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World Environmental and Water Resources Congress 2012: Crossing Boundaries, 2012 / pp.3275-3284

Source: http://dx.doi.org/10.1061/9780784479001.ch03

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World Environmental & Water Resources Congress (EWRI 2012 Congress)

Citation:
Gong, J., Zecchin, A. C., Lambert, M. F., and Simpson, A. R. (2012). “Signal separation for transient wave reflections in single pipelines using inverse filters”. *World Environmental & Water Resources Congress (EWRI 2012 Congress)*, American Society of Civil Engineers, Albuquerque, New Mexico.

Signal Separation for Transient Wave Reflections in Single Pipelines using Inverse Filters

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

School of Civil, Environmental and Mining Engineering, University of Adelaide, SA
5005, Australia; emails: jgong@civeng.adelaide.edu.au,
azecchin@civeng.adelaide.edu.au, mlambert@civeng.adelaide.edu.au,
asimpson@civeng.adelaide.edu.au

ABSTRACT

Fluid transients (water hammer waves) have been recognized as a possible tool for pipeline fault detection and condition assessment, where a number of transient-based techniques have been proposed in the past two decades. In real world applications on single pipelines, the location of the transient generator and pressure transducers are sometimes at interior points along the pipe, rather than at end points due to access limitations or other practical issues. Therefore, the pressure response trace measured at a transducer includes reflections resulting from water hammer waves traveling from both sides of the measurement locations. When multiple faults exist and are located on both sides of the transducer, reflections from faults could be intermixed, making the pressure trace very complicated and hard to interpret. As a result, separation of the signals reflected from the two opposite directions is useful for implementing pipeline fault detection techniques. This paper proposes a novel pressure response separation technique using an inverse filter. Two pressure transducers are used, and the frequency response function of the filter is derived. The signal separation is performed in the frequency domain, and then the time-domain reflection trace of each side is restored using an inverse Fourier transform. Finally, the proposed pressure signal separation technique has been verified numerically.

INTRODUCTION

With the rapid urbanization and industrialization around the world, pipeline systems have been widely used in various areas, such as water distribution and oil transmission. Pipeline systems suffer from deterioration due to various factors, including corrosion, tuberculation, aging, external loading and inappropriate operation (Rajani and Kleiner 2001). To prevent hazards caused by pipeline deterioration, such as pipe failure, regular pipeline condition assessment is important and necessary.

Among the range of techniques for pipeline fault detection and condition assessment, techniques based on fluid transients (small water hammer waves) are attractive due to their non-invasive character and the waves travel at high speed in liquid-filled pipes (Lee et al. 2005). In the last two decades, a number of transient-based pipeline fault detection (Colombo et al. 2009) and condition assessment (Stephens et al. 2008) techniques has been developed. However, various practical issues are encountered when applying the transient-based technique to real world systems (Stephens 2008). One practical problem is the overlap between the pressure reflections coming from two opposite directions (upstream and downstream sides). This problem is inevitable when a pressure transducer is located at an interior point rather than at the end of the pipe. The signal overlap increases the complexity of the measured pressure trace, thereby increasing the difficulty in data interpretation. As a result, separation of these two signals would be a helpful pre-processing step.

The research presented in this paper proposes a novel pressure wave separation technique using an inverse filter. One side-discharge valve based transient generator and two pressure transducers are used. By lagging and subtracting the two measured pressure traces, a new time domain pressure signal is obtained, which is a superposition of a single-side reflection and its time translation. This new signal is considered as the output of a linear time-invariant (LTI) system through a convolution process, where the input is the single-side reflection itself. To restore the input from the output, an inverse process is needed to conduct the deconvolution process (Proakis and Manolakis 2007). The frequency response of the inverse system is developed in this research, which is known as an inverse filter. Numerical verification is conducted based on a reservoir-pipeline-valve system. Two deteriorated sections (represented by pipe sections with changes in their hydraulic impedance) exist in the pipe, and between the two sections the transient generator and two pressure transducers are positioned. Using the proposed signal separation strategy, two additional pressure traces can be obtained from the measured pressure traces, representing reflections from the upstream side and the downstream side, respectively. Responses from each deteriorated section are much clearer in the single-side reflection traces.

PRESSURE MEASUREMENT

A typical configuration for performing transient measurement and pipeline condition assessment in long water transmission pipelines is illustrated in Fig. 1. The pipeline is assumed to be frictionless and infinite in length. The initial steady-state flow is discharging from left to right. A transient generator G_t is located at an interior point, which could be a side-discharge valve. For simplicity, only two pressure transducers are used in this figure to illustrate the relationship between the two measured pressure traces. The transducer T_{p1} is located at the same position as the generator G_t, and the transducer T_{p2} is located upstream from G_t and T_{p1} with a distance of L_0.

A step hydraulic transient (an incident wave) can be generated by abruptly shutting off the side-discharge valve at G_t. The incident pressure wave is propagating towards both the upstream side and the downstream side from the transient generator (G_t) from time t_0, as shown by W_u and W_d shown by solid lines with arrows, respectively. Reflections sourced from the upstream and downstream side of the generator also start from time t_0, and they are described by dotted lines as R_u and R_d, respectively.

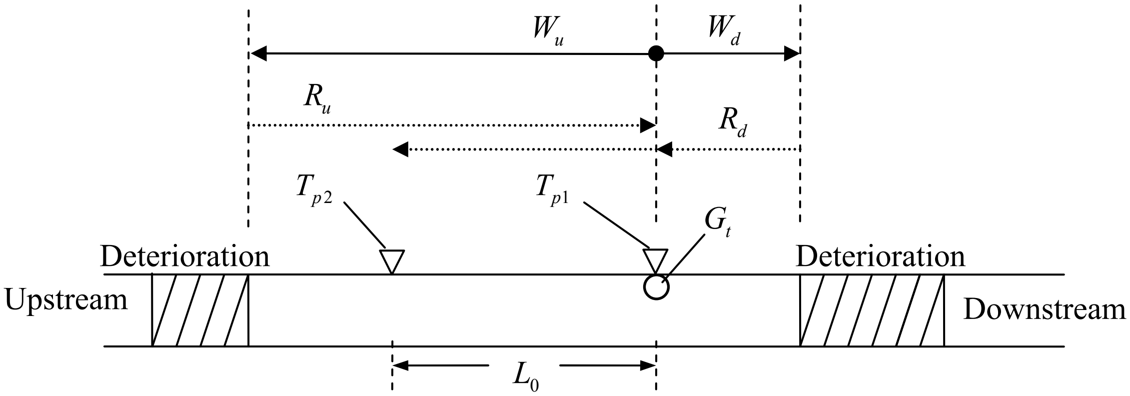

Figure 1 The propagation of the incident wave and the reflections from both the upstream and downstream directions

For the transducer T_{p1} that is located at the same location as the transient generator, signals reflected from the upstream and downstream sides are recorded once the incident wave starts. It is assumed that the pressure measured at the transducer is a linear superposition of the step-shaped incident wave and the reflected pressure waves coming from the two opposite directions. Therefore, the measured pressure trace $H_1(t)$ can be described as

$$H_1(t) = \begin{cases} H_0 & 0 \le t < t_0 \qquad \text{(1a)} \\ H_i + R_u(t) + R_d(t) & t \ge t_0 \qquad \text{(1b)} \end{cases}$$

in which t represents time and it starts from 0; H_0 is the steady-state head along the frictionless pipe; H_i is the head of the step-shaped incident wave measured at transducer T_{p1}; $R_u(t)$ and $R_d(t)$ are time domain signals representing the head of the pressure waves reflected from upstream and downstream sides, respectively. Note that $R_u(t), R_d(t) = 0$ for $t < t_0$.

For the transducer T_{p2}, which is located at a distance of L_0 upstream from the transient generator (G_t) and the first transducer (T_{p1}), the incident wave arrives at time $t_0 + t_d$, where $t_d = L_0 / a$, where a is the wave speed. The downstream reflection R_d arrives at T_{p2} always with a time delay of t_d after it reaches T_{p1}. In contrast, the upstream reflection R_u always arrives at T_{p2} with a time of t_d before it passes T_{p1}. Therefore, under the assumption that the pipeline is frictionless, the pressure trace $H_2(t)$ measured at T_{p2} can be written as

$$H_2(t) = \begin{cases} H_0 & 0 \le t < t_0 + t_d \quad (2a) \\ H_i + R_u(t + t_d) + R_d(t - t_d) & t \ge t_0 + t_d \quad (2b) \end{cases}$$

SIGNAL SEPARATION USING INVERSE FILTERS

An inverse filter is constructed herein to extract the two single-side reflections $R_u(t)$ and $R_d(t)$ from the measured pressure traces [$H_1(t)$ and $H_2(t)$]. The theoretical procedure for the signal extraction is illustrated below.

Translating the time-domain trace of $H_2(t)$ forward in time by an interval of t_d, which is achieved by replacing t with $t + t_d$ in Eqs (2a) and (2b), yields

$$H_2(t + t_d) = \begin{cases} H_0 & -t_d \le t < t_0 \quad (3a) \\ H_i + R_u(t + 2t_d) + R_d(t) & t \ge t_0 \quad (3b) \end{cases}$$

The pressure traces described by Eq. (1b) and Eq. (3b) are of interest, because they include the reflected signals. Performing subtraction between the signals $H_1(t)$ and $H_2(t + t_d)$, a new signal $P_u(t)$ is obtained as

$$\begin{aligned} P_u(t) &= H_1(t) - H_2(t + t_d) \\ &= R_u(t + 2t_d) - R_u(t) \quad t \ge t_0 \end{aligned} \tag{4}$$

Eq. (4) shows that $P_u(t)$ is a signal related only to $R_u(t)$ and its time translation. It can be assumed that $P_u(t)$ is the output when the original signal $R_u(t)$ passes through a linear system (filter). To restore the input $R_u(t)$ from the known output $P_u(t)$, an inverse filter is required (Proakis and Manolakis 2007).

In order to derive the inverse filter, a Fourier transform may be applied to Eq. (4). Theoretically, the transformation can be described as

$$\mathrm{F}[P_u(t)] = (e^{j\omega 2t_d} - 1)\,\mathrm{F}[R_u(t)] \quad t \geq t_0 \tag{5}$$

where $\mathrm{F}[\;]$ denotes the Fourier transform to the function inside the brackets; j is the imaginary unit $\sqrt{-1}$; and ω is angular frequency. Then, rearranging Eq. (5), the Fourier transform of $R_u(t)$ can be obtained from the product of an inverse filter and the Fourier transform of $P_u(t)$, which may be written as

$$\mathrm{F}[R_u(t)] = \Phi_u(\omega)\,\mathrm{F}[P_u(t)] \quad t \geq t_0 \tag{6}$$

where $\Phi_u(\omega) = 1/(e^{j\omega 2t_d} - 1)$ is the frequency response function of the filter for extracting the upstream reflection trace. Finally, the time-domain trace of $R_u(t)$ can be derived by applying an inverse Fourier transform of Eq. (6), which can be described as

$$R_u(t) = \mathrm{F}^{-1}\left[\Phi_u(\omega)\,\mathrm{F}[P_u(t)]\right] \quad t \geq t_0 \tag{7}$$

where $\mathrm{F}^{-1}[\;]$ represents the inverse Fourier transform.

The downstream side reflection $R_d(t)$ can be extracted in a similar procedure. A signal $P_d(t)$ can be obtained by delaying the signal $H_2(t)$ by a time interval of t_d, and then subtracting the signal $H_1(t)$ from the delayed pressure trace. The time-domain trace of $P_d(t)\,(t \geq t_0 + 2t_d)$ is only related to the downstream reflection $R_d(t)$ and its time translation, which can be written as

$$\begin{aligned} P_d(t) &= H_2(t - t_d) - H_1(t) \\ &= R_d(t - 2t_d) - R_d(t) \quad t \geq t_0 + 2t_d \end{aligned} \tag{8}$$

Thereafter, the downstream reflection $R_d(t)$ can be obtained by shifting $P_d(t)$ in the time domain, using an inverse filter in the frequency domain, and then transforming back to the time domain. The procedure can be described as

$$R_d(t) = \mathrm{F}^{-1}\left[\Phi_d(\omega)\,\mathrm{F}[P_d(t + 2t_d)]\right] \quad t \geq t_0 \tag{9}$$

where $\Phi_d(\omega) = 1/(1 - e^{j\omega 2t_d}) = -\Phi_u(\omega)$.

Because the inverse filter $\Phi_u(\omega)$ has a complex exponential component $e^{j\omega 2t_d}$ in the denominator, computational problems may occur when the complex exponential is close to one. Therefore, measures must be taken to avoid this problem in programming. A simple method is to adopt a magnitude threshold on the filter.

NUMERICAL VERIFICATION

Numerical simulations based on the method of characteristics (Chaudhry 1987) have been conducted to validate the proposed signal separation algorithm. Effects of friction are neglected in the numerical study. The pipeline in the numerical model is a long water transmission main in a reservoir-pipeline-valve configuration. It has a total length L = 5000 m and a uniform internal diameter D_0 = 600 mm. The steady-state head along the pipe is H_0 = 30 m. Two deteriorated sections are located in the pipeline. For simplicity, the degradation is considered only to change the impedance of the pipeline, resulting in only a change in the wave speed in these two sections, with a_0 = 1000 m/s in the original intact pipeline and a_1 = 800 m/s in the two degraded sections. A side-discharge valve based transient generator (G_t) and one pressure transducer (T_{p1}) are located at 2700 m upstream from the inline valve, and another transducer (T_{p2}) is located a further 100 m upstream. The system layout is given in Fig. 2 with the hydraulic grade line (HGL) on the top.

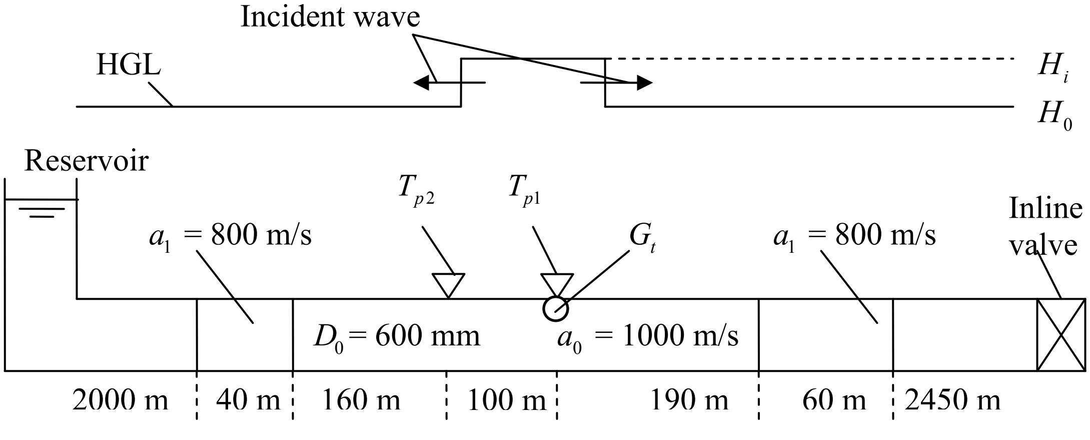

Figure 2 Pipeline configuration for numerical modeling

In the numerical simulations, the steady-state side-discharge from G_t is 0.03 m^3/s. Abruptly shutting off the side-discharge (at time t_0 = 0.1 s) introduces a step transient wave propagating towards the upstream and downstream, as shown in Fig. 2. The head of the transient wave is $H_i = 35.41$ m. The pressure traces measured at T_{p1} and T_{p2} are shown in Fig. 3 as $H_1(t)$ and $H_2(t)$. They are truncated at time $t_{end} = 4.196$ s to remove the reflections from pipe ends.

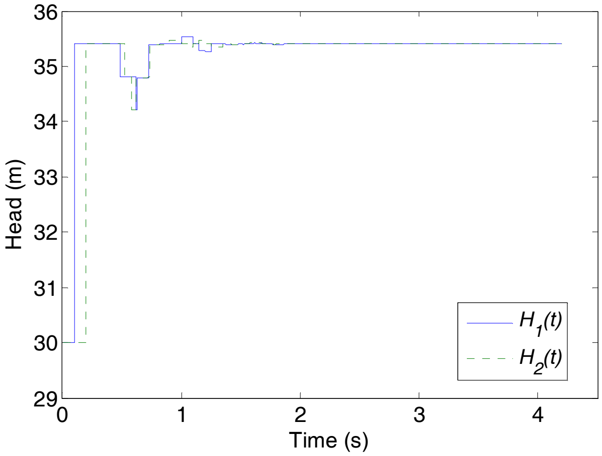

Figure 3 Pressure traces measured at the two pressure transducers

It can be seen in Fig. 3 that reflections from the two degraded sections are superimposed. The superposition of the waves makes the measured pressure traces very complex. As a result, it is very hard to estimate the location and other properties of the two deteriorated sections.

In order to have a clearer view of the reflection resulting from each degraded section, the proposed signal separation technique is applied. Using these two pressure traces, the upstream reflection R_u can be restored first. The value of t_d is derived to be 0.1 s using the distance between the two transducers (L_0 = 100 m) and the wave speed in the original pipe (a_0 = 1000 m/s). Using Eq. (4), the signal $P_u(t)\,(t_0 \le t \le t_{end})$ [Eq. (4)] is obtained and shown in Fig. 4.

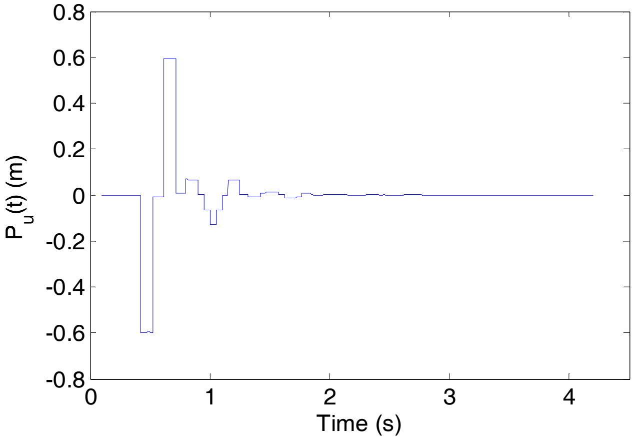

Figure 4 The pressure trace of $P_u(t)\ (t_0 \le t \le t_{end})$

Using the signal $P_u(t)\ (t_0 \le t \le t_{end})$ and Eq. (7), the time-domain trace for the upstream reflection $R_u(t)\ (t_0 \le t \le t_{end})$ can be obtained, as illustrated in Fig. 5. The first square-shaped reflection is induced by the upstream degraded section when the incident wave propagates through it. The following small perturbations are due to higher dimensional reflections within and between the two degraded sections.

Similarly, constructing signal $P_d(t+2t_d)\ (t_0 \le t \le t_{end})$ and applying Eq. (9), the downstream reflection $R_d(t)\ (t_0 \le t \le t_{end})$ can be obtained, as shown in Fig. 6. The first square-shaped reflection is induced by the downstream degraded section.

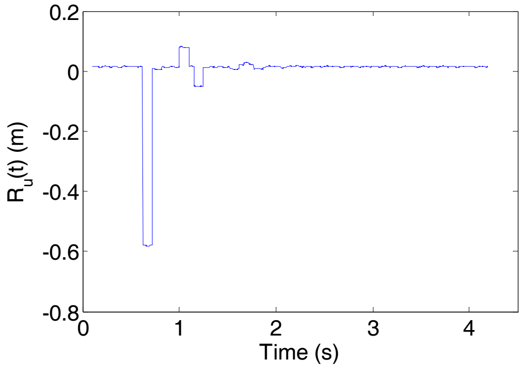

Figure 5 The pressure trace of the upstream reflection $R_u(t)\ (t_0 \le t \le t_{end})$

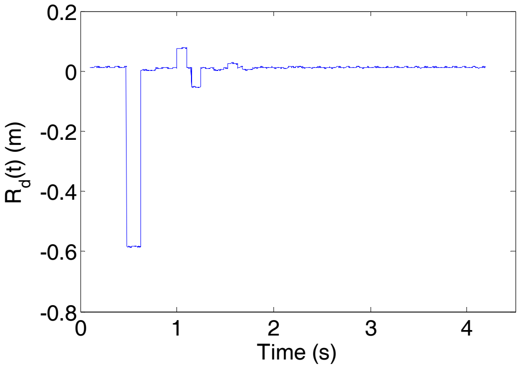

Figure 6 The pressure trace of the downstream reflection $R_d(t)\ (t_0 \le t \le t_{end})$

Compared with the original pressure traces shown in Fig. 3, the two single-side wave traces give a much clearer picture of the deterioration-induced reflection. Both the location and impedance of the deterioration can then be determined using the technique developed by Gong et al. (2011), which demonstrated that the arrival time of the deterioration-induced reflection is indicative of the location while the size of the disturbance is related to the hydraulic impedance.

To validate the results of $R_u(t)$ and $R_d(t)$, the superposition of these two signals $R_u(t)+R_d(t)\ (t_0 \le t \le t_{end})$ is obtained and then compared with the pressure perturbation $H_1(t)-H_i\ (t_0 \le t \le t_{end})$ measured at transducer T_{p1}. The two pressure traces are given in Fig. 7. It can be seen that these two traces are very similar in shape, except that the restored signal has a slight and uniform deviation from the measured trace.

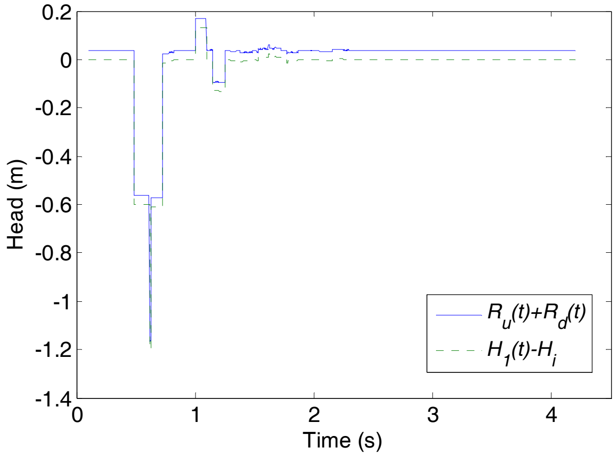

Figure 7 Comparison between the reflection restored from the two single-side reflections [$R_u(t)+R_d(t)\ (t_0 \le t \le t_{end})$] and the reflection measured by the transducer [$H_1(t)-H_i\ (t_0 \le t \le t_{end})$].

CONCLUSIONS

This research proposes a novel technique for extracting the upstream and downstream reflection traces from the pressure traces measured by two pressure transducers. Under the assumption that the pipe is lossless for transient wave reflections, inverse filters are derived and used in the frequency domain for the signal extraction. Numerical simulations have been conduced to verify the proposed technique. The time domain traces of the two reflected wave, resulting from upstream and downstream sides of the transient generator respectively, have been obtained successfully.

The signal separation technique is helpful for data interpretation in the transient-based pipeline fault detection and condition assessment. From the single-side reflection traces, better estimates as to the location and properties of the deterioration can be determined.

ACKNOWLEDGEMENTS

The research presented in this paper has been supported by the Australia Research Council through the Discovery Project Grant DP1095270. The first author thanks the Chinese Scholarship Council and the University of Adelaide for providing a joint postgraduate scholarship. Furthermore, the first author would like to thank Mr. Matthew Trinkle for the useful correspondence.

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