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Pipeline Network Features and Leak Detection by Cross-Correlation Analysis of Reflected Waves

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ABSTRACT

This article describes progress on a new technique to detect pipeline features and leaks using signal processing of a pressure wave measurement. Previous work (by the present authors) has shown that the analysis of pressure wave reflections in fluid pipe networks can be used to identify specific pipeline features such as open ends, closed ends, valves, junctions and certain types of bends. It was demonstrated that by using an extension of cross-correlation analysis, the identification of features can be achieved using fewer sensors than are traditionally employed. The key to the effectiveness of the technique lies in the artificial generation of pressure waves using a solenoid valve, rather than relying upon natural sources of fluid excitation.

This paper, uses an enhanced signal processing technique to improve the detection of leaks. It is shown experimentally that features and leaks can be detected around a sharp bend and up to seven reflections from features/leaks can be detected, by which time the wave has traveled over 95 meters. The testing determined the position of a leak to within an accuracy of 5%, even when the location of the reflection from a leak is itself dispersed over a certain distance and, therefore, does not cause an exact reflection of the wave.

Keywords: Pipe networks, Leak, Transient flows, Wave reflection, Correlations, Identification.

INTRODUCTION

With the ageing infrastructure of many cities, there has been a growing interest in the development of leak location techniques for water distribution and sewerage collection (Covas *et al* 2000). These developments have been driven by the environmental, economic, and legal liability costs of pipeline leaks. In 1994, for example, an estimated 23% of the potable water in the UK was lost in leaks and ruptures (Water Resources Council, 1994).

Traditionally, the condition of pipeline networks in water distribution systems and industrial processes has been monitored by a distributed set of pressure sensors, flow meters and valve sensors. Such sensing devices allow the state of the entire network to be monitored, from the state of valves to the presence of blockages and leaks (Seborg *et al* 1989). One disadvantage of this approach, however, is that multiple sensors are required to monitor a complex pipe network. Consequently, a complex pipe network could require many tens or even hundreds of distributed sensors. Also, this kind of monitoring is somewhat awkward as, for example networks operating in hostile or inaccessible environments.

In conjunction with these monitoring and detection systems, a number of techniques have been developed for leak identification. This is usually achieved by monitoring the flow rate through various zones of the network. The extent of a zone is then reduced by closing valves and re-monitoring flow. Eventually, the pipeline branch where the leak is located can usually be determined. This method relies on the availability of a sufficient number of valves and flow meters in the system (i.e., an *over-determined* problem (Liggett and Pudar 1992), and on the accuracy of the flow measurement.

A number of methods have been developed to assist with leak location process, for example using sensitivity analysis (Liggett and Pudar 1992, Curto and Napoli 1997), non-linear state observers (Billman and Isermann 1987), and Liapunov stability analysis (Abhulimen and

Susu 2004). Once a faulty pipeline branch has been located, the leak's position must be accurately determined. Current techniques include acoustic methods, tracer injection, video inspection (Liggett and Chen 1994), and focused electrodes (Gokhale and Graham 2004). A simple acoustic method uses a stethoscope to listen to the noise generated from a leak, success being dependent upon the operator's experience, the size of the leak, and the characteristics of the pipeline and surrounding terrain. Alternatively, acoustic sensors can be used to detect leaks (rather than locate them) by listening for the characteristic sounds. However, both acoustic and non-acoustic methods require significant levels of expertise and effort, and the water supply typically interrupted. Currently when performing leak detection or location, the effects of other legitimate pipeline disturbances, such as domestic and industrial water usage, must be minimized. Consequently, the process is usually carried out at night.

From the above overview, it is clear that there is ample scope for the development of improved solutions to the leak detection problem. In this paper, recent progress is described concerning a novel technique for pipe network analysis. Although the technique is still some way off from the practical implementation described above, it is shown in laboratory experiments that the technique is effective in identifying the location of pipeline features (junctions and bends) and leaks.

The proposed approach relies on signal processing techniques that are applied to measurements of pipeline pressure. Similar concepts were used by Mpesha *et al* (2001), who reported that measurements of flow and pressure variations at a single point can be used to generate frequency response functions that help to ascertain the position and size of a leak in branched systems. Liou (1998) used cross-correlation techniques to find the position of a leak in a pipeline from the first reflection of a pressure wave from the leak. Taken together, these results indicate that it is feasible to use signal analysis techniques to obtain valuable information from a single pressure transducer.

This work represents a continuation of the investigations and modeling work of Beck and various colleagues (Beck *et al,* 2000, and 2002). Here, the features of a pipe network were detected using an artificially generated pressure wave along with a single pressure transducer, and the signals were analysed using an extension of cross-correlation methods. In Beck *et al,* (2000), the reflections from a known pipe network were modeled using the Transmission Line Modeling (TLM) technique that had been developed previously by Beck *et al,* (1995). A computer program was then used to cross-correlate the stimulus and response signals, and it was shown that the cross-correlation technique was capable of detecting reflections and hence of identifying key features in pipe networks. This work used the second derivative of the cross-correlation multiplied by the time interval to produce clearly defined peaks showing the position of reflection points. In comparison, the work reported by Liou (1998) focused on the first reflection of the pressure wave and did not perform differentiation of the cross-correlated signal.

Beck *et al* (2002), then performed experiments on an equivalent pipe network which was constructed in the laboratory. The analysis was performed using the cross-correlation facility of a commercial signal analyzer. The main factors that made the results difficult to analyze were the accuracy with which the speed of sound was known and reflections at even large radius bends. However, it was shown that the technique could identify the reflection points in a real fluid network. The chief conclusion was that correlation analysis could be applied to practical situations, but that there were several factors that affected the accuracy of the process. For example, double differentiation of signals is undesirable owing to the tendency of the operations to amplify noise.

The current work extends this experimental work through the use of improved data analysis techniques which demonstrates the effectiveness of the improved method in terms of identifying both pipeline features (bends and joints), and leaks.

THEORY

When fluid flow (liquid or gaseous) in a pipe is suddenly stopped by a valve, pressure waves are created. These waves travel along the pipe until they reach a feature of the pipe network, where the wave is usually partly transmitted, and partly reflected back towards the source. Some of the wave energy is inevitably absorbed by the feature in the form of a pressure loss (Lighthill, 2001).

A pressure transducer can detect this pressure signal as the wave first traverses it and then again as it returns after having been reflected. If the speed of the wave c in the fluid is known, and the time t between the two passes of the wave at the pressure transducer is recorded, then the distance l to the point of reflection is half the product of the wave speed and the travel time.

$$l = \frac{c \times t}{2} \tag{1}$$

The speed of the wave in the fluid can be found from many texts (Thorley 2004). It should be noted that these equations are only true for single phase fluids in rigid pipes. If the pipe is flexible or the fluid is multiphase, the speed of sound can be dramatically lowered.

The pressure wave carries even more information, as some features in the pipe network will cause a reversal of the wave polarity. Knowledge of such shifts in polarity give an indication of the cause of the reflection. This information, however, is not directly available from observation of the pressure trace itself, since the pressure wave develops over a period of time. As such, if the pipe network has many features that cause reflections, then some of the pressure waves are likely to overlap, making identification difficult or even impossible. To overcome this problem, suitable signal processing techniques are helpful for obtaining accurate estimates of reflection times.

Cross-correlation Techniques

Signal processing techniques such as cross-correlation are well established in engineering applications (Lange 1987). Cross-correlation is used to recognize specific patterns in a signal by comparing the signal, $\boldsymbol{x}$, to a reference template, $\boldsymbol{y}$. The data from each signal is represented as an array, containing N elements of data, $\boldsymbol{x}[1], \boldsymbol{x}[2] \ldots \boldsymbol{x}[N]$ and $y[1], y[2] \ldots y[N]$. The value $r[k]$ of the cross-correlation function (Lange 1987) is given by:

$$\boldsymbol{r}[k] = \sum_{n=-\infty}^{\infty} \boldsymbol{x}[n] \times \boldsymbol{y}[n+k] \qquad (2)$$

In practice, measured signals have a finite length and so the sum in equation 2 is limited to the range $0<n<N$. A series of different values of $\boldsymbol{r}[k]$ is produced for increasing integer values of k. Increasing k effectively moves the signals over each other, and the summation produces a value indicative of how well the two signals match up, or correlate.

The computation starts with a time shift of $k = 0$ and then k is increased incrementally up to a suitable integer value. This procedure is equivalent to multiplying the overlapping elements of the two signals, and summing with appropriate time shifts. When peaks within the same signal overlap, however, the peaks of the cross-correlation are effectively added together to create a different single peak with changing gradients. The peak of the second signal corresponds to a change of gradient of the peak of the cross-correlation so, to find this peak, the cross-correlation can be differentiated twice. The first differential indicates the magnitude of the gradients and the second differential exhibits peaks at the points where the gradient changes. Therefore the points at which the peaks occur on the graph of the second differential are indications of reflected waves. This procedure is described more fully with examples in Beck *et al,* (2002).

IMPLEMENTATION

In previous work (Beck *et al* 2002), the cross-correlation process was performed using dynamic signal analyzer hardware. This posed some key problems as the signal processing capabilities were somewhat limited. First, the hardware did not enable double-differentiation of the cross-correlated signal. Second, the signal $y[n]$ was obtained from the voltage signal sent to the solenoid valve, so that the dynamics of the solenoid valve contaminated the results. Finally, the data averaging techniques that could be used were limited.

In the present study, a new implementation of the signal processing was developed. A data-logger based upon the Matlab dSPACE system was used (dSPACE, 2003), so that the data could be recorded directly into a MATLAB environment (Mathworks, 2004). Cross-correlation can be readily performed using MATLAB (Denbigh, 1998) due to its ability to work with large matrices. This allowed the implementation of the following signal processing method:

1) The first step was the automatic actuation of the solenoid valve (used to generate the pressure wave), and acquisition of the corresponding pressure measurement. This could be performed directly from the personal computer, with appropriate Matlab programming.

2) To reduce the noise, the solenoid actuation and data acquisition was repeated a number of times, M, and the average pressure measurement obtained. A short convergence test was conducted to characterise M. For these networks, the average of 16 traces was used to smooth out the data points without unduly increasing the amount of data.

3) A five-point moving average filter was now applied to further smooth the data:

$$\mathbf{x}_{\mathbf{aa}}[\mathrm{n}] = \frac{1}{5}\sum_{\mathrm{p}=-2}^{2}\mathbf{x}_{\mathbf{a}}[\mathrm{n}+\mathrm{p}] \tag{3}$$

This had the greatest effect in reducing noise and smoothing out the signal, making it more suitable for differentiation. A consequence of this averaging was that some of the data is lost. However, without the running average, the variation between one data point and the next was sufficiently large to render results of the cross-correlation, especially after double differentiation, very noisy.

4) The data was now de-trended by removing its mean value. This was a necessary step to ensure correct results from the cross-correlation function.

5) To avoid contaminating the results with the effects of the dynamics of the solenoid valve, an alternative to the solenoid voltage signal) was used for $\boldsymbol{y}[n]$. Ideally, $\boldsymbol{y}[n]$ should represent the initial pressure wave produced by the valve. Consequently, this signal was generated by using the appropriate part of the signal $x[n]$ corresponding to the pressure wave and not the reflections. Mathematically:

$$y[n] = \begin{cases} x[n] & \text{when } \mathrm{p}_1 \le \mathrm{n} \le \mathrm{p}_2 \\ \dfrac{1}{N}\displaystyle\sum_{n=1}^{N}\boldsymbol{x}_{aa}[n] & \text{otherwise} \end{cases} \tag{5}$$

where p_1 and p_2 define the start and end points of the initial pressure wave. These were determined graphically from a visual analysis of the signal $\boldsymbol{x}[n]$.

6) Finally, cross-correlation was performed on the signals $\boldsymbol{x}[n]$ and $\boldsymbol{y}[n]$, using equation 2. The resulting signal was differentiated twice, giving:

$$\dot{\boldsymbol{r}}[k] = \frac{\boldsymbol{r}[k]-\boldsymbol{r}[k-1]}{\Delta t} \tag{6}$$

and

$$\ddot{\boldsymbol{r}}[k] = \frac{\dot{\boldsymbol{r}}[k] - \dot{\boldsymbol{r}}[k-1]}{\Delta t} \tag{7}$$

where Δt is the sample time for the data acquisition system. The signal $\ddot{\boldsymbol{r}}[k]$ was plotted against the product of the measurement number (n), speed of sound of the fluid (c) and sample time (Δt) on the ordinate, representing the distance traveled by the wave.

In summary, a key contribution of this paper is the development of a signal processing routine, based in Matlab, to implement the proposed theoretical approach. The application of this routine will be demonstrated experimentally, to identify both leaks and pipeline features such as bends and junctions.

EXPERIMENTAL PROCEDURE

The experimental pipe networks used in the present work consisted of 15 mm outside-diameter copper pipe (see Figure 1). The working fluid used was air from an adjustable high-pressure line. The pressure was set at approximately 1 bar (the exact value does not affect the results). The air supply was connected to the copper pipe network via a rubber hose, which caused high attenuation so that any waves that entered from the air supply could be neglected. The output from two pressure transducers was electronically amplified before it was recorded by the dSPACE data acquisition system. The solenoid was normally closed, and was driven by a signal generator that produced a square wave with a frequency of 0.5 Hz. The system trigger was set to monitor the input to the solenoid valve and started recording the traces on the rising edge of the solenoid signal (when the valve was in the act of closing). A sampling frequency of 10 kHz was used. Since the speed of sound in air is approximately 330 m/s, the corresponding spatial resolution of the system was 3 cm, which was sufficient to determine the origin of any significant reflections.

Once the pipe network was assembled, the relevant taps were open or shut as required. After opening the high-pressure air valve, the system was allowed to run for several minutes to attain steady state, at which time the computer was set to record. After sixteen traces had been recorded, the computer was stopped and the equipment shut down if no more traces were required. The Matlab script was then run using the newly acquired data, and the various traces were studied. Each trace was recorded for 1.6 seconds, which represented the longest run that the monitoring system would allow.

To determine the distance the reflections had traveled required knowledge of the speed of the pressure wave. However, when this value was based upon that for air at ambient temperature, it was found to give incorrect results, with the speed of sound 1.5% too low. Reverse calculation from an earlier set of results gave an effective temperature of 6°C. This temperature is lower than the laboratory air supply and is almost certainly due to the elasticity of the pipe causing a decrease in the speed of sound (Massey 1979), implying that when calibrating the system, the temperature appears too low. Adjusting the wave speed greatly increased the spatial accuracy of the analysis.

EXPERIMENTAL RESULTS

Although the authors have conducted many experiments, only a small sample are described here. The first consists of a straight pipe with a straight section at right angles added to it and with a tap on the end; effectively a half T-junction as shown in Figure 1. The next two pipe networks use the same arrangement, but runs were made both with and without holes in order to investigate the effect of leaks. The final two pipe networks were more complex and again were operated with and without holes representing leaks.

Analysis of Half T-junction Network

The initial analysis was conducted with both the tap near the T-junction (node 5) and the tap at the end of the pipe (node 7) open. The main paths that were expected to be produced are shown in Table 1. The pressure data were obtained using a pressure transducer that was situated 2.16 m from the solenoid valve (node 2).

Figure 2 shows the result of this experiment (after cross-correlating, double differentiating and calibrating the abscissa in meters). With reference to Figure 2, the circles numbered 1 to 8 indicate the peaks where the distance and polarity corresponded to a predicted reflection of the pipe network. The paths corresponding to these peaks are shown in Table 1. It is clear that some of the peaks are straightforward to discern, whereas others would not be spotted if the physical arrangement of the pipe network was not known beforehand. Using this technique, even though it is possible to identify features that are already known, it would be difficult to identify the physical analogies of the peaks for a system whose lengths and features are not known.

The test was now repeated with tap 5 shut and tap 7 open and after processing, the paths identified. The peaks were marked with black circles in Figure 3. The relevant paths are outlined in Table 2 which contains the data for all the different possible paths up to a maximum length of 50 m. Where a peak matches up with a path, the predicted path length and measured path length, along with the percentage error, are stated. The "+" symbol indicates a positive peak, and the "–" symbol indicates a negative peak. It can be seen that 13 out of the 22 possible paths were identified, although some of the peaks in Figure 3 were not strongly defined, for example those for paths 20, 23 and 30. In each case, the relevant peak was adjacent to a peak of much greater magnitude of the opposite orientation. Some of the paths listed in Table 2 represent the same length and orientation, as they are the same routes, but in a different order (for example paths 16 and 13).

A number of paths over 50 m in length are shown in Table 3. As there are too many possible combinations to list, only the possible paths for the peaks actually found in Figure 3 are included.

To summaries the results from this experiment, the first large positive peak, corresponding to path 14 detected a reflection from the open tap at node 7. A repeat reflection from this point was found (path 15) which was the second largest positive peak. A second order reflection from this tap was then found (path 32) which was again repeated (path 33), and can be identified as the two prominent negative peaks. A third order reflection (path 35) which was again repeated (path 36) was also found, but the peaks were not as well defined.

Double reflections from the closed tap at point 5 were found (paths 9 and 10) and these were also repeated (paths 13 and 30), but no further reflections of this wave were detected. The reflection from the solenoid valve at point 1 was also detected (path 21), as were the second (path 27), third (path 34) and fourth (path 37) reflections. The peaks surrounded by a square could not be attributed to any particular path, but their distances are listed in Table 4. These results seem to indicate that a reflection originating at a measured distance of 8.6m was detected, and then further repeat reflections of it were also detected. This reflection corresponds to four times the distance between the valve and the pressure transducer (2.16 m), though it is not known how large a reflection is caused by the transducer and mount.

Half T-junction with a Leak

In order to ascertain whether the technique can be used to detect leaks, a hole was introduced into the half T-junction network shown in Figure 1. A 4 mm diameter hole was drilled in a small length of pipe and the pipe section was inserted into the network this is node 3.

The tap at node 5 was kept shut, while the tap at node 7 was kept open. The pressure traces from the near pressure transducer were analysed for the case when the holes were taped over and this case is shown as the denser trace in Figure 4. Using the same pipe network, but with the hole open at node 3, the analysis is shown as the thinner black trace in Figure 4. The linear distances of the major peaks from the solenoid are shown numerically in Table 5 and Table 6.

It can be seen from Figure 4 that two clear new peaks (58 and 59) have been produced through the opening of the hole. The first of these is at 11.48 m which corresponds to a direct reflection from the hole. The second of these (at 15.78 m) can be identified as a double reflection from the hole and then the valve. The hole is thus a new reflection point and its position can be found.

Leak Detection in a More Complex Network

A larger network was then set up in the laboratory (Figure 5 and Figure 6) which contained four pipes, joined by three junctions. A 4 mm hole was drilled 22.3 m from the solenoid. It was possible to cover and uncover this hole using tape. To reach the leak, the wave had to traverse two right angle T-junctions.

Pressure traces recorded with and without the hole are shown in Figure 7. It is seen that the difference between these traces is almost indiscernible as was the cross-correlation signals (Figure 8). The second derivatives of the cross-correlations multiplied by the time step are shown in Figure 9, along with the difference between them. By this stage in the processing, it is possible to tell the difference that the hole in the pipe has made to the response. A new peak is visible at about 43 m and the negative peak seen which could be seen at 38 m on the trace without the leak is no longer apparent. Many of the other reflection points, such as those at 24, 28 and 32 meters are also identified on this plot.

If the technique were to be used on a pipe network to find whether or not there were leaks, providing that the lengths of the pipes in the network were known, the two new characteristic lengths could be identified by this stage of the process. The sum of these two new characteristic lengths should correspond to one of the pipes in the network, indicating in which pipe the leak is located.

The effect of the leak is clearly seen on the difference graph shown in Figure 9. There are no differences up to about 37 m, but after this, this line starts rising to a peak at about 40 m. This distance corresponds to twice the distance between the leak and the pressure transducer, with a 5% error. There are other features that can be discerned from the difference graph. The peak at 43 m is the reflection of the leak from the valve just downstream of it. There is another peak at 56 m which is the reflection from the leak via pipe 3.

Additional experiments were conducted using a 6 mm hole in the pipe. Using the differencing techniques described above it was also possible to detect these. Surprisingly, this gave a slightly less distinct peak, probably due to the fact that the reflection was caused over a longer distance. This might be explained by the fact that the leak is a hole that is parallel to the direction of the pressure wave, so it does not represent a discrete position for reflection of the wave. Work is continuing to measure the response of different sizes of holes, with a view to identifying the size of a leak.

DISCUSSION

It stands to reason that that the greater the reflection length, the less prominent are the peaks on the graph. This result is partly due to attenuation of the pressure wave. Some techniques, such as acoustic methods, require information regarding the amplitude of the wave in order to carry out the analysis. One of the greatest advantages of the cross-correlation technique is that it does not require information about the amplitude of the pressure wave in order to function. The single criterion is that there is a discernible amplitude, which can then be used in the cross-correlation analysis.

It is also clear that even a relatively simple pipe network, such as the half T-junction, can pose problems when analysed. This difficulty is partly due to the large number of possible paths, but also due to the fact that some of the paths overlap which makes the analysis of pipe networks a challenging problem.

Both dispersion and attenuation place a maximum limit on the detection range of reflections, but the range achieved in this investigation has been shown to be large enough to identify peaks up to 100 meters from the transducer. In single phase water systems, this range would be increased as the attenuation in water is considerably lower than in air (Brown *et al*, 1969). The number of reflections was another major factor in causing the peaks to attenuate.

Physical effects due to the pipe network

There are a number of factors relating to the physical arrangement of the pipe network that affect the results. From an overall study of the results, it is evident that a closed pipe end does *not* change the polarity of the pressure wave, for example path 9 in Table 2. In contrast, the fact that an open pipe end *does* change the polarity of the pressure wave is confirmed by the trace of path 14. A good example of a pipe junction causing a change in the polarity of the reflected pressure wave is encountered in the T-junction, where a strong peak is produced in path 44. This type of result has already been discussed by Beck *et al,* (2002).

Features of the graphs

The first phenomenon to be noted is that the pressure peaks often appear in pairs, of similar size. This result is due to the fact that the pressure wave passes the pressure transducer in the direction of the solenoid, and reflects from the solenoid, and passes the pressure transducer again, but in the opposite direction, creating two peaks separated by 4.32 m. This result can clearly be seen on many of the graphs, but a striking example is in Figure 2. In theory, this effect should be seen for all peaks, but it is not apparent on some of the graphs, such as the second order reflection of the pressure transducer in Figure 3. The reason for this result is generally because one of the two peaks of the pair is obscured by a different peak. In this case, the first reflection of the pair of second order reflections from the pressure transducer (path 26) is obscured by the reflection taking path 15.

These double peaks indicate a feature that appears to reflect all the peaks. In Figure 3, for example, can be seen that the peaks surrounded by squares are repeated twice, as are the two major peaks (paths 14, 15, 32, 33, 35 and 36) and the reflections from the pressure transducer (path numbers 21, 27, 33 and 37). This effect gives an indication of the size of the pipe network, and also means that peaks revealing new information about the pipe network will not be found after the first repetition.

Potential Applications

There are many potential applications for the technique described above. Two promising applications are in the determination of the layout of a pipe network and in monitoring the status of a pipe network. It can be seen from the pipe networks studied above that the results of the analyses can be complex, and do not lend themselves to instant characterization of a pipe network. Indeed, in some cases it would be impossible to determine the layout of the pipe network simply by studying the response graphs. It is possible that optimization and search algorithms (Goldberg 1989, Vitkovsky *et al,* 2003) could be used, perhaps in conjunction with a model (Beck *et al,* 1995), to help in this identification problem.

The technique could be applied to condition monitoring (rather than layout characterization) in which an essential feature would be to be detect changes in the pipe network. It can already identify the position of a hole in a network that has been characterized without a hole. Since the technique described is able to detect blockages (Beck *et al* 2002), as well as other features such as valves and leaks, it appears to be suited for use in condition monitoring.

Practical implementation issues

The pipe networks that have been considered in this study are of considerably greater complexity than those used in earlier work (Beck *et al* 2002). However, practical networks are likely to be more complex still, and some thought must be given to how well the technique will handle these systems. Real networks are likely to possess characteristics such as a greater number of features which reflect waves, changes in pipe properties, geometry fluid flow due to demand, and higher levels of background noise.

As the number of features in the pipe network increases, the number of peaks will also increase, This will make it extremely difficult to use the technique with a single transducer. However, those features close to the transducer will still be discernable. The addition of extra pressure monitoring devices spread around the system will give additional information and should allow the method to be used on a wide variety of networks.

Changes in pipeline properties and geometry are to some extent included in the experiments that were performed. For example, the pipework was made up from 3m section of copper pipe using standard plumbing connections and some soldered joints. Consequently, joints, small changes in pipe diameter, and local changes in pipe friction, were present. Despite this, leaks could still be identified that were some distance from the measurement position. However, it remains to be seen how the technique will cope with large step changes in pipe diameter, or a variety of pipe materials which might modify the effective wave velocity in the fluid.

Changes in the fluid demand or flow rate, and increased levels of background noise, are another potential problem. However, from a signal processing perspective, one of the main advantages of cross-correlation is its ability to compare signals even in the face of high noise levels (Lange 1987). Meanwhile, changes in fluid demand are likely to introduce other pressure transients to the system, which will be superimposed on the measurement of the reflected wave. The effect of this will be to reduce the amplitude of the cross-correlated signal, but it is expected that the double-differentiated signal will still reveal pipeline features and leaks. Further experimental work is needed to explore this area.

A final issue concerning the practical implementation of the technique is how to choose the number of averages that are used. However, it should be noted that similar issues arise in many other signal processing problems, notably modal testing of vibrating structures (Ewins 2000). It could be argued that some form of averaging is unavoidable in many applications where signal processing is employed. In the present application, further work is needed to optimise the averaging techniques and provide further guidance on the number of averages that are needed.

CONCLUDING REMARKS

This work has demonstrated experimentally the application of a new technique whereby a measured pressure signal is cross-correlated and differentiated twice to detect leaks and other features in pipe networks. In comparison with earlier work by the authors, the signal processing routine has been enhanced and the approach has now been shown to be effective in identifying the location of pipeline leaks. Much of these improvements involve smoothing of the signals. There will inevitable be information loss during this process. The specific conclusions are as follows:

1. It was found that it is possible to gain information about features that are around a sharp bend in the form of a T-junction, and that reflections can be detected after they have traveled over 95 m and undergone up to seven reflections. Reflections from closed ends created no change in the orientation of the peak on the graph of the second derivative of the cross-correlation function, whereas reflections from open ends and junctions did. It was found that reflections of up to the third-order could be detected, but it was also noted

that this feature was of little use, as the second and third order reflections contained no more information than the first-order reflection and were generally less distinguishable. However, this information was available for each of the pipe lengths in the network, showing the advantages of using additional signal processing methods to extract as much data as possible from the pressure signal.

2. The effects of leaks were investigated, and it was found that leaks caused a new positive peak. It was also found that their positions could be determined accurately (to within 5%) though this accuracy was less than that for the detection of other pipe network features, almost certainly due to the fact that the disturbance caused by the leak is itself dispersed in nature, and does not cause an exact reflection of the wave.

More work is needed before the concepts developed here, can be implemented as a leak detection, condition monitoring or system identification tool. Notably, an automated method for extracting and ascribing points is required, which could be used to predict the path lengths from a pressure trace. It is also vital to examine how the signal-to-noise ratio affects the maximum length of reflected wave that can be accommodated.

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NOTATION

Symbol	Description	Unit
c	Speed of sound in the fluid	m/s
k	Delay for cross-correlation function	-
l	Distance of reflection path	m
M	Number of tests,	
n	Sample number	-
p	Offset for running average	
$\boldsymbol{r}[k]$	Amplitude of cross-correlation function	-

$\dot{\boldsymbol{r}}[n]$	First differential of amplitude of cross-correlation function	
$\ddot{\boldsymbol{r}}[n]$	Second differential of amplitude of cross-correlation function	
t	Time	s
$\boldsymbol{x}[n]$	Discrete signal 1 for cross-correlation	-
$\boldsymbol{x_a}[n]$	Resulting average measurements	
$\boldsymbol{x_{aa}}[n]$	Results after data both average and running average.	
$\boldsymbol{x_m}[n]$	Measurements recorded from each individual test	
$\boldsymbol{y}[n]$	Discrete signal 2 for cross-correlation	-

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No.	Path	Actual Path length (m)	Predicted path length (m)	% error
1	2-4-2	18.22 +	17.89 +	-1.81
2	2-4-1-2	22.54 +	22.18 +	-1.60
3	2-3-6-3-2	26.16 +	26.73 +	2.18
4	2-3-6-3-1-2	30.48 +	31.09 +	2.00
5	2-3-6-3-6-3-2	34.26 -	33.99 -	-0.79
6	2-3-6-3-6-3-1-2	38.58 -	38.22 -	0.93
7	2-4-1-4-2	40.76 -	40.33 -	1.05
8	2-4-1-4-1-2	45.08 -	44.68 -	0.89

Table 1 Possible reflection paths with both taps open (see Figure 2)

No.	Path	Actual Path length (m)	Predicted path length (m)	% error
9	2-4-2	18.22 -	18.08 -	-0.77
10	2-4-1-2	22.54 -	22.51 -	-0.13
11	2-4-1-4-2	40.76 -	No match	
12	2-4-1-4-1-2	45.08 -	No match	
13	2-4-1-3-6-3-2	48.70 +	48.15 +	-1.13
14	2-3-6-3-2	26.16 +	25.61 +	-2.10
15	2-3-6-3-1-2	30.48 +	29.96 +	-1.71
16	2-3-6-3-1-4-2	48.70 +	48.15 +	-1.13
17	2-3-6-3-6-3-2	34.26 -	No match	
18	2-3-6-3-6-3-1-2	38.58 -	No match	
19	2-3-6-3-6-3-6-3-2	42.36 +	No match	
20	2-3-6-3-6-3-6-3-1-2	46.68 +	46.30 +	-0.81
21	2-1-2	4.32 -	4.20 -	-2.78
22	2-1-4-2	22.54 -	22.51 -	-0.13
23	2-1-4-1-2	26.86 -	26.70 -	-0.60
24	2-1-4-1-4-2	45.08 -	No match	
25	2-1-4-1-4-1-2	49.40 -	No match	
26	2-1-3-6-3-2	30.48 +	29.96 +	-1.71
27	2-1-3-6-3-1-2	34.80 +	34.58 +	-0.63
28	2-1-3-6-3-6-3-2	38.58 -	No match	
29	2-1-3-6-3-6-3-1-2	42.90 -	No match	
30	2-1-3-6-3-6-3-6-3-2	46.68 +	46.30 +	-0.81

Table 2 Possible reflection paths up to 50 m with tap 5 shut and tap 7 open (see Figure 3)

No.	Path	Actual Path length (m)	Predicted path length (m)	% error
31	2-4-1-3-6-3-1-2	53.02 +	52.70 +	-0.60
32	2-3-6-3-1-3-6-3-2	56.64 -	55.90 -	-1.31
33	2-3-6-3-1-3-6-3-1-2	60.96 -	60.26 -	-1.15
34	2-1-3-6-3-1-3-6-3-1-2	65.28 -	65.0 -	-0.43
35	2-3-6-3-1-3-6-3-1-3-6-3-2	87.12 +	87.0 +	-0.14
36	2-3-6-3-1-3-6-3-1-3-6-3-1-2	91.44 +	91.0 +	-0.48
37	2-1-3-6-3-1-3-6-3-1-3-6-3-1-2	95.76 +	95.5 +	-0.27

Table 3 Possible reflection paths over 50 m with tap 5 shut and tap 7 open (see Figure 3)

Peak number (from left to right)	Predicted path length (m)
1	17.19 +
2	21.32 +
3	47.32 -
4	51.51 -
5	77.5 +
6	81.7 +

Table 4 Distances for unrecognized peaks with tap 5 shut and tap 7 open (see Figure 3)

No.	Path	Actual Path length (m)	Predicted path length (m)	% error
56	2-5-8-5-2	27.84 +	27.23 +	-2.19
57	2-5-8-5-1-2	32.18 +	31.61 +	-1.47

Table 5 Major reflection paths of network without a hole (see Figure 4)

No.	Path	Actual Path length (m)	Predicted path length (m)	% error
58	2-4-2	11.56 +	10.98 +	-4.19
59	2-4-1-2	15.88 +	15.37 +	-2.60
60	2-5-8-5-2	27.84 +	27.09 +	-2.34
61	2-5-8-5-1-2	32.16 +	31.48 +	-1.81

Table 6 Major reflection paths of network without a hole (see Figure 4)

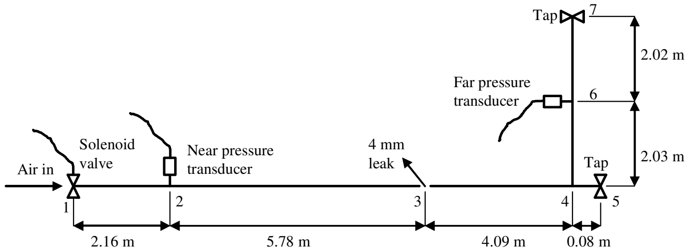

Figure 1 Layout of the half T-junction pipe network

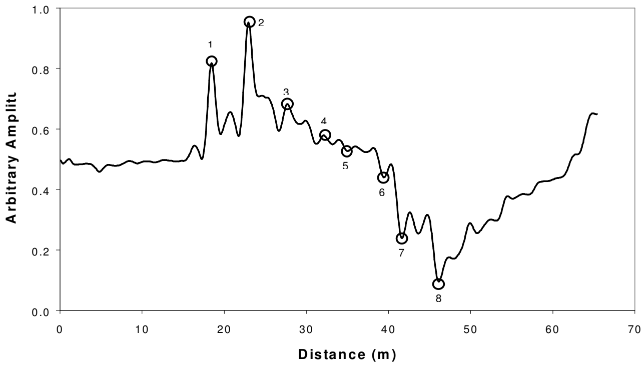

Figure 2 Results from the half T-junction pipe network with both taps open (see Table 1).

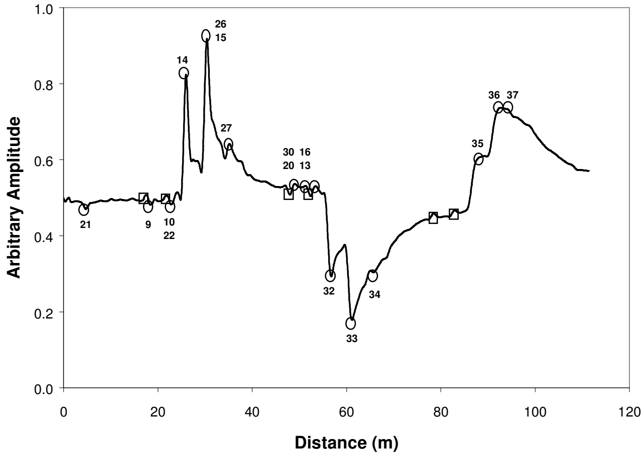

Figure 3 Results from the half T-junction pipe network with tap 5 shut and tap 7 open (see Table 2 to Table 4).

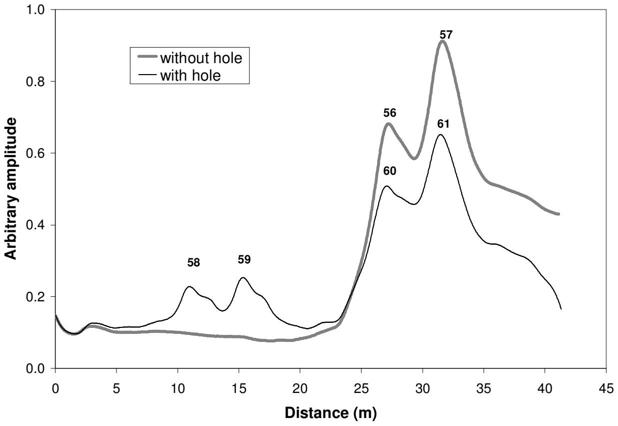

Figure 4 Results from the half T-junction pipe network with and without a hole (see Table 5 and Table 6)

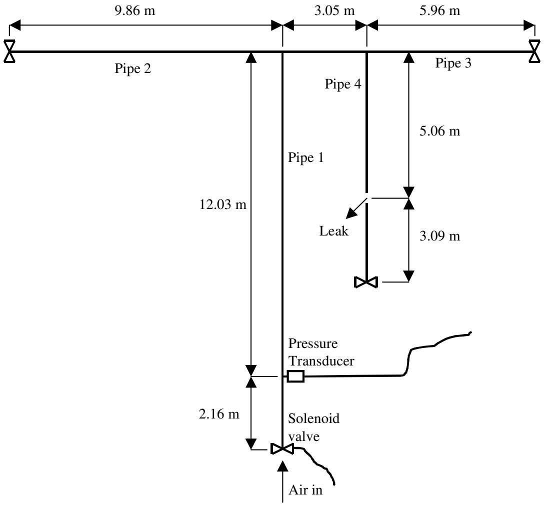

Figure 5 Layout of the larger pipe network

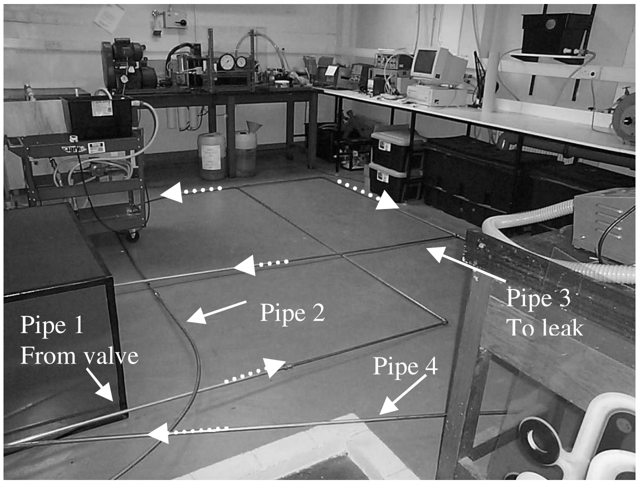

Figure 6 View of the larger pipe network

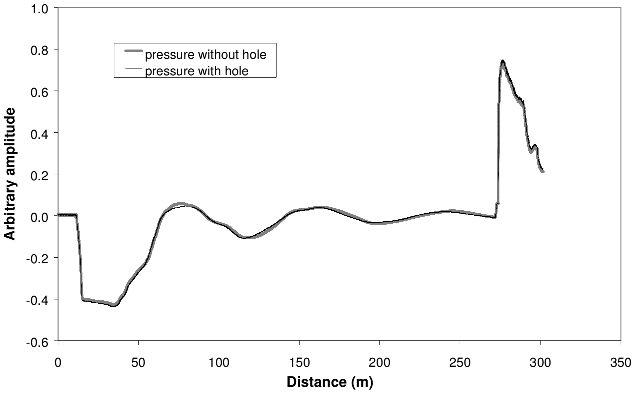

Figure 7 Pressure readings from larger pipe network with and without a hole

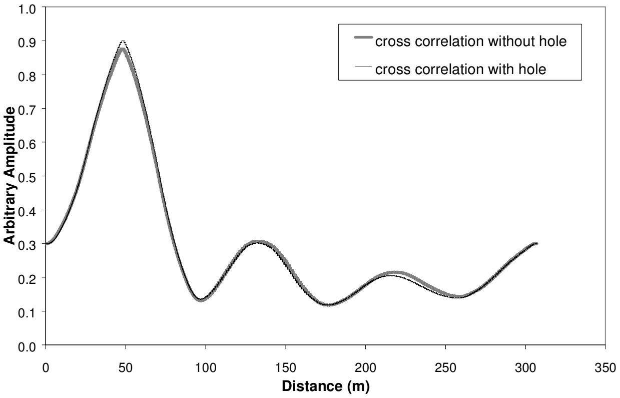

Figure 8 Cross-correlations from large network with and without a hole

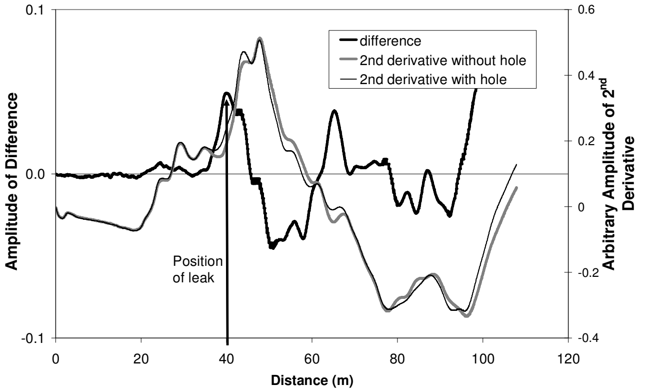

Figure 9 Second derivative of the cross-correlations from large network with and without a hole. The difference between the two cross-correlations is also shown.