Jinzhe Gong, Martin F. Lambert, Aaron C. Zecchin, Angus R. Simpson

Experimental verification of pipeline frequency response extraction and leak detection using the inverse repeat signal

Journal of Hydraulic Research, 2016; 54(2):210-219

Experimental verification of pipeline frequency response extraction and leak detection using the inverse repeat signal

JINZHE GONG, Research Associate, *School of Civil, Environmental and Mining Engineering, University of Adelaide, SA 5005, Australia.*

Email: jinzhe.gong@adelaide.edu.au (author for correspondence)

MARTIN F. LAMBERT (IAHR Member), Professor, *School of Civil, Environmental and Mining Engineering, University of Adelaide, SA 5005, Australia.*

Email: martin.lambert@adelaide.edu.au

AARON C. ZECCHIN (IAHR Member), Lecturer, *School of Civil, Environmental and Mining Engineering, University of Adelaide, SA 5005, Australia.*

Email: aaron.zecchin@adelaide.edu.au

ANGUS R. SIMPSON, (IAHR Member), Professor, *School of Civil, Environmental and Mining Engineering, University of Adelaide, SA 5005, Australia.*

Email: angus.simpson@adelaide.edu.au

Running Head: Pipeline frequency response extraction and leak detection.

Experimental verification of pipeline frequency response extraction and leak detection using the inverse repeat signal

ABSTRACT

This paper presents the original design of a side-discharge valve based transient generator that can generate two types of pseudorandom binary signals: the maximum length binary signal and the inverse repeat signal (IRS). These two signals are both wide bandwidth, persistent and periodic, but the IRS has the advantageous property that it is antisymmetric within each period. The two signals are used to extract the frequency response function (FRF) of a single water pipeline in the laboratory. The experimental results demonstrate that the FRF extracted by the IRS is closer to the theoretical linear results as obtained from the transfer matrix method due to it being able to cancel the effect of even-order nonlinearities. The customised transient generator is then applied to a pipeline with a leak. The location of the leak is successfully determined using the first three resonant peaks as extracted by the IRS.

Keywords: fluid transient; frequency response function; leak; pipeline; pseudorandom binary signal; water hammer.

1. **Introduction**

The analysis of the dynamic response of pressurised pipeline systems is essential for the design, operation and also for the integrity monitoring of the system. In hydraulic pipeline systems, dynamic analysis is typically conducted by introducing a transient or water hammer wave into the system and then measuring and analysing the pressure response at a given location. The system response function, which is known as the frequency response function (FRF) in the frequency domain (Ljung, 1999), gives information about the physical characteristics of a pipeline system.

Frequency-domain analysis is of particular interest since it allows the study of the frequency dependent effects, such as fluid-structure interaction (Tijsseling, 1996) and unsteady friction (Vítkovský, Stephens, Bergant, Simpson, & Lambert, 2006). In the last decade, the analysis of the FRF of pipeline systems under linear system theory has also been used in integrity monitoring of water pipelines, such as the detection of leaks (Covas, Ramos, & de Almeida, 2005; Duan, Lee, Ghidaoui, & Tung, 2011; Gong, Lambert, Simpson, & Zecchin, 2013, 2014; Lee, Vítkovský, Lambert, Simpson, & Liggett, 2005a, 2005b; Mpesha, Gassman, & Chaudhry, 2001; Sattar & Chaudhry, 2008), discrete blockages (Lee, Vítkovský, Lambert, Simpson, & Liggett, 2008; Sattar, Chaudhry, & Kassem, 2008), extended blockages (Duan, Lee, Ghidaoui, &

Tung, 2012, 2013), and general parameter identification (Zecchin, White, Lambert, & Simpson, 2013).

Experimental verifications of the FRF-based techniques, however, are limited. One important factor that impedes the application is that the linear system FRF of a real pipeline is difficult to obtain. The generation of an appropriate excitation transient signal is challenging because of high back-pressure in the pipeline and limitations in the manoeuvrability of valves or other hydraulic components that are used as the signal generator (Lee, Vítkovský, Lambert, & Simpson, 2008). In early studies, the extraction of the FRF of a pipeline was conducted through oscillating specially designed valves or hydraulic components at a number of frequencies in sequence, which is known as a frequency sweep (or sine-sweep) (Svingen, 1996). An alternative to the time-consuming frequency sweeping technique is to extract the FRF within a single operation using a wide bandwidth input signal. Side-discharge valves are typically used to generate pulse or step signals in pressurised pipelines (Lee, Lambert, Simpson, Vítkovský, & Liggett, 2006). The pulse signal needs to be sharp and its amplitude has to be large enough to ensure a sufficient signal-to-noise ratio (SNR) in the high frequency components. However, the large amplitude requirements of the pulse signal may also risk damage to the pipeline system (Lee, Vítkovský, Lambert, & Simpson, 2008).

A desirable transient excitation signal for the linear system FRF extraction should have a wide bandwidth, high SNR and low amplitude. Developments in other disciplines have shown that the pseudorandom binary signal (PRBS), which is a sequence with values of 1 and 0, has these desired characteristics (Godfrey, 1993; Tan & Godfrey, 2002). The PRBS is predetermined and periodic. Its spectrum has a wide bandwidth. When repeated period by period, the periodicity enables the SNR to be increased by synchronous averaging of the response periods, and the persistency allows the energy to be distributed over a long time period so that the amplitude of the signal can be small.

In the application to pressurised water pipeline systems, Liou (1998) conducted numerical studies on IRF extraction of a pipeline using the maximum length binary signal (MLBS) which is the most commonly used type of PRBS. Lee, Vítkovský, Lambert, & Simpson (2008) designed and fabricated the first side-discharge valve-based transient generator for the extraction of the FRF of a pipeline in the laboratory using MLBS (referred to as PRBS in that paper). The valve was electronically controlled by a single solenoid to produce discrete pulse sequences that follow a MLBS-based pattern. A pulse was generated by abruptly opening and then closing the side-discharge valve when a digit ‘1’ was encountered in a MLBS sequence. However, the discrete pulse sequence is not the standard signal form for PRBS-based system identification, where the continuous form is desired.

Another particular challenge for the application of FRF-based pipeline fault detection is the linearisation error. All the existing FRF-based pipeline fault detection techniques were developed using linear systems theory. However, like most systems in the real world, pipeline systems also have nonlinearities. For unsteady pipe flow, the friction term is nonlinear, and the governing equations of some hydraulic components, such as oscillating valves, orifices and leaks, are also nonlinear (Chaudhry, 1987; Wylie & Streeter, 1993). The nonlinearity is constant in repeated tests and different from experimental uncertainties or measurement noise that is more stochastic in nature and can be reduced by averaging the results of multiple tests. Linearisation is used in the development of FRF-based pipeline fault detection techniques, and as a result, linearisation error is introduced. The linearisation error can have great impact on the accuracy of the FRF-based pipeline integrity assessment, because discrepancies are expected between the FRF as predicted by the linear model and that measured from real pipeline systems. The linearisation error associated with an oscillating valve was discussed in Lee, Vítkovský, Lambert, Simpson, & Liggett (2002), Lee et al. (2005a), Lee and Vitkovsky (2010), Lee (2013), Gong, Lambert, Zecchin, & Simpson (2011) and Gong, Lambert et al. (2013) by numerical analysis, and it was found that the linearisation error is proportional to the normalised amplitude of the valve oscillation. However, until now, there has no experimental study on how to reduce the effects of nonlinearity on the extracted pipeline FRF.

This research addresses the challenge of FRF extraction of real pipelines and the linearisation error in FRF-based pipeline fault detection. It proposes a practical technique for extracting the linear system FRF of pressurised pipelines for the purpose of leak detection. A side-discharge valve controlled by two solenoids has been designed and fabricated as a transient generator for FRF extraction using persistent MLBS and inverse repeat binary signal (IRS), which is obtained by doubling the MLBS and inverting every other digit of the double sequence. Research in other disciplines shows that IRS is more suitable for extracting the linear dynamics of a system, especially when the system has some nonlinearities (Godfrey, 1993). Laboratory experiments were conducted in a reservoir-pipeline-valve (RPV) system, with three different values of the amplitude of valve perturbation, to determine the FRF. In each case study, experimental FRF results extracted by MLBS and IRS respectively were compared with the theoretical linear system FRF obtained from the transfer matrix method. The experimental results verify that the IRS is better than MLBS in terms of extracting the linear FRF of a pipeline system. An orifice is then placed on the pipe wall to simulate a leak and IRS is used to extract the FRF.

The location of the leak is successfully determined from the first three resonant responses, which verifies the usefulness of the proposed pipeline linear FRF extraction technique.

2. **Inverse repeat binary signal**

Research in other disciplines has shown that, compared to the MLBS, the antisymmetric inverse repeat binary signal (IRS) can yield to a better estimation of the linear dynamics of a system when some nonlinearities are present (Godfrey, 1993; Roinila, Vilkko, & Suntio, 2010). To illustrate this, the output signal of a sampled nonlinear system can be represented as a Volterra series expansion (Godfrey, 1993):

$$\begin{aligned} y(n) &= \sum_{k=0}^{M} s_1(k)x(n-k) \\ &+ \sum_{k_1=0}^{M}\sum_{k_2=0}^{M} s_2(k_1,k_2)x(n-k_1)x(n-k_2)+\cdots \\ &+ \sum_{k_1=0}^{M}\cdots\sum_{k_i=0}^{M} s_i(k_1,\cdots,k_i)x(n-k_1)\cdots x(n-k_i) \end{aligned} \tag{1}$$

where $y(n)$ and $x(n)$ are system output and input, respectively; M is the length of total data sequence of interest; s_1 is the linear kernel of system dynamics and $s_2,\cdots,s_i$ are the nonlinear kernels. The cross-correlation function $\phi_{xy}(n)$ between the input and the output can then be written as:

$$\begin{aligned} \phi_{xy}(n) &= \sum_{k=0}^{M} s_1(k)\phi_{xx}(n-k) \\ &+ \sum_{k_1=0}^{M}\sum_{k_2=0}^{M} s_2(k_1,k_2)\phi_{xx}(n-k_1)\phi_{xx}(n-k_2)+\cdots \\ &+ \sum_{k_1=0}^{M}\cdots\sum_{k_i=0}^{M} s_i(k_1,\cdots,k_i)\phi_{xx}(n-k_1)\cdots\phi_{xx}(n-k_i) \end{aligned} \tag{2}$$

where $\phi_{xx}(n-k_1)\cdots\phi_{xx}(n-k_i)$ represents the i th order autocorrelation function of the input and it can be described by

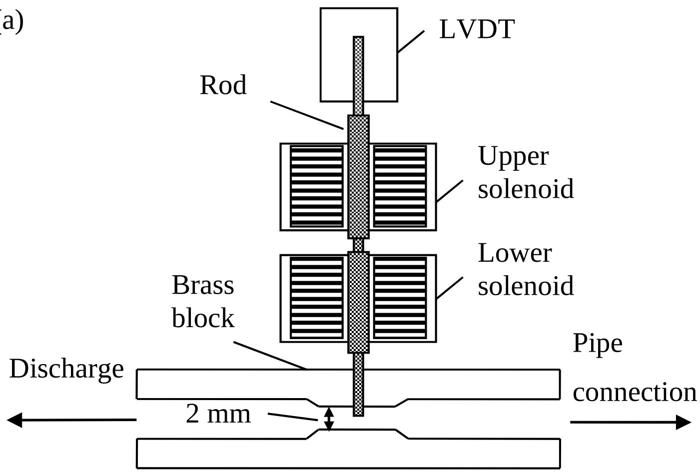
$$\phi_{xx}(n)_i = \sum_{k_1,\cdots,k_i}^{M} x(k)x(n-k_1)\cdots x(n-k_i) \tag{3}$$

Under linear time invariant systems theory, the FRF is the ratio of the Fourier transform of the cross-correlation between the input and the output [$\phi_{xy}(n)$] to that of the autocorrelation of the input [$\phi_{xx}(n)$].The even kernel components shown in Eq. (2) are cancelled out if the input signal is periodic and antisymmetric, i.e. $x(n) = -x(n + P/2)$ where P is the number of digits in one period (Godfrey, 1993; Roinila et al., 2010). Once the nonlinear effect caused by the second-order kernel (s_2) is removed, which is usually the dominating nonlinear kernel, the FRF as calculated is close to the linear part of the system dynamics. Because the linear system FRF is required in the FRF-based pipeline fault detection, the antisymmetric IRS is believed to be more suitable for extracting the linear system FRF of a pipeline system for this purpose.

3. **Experimental apparatus**

A customised side-discharge valve-based transient generator was developed in the laboratory to generate MLBS and IRS transient pressure signals within a pressurised pipeline for the purpose of FRF extraction. A schematic diagram of this transient generator is given in Fig. 1. A brass block with a small diameter hole (2 mm as the minimum) drilled through the long axis forms the conduit for the water to escape from the pipeline. A rod with 3 mm diameter and connected with the shaft of the two solenoids controls the valve opening. Compared to the single solenoid design in Lee, Vítkovský, Lambert, and Simpson (2008), the use of two solenoids acting in different directions enables a much faster manoeuvre for both opening and closure. The rod is also connected with a linear voltage displacement transducer (LVDT) at the top to measure its movement during signal generation. The calibrated equivalent opening of the valve ($C_d A_V$), when fully open, is 2.7×10^{-6} m^2. The opening of the side-discharge valve is very small compared to the cross sectional area of any municipal water pipelines so that the valve would not have any significant effects on the resonant frequencies of a pipeline system.

(a)



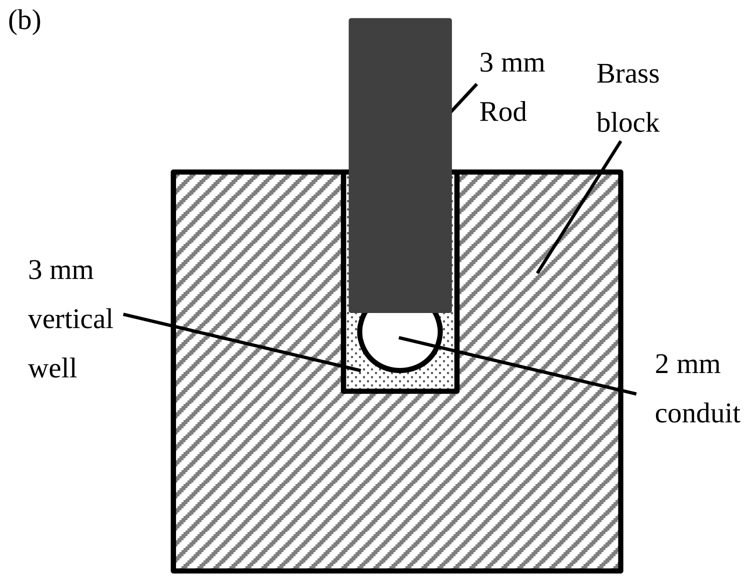


Figure 1 (a) Customized transient generator used for generating MLBS and IRS, and (b) cross-section of the conduit where the vertical rod locates.

The two solenoids, which are electronically controlled by an external PRBS signal generator, drive the rod to oscillate between two positions (valve fully open and partially closed). The rod moves only when there is a shift in the binary value of the PRBS. When the MLBS or IRS changes from 1 to 0, the solenoids drive the valve from fully open to partially closed and the valve remains partially closed until the binary value changes back to 1, which triggers the solenoids to open the valve fully. For example, if the binary sequence is ‘1101’, the valve presented in this paper will remain open for the first two steps, became partially closed in the third step, then open and keeps open until another ‘0’ is encountered. As a result, the opening of the valve follows a continuous form of MLBS or IRS, which is the desirable form of signal for system identification.

The movement of the rod is converted into an equivalent dimensionless valve opening coefficient, which is defined as $\tau = C_d A_V / (C_d A_V)_s$, where the subscript s represents steady-state reference value (Chaudhry, 1987). The average value of τ during the steady oscillatory condition is represented by τ_0. The normalised τ perturbation, $(\tau - \tau_0)/\tau_0$, is used as the input to the pipeline system. The normalised amplitude of the valve oscillation, $A_{in} = \max(\tau - \tau_0)/\tau_0$, is adjustable (i.e. the maximum displacement of the oscillating rod is adjustable).

The MLBS is generated by a 10-stage shift register based on a clock frequency of 100 Hz. As a result, its period is 10.23 s. The IRS is obtained by doubling the MLBS and reversing every other digit, so that the period of the IRS is 20.46 s. The bandwidth of the MLBS and the IRS (where the power of the signal drops to half the maximum) are both 44.3 Hz. The MLBS and the IRS can be generated continuously to produce a persistent MLBS or IRS perturbation in the opening of the valve.

The customised valve is connected to an experimental pipeline in the Robin Hydraulics Laboratory in the University of Adelaide. A schematic diagram of the experimental pipeline system is given in Fig. 2. The pipeline is made of copper and has a length of 37.53 m and an internal diameter of 22 mm. The pipeline is bounded by a closed in-line valve at one end and a pressurised tank with a head of 38.50 m at the other end, forming a reservoir-pipeline-valve (RPV) system. For a RPV system, the upstream side of the valve is the optimal excitation and observation point (Lee et al., 2006). The customised side-discharge valve-based generator is located 145 mm upstream from the closed in-line valve, and it has an elevation of 2.0 m above the upstream end of the pipeline. The head response of the pipeline system is measured upstream of the generator by a pressure transducer (Druck PDCR 810) mounted on the main pipe. The output of the transducer is connected to a customised amplifier and then collected by a data acquisition card (Measurement Computing USB-1608FS). The output of the LVDT (movement of the rod) is also recorded by the data acquisition card. The data acquisition is controlled by LabView software installed on a laptop computer. The sampling frequency used in this research is 5 kHz.

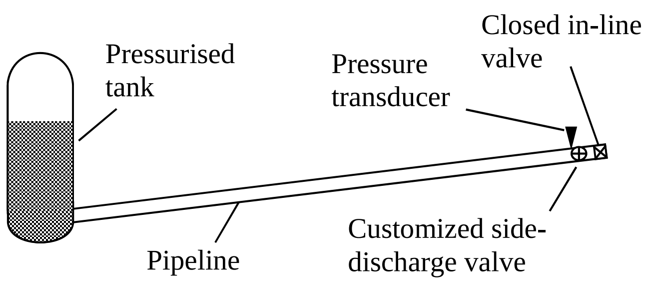


Figure 2 Schematic diagram of the experimental pipeline used in this research.

4. **Experimental extraction of the FRF using MLBS and IRS**

Three case studies have been conducted in the laboratory with a range of amplitudes of the relative dimensionless valve perturbation, A_{in}. In each case study, both the MLBS and the IRS input signals were used, and the experimental FRF of the pipeline was estimated and compared with the theoretical linear theory FRF determined from the transfer matrix method (Chaudhry, 1987). The repeatability was confirmed by conducting multiple tests in each case study. When the side-discharge valve was fully open, the steady-state flow through the side-discharge valve was 7.4×10^{-5} m^3s^{-1}. The corresponding Reynold's number is calculated as approximately 4268 and the flow regime is smooth pipe turbulent flow. As a result, the frequency-domain unsteady friction model developed by Vítkovský et al. (2003) was used in the numerical simulations to derive the theoretical FRD. This unsteady friction model is based on the smooth pipe unsteady friction weighting function proposed by Vardy and Brown (2003).

In the experimental study conducted, each individual experiment lasted for 10 minutes. The first few seconds of data were measured under steady state (with the side-discharge valve open) to observe the initial steady-state head variation of the system. Then the IRS, or MLBS, excitation was started. It was observed that the pressure in the pressurised tank became relatively stable after approximate 150 s of the start of the IRS or MLBS excitation. This is the time needed for the pressure regulator on the tank to adapt to the new condition imposed by the oscillating valve. As a result, in the process of the experimental FRF estimation, the first 245.52 s of data (24 periods of MLBS or 12 periods of IRS) in each test were removed to ensure that the data used in FRF calculation were under steady oscillatory flow conditions.

4.1. Case study No.1: input signal amplitude $A_{in} \approx 0.5$

Discharge from the valve was measured using a volumetric method during each test. In this case study, the steady-state discharge when the valve was at its most closed position was 2.7×10^{-5} m^3s^{-1}, and the mean discharge out of the valve during MLBS or IRS excitation was measured as 4.8×10^{-5} m^3s^{-1}. The Darcy-Weisbach friction factor was estimated as 0.04 by the mean discharge and it was used in the determination of the theoretical linear FRF using the transfer matrix method.

The normalised IRS τ perturbation (input) and the corresponding head perturbation (output) are given in Figs. 3 and 4. The envelopes of the power spectrum of these two signals are given in Figs. 5a and 5b. The measurements of the MLBS τ perturbation and its corresponding head response are not shown in the paper (for any of the three case studies) for the sake of brevity.

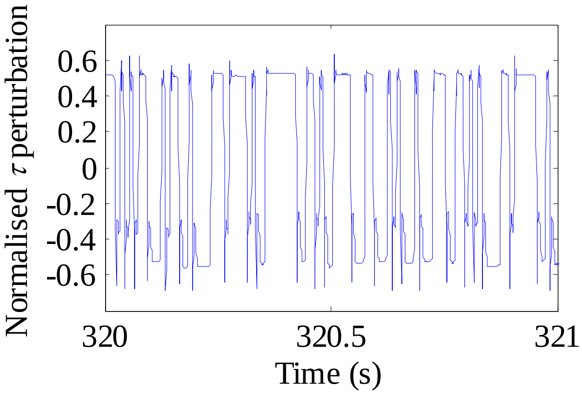


Figure 3 Normalised IRS τ perturbation (input) in the case study No.1.

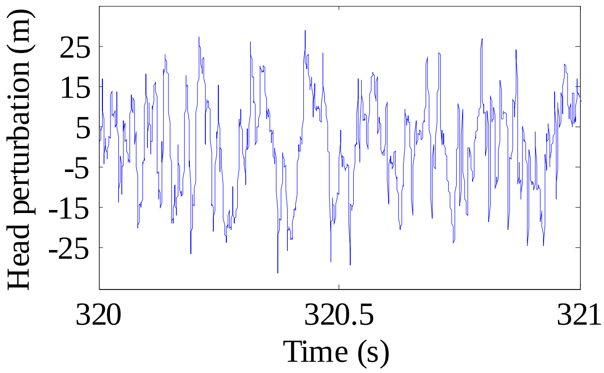
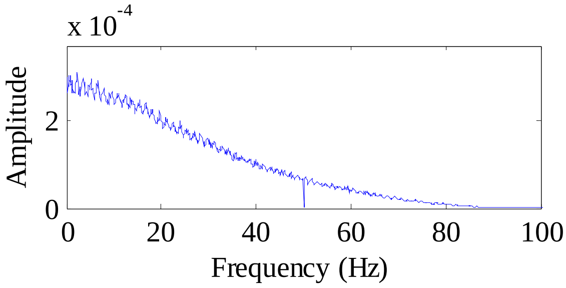


Figure 4 Head perturbation (output) in the case study No.1.

(a)



(b)

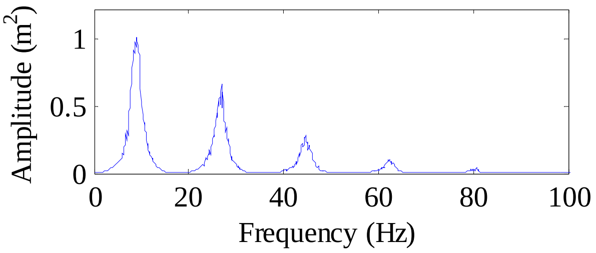


Figure 5 Envelope of power spectrum: (a) the normalised IRS τ perturbation (input); and (b) the head perturbation (output) for case study No.1.

The measured valve perturbation (Fig. 3) follows an IRS pattern, but with small variations due to the mechanics of the side-discharge valve. Those small variations are considered as part of the input signal in the FRF determination so the effects resulting from them are not significant. The measured head response (Fig. 4) shows little visible structure in the time domain, and the maximum magnitude is approximate ± 28 m. The power spectrum of the input (Fig. 5a) shows the frequency components included and their strength. Note that, for IRS, theoretically power shall be nil at half the clock frequency (Godfrey, 1993). The experimental spectrum as shown in Fig. 5a is very low at the 50 Hz (clock frequency is 100 Hz), which is consistent with the theory. The power spectrum of the output (Fig. 5b) demonstrates that the frequency response of the system reaches peaks at the odd harmonics of the fundamental frequency, and the responses at the first three harmonics are relatively strong.

The pipeline FRF is determined using linear systems theory from the data measured in the IRS and the MLBS experiments. The results of the experimental FRF in this case study are shown in Fig. 6 with comparison to the theoretical linear system FRF. Each FRF is normalised by dividing it by the corresponding peak value around the first resonant frequency. The horizontal axis is normalised by dividing the frequency values by the fundamental frequency of the pipeline, which was estimated as 8.94 Hz from the extracted FRF.

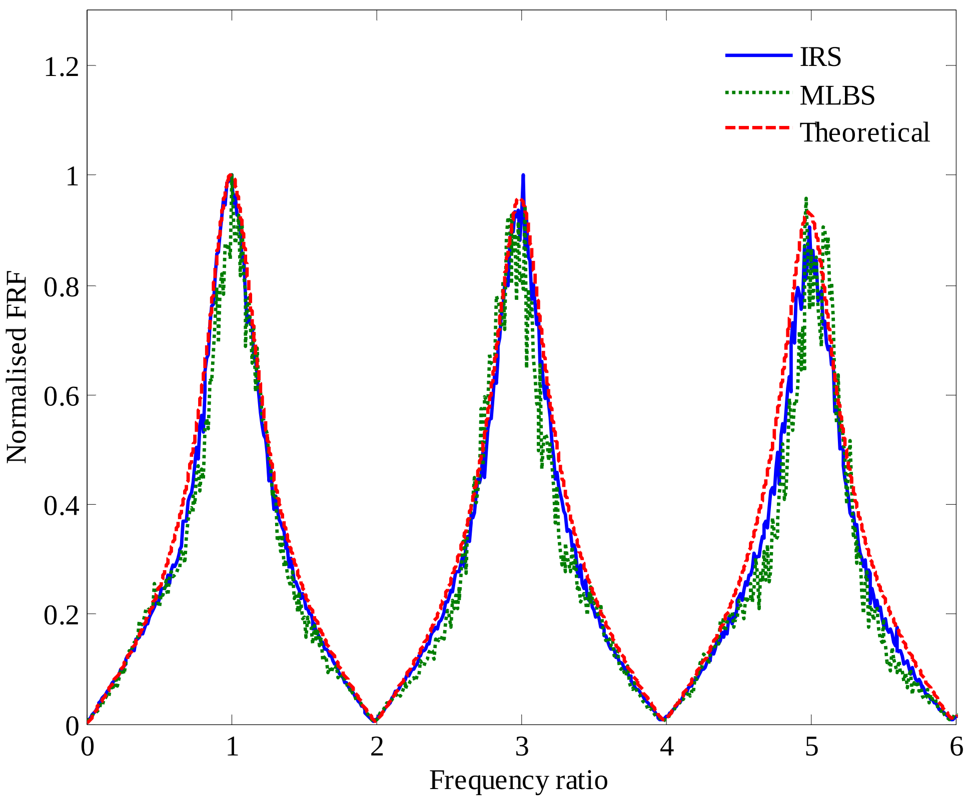


Figure 6 Comparison between the experimental FRF induced by IRS and MLBS excitation with the theoretical FRF in case study No.1.

It can be seen from Fig. 6 that the experimental FRF results show significant variations when compared with the smooth theoretical linear FRF. In the experimental FRF determined from MLBS, the third peak is greater than the second peak, while the theoretical FRF shows that the third peak should be the smallest one. Note that the relative sizes of the resonant responses are important in FRF-based pipeline leak or blockage detection. Experimental FRF with such degree of variation would lead to significant error in fault detection. A major source of these variations is attributed to the nonlinearity associated with the oscillating valve. In this case study, the amplitude of the normalised τ perturbation (A_{in}) is approximately 0.5, which can introduce a significant linearisation error in the linearised frequency-domain analysis (Lee & Vitkovsky, 2010; Lee et al., 2005a), because the linearised transfer matrix for an oscillating valve is just first-order accurate for small valve perturbations given that $A_{in} \ll 1$.

It is important to compare the FRF results between the MLBS and the IRS. From Fig. 6, the FRF induced by IRS is much smoother when compared with that obtained from MLBS. In addition, the resonant frequencies as shown in the FRF from IRS are closer to the theoretical resonant frequencies. The FRFs from MLBS and from IRS were obtained using the same experimental apparatus and the same FRF calculation algorithm. The only difference was in the properties of the input signal: the IRS is antisymmetric but the MLBS is not. The discrepancy between the two experimental FRFs indicates that the properties of the input signal can have great influence on the FRF extracted, and the IRS is better in estimating the linear system FRF of a pipeline system.

4.2. Case study No.2: input signal amplitude $A_{in} \approx 0.2$

In the second case study, the maximum allowable displacement of the rod in the customised side-discharge valve was reduced to lessen the nonlinear effects as imposed by the valve perturbation. The steady-state discharge when the valve was at its most closed position was 5.9×10^{-5} m^3s^{-1}, and the mean discharge out of the valve was 6.5×10^{-5} m^3s^{-1} under steady-oscillatory flow condition. The Darcy-Weisbach friction factor was 0.041. Sections of the normalised IRS τ perturbation (input) and its corresponding head perturbation (output) in this case study are shown in Figs. 7 and 8 respectively.

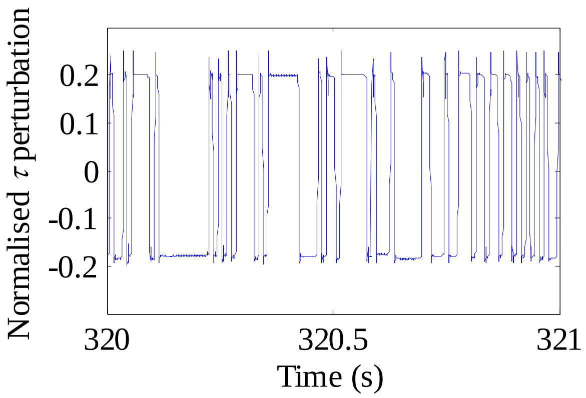


Figure 7 Normalised IRS τ perturbation (input) in the case study No.2.

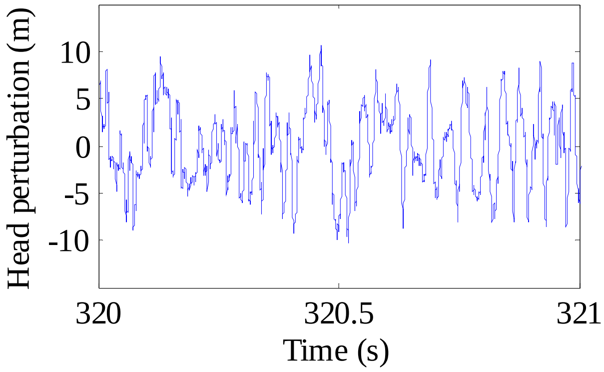


Figure 8 Head perturbation (output) in the case study No.2.

In the second case study, the magnitude of the head perturbation was decreased to approximately ± 11 m (Fig. 8). This indicates that the magnitude of the head perturbation under PRBS excitation is controllable by the value of A_{in}, and thus it can be adjusted to cater for various situations to eliminate the risk of damaging the pipeline. This experimental finding is consistent with the theoretical analysis presented in Lee et al. (2005b), which concludes that the magnitude of the resonant head response induced by an oscillating valve is proportional to the amplitude of valve perturbation.

The experimental FRF induced by the IRS and the MLBS are estimated and compared with the theoretical linear FRF in Fig. 9. The amplitude of valve oscillation in Case No. 2 is much smaller than that in Case No.1, thus theoretically the nonlinearity induced by the oscillating valve should be smaller (Lee & Vitkovsky, 2010; Lee et al., 2005a). The results of Case No. 2 show that both the experimental FRFs are close to the theoretical linear results in terms of the peak values and the resonant frequencies, and they are much smoother than those in Case No.1 (Fig. 6). This finding is consistent with previous numerical studies in Gong, Simpson, et al. (2013) and it confirms that the significant variation in frequency responses in Case No. 1 is induced by the nonlinear response of the system. It also provides experimental verification that the amplitude of the valve perturbation can significantly affect the accuracy of the FRF estimation. A smaller amplitude in the valve perturbation yields a better estimate of the linear FRF (with less variation). The experimental FRF extracted using IRS is even more consistent than that induced by MLBS. This once again verifies that the IRS is better in estimating the linear dynamics of a pipeline system than the MLBS.

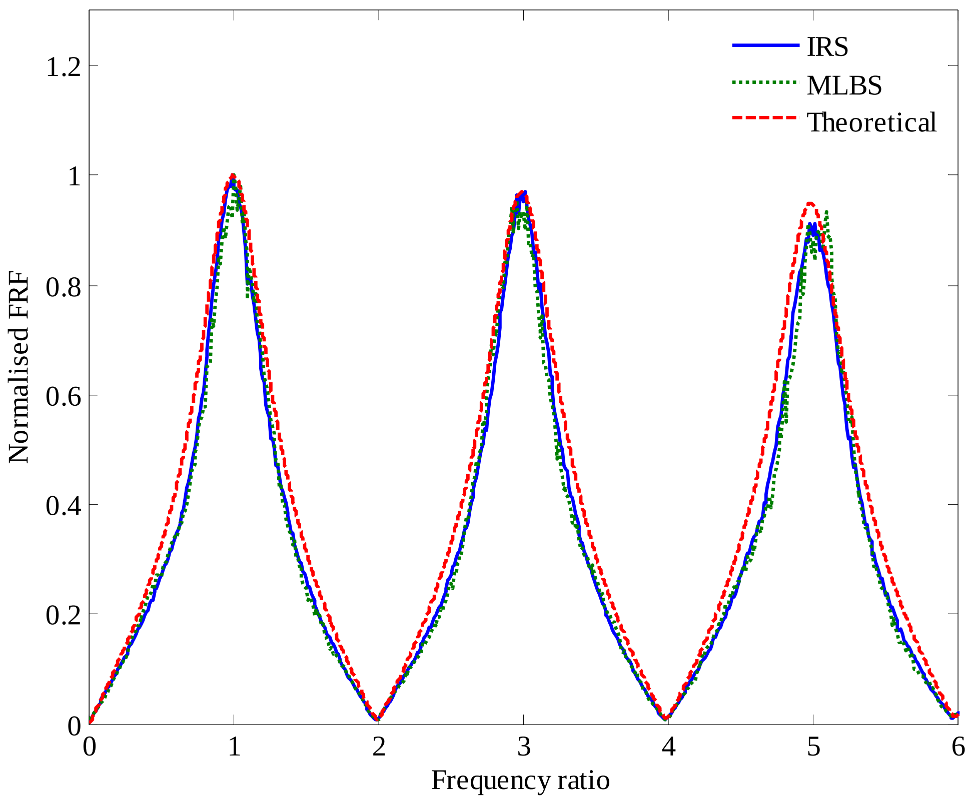


Figure 9 Comparison between the experimental FRF induced by IRS and MLBS excitation with the theoretical FRF in case study No.2.

4.3. Case study No.3: input signal amplitude $A_{in} \approx 0.06$

A third case study was considered with an even smaller amplitude of the valve perturbation ($A_{in} \approx 0.06$). The steady-state discharge when the valve was at its most closed position was 7.0×10^{-5} m^{3}s^{-1}, and the mean discharge out of the valve was 7.2×10^{-5} m^{3}s^{-1} under steady-oscillatory condition. The Darcy-Weisbach friction factor was 0.04. Sections of the normalised IRS τ perturbation (input), and its corresponding head perturbation (output), in this case study, are shown in Figs. 10 and 11 respectively.

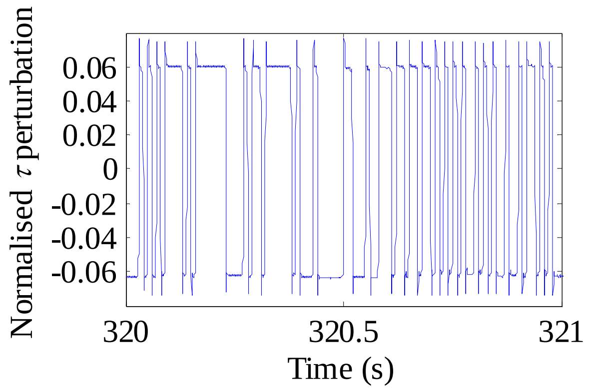


Figure 10 Normalised IRS τ perturbation (input) in the case study No.3.

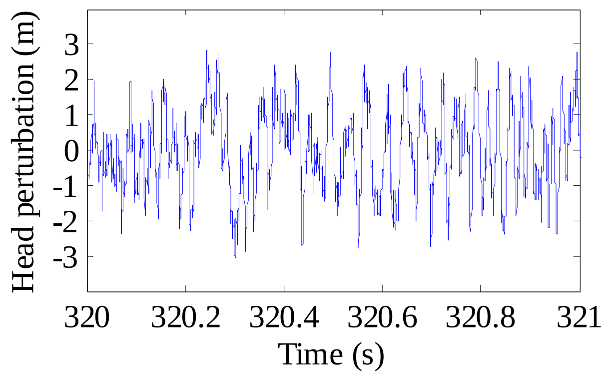


Figure 11 head perturbation (output) in the case study No.3.

In the third case study, the magnitude of the head perturbation (Fig. 11) was further decreased to approximately $\pm$ 3 m. The experimental FRF extracted by using the IRS and the MLBS are estimated and the results are compared with the theoretical FRF in Fig. 12.

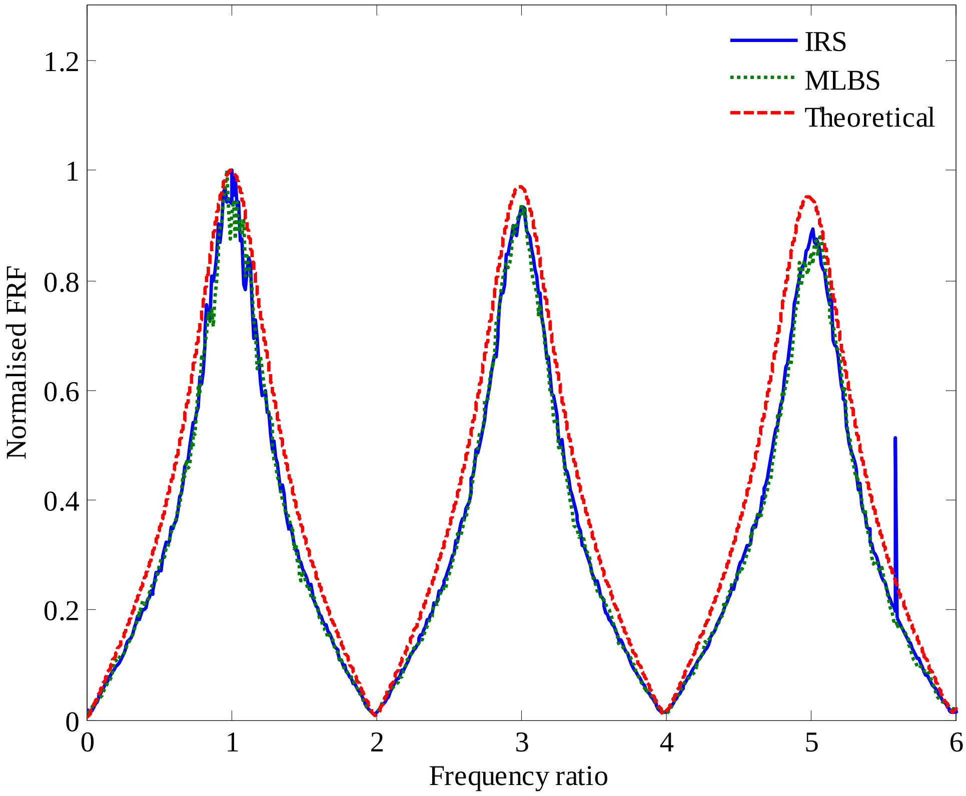


Figure 12 Comparison between the experimental FRF induced by IRS and MLBS excitation with the theoretical FRF in case study No.3.

Compared to the results obtained in the Case No.2 (Fig. 9), both the experimental FRF results extracted in Case No.3 show a greater discrepancy from the theoretical FRF. Other than the effects of nonlinearity, which is believed to be mild in this case study since A_{in} is small, the error in the experimental FRF is related to the low signal-to-noise ratio (SNR) in the measurement. The measurement noise is mainly from the background pressure fluctuations in the system resulting from the turbulence created at the side-discharge valve. When the side-discharge valve was fully open and remained fully open, the background pressure fluctuations observed by the transducer were approximately ±1 m in magnitude. In comparison, the transient pressure waves used in Case 3 (induced by oscillating the valve), were just approximately ±3 m. In the experimental FRF extracted by IRS, a spike is observed at 50 Hz. This is a false response and attributed to the low signal power of the IRS at this frequency (therefore low SNR), as discussed in Fig. 5a.

Overall, the experimental results of the three case studies verify that greater valve perturbation introduces greater nonlinearity. The IRS yields better estimation of the linear FRF of a pipeline than the MLBS when the nonlinear effect is significant. Because the linear system FRF is required in existing FRF-based pipeline integrity assessment techniques, the IRS is recommended to be used for extracting the linear system FRF of a pipeline system.

5. Application to leak detection

A free discharging orifice with a diameter of 2 mm was located at 31.21 m downstream from the tank to simulate a leak. The dimensionless leak location, which is defined as the ratio of the distance between leak and tank to the total length of the pipeline, is calculated as $x_L^* = 0.8316$. IRS with an amplitude of $A_{in} \approx 0.2$ was used as the excitation signal to extract the experimental FRF, and the results are given in Fig. 13. It can be seen that the experimental FRF is close to the theoretical linear FRF as derived from the transfer matrix method with unsteady friction.

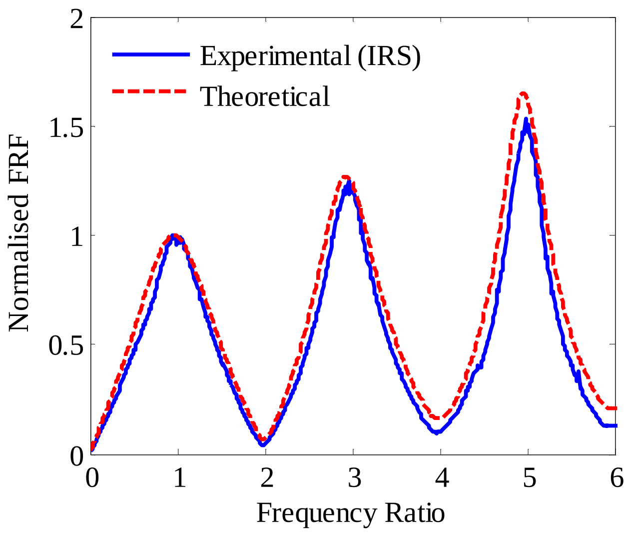


Figure 13 Experimental and theoretical FRF for a pipeline with a leak.

The leak detection technique proposed in Gong, Lambert, et al. (2013) is used to determine the location of the leak. This technique uses the relative sizes of the first three resonant peaks to determine the dimensionless leak location. When the FRF is normalised by the first resonant peak (i.e. the first peak is set to unity), the algorithm can be written as

$$x_L^* = \frac{1}{\pi}\arccos\left(\pm\frac{1}{2}\sqrt{1+\frac{\left(|h|_5^*-1\right)|h|_3^*}{\left(|h|_3^*-1\right)|h|_5^*}}\right) \tag{4}$$

where $|h|_3^*$ and $|h|_5^*$ are the values of the normalised frequency responses at the second and the third resonant peaks (which are the third and the fifth harmonics of the fundamental frequency of the pipeline). The values are read as $|h|_3^*$= 1.25 and $|h|_5^*$= 1.54 from the experimental FRF. As $|h|_3^*$ >1, this indicates that the leak location $x_L^* \in (0.5, 1)$. As a result, the experimental leak location as determined from Eq. (4) is 0.8115, which has an absolute error of 0.02 when compared with the real location 0.8316. The experimental results demonstrate that the customised PRBS transient generator is able to extract the linear system FRF of a pipeline system with enough accuracy for accurate leak detection.

6. **Challenges in the field**

This research has proposed a technique for extracting the linear system FRF of a water pipeline for the purpose of leak detection, and it has been verified by laboratory experiments. However, challenges are expected in field applications.

The customised side-discharge valve is a tool to extract the linear system FRF of a pipeline system. It can be applied to any pressurised pipelines with various materials. A practical issue for the customised side-discharge valve itself is that a cooling system is required to ensure the solenoids do not overheat. In the laboratory, an air cooling system was used which blows air around the solenoids. A similar air cooling system can be developed and used in the field.

Current FRF-based leak detection techniques require the pipeline system has a configuration equivalent to reservoir-pipeline-valve or reservoir-pipeline-reservoir. This requirement is sometimes difficult to meet in complex pipeline networks. A possible solution is to close an inline valve at one end of a branch and assuming the open boundary on the other end is acting as a reservoir (Lee et al., 2005a). The customised side-discharge valve and a pressure transducer can be connected to the upstream side of the closed inline valve to make excitation and take measurement.

7. **Conclusions**

This paper presents a technique for extracting the linear frequency response function (FRF) of a pressurised pipeline for the purpose of FRF-based pipeline leak detection. Both the persistent maximum length binary signal (MLBS) and the inverse-repeat signal (IRS) are used as the input. The original design of a dual-solenoid side-discharge valve-based transient generator has enabled the laboratory experiments.

Three case studies, with different values of valve perturbation magnitudes, have been conducted in the laboratory to extract the linear FRF of an intact pipeline. The research provides the first experimental verification that greater amplitude of valve perturbation leads to greater head perturbations in the system and greater nonlinear responses. When the nonlinearity induced by the oscillating valve is significant (see case study No.1), the FRF determined under linear systems theory contains significant variations. The relative sizes of the resonant responses are difficult to determine accurately, and therefore, introducing error in the FRF-based leak detection.

The experimental results also verify, for the first time, that the linear system FRF estimation of a real pipeline is affected by the properties of the input signal. Compared to the MLBS, the IRS can yield more accurate estimation of the linear system FRF (see Figs 6 and 9). The antisymmetric property of IRS enables part of the nonlinear responses of a system to be cancelled out in the calculation of the cross-correlation function of the input and the output. However, if the amplitude of valve perturbation and the magnitude of the corresponding head response are too small relative to the background pressure noise in the pipeline (see case study No.3), the signal-to-noise ratio could be poor and the estimated FRF can be affected by background pressure noise, which, in this research, is mainly resulting from the turbulence created at the side-discharge valve.

IRS is used to extract the FRF of a pipeline with a leak. The location of the leak is successfully determined by applying the leak detection technique proposed by Gong, Lambert, et al. (2013) to the first three resonant peaks in the FRF, which verifies the usefulness of the linear FRF extraction technique and the leak detection algorithm. This customised side-discharge valve provides possibilities for accurate extraction of the linear FRF of pressurised water pipelines in practice. Although challenges are expected in the field, this research is a step forward to the practical application of FRF-based pipeline leak detection.

Acknowledgments

The authors thank technicians Mr. Brenton Howie, Mr. Simon Order and Mr. Stan Woithe in the Robin Hydraulics Laboratory at the University of Adelaide for their support in the design and fabrication of the customised transient generator.

Funding

The research presented in this paper has been supported by the Australian Research Council through the Linkage Project Grant LP130100567.

Notation

A_{in} = amplitude of the input (-)

A_V = area of valve orifice (m^2)

C_d = coefficient of discharge for valve (-)

k = integer 0, 1, 2 … (-)

M = the length of total data sequence of interest (-)

P = number of digits in one period of a signal (-)

s_1 = linear kernel of a system (-)

$s_2, \cdots, s_i$ = nonlinear kernels of a system (-)

$x(n)$ = input signal (-)

$y(n)$ = output signal (-)

x_L^* = dimensionless leak location (-)

τ = dimensionless valve opening (-)

τ_0 = mean dimensionless valve opening (-)

$\phi_{xx}(n)$ = autocorrelation of the input (-)

$\phi_{xy}(n)$ = cross-correlation between the input and the output (-)

References

Chaudhry, M. H. (1987). *Applied hydraulic transients* (Second ed.). New York: Van Nostrand Reinhold Company Inc.

Covas, D., Ramos, H., & de Almeida, A. B. (2005). Standing wave difference method for leak detection in pipeline systems. *Journal of Hydraulic Engineering, 131*(12), 1106-1116. doi: 10.1061/(ASCE)0733-9429(2005)131:12(1106)

Duan, H.-F., Lee, P. J., Ghidaoui, M. S., & Tung, Y.-K. (2011). Leak detection in complex series pipelines by using the system frequency response method. *Journal of Hydraulic Research, 49*(2), 213-221. doi: 10.1080/00221686.2011.553486

Duan, H.-F., Lee, P. J., Ghidaoui, M. S., & Tung, Y.-K. (2012). Extended blockage detection in pipelines by using the system frequency response analysis. *Journal of Water Resources Planning and Management, 138*(1), 55-62. doi: 10.1061/(asce)wr.1943-5452.0000145

Duan, H.-F., Lee, P. J., Kashima, A., Lu, J., Ghidaoui, M. S., & Tung, Y.-K. (2013). Extended blockage detection in pipes using the system frequency response: analytical analysis and experimental verification. *Journal of Hydraulic Engineering, 139*(7), 763-771. doi: 10.1061/(asce)hy.1943-7900.0000736

Godfrey, K. (1993). *Perturbation signals for system identification*. New York: Prentice Hall Inc.

Gong, J., Lambert, M. F., Simpson, A. R., & Zecchin, A. C. (2013). Single-event leak detection in pipeline using first three resonant responses. *Journal of Hydraulic Engineering, 139*(6), 645-655. doi: 10.1061/(ASCE)HY.1943-7900.0000720

Gong, J., Lambert, M. F., Zecchin, A. C., & Simpson, A. R. (2011, September). *Frequency response measurement of pipelines by using inverse-repeat binary sequences.* Paper presented at the CCWI 2011: Computing and Control for the Water Industry: Urban Water in Management - Challanges and Opportunities, Exeter, UK.

Gong, J., Simpson, A. R., Lambert, M. F., & Zecchin, A. C. (2013). Determination of the linear frequency response of single pipelines using persistent transient excitation: a numerical investigation. *Journal of Hydraulic Research, 51*(6), 728-734. doi: DOI: 10.1080/00221686.2013.818582

Gong, J., Zecchin, A. C., Simpson, A. R., & Lambert, M. F. (2014). Frequency response diagram for pipeline leak detection: comparing the odd and the even harmonics. *Journal of Water Resources Planning and Management, 140*(1), 65–74. doi: DOI: 10.1061/(ASCE)WR.1943-5452.0000298

Lee, P. J. (2013). Energy analysis for the illustration of inaccuracies in the linear modelling of pipe fluid transients. *Journal of Hydraulic Research, 51*(2), 133-144. doi: 10.1080/00221686.2012.734861

Lee, P. J., Lambert, M. F., Simpson, A. R., Vítkovský, J. P., & Liggett, J. A. (2006). Experimental verification of the frequency response method for pipeline leak detection. *Journal of Hydraulic Research, 44*(5), 693–707. doi: 10.1080/00221686.2006.9521718

Lee, P. J., & Vitkovsky, J. P. (2010). Quantifying linearization error when modeling fluid pipeline transients using the frequency response method. *Journal of Hydraulic Engineering, 136*(10), 831-836. doi: 10.1061/(asce)hy.1943-7900.0000246

Lee, P. J., Vítkovský, J. P., Lambert, M. F., & Simpson, A. R. (2008). Valve design for extracting response functions from hydraulic systems using pseudorandom binary signals. *Journal of Hydraulic Engineering, 136*(4), 858-864. doi: 10.1061/(ASCE)0733-9429(2008)134:6(858)

Lee, P. J., Vítkovský, J. P., Lambert, M. F., Simpson, A. R., & Liggett, J. A. (2002, May). *Leak detection in pipelines using an inverse resonance method.* Paper presented at the 1st Annual Environmental & Water Resources System Analysis Symposium in conjunction with ASCE Environmental & Water Resources Institute Annual Conference, Roanoke, Virginia, USA.

Lee, P. J., Vítkovský, J. P., Lambert, M. F., Simpson, A. R., & Liggett, J. A. (2005a). Frequency domain analysis for detecting pipeline leaks. *Journal of Hydraulic Engineering, 131*(7), 596-604. doi: 10.1061/(ASCE)0733-9429(2005)131:7(596)

Lee, P. J., Vítkovský, J. P., Lambert, M. F., Simpson, A. R., & Liggett, J. A. (2005b). Leak location using the pattern of the frequency response diagram in pipelines: a numerical study. *Journal of Sound and Vibration, 284*(3-5), 1051–1073. doi: 10.1016/j.jsv.2004.07.023

Lee, P. J., Vítkovský, J. P., Lambert, M. F., Simpson, A. R., & Liggett, J. A. (2008). Discrete blockage detection in pipelines using the frequency response diagram: numerical study. *Journal of Hydraulic Engineering, 134*(5), 658-663. doi: 10.1061/(ASCE)0733-9429(2008)134:5(658)

Liou, C. P. (1998). Pipeline leak detection by impulse response extraction. *Journal of Fluids Engineering, 120*(4), 833-838. doi: 10.1115/1.2820746

Ljung, L. (1999). *System identification - theory for the user* (Second ed.). Upper Saddle River, New Jersey: Prentice-Hall, Inc.

Mpesha, W., Gassman, S. L., & Chaudhry, M. H. (2001). Leak detection in pipes by frequency response method. *Journal of Hydraulic Engineering, 127*(2), 134-147. doi: 10.1061/(ASCE)0733-9429(2001)127:2(134)

Roinila, T., Vilkko, M., & Suntio, T. (2010). Frequency-response measurement of switched-mode power supplies in the presence of nonlinear distortions. *IEEE Transactions on Power Electronics, 25*(8), 2179-2187. doi: 10.1109/TPEL.2010.2043688

Sattar, A. M., & Chaudhry, M. H. (2008). Leak detection in pipelines by frequency response method. *Journal of Hydraulic Research, 46*(sup 1), 138-151. doi: 10.1080/00221686.2008.9521948

Sattar, A. M., Chaudhry, M. H., & Kassem, A. A. (2008). Partial blockage detection in pipelines by frequency response method. *Journal of Hydraulic Engineering, 134*(1), 76-89. doi: 10.1061/(ASCE)0733-9429(2008)134:1(76)

Svingen, B. (1996, April). *Fluid structure interaction in slender pipes.* Paper presented at the7th International Conference on Pressure Surges and Fluid Transients in Pipelines and Open Channels, Harrogate, UK.

Tan, A. H., & Godfrey, K. R. (2002). The generation of binary and near-binary pseudorandom signals: an overview. *IEEE Transactions on Instrumentation and Measurement, 51*(4), 583-588. doi: 10.1109/TIM.2002.802243

Tijsseling, A. S. (1996). Fluid-structure interaction in liquid-filled pipe systems: a review. *Journal of Fluids and Structures, 10*(2), 109-146. doi: 10.1006/jfls.1996.0009

Vardy, A. E., & Brown, J. M. B. (2003). Transient turbulent friction in smooth pipe flows. *Journal of Sound and Vibration, 259*(5), 1011-1036. doi: 10.1006/jsvi.2002.5160

Vítkovský, J. P., Bergant, A., Simpson, A. R., & Lambert, M. F. (2003, April). *Frequency-domain transient pipe flow solution including unsteady friction.* Paper presented at the International Conference on Pumps, Electromechanical Devices and Systems Applied to Urban Water Management, Valencia, Spain.

Vítkovský, J. P., Stephens, M. L., Bergant, A., Simpson, A. R., & Lambert, M. F. (2006). Numerical error in weighting function-based unsteady friction models for pipe transients. *Journal of Hydraulic Engineering, 132*(7), 709-721. doi: 10.1061/(ASCE)0733-9429(2006)132:7(709)

Wylie, E. B., & Streeter, V. L. (1993). *Fluid transients in systems.* Englewood Cliffs, New Jersey, USA: Prentice Hall Inc.

Zecchin, A. C., White, L. B., Lambert, M. F., & Simpson, A. R. (2013). Parameter identification of fluid line networks by frequency-domain maximum likelihood estimation. *Mechanical Systems and Signal Processing, 37*(1-2), 370-387. doi: 10.1016/j.ymssp.2013.01.003