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Detection of extended blockages in pressurised pipelines using hydraulic transients with a layer-peeling method

Wei Zeng[1], Jinzhe Gong[1], Martin Lambert[1], Angus Simpson[1], Benjamin Cazzolato[2], Aaron Zecchin[1]

1, School of Civil, Environmental and Mining Engineering, University of Adelaide, SA 5005, Australia.

2, School of Mechanical Engineering, University of Adelaide, SA 5005, Australia.

w.zeng@adelaide.edu.au

Abstract Water distribution systems (WDSs) are one of society's most important infrastructure assets. They consist of buried pipes that are often old and their condition is extremely difficult and expensive to determine. This research proposes a non-invasive layer-peeling method using hydraulic transient waves to detect extended blockages in pressurised pipelines. In the numerical study, hydraulic transient pressure waves are injected into a pipeline at a dead-end. Wave reflections caused by multiple extended blockages (uniform and non-uniform) are simulated using the method of characteristics (MOC). The impulse response function (IRF) of the pipeline is then obtained using the simulated pressure response at the dead-end. The original layer-peeling method previously applied to tubular music instruments is further developed by considering the differences between the instruments and pressurised pipelines (boundary conditions, fluid properties). Using the IRF and the modified layer-peeling method, the internal pipe diameter values are estimated section by section from the dead-end to the upstream end of the pipeline. The blocked pipe sections are then accurately identified from the reconstructed pipe wall thickness distribution profile.

1. Introduction

Water distribution systems (WDS) normally consist of buried pipeline networks that are often old and suffering many problems such as leaks, blockages and wall deterioration. Hydraulic transient waves have been used to detect leaks [1], discrete blockages [2-5] and extended pipe wall deterioration (e.g. due to internal or external corrosion) [6, 7]. Recently, the detection of extended blockages in pipelines has drawn increasing attention [8, 9]. Extended blockages are common in ageing water pipelines (e.g. caused by tuberculation) can significantly reduce the water transmission efficiency. Developing cost-effective techniques to detect extended blockages is essential in enabling strategically targeted pipe maintenance, replacement and rehabilitation.

In transient-based methods, typically a pulse or a step pressure wave is injected into a pipeline by abruptly operating a valve. The blockages in the pipeline may result in specific wave reflections, which will be collected by pressure transducers. These wave reflections can be then analysed in the time domain to detect and localise blockages [4, 10]. The spatial resolution can be improved by using the impulse response function (IRF) extracted from the measured pressure traces [9]. Detection of an extended or a discrete blockage can also be conducted in the frequency domain according to the shift of the resonant frequencies of the frequency response function (FRF) of the pipeline system [11]. The reconstructive MOC technique developed for the detection of thinner-walled pipe sections [12]

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theoretically can be adapted to extended blockage detection. However, it neglects wave dissipation or dispersion (e.g. caused by unsteady friction).

In the acoustic research field, a technique named layer-peeling method was built and applied to reconstructions of the geometry of short air ducts with varying cross sections [13, 14], such as musical wind instruments [15]. However, there is no application of the layer-peeling concept to pipeline blockage detection using hydraulic transients to date.

The research reported in this paper develops a novel approach to detect extended blockages in pressurised pipelines by a modified layer-peeling algorithm. The new technique enables the reconstruction of the inner diameter and wave speed along the pipelines. To validate the new layer-peeling-based approach, numerical simulations have been conducted for pipes with and without friction, and with uniformly and non-uniformly distributed blockages. For all the numerical cases, the extended blockages are successfully detected.

2. Methodology

The modified layer-peeling method has three major components as shown in Figure 1: ① obtaining the directional IRF ($p_{1,l}^{+}$ and $p_{1,l}^{-}$), ② formulating the wave dissipation and dispersion (h_i) and ③ formulating the wave transmission ($s_{i,i+1}$ and $s_{i+1,i}$) and reflection coefficients ($r_{i,i+1}$ and $r_{i+1,i}$). The superscripts + and – represent forward and backward directions, respectively, and the subscripts l and r represent the left and right boundaries of a discretised pipe section, respectively.

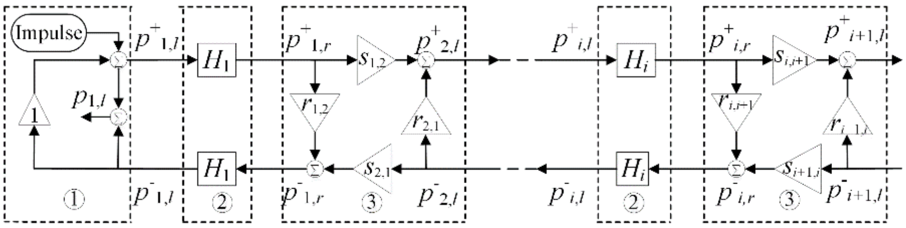

Figure 1. Block diagram describing the wave propagation process in a pipeline.

2.1 Impulse response function (IRF)

In the conventional layer-peeling method [15], an acoustic source tube with properties designed to control wave reflections is attached to one end of the musical instrument. However, it is not feasible to connect a long source tube to a water pipeline due to the sheer size of water transmission line systems. Instead, a dead-end boundary condition is considered by closing an inline valve, as shown in Figure 2.

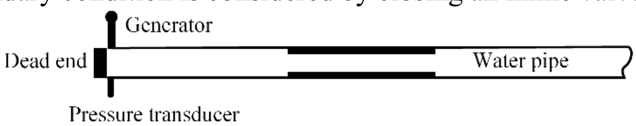

Figure 2. Schematic diagram of the testing systems.

The IRF $z(t)$ is defined as the response measured at the output when an ideal impulse input is injected into a system. In this paper, a combined *truncation regularisation* and *Tikhonov's regularisation* algorithm [16] shown in Equation (1) is used to determine the IRF.

$$\mathbf{z} = \left(\sum_{i=1}^{J} \frac{\lambda_i}{\lambda_i^2 + \alpha_c} \mathbf{p}_i \mathbf{q}_i^T \right) \mathbf{y} \tag{1}$$

in which $\mathbf{y}$ is the pressure response, J is the truncation point, α_c is an regularisation parameter, $\mathbf{p}_i$, $\mathbf{q}_i$ amd λ_i can be obtained from the signal input with detailed processes in [16].

Due to the dead end, the directional impulse reflection $p_{1,l}^{-}$ would be fully reflected by the end boundary, and will again enter into the pipeline system, as shown in the first dashed box in Figure 1. Thus, the directional IRF $p_{1,l}^{-}$ and the forward-propagating wave $p_{1,l}^{+}$ into the pipeline can be written as

$$p_{1,l}^{-} = 0.5 p_{1,l} \tag{2}$$

$$p_{1,l}^{+} = p_{impulse}^{+} + 0.5p_{1,l} \quad (3)$$

where $P_{impulse}^{+}$ represents an impulse signal.

2.2 Wave dissipation and dispersion

For a fluid-filled pipe, the wave speed (a) in the fluid which depends on the properties of the fluid and the pipe wall can be written as [17],

$$a = \sqrt{\frac{K/\rho}{1+(K/E)(D/e)c_1}} \quad (4)$$

where K represents the bulk modulus of the water; ρ is the density of water; $E$is the Young's modulus of elasticity of the pipe wall; D is the pipe's inner diameter;e is the wall thickness of the pipe; and c_1 is the pipeline restraint factor. For a pipe section with extended blockage, the wave speed may change due to the change of *D/e*.

Pressure waves in pipelines experience frequency-dependent dissipation and dispersion due to unsteady friction and viscoelasticity from the pipe wall [18, 19]. In this paper, only the effect of unsteady friction is considered for brevity (i.e. metallic pipes are considered). The wave dissipation and dispersion in the i_{th} pipe section (within which the properties are assumed uniform) can be described by a transfer function h_i such that

$$P_{i,r}^{+} = P_{i,l}^{+} H_i \quad (5)$$

$$P_{i,r}^{-} = P_{i,l}^{-} / H_i \quad (6)$$

with

$$H_i = e^{-j\omega\Delta x_i / a_{c,i}} \quad (7)$$

in which Δx_i is the length of i_{th} pipe section, ω is the angular frequency, j is the imaginary unit and a_c is the complex wave speed described by

$$a_c = a\sqrt{\frac{1}{(1-gARj/\omega)}} \quad (8)$$

where g is acceleration due to gravity, A is the cross section area and R is the linearised resistance term with more details discussed in [20, 21].

2.3 Wave transmission and reflection

If an incident pressure wave p meets a discontinuity in the pipe, a reflected wave p_r will be generated. The incident wave will change to p_s after passing the discontinuity. The reflection coefficient $r_{i,i+1}$ and the transmission coefficient $s_{i,i+1}$ are determined as [10]

$$r_{i,i+1} = \frac{p_r}{p} = \frac{B_{i+1}-B_i}{B_{i+1}+B_i} \quad (9)$$

$$s_{i,i+1} = \frac{p_s}{p} = \frac{2B_{i+1}}{B_{i+1}+B_i} = 1 + r_{i,i+1} \quad (10)$$

in which $B = a/gA$ is the characteristic impedance. By switching the subscribes i and i+1 in Equations (9) and (10), $r_{i+1,i}$ and $s_{i+1,i}$ can be also calculated.

At the interface of two sections as shown in box ③ in Figure 1, the forward-propagating wave $p_{i+1,l}^{+}$ travelling into section i+1 is the sum of the transmitted wave of $p_{i,r}^{+}$ and the reflected wave of $p_{i+1,l}^{-}$. Meanwhile, the backward-propagating wave $p_{i,r}^{-}$travelling into section i is the sum of the reflected wave of $p_{i,r}^{+}$ and the transmitted wave of $p_{i+1,l}^{-}$. Thus, the following formula can be written based on the analysis above to represent the wave transmission and reflection at an interface:

$$\begin{bmatrix} p_{i+1,l}^{+} \\ p_{i+1,l}^{-} \end{bmatrix} = \frac{1}{1-r_{i,i+1}} \begin{bmatrix} 1 & -r_{i,i+1} \\ -r_{i,i+1} & 1 \end{bmatrix} \begin{bmatrix} p_{i,r}^{+} \\ p_{i,r}^{-} \end{bmatrix} \quad (11)$$

As shown in Figure 3, the initial reflected waves $p_{i,r}^{-}(iT/2)$ (dashed lines) are only caused by the reflection of the main transmitted waves $p_{i,r}^{+}(iT/2)$ along the diagonal in the diagram. Thus,

$$r_{i,i+1} = \frac{p_{i,r}^{-}(iT/2)}{p_{i,r}^{+}(iT/2)} \tag{12}$$

And the characteristic impedance of the i_{th} section can be obtained as

$$B_{i+1} = \frac{1+r_{i,i+1}}{1-r_{i,i+1}} B_i \tag{13}$$

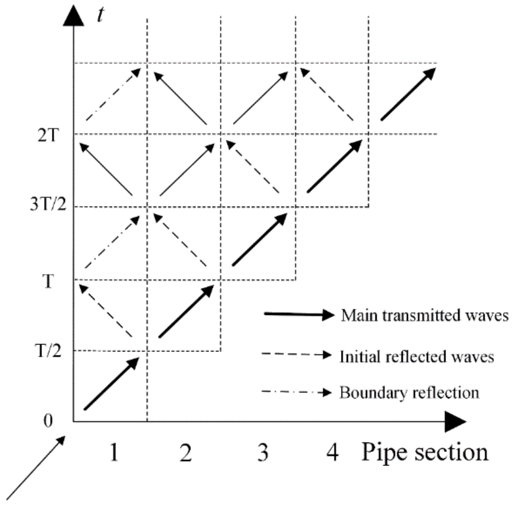

Figure 3. Space-time diagram of the wave propagation.

2.4 Procedures of the Modified Layer-peeling Method

The steps for reconstructing a pipeline with *N* sections using the modified layer-peeling method are described as follows:

Step 1: Calculate the system directional IRF through Equation (1).

Step 2: Use the system IRF to calculate the directional IRF $p_{1,l}^{-}$ and forward-propagating wave $p_{1,l}^{+}$ through Equations (2) and (3).

Step 3: Use the waves at the left side of the i_{th} (i=1 for the first step) section $p_{i,l}^{+}$ and $p_{i,l}^{-}$ to calculate the waves at the right side of the i_{th} section $p_{i,r}^{+}$ and $p_{i,r}^{-}$through Equations (5) and (6).

Step 4: Use the waves at the right side of the i_{th} section $p_{i,r}^{+}$and $p_{i,r}^{-}$ to calculate the reflection ratio $r_{i,i+1}$through Equation (12), and then obtain the characteristic impedance B_{i+1}through Equation (13).

Step 5: Use the waves at the right side of the i_{th} section $p_{i,r}^{+}$, $p_{i,r}^{-}$ and $r_{i,i+1}$ to calculate the waves at the left side of the $(i+1)_{\text{th}}$ section $p_{i+1,l}^{+}$ and $p_{i+1,l}^{-}$ through Equation (11).

Step 6: Repeat steps 3 to 5 for i=2, …, N-1 to calculate the characteristic impedances, wave speeds and inner diameter for the remaining sections.

3. Numerical cases

Numerical verifications have been conducted on reservoir-pipeline-valve systems to verify the proposed approach for extended blockage detection. The transient pressure traces are simulated using the method of characteristics (MOC) [17]. Two cases are considered: a frictionless case and a case with unsteady friction.

3.1 Case 1: Frictionless pipe

The first case study was conducted for a frictionless metallic pipeline with a uniform blockage and a non-uniform blockage. The pipeline configuration and properties are given in Figure 4. A pressure pulse wave, shown in Figure 5(a) was injected into the pipeline at the upstream face of the closed valve, and the wave reflections that was given in Figure 5(b) were simulated using a frictionless MOC model (time step = 0.001 s for all the numerical cases). The IRF shown in Figure 5(c) was obtained using Equation (1) with the injected wave and the reflected wave.

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The modified layer-peeling method neglecting any wave dissipation and dispersion (Model 1) was then applied to the signals in Figure 5. The reconstructed inner diameter and wave speed distributions of the pipe are virtually coincident with the theoretical values, as shown in Figure 6.

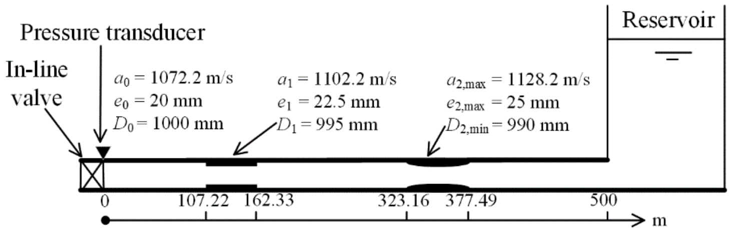

Figure 4. A frictionless pipeline system with one uniform extended blockage and one non-uniform extended blockage.

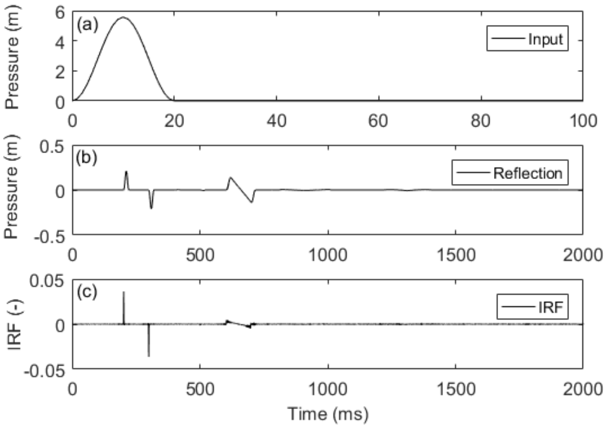

Figure 5. Signals: (a) wave input; (b) wave reflections and (c) IRF.

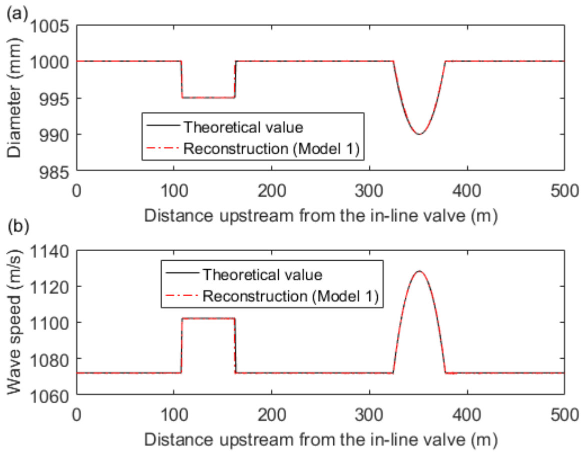

Figure 6. Reconstruction using the modified layer-peeling method (Model 1) for the frictionless pipe: (a) inner diameter and (b) wave speed.

3.2 Case 2: with unsteady friction

A small-diameter pipe with one uniform blockage section as shown in Figure 7 was chosen to highlight the effect of unsteady friction. The pressure wave reflections at the dead end with a pulse wave input were simulated using an unsteady friction MOC model [21].

The pipeline was initially reconstructed using the modified layer-peeling method of Model 1, without considering the unsteady friction, and the result plotted as the dot-dashed line in Figure 8 shows obvious error. Another reconstruction was conducted using the modified layer-peeling method incorporating the transfer function that describes the unsteady friction using Equation (8), and this is referred to as Model 2. The result shown as the dashed line in Figure 8 illustrates that the error is eliminated along the pipeline except at points where the impedance changes sharply.

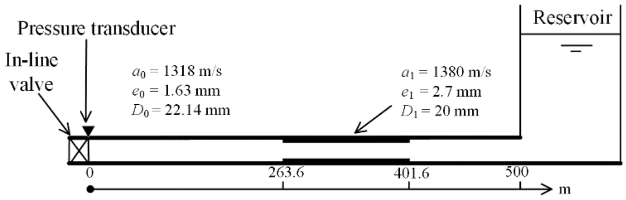

Figure 7. A pipeline system with a uniform extended blockage and unsteady friction.

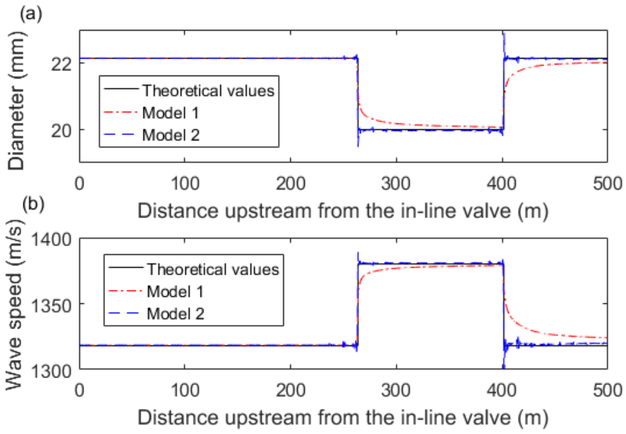

Figure 8. Reconstruction using Model 1 (neglecting effect of friction) and Model 2 (with unsteady friction considered) for the unsteady friction case: (a) inner diameter and (b) wave speed.

4. Conclusions

A novel approach for detecting extended blockage in water pipelines is presented in this paper. The layer-peeling method previously applied to tubular musical instruments has been modified to accommodate the differences between musical instruments and water pipelines. The long source tube, which was used in the original method, has been eliminated. Unsteady friction of the transient flow in pipelines has been considered and incorporated into the new algorithm. Numerical simulations have demonstrated that the proposed technique can reconstruct multiple extended blockages (including non-uniformly distributed blockages) in pipelines with unsteady friction.

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