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Leak location in pipelines using the impulse response function

Localisation de fuite dans les canalisations en utilisant la réponse impulsionnelle

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ABSTRACT

Current transient-based leak detection methods for pipeline systems often rely on a good understanding of the system—including unsteady friction, pipe roughness, precise geometry and micro considerations such as minor offtakes—in the absence of leaks. Such knowledge constitutes a very high hurdle and, even if known, may be impossible to include in the mathematical equations governing system behavior. An alternative is to test the leak-free system to find precise behavior, obviously a problem if the system is not known to be free of leaks. The leak-free response can be used as a benchmark to compare with behavior of the leaking system. As an alternative, this paper uses the impulse response function (IRF) as a means of leak detection. The IRF provides a unique a relationship between an injected transient event and a measured pressure response from a pipeline. This relationship is based on the physical characteristics of the system and is useful in determining its integrity. Transient responses of completely different shapes can be directly compared using the IRF. The IRF refines all system reflections to sharp pulses, thus promoting greater accuracy in leak location, and allowing leak reflections to be detected without a leak-free benchmark, even when complex signals such as pseudo-random binary signals are injected into the system. Additionally, the IRF approach can be used to improve existing leak detection methods. In experimental tests at the University of Adelaide the IRF approach was able to detect and locate leaks accurately.

RÉSUMÉ

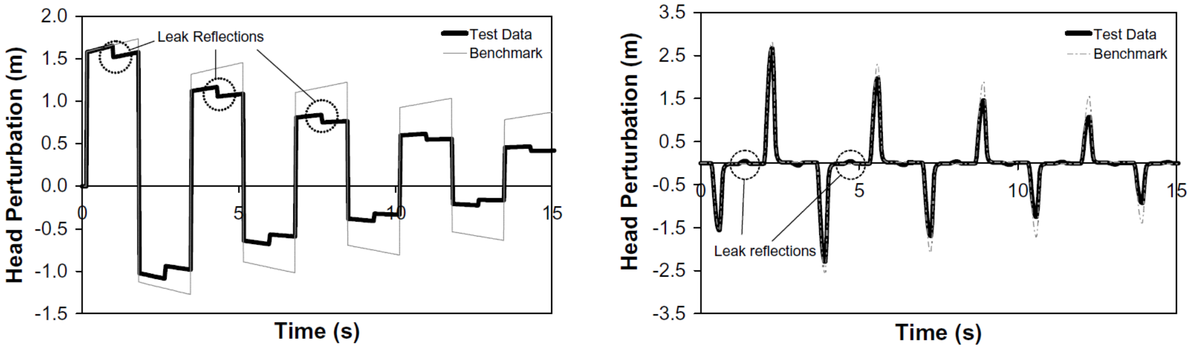
Les méthodes courantes de détection de fuite, basées sur le transitoire, pour les systèmes de canalisation reposent souvent sur une bonne connaissance du système—incluant le frottement instationnaire, la rugosité des conduites, la géométrie précise et des micro considérations telles que les evacuations mineures—en l'absence de fuites. Une telle connaissance constitue un obstacle majeur et, même si on en disposait, elle serait impossible à inclure dans les équations mathématiques régissant le comportement du système. Une alternative est d'examiner le système étanche pour en trouver le comportement précis, évidemment un problème si le système n'est pas connu pour être exempt de fuites. La réponse étanche peut être employée comme test-repère pour comparer le comportement du système avec fuite. Comme alternative, cet article utilise la réponse impulsionnelle (IRF) comme un moyen de détection de fuite. L'IRF fournit une relation unique entre un événement transitoire injecté et une réponse mesurée de pression d'une canalisation. Cette relation est basée sur les caractéristiques physiques du système et est utile pour déterminer son intégrité. Des réponses transitoires de formes complètement différentes peuvent être directement comparées en utilisant l'IRF. L'IRF fait ressortir toutes les réflexions du système aux impulsions brusques, favorisant de ce fait une plus grande exactitude dans la localisation de la fuite, et permettant à des réflexions de fuite d'être détectées sans le test-repère étanche, même lorsque des signaux complexes tels que les signaux binaires pseudo-aléatoires sont injectés dans le système. En plus, l'approche IRF peut être employée pour améliorer des méthodes de détection de fuite existantes. Dans les essais expérimentaux à l'université d'Adelaïde l'approche IRF a pu détecter et localiser des fuites avec exactitude.

Keywords: Leakage, frequency response, linear systems, transients, water pipelines.

1 Introduction

When a propagating transient (pressure wave) signal arrives at a leak in a pressurised pipeline, part of the energy in the transient is reflected. The arrival time of the reflected signal is the time needed for the signal to travel from the transient source, reflect off the leak and travel to the measurement station. Given a known wave speed, the location of the fault can be determined from this arrival time. This technique was used in Jönsson and Larson (1992), Brunone (1999), Covas and Ramos (1999), Jönsson (2001), Ferrante and Brunone (2003b) and many others.

Any leak-reflected signal can be differentiated from other reflections by comparing the measured response to a benchmark response when the system is leak free (refer to Fig. 1). Any discrepancies between the two signals are identified as possible leak reflections. A benchmark can be generated when the system is known to be leak free or from an accurate numerical model, where a detailed understanding of the system is required. This approach relies on a comparison between the measured result and the leakfree behaviour of the *same* transient in the pipeline. However, internal conditions of pipelines may change with age and for an aging pipeline with unknown characteristics, this modelled leak-free benchmark cannot be easily determined. Obviously, this approach can only detect changes from a benchmark state and cannot detect leaks that are present when the benchmark was taken. To complicate matters, precisely identical transients are difficult to reproduce.



(a) (b)

Figure 1 (a) Detection of a leak in a step input signal generated by a closure of the side-discharge valve from a fully opened position. (b) Detection of a leak with a pulse input signal generated by the rapid perturbation (open and close) of an initially-closed side-discharge valve.

For leak detection techniques that use a leak-free benchmark, problems arise when the induced transient is not perfectly repeatable and the operator wishes to determine whether the state of the system has changed *between* two different tests, for example, from the time Fig. 1(a) was conducted to Fig. 1(b). In the case presented, the two measured transient events are of such different shapes that direct comparison of the results is not possible. Given that the aim of a leak detection procedure is to determine the integrity of a pipeline, the information provided by such a procedure should be solely indicative of its state and independent of the shape of the injected transient. In reality, if the state of a system remains unchanged –as it is between Fig. 1(a) and 1(b)– then information extracted from that system should indicate that fact.

The system response function for an intact pipeline (within the frequency range of the injected signal) is similar for different flows in the system, different lengths or sizes of the pipeline and for all different types of injected signal. A leak in the system can be identified as a change from this known function shape. The use of the impulse response function (IRF) in place of the original transient trace removes the need for a leak-free benchmark to identify system reflections and allows all reflections from the system to be converted to sharp impulses with a well-defined peak for accurate measurement of time delays.

The impulse response functions for the step and the pulse signals in Fig. 1 are shown in Fig. 2. The IRF is the same for the two different signals, correctly indicating that the state of the pipeline is the same between the two tests. This conclusion cannot be reached by observing the raw transient traces alone. The estimation of the arrival time of leak reflections using the raw transient trace is prone to error, as can be seen from the shapes of the leak reflections from the original transient signal and the IRF (in Figs 1b and 2) and directly compared in Fig. 3. In the original reflection, the “peak” of the reflection is unclear and can be taken as either as point “A” or point “B”. The IRF has converted the shape of the original reflection to a sharp impulse with a clearly defined maximum point. Unlike generators of electrical signals, mechanical valves cannot produce rapid changes in pressure and injected transients are often smooth with no clearly visible reference points, indicating the need for the IRF.

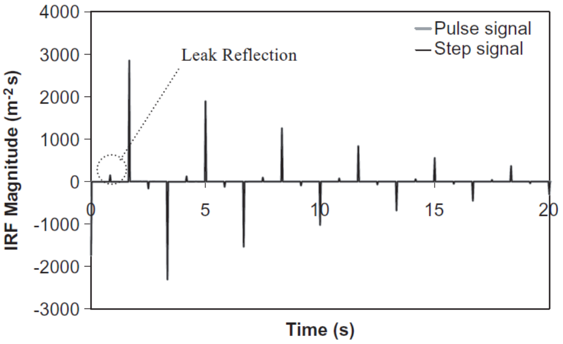


Figure 2 Impulse response functions of the two different test traces in Fig. 1.

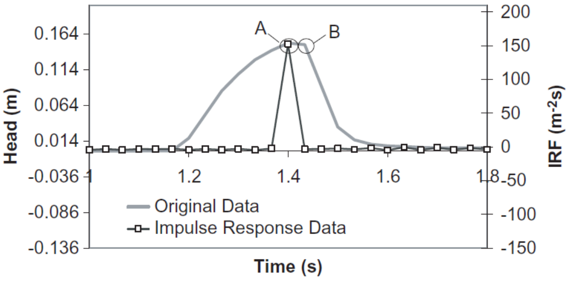


Figure 3 Comparison between the leak reflection from the original transient signal and the impulse response function.

This paper investigates the use of the IRF to improve the operation of reflection-based leak detection procedures, including the method for extracting the IRF from the raw signal and an experimental validation of the approach.

2 Background

While there have been publications in other fields that make use of the IRF for the determination of system characteristics, examples of this approach for fluid systems are few, such as Sharp (1996). He investigated the use of the IRF for measuring the internal geometry of musical instruments and short air ducts. Suo and Wylie (1989) proposed the use of the IRF as a modelling tool in the IMPREM technique. The IRF from a pipeline was determined numerically by a method of characteristics model. The head response (output) from a pipeline was predicted through a convolution between this IRF and the input signal. This procedure can efficiently predict the response from a system without requiring additional model runs. It was adopted in Ferrante and Brunone (2003a) and Kim (2005). These papers illustrate the successful use of the IRF as a response prediction tool in a numerical system.

In a numerical exercise Liou (1998) extracted the IRF at different positions along a pipe using a pseudo-random binary signal. The maximum magnitude of the impulse response for each measurement position was plotted and the linear decrease in the maximum response with distance of measurement position from the transient source was noted. The decrease in the response magnitude is caused by frictional losses in the pipe section joining the transient source and the measurement point A leak imposes a change of flow rate, giving a different value of the frictional loss upstream and downstream of the leak. The leak can be detected as the point where there is a slope change on the plot of the maximum IRF magnitude against distance from the transient source. This approach is equivalent to finding the leak by locating a change in slope of the hydraulic grade line (HGL) caused by the leak. A change in the HGL slope is typically very small for all but large leaks; therefore, the method is insensitive for small and moderate leak sizes. Use of the IRF to detect a change in HGL slope for this purpose brings little improvement.

In a numerical experiment Vítkovský *et al.* (2003) showed the incorporation of the impulse response directly in a leakdetection procedure by using the IRF in place of the original transient signal, thus removing the need for a system benchmark for comparison and increasing the accuracy of leak location. The extraction of the IRF from data obtained on an experimental system has yet to be conducted and is the focus of this paper.

This paper should not be considered as a presentation of an alternative technique of leak detection; instead, it presents a method for improving existing leak detection techniques. For example, the improvement in the sharpness of the reflected leak signal through the IRF will improve detection sensitivity using the wavelet approach presented in Ferrante and Brunone (2003b) and also other reflection based techniques developed in Jönsson and Larson (1992), Brunone (1999), Covas and Ramos (1999) and Jönsson (2001). The use of artificial neural networks for leak detection (Stoianov *et al.*, 2002) can also benefit from this development as the network need not be recalibrated for different transient signals.

Calculation of the IRF in a physical system is included in this paper. The IRF extraction procedure used in Suo and Wylie (1989) must be modified in a physical system to take into account the effect of signal bandwidth—the frequency content of the signal. In addition, the definition of the system input in Suo and Wylie (1989), Ferrante and Brunone (2003a) and Kim (2005) should be changed to accommodate a variety of transient signals.

3 Extraction of the impulse response function

Impulse response extraction is a procedure that refines the shape of the output signal such that each reflected signal in the trace is replaced by an impulse having a sharp, well-defined spike (Lynn, 1982). The definition of the impulse response of a system is the response measured at the output when a unit impulse (a sharp spike of a magnitude of 1.0) is applied at the input (refer to Fig. 4). When a complicated signal is applied, it can be considered as a sequence of weighted impulses and each point in the input generates a scaled version of the impulse response at the output. The overall response from the entire input signal is the sum of these scaled and time-lagged impulse responses—a process known as *convolution* between the input and the system IRF.

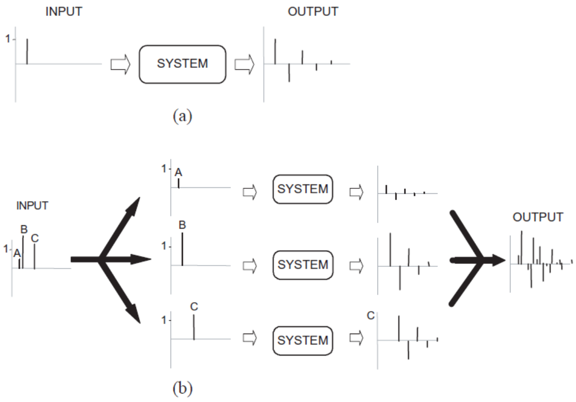


Figure 4 (a) Response from a single impulse. (b) The overall response from the system when a complex signal is applied at the input.

From Lynn (1982) and Lee *et al.* (2003a), the frequency response function, *F(ω)*, relates the correlation spectrums of the input, X, and output, Y, of a system by

$$S_{XY}(\omega) = S_{XX}(\omega) \cdot F(\omega) \tag{1}$$

The time equivalent of this equation is

$$r_{xy}(t) = \int_{-\infty}^{\infty} r_{xx}(t^*) I(t - t^*) dt^* \tag{2}$$

where *t* is the time, *ω* is angular frequency, *I(t)* is impulse response function, S_{XX} is Fourier transform of the autocorrelation of the input signal, S_{XY} is Fourier transform of the cross-correlation between the input and the output, r_{xy} is crosscorrelation function between x and y, r_{xx} is auto-correlation function of the input, and the integral in Eq. (2) is known as the *convolution integral*. The auto-correlation spectrum (S_{XX}) and the cross-correlation spectrum (S_{XY}) are complex and Hermitian. Equations (1) and (2) assume that the input to the system is independent of the output and apply to open-loop systems where there is no feedback. Note that Eqs (1) and (2) are stochastic equivalents of the basic systems equations with the inclusion of a match filter to increase noise tolerance.

3.1 Deconvolution

Extracting the IRF from the original time series can become complicated using Eq. (2). It involves a process known as *deconvolution*, where *I(t)* is calculated from the convolution integral of Eq. (2). Li *et al.* (1994), Dallabetta (1996), and Liou (1998) approximated the auto-correlation of the input time series (r_{xx}) in Eq. (2) by a Dirac delta function when a wide-band signal was injected into the system. As the convolution of any function with the Dirac delta function is the signal itself, the IRF of the system in this case is proportional to the cross-correlation between the input and output signals. However, a transient signal that has a bandwidth approximating a Dirac delta function is difficult to produce in hydraulic systems. Every transient signal contains a finite amount of energy distributed over a range of frequencies, this range being the signal *bandwidth*. A signal containing sharp variations in time has a larger bandwidth compared to smooth, slow signals. Mechanical valves need to operate against the high back-pressures of the system and cannot make rapid manoeuvres under these conditions. The use of a commercial solenoid side-discharge valve can produce signals of only 300 Hz bandwidth so that the approximation used in Li *et al.* (1994), Dallabetta (1996), and Liou (1998) cannot be applied.

Alternatively, in the case where the bandwidth of an injected signal is not close to the Nyquist frequency (equal to half of the sampling frequency), a fast deconvolution method, known as the *Fourier-quotient method*, can be used (Starck *et al.*, 2002; Sharp, 1996). This approach uses the fact that the IRF and the frequency response function (FRF) form a Fourier transform pair,

$$I(t) = \Im^{-1}[F(\omega)] \tag{3}$$

where $\Im^{-1}$ is the inverse Fourier transform. The extraction of the IRF can be achieved by first determining the FRF, as in Eq. (1), and then taking the inverse Fourier transform (Sharp, 1996). Equation (3) should be used with care as the portion of the FRF beyond the input signal bandwidth is susceptible to random noise contamination due to low input signal energy (Lee *et al.*, 2005). In Sharp (1996), this contamination of the FRF was reduced by adding a small non-zero term to *S*XX across all frequencies, which prevents the division of *S*XY by small values in the extraction of the FRF using Eq. (1). A procedure that can achieve a similar outcome is to filter the FRF through a window function, thus removing the noise component at high frequencies. The equation for the IRF, taking into account the windowing process, is

$$I'(t) = \Im^{-1}[W(\omega)F(\omega)] \tag{4}$$

where *W* is the window function and *I'* is the resultant IRF. The need for this window function is shown later in the paper.

3.2 Definition of the system input

The input to a transient pipeline system is any parameter that can describe the injected transient event and the output is any measured transient response. In Wylie and Streeter (1993), and Ferrante and Brunone (2003a), the inputwas the discharge perturbation at the transient generating valve throughout the duration of the transient. The application of this approach is limited to cases where the transient generating valve is inline and the valve is fully closed after the manoeuvre. In other cases, the discharge perturbation at the generating valve is a function of the measured head response and a feedback loop is established in the system. Such a feedback process is not accounted for in Eqs (1) and (2). An improved definition is to use the *induced* discharge perturbation at the valve (Lee *et al.*, 2004). For any generated transient event, the change in discharge (as a time series) at the valve during the valve movement is used as the input to the system. This definition adheres to the open-loop approximation in the equations and was shown to reduce non-linearity errors associated with large valve movements (Lee *et al.*, 2003b, 2005).

The discharge perturbation at the valve can be determined from the pressure variation during the valve manoeuvre for a fast valve movement. This pressure variation is converted into an equivalent discharge through the Joukowsky equation,

$$x = \Delta Q = -\frac{2gA\Delta H}{a} \tag{5}$$

where g is the acceleration due to gravity, a is wave speed, A is pipe cross-sectional area, ΔQ is induced discharge variation by the valve movement (input) and ΔH is the induced head variation by the valve movement (measured). The determination of the discharge input in this fashion is only valid if the head change substituted into Eq. (5) is the result of the valve perturbation alone. The valve movement should be fast to prevent contamination of the resultant head change by possible reflections from the system, including linepack. Details concerning this approach are shown in Lee *et al.* (2004, 2005).

4 Extraction of the impulse response function in an experimental system

An experiment leading to the extraction of the IRF was carried out in the Robin hydraulics laboratory at the School of Civil and Environmental Engineering at University of Adelaide. A schematic of the pipeline is shown in Fig. 5. The apparatus comprises a straight 37.53m length of copper pipe, 22.1mm internal diameter and 1.6 mm wall thickness and roughness height of 0.0015mm (Bergant and Simpson, 1995). The pipe slope is constant throughout with a vertical to horizontal ratio of 1 : 18.5. The elevation difference between the two ends of the pipe is 2m. To ensure fluid homogeneity and prevent corrosion of pipeline components, deionised water is used in the system. The pipe connects two electronically regulated pressure tanks with in-line ball valves (Whitney 65TF16, internal diameter 22.2 mm) located at the boundaries for flow control. The tanks are pressurised by an air compressor during the transient test. Electronic pressure relief valves are mounted at the top of the tanks to allow automatic control of pressures at the reservoirs. The tanks have a maximum pressure rating of 70mhead. Pressure signals are measured using Druck PDCR 810 flush-faced pressure transducers with an absolute pressure range of 0 to 600 kPa. The pressure transducers have a rise time of 5×10−6 s and the measurement uncertainty is rated at 0.1% of the full measurement span. The data acquisition card (PCI – 20428W−1) has a maximum single channel sampling rate of 100 kHz and can gather data with up to 16 channels. The data acquisition is controlled using Visual Designer software installed on a Pentium 150MHz computer. The pressures are sampled at a frequency of 2000 Hz. To minimise electronic noise, the pressure transducers are driven by 24VDC batteries.

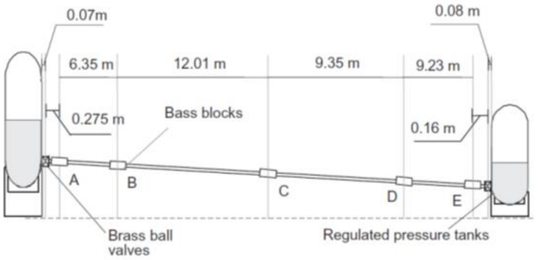
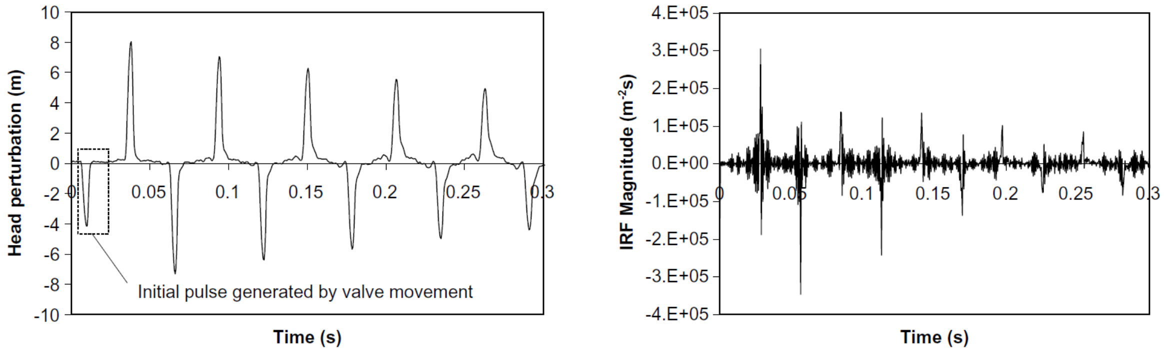


Figure 5 Schematic of experimental pipeline at the University of Adelaide.

For this investigation, the boundary heads were set at 37 and 36.5m giving a flow velocity = 0.5ms^{-1} and a Reynolds number = 11, 000 with all inline valves fully open. The transient was generated by a pulse perturbation of a side-discharge valve located close to the midpoint of the pipe (point “C” in Fig. 5) and the transient was measured at this position. The resultant transient trace—the output from the system—is shown in Fig. 6(a). The section of the transient trace associated with the valve movement is boxed in the figure. The input is defined as the discharge perturbation induced by the valve motion and is calculated from Eq. (5) using the boxed section of the transient signal as the time series for ΔH.



(a) (b)

Figure 6 (a) Transient trace. (b) Unfiltered impulse response function from the leak-free experimental pipeline.

The amplitude spectrum of the resultant input is shown in Fig. 7. The spectrum indicates that beyond 300 Hz, the amplitude of the input has fallen below 5% of its maximum level. At higher frequencies, the energy of the input approaches zero and the signal to noise ratio of the extracted FRF is poor. This result is illustrated in the FRF for the experimental data with frequencies ranging from zero to 1000 Hz (the Nyquist frequency for a sampling frequency of 2000 Hz) in Fig. 8. From the figure, the lower frequencies (< 300 Hz) consist of regular harmonic peaks whereas the higher frequencies contain mainly random noise. The bandwidth of the signal—the range of frequencies that contain useful information from the system—is between zero and 300 Hz.

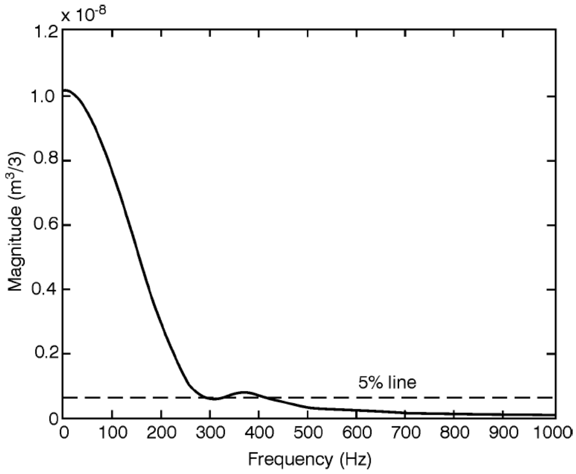


Figure 7 Spectrum of the injected pulse signal.

Using this set of input and output from the system, the IRF is determined using Eq. (3). The resultant IRF is shown in Fig. 6(b). Unlike the numerical results in Fig. 2(b), the IRF from the experiment displays a significant level of distortion and the spikes in the IRF are no longer visible as discrete boundary reflections. This distortion is caused by the noise in the higher frequencies in the FRF (refer to Fig. 8). A window function should be multiplied into the FRF using Eq. (4) to remove this noise component outside the bandwidth of the signal. In this paper two different window functions were considered, the Hamming and the Blackman windows, both chosen for their ability to create a smooth reduction in the FRF at higher frequencies.

The effect of using the Hamming and Blackman window on the FRF prior to the inverse Fourier transform is shown in Fig. 9. Both windows have a width of 2000 Hz, the sampling frequency of the experiment. From Fig. 9, the distortion in the IRF was removed using the filters, with the Blackman window producing the better result.

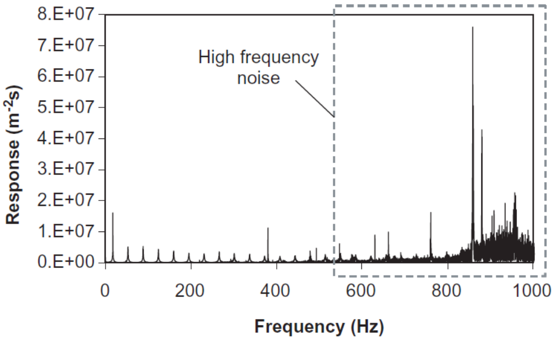


Figure 8 Bandwidth-related high-frequency noise in FRF.

5 Experimental leak detection using the impulse response function

For any injected transient signal, the resultant IRF of an intact pipeline consists of a series of sharp pulses about zero (refer to Fig. 9). Note that the form of the IRF is automatically time-shifted such that the start of a transient signal corresponds to *t* = 0 in the IRF. Each of these pulses corresponds to a reflection from the system. Detection of pulses at times that do not correspond to arrival times of boundary reflections indicates the possible presence of a leak in the system (refer to Fig. 2b). The form of the IRF is not affected by the shape of the injected signal; it is solely dependent on the state of the system. This property of the IRF removes the need for a system benchmark for comparison and allows results of different transient tests to be compared directly (as illustrated in Fig. 2). The IRF approach also refines all system reflections, increasing the accuracy of the leak detection procedure. As shown later in the paper, the IRF allows the use of more complex signals for this purpose, previously not possible using the raw transient trace without a detailed leak-free benchmark. This development allows the design of more sophisticated transient signals in the future that take advantage of developments in advanced signal processing fields.

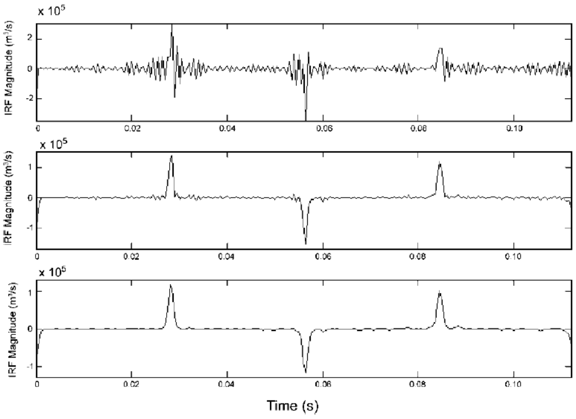
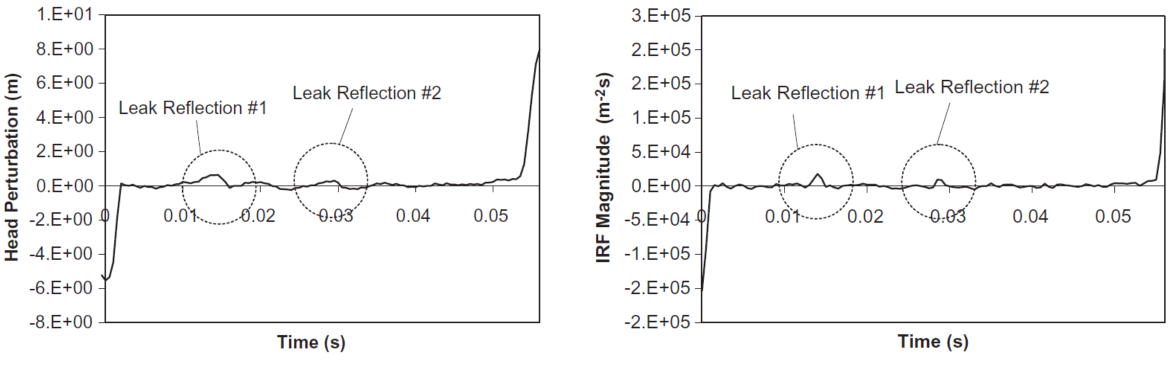


Figure 9 Effect of each window on the form of the impulse response function, with (a) the unfiltered impulse response function, (b) the filtered impulse response function using Hamming, and (c) the filtered impulse response function using Blackman.

The investigation into the detection of leaks using the IRF was conducted in the experimental apparatus of Fig. 5 with the in-line valve fully closed (at “E”) and the upstream reservoir set at 39.6 m. A leak 28.06mfrom the upstream boundary (position “D” in Fig. 5) has an orifice diameter 1.5mm and $C_dA_L/A = 4.17 \times 10^{-3}$. The elevation at the leak is 0.5 m. A pressure transducer was placed in the system to measure the transient response 0.16m from the inline valve (position “E” in Fig. 5).

To illustrate the refinement of the system reflections through the IRF extraction procedure, the transient was generated by a simple pulse perturbation (close–open–close) of a side-discharge solenoid valve located at the pressure transducer (position “E” in Fig. 5). The form of the pulse is the same as the one used in Fig. 6. The measured transient trace is shown in Fig. 10(a) and the extracted

IRF in Fig. 10(b). For the purpose of comparing the shapes of the reflected signals between the transient trace and the IRF, the leak reflections in both figures are circled. Two leak reflections, labelled “#1” and “#2”, are present in the data. Reflection #1 occurs when the original transient signal travels away from the source, partially reflects from the leak and the reflection returns to the measurement station. The primary signal subsequently reflects from the downstream boundary, travels through the leak once again and forms reflection #2. Comparing the form of the reflections between the original signal and the IRF, the reflections are noticeably sharper in the case of the IRF. In particular, the poorly formed reflection #2 in the original transient trace is enhanced and is more evident in the IRF.



(a) (b)

Figure 10 (a) Original transient trace for the transient event measured by the pressure transducer and (b) extracted impulse response function.

For the IRF the arrival times of reflections #1 and #2 (based on the peak positions of the reflections on the time axis) are 0.014 s and 0.0285 s, respectively. The first arrival time corresponds to a leak position 9.29 m upstream of the measurement transducer, which is almost equal to the true leak location of 9.23 m. For comparison, the arrival time of the first leak reflection is estimated from the raw transient signal. This arrival time was measured in two ways: as the time lag from the start of the transient to the start of the reflected signal and also as the time lag between the peaks of the injected signal and the observed reflection. In both cases, the estimated arrival time is 0.0145 s, placing the leak 9.63 m upstream of the transient source. The latter location is less accurate than the result from the IRF.

6 Complex signals for leak detection using the impulse response function

The transient pulse input used in the previous section is an example of a signal that has high bandwidth. However, this input is of a short duration (with low energy) and is susceptible to contamination from noise. More complex input signals can possess both high bandwidth and high energy. Developments in other fields have shown that a type of wide bandwidth continuous signal of low amplitude is a *pseudo-random binary signal* (PRBS) or maximum length sequence signal (Pande, 1982; Dallabetta, 1996). PRBS is commonly used in electrical systems for the determination of the system response functions (Tan and Godfrey, 2001). These signals consist of a series of randomly spaced and equal magnitude pulses that are set to repeat periodically and have a similar spectrum to that of a single input pulse. The periodicity of the random sequence provides the signal with a high degree of noise tolerance and removes the statistical variability often associated with signals of a pure random nature (Liou, 1998). The energy of the signal can be distributed over a longer time-frame, allowing the amplitude of each individual pulse to be small while maintaining the same signal bandwidth (Niederdränk, 1997; Liou, 1998). The complex form of this signal will not allow leaks to be located using the raw transient trace; therefore, use of the IRF is necessary.

To illustrate the application of the IRF in this situation, consider the following numerical example. A transient is generated by perturbing (close–open–close) a downstream in-line valve in the pipeline of Fig. 11 where a leak of *C*d*A*L = 1.4 × 10−4 m2 (0.198%) is located 1,400m from the upstream boundary. The transient data are generated using a method of characteristics model with a computational time step of 0.167 s (100 reaches). The resultant input (valve tau fluctuation) and the output (measured head response) are given in Fig. 12(a) and 12(b). From the measured transient trace, the form of the signal is complex and the detection of a leak reflection using this raw transient data without an accurate leak-free benchmark is not possible. In comparison, the IRF extracted from this transient event is shown in Fig. 12(c). From the IRF, the position of the leak-reflected signal is evident and is circled. In cases where complex signals are used, the IRF simplifies the data such that the leak reflections can be determined without a leak-free benchmark. The refinement of the extracted information using complex signals can be carried out using the procedures presented in this paper.

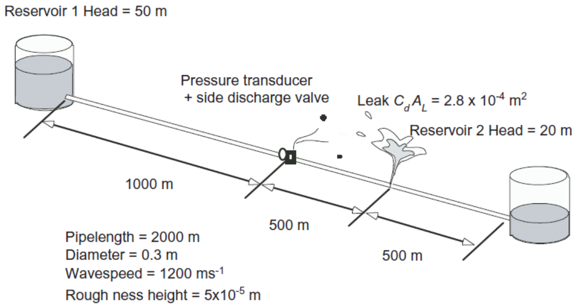


Figure 11 System layout for numerical simulations.

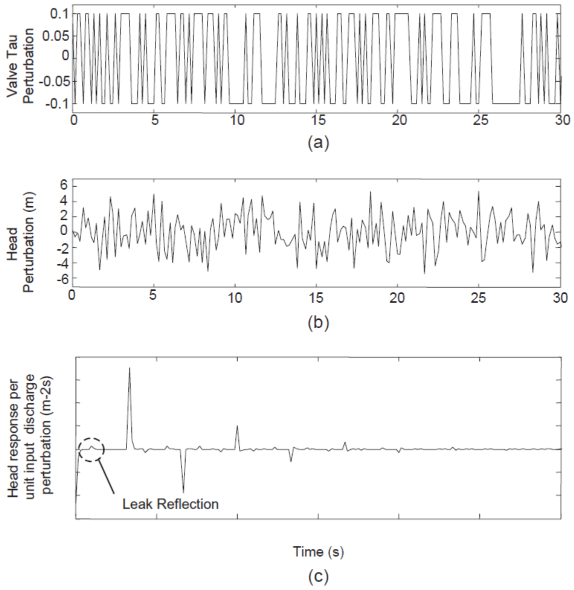


Figure 12 (a) Input, (b) output, and (c) IRF for PRBS signal.

7 Limitations to the proposed approach

This paper illustrates that the amount of information contained in the transient trace is related to the bandwidth (frequency content) of the injected signal. As a result, it is important to maximise the input bandwidth. The time domain analog is that the input signal must be sharp to identify details of the fault. Transients generated by pump trips and the manual closure of valves will not be appropriate for this technique and will lead to inaccuracy. The rapid pressure perturbation generated by a solenoid valve used in this paper has a pulse width of approximately 4ms and a corresponding bandwidth of 300 Hz. Even this rapid manoeuvre may seem inadequate for the task when one realises that this pulse has a physical wave length of over 4 metres—and it is being used to detect and identify faults (such as a small hole in the pipe wall) that are a few *millimetres* in size. The solution to the problem may depend on more sophisticated input signal designs—to allow details of the fault to be seen within the IRF.

The proposed IRF extraction procedure assumes system linearity. Transient signals in pipelines are weakly non-linear systems and this approximation of linearity is valid under most conditions. In cases, where the system displays strongly nonlinear behavior, the resultant IRF will no longer be a unique descriptor of the system and a different IRF may result when a different input signal is used. In this paper, the IRF is used as a means to refine the shape of the transient reflection. This property of the IRF will hold even in highly non-linear conditions. For this reason, the IRF procedure may be considered as a signal processing/refining step in highly non-linear systems.

As for all transient leak detection techniques, this approach is dependent on a good estimation of system wave speed. This can be measured insitu using multiple measurement stations or from the arrival times of reflections from system boundaries. Techniques for estimating the wavespeed are described in previous literature (Jönsson and Larson, 1992; Brunone, 1999; Covas and Ramos, 1999; Jönsson, 2001). Though not presented in this paper, the size of the reflection is directly related to the size of the leak and similar procedures to those presented in Brunone (1999) and Covas and Ramos (1999) can be used to size to leak. A slight reduction in the reflection magnitude will result from the windowing process and may affect the estimated leak size.

8 Conclusions

This paper has presented the impulse response function as a means of leak detection in pressurised fluid pipelines. The experimental extraction of the impulse response function indicates that frequency content of the injected transient signal must be taken into account to minimise distortion. All frequencies beyond the frequency range—bandwidth—of the injected signal should be removed prior to the calculation of the impulse response function. The impulse response function can be used to augment and improve existing leak detection methods.

The impulse response function can increase the accuracy of the leak location procedure through refinement of the system reflection. In addition, the impulse function removes the previous reliance on a leak-free benchmark as the form of the function is unaffected by the shape of the transient signal. This property allows a means of comparing transient traces of different shapes
and the use of more sophisticated signals—such as PRBS—for leak detection. Sophisticated signals cannot detect leaks using the raw transient trace unless accurate knowledge of the leak-free behaviour of the system is available. The impulse response function can facilitate future research in signal designs for extracting the maximum information from pipelines using fluid transients.

Notation

A = Pipe cross-sectional area
a =Wave speed
A_L = The area of the leak orifice
C_d = Discharge coefficient
C_dA_L = Lumped leak discharge coefficient
F = Frequency response function
g = Gravitational acceleration
H = Head
I = Impulse response function
Q = Discharge
r = Correlation function (time domain)
S = Correlation function (frequency domain)
t = Time
W =Window function (filter)
x = Distance along the pipe or input to the system (time domain)
X = Input to the system (frequency domain) or fitting parameters
Y = Output from the system (frequency domain)
y = Output from the system (time domain)

Greek symbols
ΔH = Induced-head perturbation at the transient-generating valve
ΔQ = Induced discharge perturbation at the transient generating valve
ω = Frequency

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