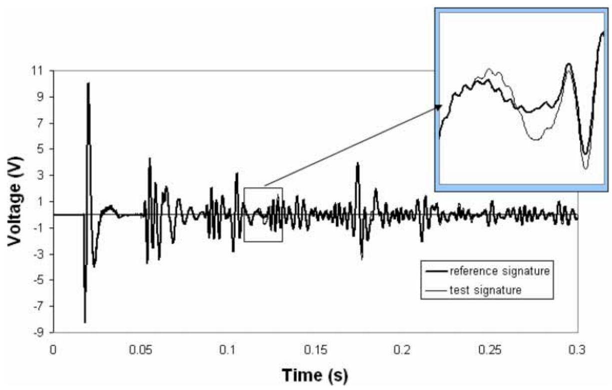

Fig. 4 Comparison of reference and test signatures

the acoustic wave across the microphone. Note that the speed of sound in air is ∼340 m/s. Hence, it takes ∼0.018 s for the acoustic wave to travel the 6.11 m between the loudspeaker and microphone. The subsequent peaks recorded in the traces are the reflected signals produced by the various features in the pipeline, such as 'T-sections' and bends.

The difference between the two signals in Fig. 4, which can be seen in the expanded section in this figure, is a result of the reflections made by the hole that was introduced in to the pipeline. Figure 5 shows the difference between these two signals. In this figure, the x-axis has been converted to a distance measure through knowledge of the speed of sound. This figure shows that the acoustic signals that had travelled <39.68 m remained unchanged following the introduction of the hole, i.e. the signal prior to 39.68 m is close to 0 in Fig. 4. This indicates that the distance from the speaker to the hole and then back to the microphone is ∼39.68 m, thus indicating that the hole is located 16.79 m [(39.68-6.11)/2] from the microphone. The actual distance is 16.80 m, and, hence, the system provides an accurate method to detect and locate pipe defects. Thorough testing has revealed that the accuracy of the technique tends to be in the range of 1 or 2 cm in the pipelines tested in the laboratory.

Further testing using steel pipes has indicated that for the case of stagnant air, under atmospheric conditions, there is no significant difference between the results obtained for steel and PVCu pipe. Details regarding the results of these tests and the many other tests that have been conducted during the investigation into the use of acoustic reflectometry for the detection of blockages in pipelines are available in reference [**10**]. The results reported in reference [**10**] also highlight the minimal impact that the diameter of the pipeline has on the technique, with the approach being successfully applied to PVCu and steel pipelines with internal diameters ranging from between 50 and 300 mm.

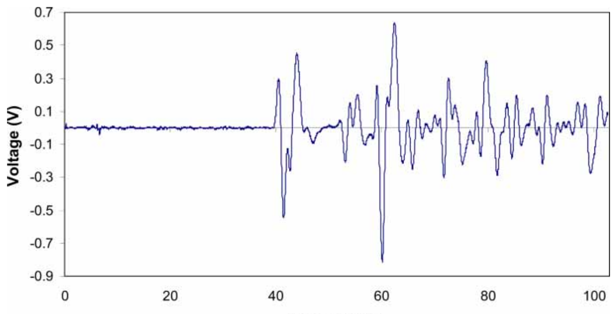

Fig. 5 Difference between reference and test signatures

3.2 Application to an extended length of pipeline

Natural gas pipelines are typically many kilometres long and hence, an important aspect of this study was to determine the range over which the technique could be applied. To facilitate this, a 524 m long steel pipeline, with an inside diameter of 181 mm and shell thickness of 18.3 mm, was made available for this study. Figure 6 provides a photograph of the pipeline used in this study. The photograph shows five similar pipelines, only one of which was used in this test. The pipeline contained stagnant air at atmospheric pressure and contained no bends or other features, such as valves. The loudspeaker can be seen attached to the end of the pipe in Fig. 6. A microphone was inserted ∼0.2 m downstream of the loudspeaker.

A series of tests were conducted on this pipeline. These tests involved recording the acoustic reflection under the following conditions:

1. The end of the pipe was left open to the atmosphere.
2. A wooden plate was secured at the end of the pipe, hence closing the pipeline.
3. A 6 mm diameter circular hole was drilled into the wooden plate at the end of the pipe.
4. A 25 mm diameter circular hole was drilled into the wooden plate at the end of the pipe.

Figure 7 shows the signal that was recorded under the first test. The point marked B on this graph shows the signal that has been reflected from the open-end of the pipe. Point C is the second reflection from the open-end of the pipe. This signal was initially reflected from the end of the pipe, it was then reflected off the speaker and reflected once again off the open-end of the pipe and then recorded by the microphone. This signal has therefore travelled a little over 2 km. The expanded graph to the lower right of Fig. 7 shows the third reflection from the open-end of the pipe, which can be identified after passing the raw signal through a

Fig. 6 524 m length of steel pipeline

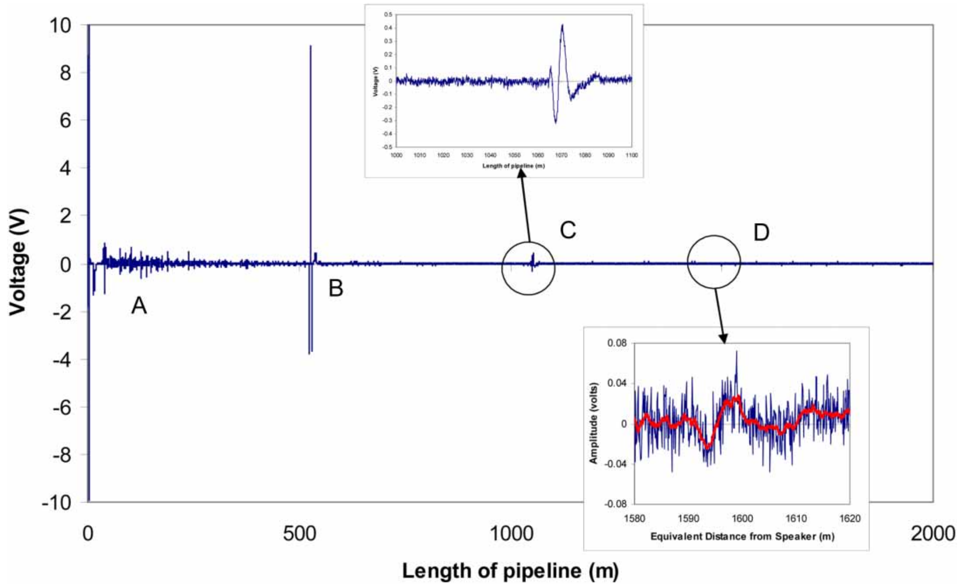

Fig. 7 Reference signal

low-pass filter (the blue line is the raw data and the red line the filtered signal). By identifying the attenuation of the signal resulting from it being reflected from the open-end of the pipe it was possible to determine that it would be possible to measure the signal reflected from the open-end of a straight length of pipe with a length of >5 km using the current system. Tests using a longer length of pipeline are currently being arranged.

The sensitivity of the approach is evident from the signal that is recorded in region A in Fig. 7. Analysis of this section of the signal indicated that although it has the appearance of random noise, the signal has a structure and that during this period the measured signal is the reflection produced by the weld joints along the pipe. These weld joints are located every 12.5 m.

Figure 8 shows the change to the acoustic signal measured at a distance of ~1000 m when the end of the pipeline is capped off (light blue trace), relative to the open-end result and when there is a 6 mm (red trace) and 25 mm (green trace) hole located in this end-plate, relative to the closed-end result. Analysis of these results showed that the technique was able to identify the length of the pipeline to within 50 cm. The results of this test indicate that the technique is able to detect a relatively small sized hole over a large distance, suggesting that the technique may well be suitable for application to the natural gas pipelines.

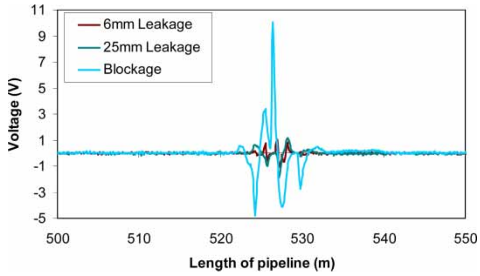

Fig. 8 Test signatures from the 524 m length of pipe

3.3 Detection of a water deposit

A specific issue with the natural-gas pipelines is the formation of hydrate blockages [**11**]. Natural gas hydrates can form very rapidly in a pipeline and can lead to a complete blockage of a pipeline in a matter of hours. Such a blockage can prove to be extremely costly as its removal may require production to be halted. Under appropriate conditions, a hydrate blockage will form at a location in a pipeline where deposits of water exist. It is therefore important for the acoustic technique to be able to detect and locate water deposits and the subsequent build-up of hydrates. The early detection of a hydrate build-up means that preventative action, such as injecting inhibitors into the pipe, can be employed before the blockage has fully formed. To test the ability of the system to detect small water deposits, the pipeline layout illustrated in Fig. 9 was used. A loudspeaker was connected to one end of a PVC pipe, of inside diameter of 42 mm, with the other

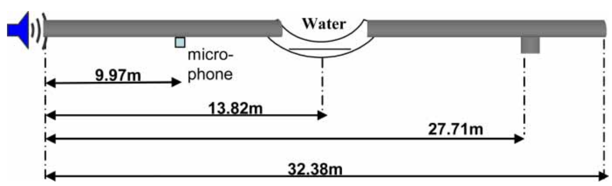

Fig. 9 Experimental set-up for water deposit testing

end open to the atmosphere. At a distance of 13.52 m from the loudspeaker, a 0.60 m length of flexible tube, with inside diameter of 50 mm, was inserted. A T-piece was located close to the end of the pipe.

As before, an acoustic wave was injected into the fluid through the loudspeaker and the reference signature of the empty pipeline was measured using the microphone positioned ∼10 m from the loudspeaker. The difference between this signal and that measured when varying amounts of water were injected into the flexible pipe section is displayed in Fig. 10. The percentage in this figure refers to the percentage of the pipeline diameter that is covered in water at the central point of the water deposit. This figure illustrates that the technique accurately detects the water deposit and identifies that the acoustic signal reflected by the water has travelled ∼18 m before reaching the microphone, establishing the water deposit to be located at a distance of ∼14 m from the loudspeaker.

The expanded plot in Fig. 10 illustrates the difference that the varying deposit size has on the signal measured at ∼18 m on the x-axis. This figure shows that as the size of the water deposit increases, the amplitude of the reflected signal increases and the time at which the reflection is first recorded is reduced. This is to be expected as the length of the water deposit will also be increasing.

Further information can be extracted from the reflected signals through time-frequency analysis techniques. Time-frequency methods have become powerful tools in the analysis of transient signals. There have been many time-frequency analysis methods that have been proposed, with the Wigner–Ville distribution method being one of the most popular.

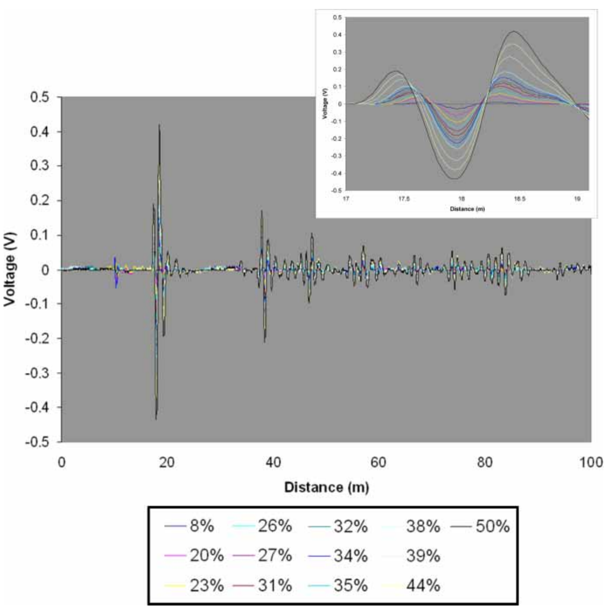

Fig. 10 Difference signal for varying water deposits

The concept was first introduced by Wigner and was later re-introduced by Ville. The Wigner–Ville is the Fourier transform of the signal's autocorrelation function with respect to the delay variable. It can be thought of as a short-time Fourier transform where the windowing function is a time-scaled, time-reversed copy of the original signal [**12–14**]. A smoothed, pseudo Wigner–Ville distribution has been used in the results presented in this paper to evaluate the time and frequency component of the reflected signals.

Figure 11 shows the results of a time-frequency analysis using the Wigner–Ville distribution technique for the cases when the water deposit filled 8, 20, 35, and 50 per cent of the pipeline diameter. The plots in Fig. 11 show the relative frequency content of the acoustic signal through time, the red patches highlighting the primary frequency content in the signal. The signal reflected from the smaller deposits have a lower amplitude and therefore, the plots for the 8 and 20 per cent deposits have a noisier appearance. The important feature of the plots in Fig. 11 is that as the size of the deposit increases, the primary frequency content of the reflected signal reduces. For example, the primary frequency content from the 8 per cent deposit is ∼450 Hz. However, for the 50 per cent deposit this frequency has reduced to ∼250 Hz. This reduction can be explained by analysing the expanded section of Fig. 10. This plot shows that the location of the first and second peaks, which indicate the start and end of the water deposit, varies as the size of the deposit increases. However, the location of the first trough, which indicates the location of the maximum height of the water deposit remains fixed for each test. The signals for the smaller deposits therefore appear to contain higher frequency information than the signals measured for the larger deposits. This result suggests that the structure and size of a water deposit or other blockage can be identified through analysis of the reflected signals in the time and frequency domain. This is particularly important for the detection of hydrate blockages in natural gas pipelines as the extent of any blockage can be of critical importance.

3.4 Results for pipeline networks

In this section, the applicability of using the acoustic technique for detecting defects in pipeline networks is discussed. Natural-gas distribution pipelines are arranged in complex networks, and, hence, it is necessary for the applicability of the acoustic technique to such systems to be evaluated. The major problem with a pipeline network is that although detecting a pipeline defect will be no different to a single pipe, locating the position of the defect is more complicated and requires multiple acoustic sources and sensors.

The configuration used for these tests is displayed in Fig. 12. The pipeline material for these tests was

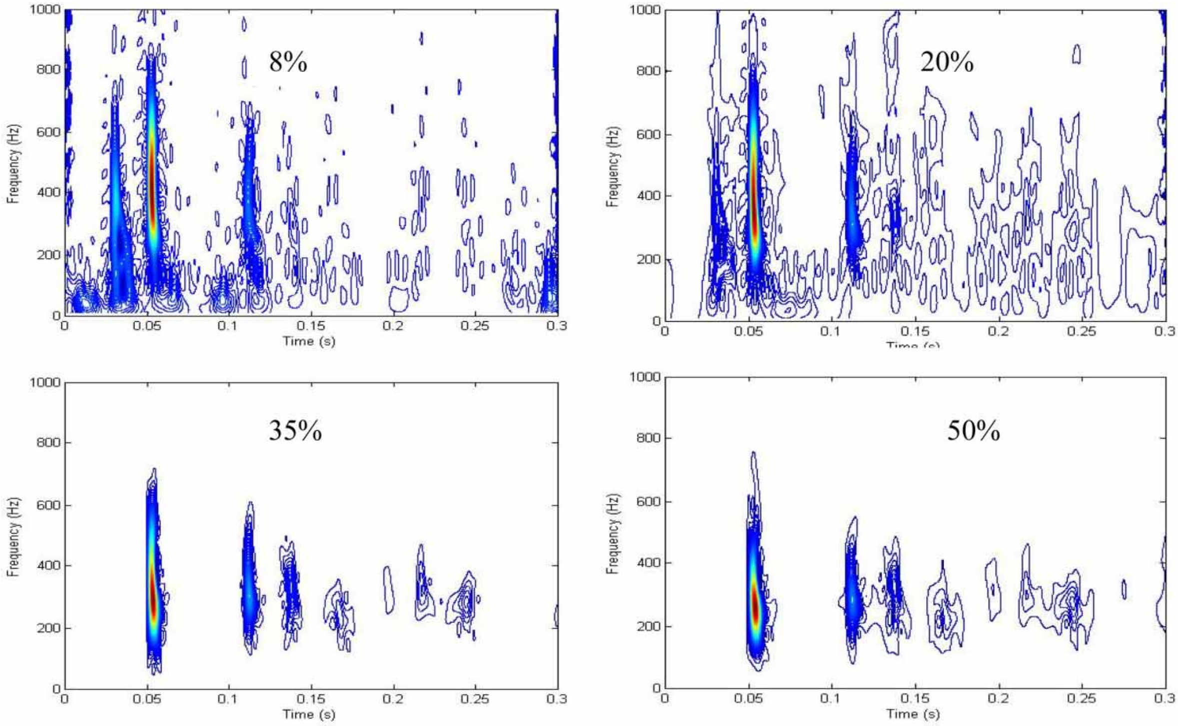

Fig. 11 Time-frequency analysis of blockage signals

PVCu of 44 mm internal diameter. As with the previous experiments, the tests were carried out with the pipe containing stagnant air.

The network used in this experiment contained two independent loudspeakers, s1 and s2, and two microphones, m1 and m2. An acoustic square wave was injected into the pipeline network using the two loudspeakers in turn and the resulting acoustic signal was recorded from each of the microphones. The network contained a hole at the point marked hole, which was a distance of 4.14 m from m1 and 3.02 m from m2. The hole was circular with a diameter of ~10 mm.

Figure 13 shows the differences in the signal that result before and after the hole was introduced into the network using loudspeaker, s1, and microphone, m1. This figure indicates that it is ~0.024 s before the reflection from the defect is received at the microphone. Knowledge of the speed of sound and the distance between s1 and m1 identifies the location of the hole to be ~4.1 m from m1. With there being a network in this example, this means that the defect is located at either point A or B in Fig. 9; both these points being located 4.1 m from m1. A similar test using s2 and m2 reveals that the hole is located ~3.0 m from m2, which indicates a defect located at point A or C. Therefore, the only consistent location of the defect is at point A. This example serves to illustrate, how multiple sources and sensors are required in pipeline network. The exact number of sources and sensors will depend on the complexity of the network.

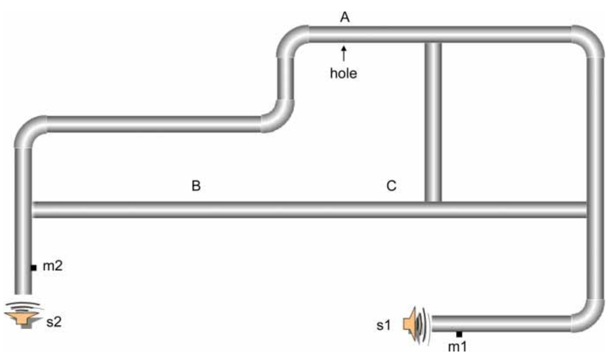

Fig. 12 A schematic drawing of the pipe network

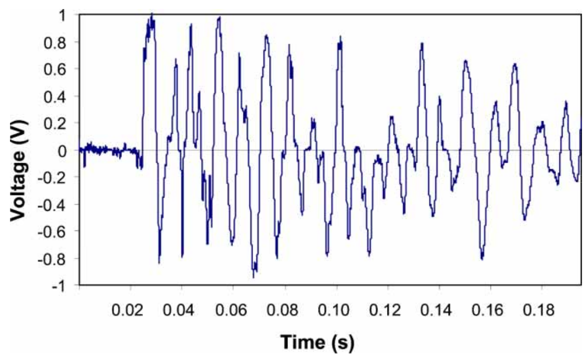

Fig. 13 Test signature relative to reference for pipeline network

4 CONCLUSIONS

This paper has detailed the results that were obtained from a series of experiments designed to evaluate the capability of acoustic reflectometry for detecting leakage and blockage in natural-gas pipelines. The primary conclusions from the work, which has been completed so far are as follows.

1. The method has been shown to be largely unaffected by whether the pipeline is made from steel or PVCu. This is important as natural-gas can be transported in either type of pipeline.
2. The approach provides an indication of the relative size of any pipeline defect. Tests indicate that the proposed approach is capable of identifying holes and blockages as small as 1 per cent of the pipeline diameter.
3. Initial results indicate that the approach is unaffected by ambient noise conditions. Moreover, in situations where background noise does exist, the frequency content of the acoustic wave can be adjusted to reduce the interference.
4. Although tests have successfully been carried out when there is gas-flow in the pipe, the experiments in this paper have shown that the approach is capable of detecting pipeline defects under stagnant conditions. For this reason, it can be used to detect wall failures (with the potential for leakage) in pipelines where there may only be occasional fluid flow.
5. A particularly strong advantage of the method is that it enables blockage to be detected as readily as leakage. Initial results indicate that further information regarding the structure of the defect may be revealed through frequency analysis of the acoustic reflections.
6. The use of multiple acoustic sources and sensors enables defects to be detected and located in complex pipeline networks. No prior knowledge of the pipeline layout is required, unlike many other leakage detection methods, and the method remains one, which is particularly suitable for remote operation.
7. Linking the source and the sensors into a Supervisory control and data acquisition (SCADA) system enables the health of the pipeline to be monitored continuously and remotely. Leakage or blockage may then be detected and located almost in real time.

Although there appears to be clear benefits in using the proposed approach for monitoring the health of natural-gas pipelines, it is recognized that the research completed so far is limited both as to physical understanding and experimental validation in realistic pipeline configurations. These issues are currently being addressed so that the technique can be applied with greater confidence in real operational pipeline systems. In particular, the focus of current research is in to the effects of increased pressure and flow conditions.

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