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Impulse leakage analysis for series pipelines

Sanghyun Kim and Jayong Koo

ABSTRACT

Formulations of the transient behaviour in series pipe systems are derived using impulse response analysis. The impact of leakage is incorporated into the transfer functions of the complex head and discharge. The impedance transfer functions along a series pipeline are derived to simulate impact of pressure and discharge about a maneuver of valve located at the end of pipe system. An algorithm is proposed to predict leak quantity and location for a series pipeline systems. Genetic Algorithm (GA) is integrated into the impulse response method. The objective functions for the leakage detection can be made using the pressure-head response at the valve, or the pressure-head or the flow response at a certain point of the pipeline located upstream from the valve. Frequency dependent-friction is used to consider the impact of unsteady friction in the transient flow. Simulation and calibration results show that the proposed method of leak detection has significant potential for improved leak management for series pipe systems.

Key words | genetic algorithm, impulse response method, leak detection method, leak management, transient

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INTRODUCTION

Losses of water, deterioration of pipeline systems, and many environmental issues are associated with pipeline leakage. The leak detection techniques of pipe systems have evolved in a few different ways. Pudar and Liggett (1992) introduced the inverse analysis to calibrate leaks in the steady-state network problem. Liggett and Chen (1994) incorporated the method of characteristics into the inverse transient analysis to detect and calibrate leak. Liou and Tian (1995) presented the Cauchy algorithm and time-marching algorithm for leak detection through transient flow simulations and addressed the data noise limiting leak detectability. The extraction of a system's impulse response by a cross-correlation method suggested an efficient methodology for removing the impact of detrimental noise in the detection of leaks in a system (Liou 1998). A transient test-based technique for leak detection considered the effects of wave propagation from the leak position of the pipeline system (Brounone 1999). The genetic algorithm was integrated into the inverse transient analysis to calibrate the friction factors and leaks in water distribution system (Vitkovsky *et al.* 2000). Mpesha *et al.* (2001) proposed an innovative leak detection method based on the analysis in the frequency domain. An inverse transient analysis in series pipe systems is performed based on the method of characteristics (Nash & Karney 1999). Even though discretization errors of wave-speed adjustment approach of method of characteristics is found to be small in numerical studies of several series pipe systems, the constraint of a Courant number is required to control numerical dissipation (Ghidaoui *et al.* 1998). An Artificial Neural Network is introduced to detect the location of leakage in water distribution systems (Mounce *et al.* 2002).

In the present study, an alternative leak detection algorithm is presented which requires the time series of pressure or flow-rates at any points of a series pipe system about a simple operation of the valve. This paper addresses

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the free vibration analysis in the steady oscillatory flow and then the impulse response analysis of series pipe systems with leakages is presented. The frequency dependent friction is incorporated to consider the impact of unsteady friction in the laminar or turbulent flow of the low Reynolds number. The integrations of genetic algorithm (GA) into the impulse response method provide the calibration methods of leak location.

MATERIAL AND METHOD

Transient analysis in a series pipe system

The momentum and continuity equations for the transient flow in a pipeline are respectively given as follows:

$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + \frac{f|Q|Q}{2DA} = 0 \quad (1)$$

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \quad (2)$$

where, x is distance along a pipeline, t is time, a is the wave speed, g is the gravitational acceleration, A is the cross sectional area of a pipe, Q is discharge of flow, H is the head, f is the Darcy-Weisbach friction factor, and D is the pipe diameter (Wylie & Streeter 1993).

Derivations from equations (1) and (2) assuming a steady oscillatory flow and linearized friction, provide the complex head and discharge as a function of distance, x, as follows (Wylie & Streeter 1993):

$$H(x) = H_U \cosh \gamma x - Z_C Q_U \sinh \gamma x \quad (3)$$

$$Q(x) = -\frac{H_U}{Z_C} \sinh \gamma x + Q_U \cosh \gamma x \quad (4)$$

where, subscript U denotes the upstream section. Propagation constant γ, characteristic impedance Z_c, and complex frequency s' are respectively defined as:

$$\gamma = \sqrt{Cs'(Ls' + R)} \quad (5)$$

$$Z_C = \gamma / Cs' \quad (6)$$

$$s' = \sigma + i\omega \quad (7)$$

where, the capacitance(C) is gA/a^2, the inertance(L) is $1/gA$, the resistance(R) is $f\bar{Q}/gAD^2$, σ is a decay factor, and ω is the frequency.

The hydraulic impedance $Z(x)$ is defined as the ratio of the complex head, $H(x)$, to the complex discharge, $Q(x)$.

$$Z(x) = H(x)/Q(x) \quad (8)$$

The propagation constant, γ, and characteristic impedance, Z_c, are varied in each pipe segments of a series pipe system. These parameters must necessarily be considered to obtain the impedance of the series pipeline (Figure 1). The impedance of node number 3 can be expressed as

$$Z_3 = -Z_{c3} \tanh \gamma_3 l_3 \quad (9)$$

where, γ_3 is the propagation constant at the pipe section 3 between node 3 and upstream reservoir, Z_{c3} is the characteristic impedance of the pipe section 3, and l_3 is the length of the pipe section 3.

The impedance of node number 2 can be expressed as

$$Z_2 = (Z_3 - Z_{c2} \tanh \gamma_2 l_2)/(1 - Z_3/Z_{c2} \tanh \gamma_2 l_2) \quad (10)$$

where, γ_2 is the propagation constant at the pipe section 2 between node 3 and node 2, and Z_{c2} is the characteristic impedance of the pipe section 2, and l_2 is the length of the pipe section 2.

The impedance at the end of pipe system is

$$Z_1 = (Z_2 - Z_{c1} \tanh \gamma_1 l_1)/(1 - Z_2/Z_{c1} \tanh \gamma_1 l_1) \quad (11)$$

where, γ_1 is the propagation constant at the pipe section 1 between node 2 and node 1, and Z_{c1} is the characteristic impedance of the pipe section 1, and l_1 is the length of the pipe section 1.

The valve action at the end of the pipeline system can be considered introducing the boundary condition of the

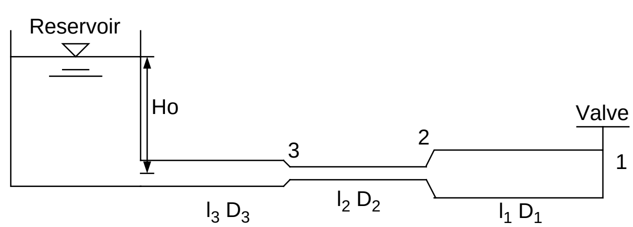

Figure 1 | A series pipe system.

Reservoir Pipeline Valve system as

$$q_D(t) = (C_d A)_t \sqrt{2gh_D(t)} \tag{12}$$

where, $q_D(t) = q_{D0} + \Delta q_D(t)$ and $h_D(t) = h_{D0} + \Delta h_D(t)$, q_{D0} and h_{D0} are the initial discharge and pressure head, respectively.

The valve boundary condition of the reference state such as the initial state of closing a valve or the final state of opening a valve is

$$q_{Dr} = (C_d A)_r \sqrt{2gh_{Dr}} \tag{13}$$

where, the subscript r refers to the reference state.

In conjunction with the valve boundary conditions of equations (12) and (13), the application of discrete convolution provide the explicit expression of the plus sign of discharge variation at the valve as (Suo & Wylie 1989),

$$\Delta q_D(t) = -b + \sqrt{b^2 - c} \tag{14}$$

where,

$$c = q_{D0}^2 - \frac{\tau^2 q_{Dr}^2 (h_{D0} + \Delta h'_D)}{h_{Dr}}, \quad b = q_{D0} - \frac{\tau^2 q_{Dr}^2 r_{Dh}(0) \Delta t}{2h_{Dr}},$$

$r_{Dh}(0)$ is the pressure response function depending upon the discharge pulse at the valve, and τ is the relative opening of the valve.

The pressure head response of a discharge impulse at the node 1 can be expressed as

$$r_{Dh}(t) = \frac{1}{\pi} \operatorname{Re}\left[\int_0^\infty Z_{valve} \cdot e^{i\omega t} d\omega \right] \tag{15}$$

where, Z_{valve} is the hydraulic impedance at the valve.

The pressure head response along pipe section 1 can be expressed as

$$r_{x1h}(t) = \frac{1}{\pi} \operatorname{Re}\left[\int_0^\infty (Z_{valve} \cosh \gamma_1 x_1 + Z_{c1} \sinh \gamma_1 x_1) \cdot e^{i\omega t} d\omega \right] \tag{16}$$

where, x_1 is the distance from the node 1 to the response point.

The flow response along pipe section 1 can be expressed as

$$r_{x1q}(t) = \frac{1}{\pi} \operatorname{Re}\left[\int_0^\infty \left(\frac{Z_{valve}}{Z_{c1}} \sinh \gamma_1 x_1 + \cosh \gamma_1 x_1 \right) \cdot e^{i\omega t} d\omega \right] \tag{17}$$

The pressure head response along pipe section 2 is

$$r_{x2h}(t) = \frac{1}{\pi} \operatorname{Re}\left[\int_0^\infty \left(\cosh \gamma_2 x_2 \cdot (Z_{valve} \cosh \gamma_1 l_1 + Z_{c1} \sinh \gamma_1 l_1) + Z_{c2} \sinh \gamma_2 x_2 \cdot \left(\frac{Z_{valve}}{Z_{c1}} \sinh \gamma_1 l_1 + \cosh \gamma_1 l_1 \right) \right) \cdot e^{i\omega t} d\omega \right] \tag{18}$$

where, x_2 is the distance from the node 2 to the response point.

The flow response along the pipe section 2 is

$$r_{x2q}(t) = \frac{1}{\pi} \operatorname{Re}\left[\int_0^\infty \left((Z_{valve} \cosh \gamma_1 l_1 + Z_{c1} \sinh \gamma_1 l_1) \cdot \frac{\sinh \gamma_2 x_2}{Z_{c2}} + \cosh \gamma_2 x_2 \cdot \left(\frac{Z_{valve}}{Z_{c1}} \sinh \gamma_1 l_1 + \cosh \gamma_1 l_1 \right) \right) \cdot e^{i\omega t} d\omega \right] \tag{19}$$

The pressure head response along pipe section 3 is

$$r_{x3h}(t) = \frac{1}{\pi} \operatorname{Re}\left[\int_0^\infty \left\{ \cosh \gamma_3 x_3 \cdot \left(\cosh \gamma_2 l_2 \cdot (Z_{valve} \cosh \gamma_1 l_1 + Z_{c1} \sinh \gamma_1 l_1) + Z_{c2} \sinh \gamma_2 l_2 \cdot \left(\frac{Z_{valve}}{Z_{c1}} \sinh \gamma_1 l_1 + \cosh \gamma_1 l_1 \right) \right) + Z_{c3} \cdot \sinh \gamma_3 x_3 \cdot \left((Z_{valve} \cosh \gamma_1 l_1 + Z_{c1} \sinh \gamma_1 l_1) \times \frac{\sinh \gamma_2 l_2}{Z_{c2}} + \cosh \gamma_2 l_2 \cdot \left(\frac{Z_{valve}}{Z_{c1}} \sinh \gamma_1 l_1 + \cosh \gamma_1 l_1 \right) \right) \right\} \cdot e^{i\omega t} d\omega \right] \tag{20}$$

where, x_3 is the distance from the node 3 to the response point.

The flow response along the pipe section 3 is

$$r_{x3q}(t) = \frac{1}{\pi}\mathrm{Re}\left[\int_0^\infty\left\{\left(\cosh\gamma_2 l_2 \cdot (Z_{valve}\cosh\gamma_1 l_1 + Z_{c1}\sinh\gamma_1 l_1) + Z_{c2}\sinh\gamma_2 l_2\cdot\left(\frac{Z_{valve}}{Z_{c1}}\sinh\gamma_1 l_1 + \cosh\gamma_1 l_1\right) \cdot \frac{\sinh\gamma_3 x_3}{Z_{c3}} + \cosh\gamma_3 x_3 \cdot (Z_{valve}\cosh\gamma_1 l_1 + Z_{c1}\sinh\gamma_1 l_1)\frac{\sinh\gamma_2 l_2}{Z_{c2}} + \cosh\gamma_2 l_2\cdot\left(\frac{Z_{valve}}{Z_{c1}}\sinh\gamma_1 l_1 + \cosh\gamma_1 l_1\right)\right)\right\}\cdot e^{i\omega t}d\omega\right] \tag{21}$$

Frequency dependent friction

The frequency dependent friction can be accounted by replacing the propagation operator, γx, and the characteristic impedance, Z_c, by the following equations as (Suo & Wylie 1989; Wylie & Streeter 1993)

$$\Gamma(s') = \frac{s'x}{a}\left(1 - \frac{2J_1\left(i\frac{D}{2}\sqrt{\frac{s'}{\nu}}\right)}{i\frac{D}{2}\sqrt{s'\nu}J_0\left(i\frac{D}{2}\sqrt{\frac{s'}{\nu}}\right)}\right)^{-1/2} \tag{22}$$

$$Z(s) = \frac{a}{gA}\left(1 - \frac{2J_1\left(i\frac{D}{2}\sqrt{\frac{s'}{\nu}}\right)}{i\frac{D}{2}\sqrt{\frac{s'}{\nu}}J_0\left(i\frac{D}{2}\sqrt{\frac{s'}{\nu}}\right)}\right)^{-1/2} \tag{23}$$

where, J_0 and J_1 are the first-type Bessel function of zero and first order, respectively.

Impedance transfer function of leakage

The impedance transfer function with a leak is derived in the RPV system. The impedance at the upstream of leak position is expressed as

$$Z_{upleak} = -Z_c \tanh\gamma x_{up} \tag{24}$$

where, x_{up} is the distance from upstream reservoir to the leak point.

The impedance at the downstream of leak position can be derived using the point matrix for leak (Mpesha *et al.* 2001) as

$$Z_{downleak} = \frac{Z_{upleak}}{1 - \frac{Q_{olk}}{2\cdot H_o}Z_{upleak}} \tag{25}$$

where, Q_{olk} is the mean discharge of leak and H_o is the mean head pressure.

Leak detection algorithm

Many algorithms of leak detection have used the measured time series of pressure or discharge to calibrate the possible leak locations (Liggett & Chen 1994; Nash & Karney 1999; Vitkovsky *et al.* 2000). In this study, the detection scheme of the leak parameters is designed using the genetic algorithm (GA). The impulse response method is integrated into the GA. The GA is a powerful search tool that utilized evolutionary based principles to find optimal solutions (Goldberg 1989). As in the case of evolution, the GA starts with a population of potential solution. A string of chromosome represents a possible solution of the problem. The fitness of each solution is estimated by employing an objective function. The objective function of the time series of the pressure head can be expressed as

$$Minimize\left\{\sum_{t=1}^{end}(h_m(t) - h_o(t))^2\right\} \tag{26}$$

where, $h_m(t)$ is the time series of the measured or specified pressure head and $h_o(t)$ is the time series of the computed pressure head using leak location and quantity from GA operation.

The objective function of the time series of flowrate is

$$Minimize\left\{\sum_{t=1}^{end}(Q_m(t) - Q_o(t))^2\right\} \tag{27}$$

where, $Q_m(t)$ is the time series of the measured or specified discharge and $Q_o(t)$ is the time series of the computed discharge using leak location and quantity from GA operation.

The hybrid objective function can be expressed as

$$Minimize\left\{\sum_{t=1}^{end}\left[(h_m(t)-h_o(t))^2+(Q_m(t)-Q_o(t))^2\right]\right\} \quad (28)$$

Constraints of the system can be feasibly considered in the objective function by integrating the penalty function. Three processes; reproduction, crossover and mutation are used to generate a new population of solutions. The binary tournament selection is used for the generation of the new population. The uniform crossover operator is selected to resolve problems associated with the diversity of the feature combination. Creep mutation is useful in the detection of the small leak because it can slide the generations toward the optimal solution rather than having to jump toward it. Creep mutation operator restricts random mutation of

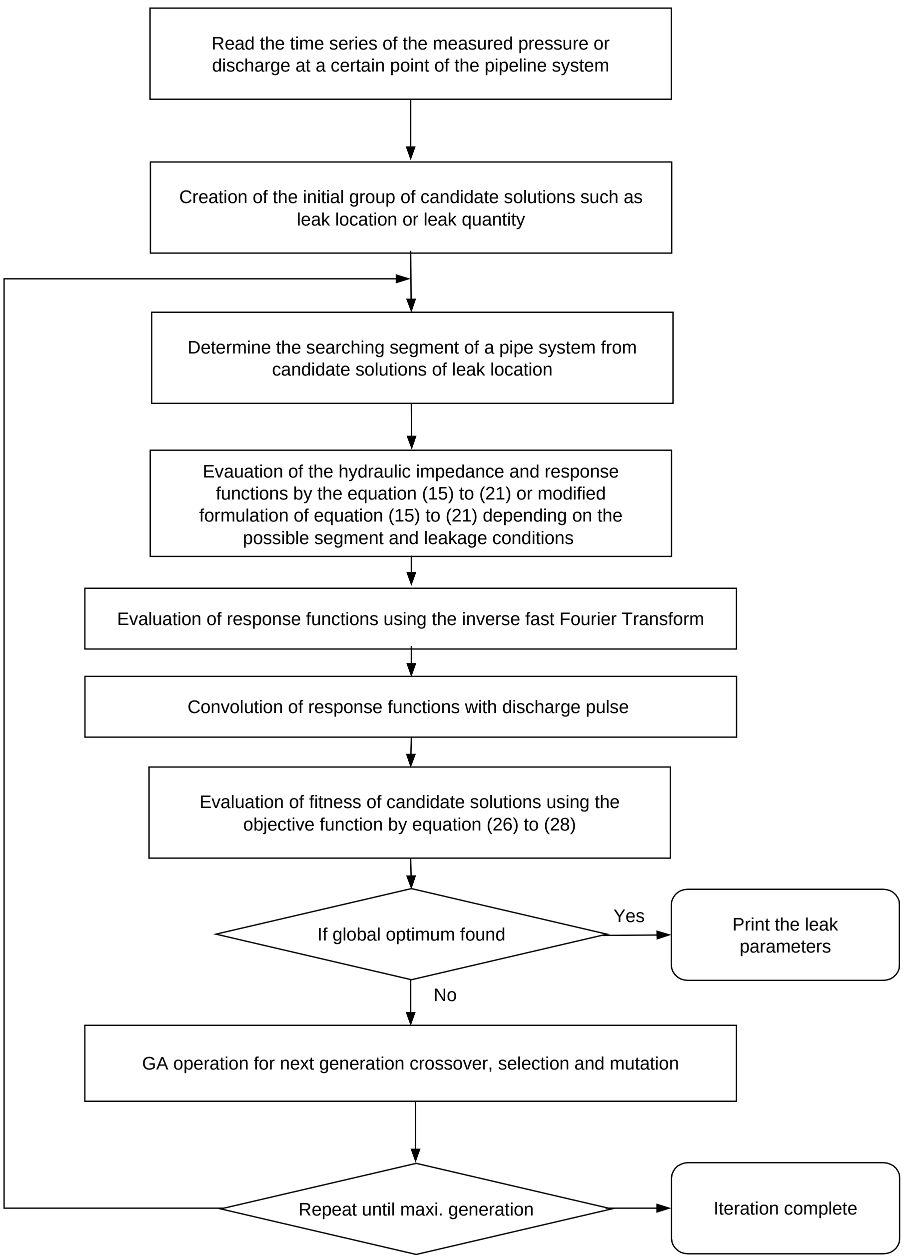

Figure 2 | Leak detection algorithm of impulse response method for a series pipe system.

a string to make the smallest possible changes. A string has the opportunity to change up to next larger adjacent value or down to the next adjacent lower value. Figure 2 shows the flowchart of the integration of the impulse response method with GA for the leak detection. Response functions from equations (15) to equation (21) are modified considering the possibility of leakage in three different segments of a pipeline system.

RESULTS AND DISCUSSION

Example pipeline

A hypothetical series pipeline system with a control valve at the downstream end is used to evaluate the potential of a proposed algorithm as shown in Figure 3. The lengths of pipeline segments, l_1, l_2 and l_3, are 30 m, 40 m and 30 m, respectively. Diameters of each pipeline segments are 0.02 m, 0.015 m and 0.025 m, respectively. Darcy-Weisbach friction factors of pipeline segments are assumed to be 0.015, 0.025 and 0.02. The wave propagation speed is assumed to be 1,300 m/sec and the viscosity of water is $1.17 * 10^{-6}\,m^2/sec$. The pipeline passes water from upstream reservoir to another reservoir at various flow rates depending upon difference of heads, H1-H2, between upstream and downstream reservoirs. Either laminar or turbulent flow conditions can be introduced with steady state discharges as $1.767 * 10^{-5}\,m^3/sec$ and $8.835 * m^3/sec$.

Water hammer waves are introduced as the control valve executes a closure from a full gate opening in 0.024 and 0.3 seconds. Transient conditions of pipeline example of Figure 3 fulfill assumptions of this approach such as a steady oscillatory flow or linearized friction (Wylie & Streeter 1993). The time series of pressure variation and discharge are monitored both at end valve point and 20 m point from the upstream reservoir. Considering the length of pipeline and wave speed, 82.68 rad/sec is used as a maximum frequency of impulse response function. The number of samples for Fast Fourier Transform is determined to be 2048.

The leakage impact of a pipeline can be considered using equation (25). A leakage is introduced at 55.55 m from the end valve as shown in Figure 3. The quantities of leakage are assumed as 1% and 10% of the mean discharges. The forward calculation is performed to obtain the measured time history of pressure and discharges. The location and quantities of leakage are calibration parameters. Three types of objective functions from equation (26) to equation (28) can be used. Two thousand and five hundred iterations of GA evaluations are performed and the array of possible parameters is specified to 2^{15}. Crossover probability is 0.5 and jump mutation and creep mutation probability are 0.02 and 0.04, respectively according to the recommendation of Carroll (1998). The calibration of leak location frequently suffers from multiple-local-optima problems. In order to refine the calibration, the leak detection procedure predetermines searching ranges by 'pre-calibration process'. Searching intervals of leak location and quantity are determined as

$$X_{\text{interval}} = X_{1stCal} \pm X_{1stCal} \cdot 0.1 \quad (29)$$

$$Qleak_{\text{interval}} = Qleak_{1stCal} \pm Qleak_{1stCal} \quad (30)$$

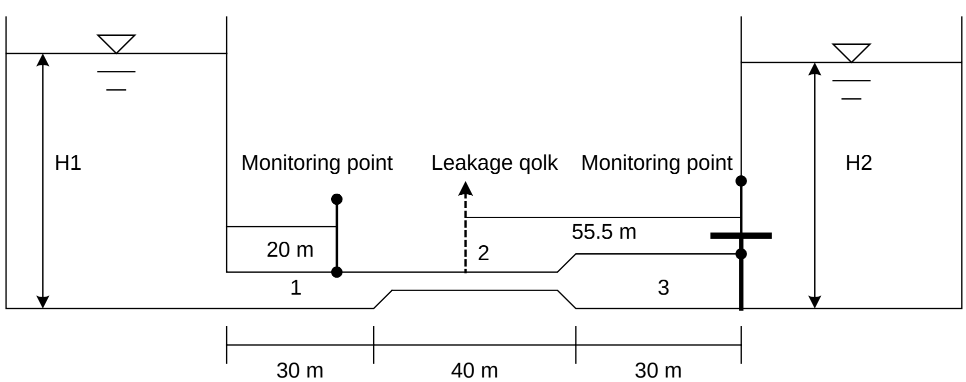

Figure 3 | A series pipeline system for evaluation of leak detection scheme.

where, X_{1stCal} and $Qleak_{1stCal}$ are pre-calibration results of leak location and quantity, respectively.

The impact of scale is minimized in the calibration procedure using the normalized pressure, $H/(av/g)$ and discharges, Q/Q_0 where, H is pressure head, a is wave speed, vis steady state velocity, g is the gravitational acceleration, Q is discharge and Q_0 is the mean discharge. Evaluated objective functions of equation (26) (27) and (28) are defined to fitness functions.

Table 1 shows the leak detection results of the proposed algorithm on the various conditions such as flow, valve maneuver, leak quantity, monitoring locations of data and objective functions. Most predictions of leak location and quantity are well matched with the exact leakage conditions. The difference of predictability of leakage between laminar and turbulent flow is negligible. Low Reynold Number of turbulent condition is a possible interpretation of similar calibration results. Valve actions and objective functions also impact no significant difference of leakage calibration. The results by the monitoring location at 80 m from end valve provide more accurate predictions of leak location than the data acquisition's calibrations at the end

Table 1 | The calibrations of leakage for a series pipeline system by the impulse response method with genetic algorithm using frequency-dependent friction; the numbers of underline are the exact location of leak in meter and the quantity of leak in m^3/sec, Re; Reynold number, Q_{leak}; The leak discharge in m^3/sec, X_{leak}; The location of leak in meter, FIT; Fitness

Flow	**Laminar ($Q_o = 1.767 * 10^{-5}$ m^3/sec, Re = 1282.05)**						**Turbulent ($Q_o = 8.83 * 10^{-5}$ m^3/sec, Re = 6410.26)**					
Valve closure	**Sudden (τ = 0.024 sec)**			**Slow (τ = 0.3 sec)**			**Sudden (τ = 0.024 sec)**			**Slow (τ = 0.3 sec)**		
Param.	**Q_{leak}**	**X_{leak}**	**FIT**	**Q_{leak}**	**X_{leak}**	**FIT**	**Q_{leak}**	**X_{leak}**	**FIT**	**Q_{leak}**	**X_{leak}**	**FIT**
Q_{leak}/Q_0: 1%	1.8e-7	55.82	1.5e-7	1.8e-7	55.83	3e-10	8.9e-7	55.68	9.6e-7	8.8e-7	55.82	9.6e-9
Valve Eq (26)	1.8e-7	55.55		1.8e-7	55.55		8.8e-7	55.55		8.8e-7	55.55	
Q_{leak}/Q_0: 10%	1.8e-6	55.23	8.1e-5	2.0e-6	57.17	3e-6	8.8e-6	55.44	2.9e-5	8.8e-6	55.46	2.8e-6
Valve Eq (26)	1.8e-6	55.55		1.8e-6	55.55		8.8e-6	55.55		8.8e-6	55.55	
Q_{leak}/Q_0: 1%	1.8e-7	55.49	3.9e-8	1.8e-7	55.86	1e-10	8.8e-7	55.50	1.7e-6	8.8e-7	55.58	4.3e-9
80 m Eq (26)	1.8e-7	55.55		1.8e-7	55.55		8.8e-7	55.55		8.8e-7	55.55	
Q_{leak}/Q_0: 10%	1.8e-6	55.61	1.5e-6	1.7e-6	55.39	1.3e-8	8.8e-6	55.46	2.7e-5	8.9e-6	55.72	1.0e-6
80 m Eq (26)	1.8e-6	55.55		1.8e-6	55.55		8.8e-6	55.55		8.8e-6	55.55	
Q_{leak}/Q_0: 1%	1.8e-8	55.55	1e-11	1.8e-7	55.85	9e-10	8.8e-7	55.59	4.1e-7	8.8e-7	55.41	2.oe-7
80 m Eq (27)	1.8e-8	55.55		1.8e-7	55.55		8.8e-7	55.55		8.8e-7	55.55	
Q_{leak}/Q_0: 10%	1.8e-6	55.77	2.3e-5	1.8e-6	54.54	1.7e-6	8.8e-6	55.54	8.2e-9	8.7e-6	55.30	1.2e-6
80 m Eq (27)	1.8e-6	55.55		1.8e-6	55.55		8.8e-6	55.55		8.8e-6	55.55	
Q_{leak}/Q_0: 1%	1.8e-8	55.55	2e-10	1.8e-7	55.54	9e-10	8.8e-7	55.56	1.3e-6	8.8e-7	55.54	6.7e-8
80 m Eq (28)	1.8e-8	55.55		1.8e-7	55.55		8.8e-7	55.55		8.8e-7	55.55	
Q_{leak}/Q_0: 10%	1.8e-6	55.47	1.9e-5	1.7e-6	54.46	5.5e-6	8.7e-6	55.50	2.4e-8	8.8e-6	55.46	3.3e-6
80 m Eq (28)	1.8e-6	55.55		1.8e-6	55.55		8.8e-6	55.55		8.8e-6	55.55	

Table 2 | The calibrations of Darcy-Weisbach friction factors a series pipeline system by the impulse response method with genetic algorithm; the numbers of underline are the exact friction factors of series pipeline system. Re; Reynold number, Q_{leak}; f_1, f_2, f_3; Darcy-Weisbach friction factors of pipeline segment 1, 2 and 3, respectively in Figure 2

Valve closure	Sudden (τ = 0.024 sec)			Slow (τ = 0.3 sec)		
Steady state flow conditions	f_1	f_2	f_3	f_1	f_2	f_3
($Q_o = 8.83 * 10^{-5}\,m^3$/sec, Re = 6410.26)	0.015	0.025	0.02	0.015	0.025	0.02
	<u>0.015</u>	<u>0.025</u>	<u>0.02</u>	<u>0.015</u>	<u>0.025</u>	<u>0.02</u>
($Q_o = 3.53 * 10^{-4}\,m^3$/sec, Re = 25461.04)	0.015	0.025	0.02	0.016	0.025	0.023
	<u>0.015</u>	<u>0.025</u>	<u>0.02</u>	<u>0.015</u>	<u>0.025</u>	<u>0.02</u>

valve. The propagation of leakage information near the leak position is less effected by the degradation of pressure and discharge changes by the leakage. The proposed method shows a potential of leak detection capability between 10 to 1% leak of the mean discharge. The prediction accuracy and convergence of the method can be improved introducing more elaborated calibration tools.

Multiple leakage prediction is an important issue because number of leakage is another unknown variable. Theoretically, the developed method can represent more than 2 leakages through multiple application of equation (25) in any segment of pipeline system. However, calibration of multiple leakages should require extensive power of computation because number of variables such as leak locations and quantities are larger than the variable number of single leakage. The number of leakage can be determined using ascending order of stepwise calibration from a single to multiple leakages based on the objective functions of equation (26) to (28). Elaborate calibration application for more general multiple leakage seems one of demanding future research topics.

Proposed method can be used to calibrate friction factors along a series pipeline system in Figure 3. Identical procedure to leak calibration is employed to evaluate friction calibration of the impulse response analysis. Pressure time series at the end of valve are used for objective function of equation (26). Turbulent flow conditions with high Reynold numbers, 6410.26 and 25641.04, are introduced to consider flow conditions of field pipelines having larger diameters than those of example pipeline in Figure 3. Calibration parameters are Darcy-Weisbach friction factors of each pipeline segments because frequency dependent friction is less apparent in high Reynold number (Wylie & Streeter 1993).

Table 2 shows friction factors of three pipeline segments of Figure 3 can be simultaneously calibrated using method suggested in this approach. A convergence of local minima on the condition of slow valve action, 0.3 sec, and higher Reynold number, 25461.04, may need further iteration to refine calibration. The proposed method shows a potential of multiple friction calibration as well as a leakage prediction in various steady flow conditions and valve actions.

CONCLUSIONS

The pressure head and discharge responses about the leakage impact are derived at any point of a series pipeline system. A numerical test of the proposed method shows a potential of leak detection algorithm in a series pipeline system. The impulse response method provides several advantages to other conventional methods. The accuracy of leak location and quantity can be apparently improved compared to other numerical based approaches such as method of characteristics and finite difference method because the impulse response method does not necessarily divide the system into numerous elements and nodes. The integration of unsteady flow in the frequency domain provides the flexibility of spatial representation of system. The calibration parameters can be optimised in real numbers. A series pipeline system can be described without the constraints of Courant number. However, the simulation of time domain information is restricted due to the frequency based modelling. The proposed method can be also applied in the calibration of multiple friction factors.

This study provides useful guidelines about locations and frequency of pressure monitoring aiming the design of the supervised control and data acquisition system for leak detection and management of a series pipe system.

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REFERENCES

Brunone, B. 1999 Transient test-based technique for leak detection in outfall pipes. *J. Water Resour. Plng. and Mgmt., ASCE* **125**(5), 302–306.

Carroll, D. L. 1998 *FORTRAN Genetic Algorithm Driver*. Univ. of Illinois, Urbana, IL, USA.

Ghidaoui, M. S., Karney, B. W. & Mclnnis, D. A. 1998 Energy estimates for discretization errors in water hammer problems. *J. Hydr. Engrg. ASCE* **124**(4), 384–393.

Goldberg, D. E. 1989 *Genetic Algorithms in Search, Optimization and Machine Learning*. Addison-Wesley Publishing Co., Inc, Reading, Mass., USA.

Liggett, J. A. & Chen, L. 1994 Inverse transient analysis in pipe networks. *J. Hyd. Engrg., ASCE* **120**(8), 934–955.

Liou, C. P. & Tian, J. 1995 Leak detection-transient flow simulation approaches. *J. Eng. Reso. Tech., ASME* **117**(3), 243–248.

Liou, C. P. 1998 Pipeline leak detection by impulse response extraction. *Trans. ASME* **120**, 833–838.

Mounce, S. R., Day, A. J., Wood, A. S., Khan, A., Widdop, P. D. & Machell, J. 2002 A neural network approach to burst detection. *Wat. Sci. Tech.* **45**(4–5), 237–246.

Mpesha, W., Gassman, S. L. & Chaudhry, M. H. 2001 Leak detection in pipes by frequency response method. *J. Hydr. Engrg., ASCE* **127**(2), 134–147.

Nash, G. A. & Karney, B. W. 1999 Efficient inverse transient analysis in series pipe systems. *J. Hydr. Engrg., ASCE* **125**(7), 761–764.

Pudar, R. S. & Liggett, J. A. 1992 Leaks in pipe networks. *J. Hydr. Engrg., ASCE* **118**(7), 1031–1046.

Suo, L. & Wylie, E. B. 1989 Impulse response method for frequency-dependent pipeline transients. *J. Fluids Engrg. Trans. ASME* **111**(4), 478–483.

Vitkovsky, J. P., Simpson, A. R. & Lambert, M. F. 2000 Leak detection and calibration using transients and genetic algorithms. *J. Water Resour. Plng. and Mgmt., ASCE* **125**(5), 302–306.

Wylie, E. B. & Streeter, V. L. 1993 *Fluid transient in systems*. Prentice Hall, Inc., Englewood Cliffs, N.J., USA.

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