Springer

Journal of Mechanical Science and Technology 22 (2008) 1930~1936

Journal of
Mechanical
Science and
Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-0735-8

Leak detection in pipe using transient flow and genetic algorithm †

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(Manuscript Received April 16, 2008; Revised June 18, 2008; Accepted July 23, 2008)

Abstract

An inverse transient method with genetic algorithm (GA) was applied to leak detection in pipeline. Transient flow caused by valve operation was calculated using the characteristics method. The location and discharge of leak were determined so that the difference of the calculated pressure may be minimized from the reference pressure calculated under a given leak condition. Calculations were done for the leak at one and two locations in pipeline. Furthermore, the effect of noise in pressure data was discussed, and the leak locations and leak discharges can be predicted precisely even in the case of noisy data.

Keywords: Leak detection; Transient flow; Genetic algorithm; Characteristic method

1. Introduction

In many water-distribution systems, a significant percent of water is lost due to leak from pipes. Leaks waste both a precious natural resource and money, and create a public health risk. The presence of leaks in pipe network also lowers efficiency and reliability of system. In addition, leaks may cause traffic accidents and serious structure damage to neighboring properties and roads. If the transporting fluids are hazard, the risks associated with leak get higher. For these reasons, leak detection in pipe has been an important issue.

A number of leak detection methods have been developed. A simple acoustic method used a stethoscope to listen to the noise or vibration generated from a leak. Its success is dependent on the operator's experience, the size of the leak, and the characteristics of the pipeline. However, this method requires high levels of expertise and effort. Hence, a simple, cheap, and reliable method for leak detection would be a great economic value.

A transient flow occurred in a hydraulic system causes a pressure wave to propagate within a pipeline system until a new steady-state is attained. The reflected pressure wave contains information concerning the status of the system. Leaks in a pipeline contribute to damping of pressure and leak importing evidence in the reflected pressure wave. The measurement and analysis of these pressure waves can be used to detect both size and location of leak. Several leak detection methods use this transient behavior.

Liggett and Chen [1] proposed the inverse transient analysis to detect leak in water distribution system. They used the Levenberg-Marquardt (LM) method to minimize the difference between measured pressure data and numerical model results. Vitkovsky and Simpson [2] used the Genetic Algorithm (GA) technique in conjunction with the inverse transient method to detect leaks and friction factors in water distribution systems.

Jösson and Larson [3] used the reflected waves of transient pressure from leak to detect leak. They used spectral analysis of pressure wave to detecting the frequency by the reflected waves from leak. From this frequency by leak, they calculated location of leak.

† This paper was presented at the 9th Asian International Conference on Fluid Machinery (AICFM9), Jeju, Korea, October 16-19, 2007.

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In the present study, the inverse transient method with genetic algorithm was used for leak detection. Reference pressure waves at a point and modeled pressure waves at that point calculated by characteristic method are evaluated to minimize difference between two values. The cases with one leak and two leaks were investigated to detect leak. Furthermore, the effect of noise of measured pressure was discussed.

2. Inverse transient method

2.1 Transient analysis

Considering a circular pipe without leak under the usual assumption, the one dimensional motion and continuity equations can be written in the following form [4].

$$\frac{\partial H}{\partial x}+\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{fQ|Q|}{2gDA^2}=0 \tag{1}$$

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

These basic differential equations can be nondimensionalized by introducing the following nondimensional variables:

$$H^*=\frac{(H-H_0)}{H_0},\quad t^*=\frac{t}{L/a},\quad x^*=\frac{x}{L},\quad Q^*=\frac{Q}{Q_0} \tag{3}$$

The basic equations can be transformed into four ordinary differential equations by the characteristics method. The characteristic equations are

$$\frac{dH^*}{dt^*}+\frac{1}{F}\frac{dQ^*}{dt^*}+RQ^*\left|Q^*\right|=0$$

$$\text{(along } \frac{dx^*}{dt^*}=1\text{)} \tag{4}$$

$$-\frac{dH^*}{dt^*}+\frac{1}{F}\frac{dQ^*}{dt^*}+RQ^*\left|Q^*\right|=0$$

$$\text{(along } \frac{dx^*}{dt^*}=-1\text{)} \tag{5}$$

in which $H_J = aQ_0/gA$, $F = H_0/H_J$, and $R = fQ_0L/2aDAF$.

It is convenient to visualize the solution as it develops on the independent *x-t* variable plane. Eqs. (4) and (5) are referred to as compatibility equations, each one being valid only on the appropriate characteristic line. Using finite difference method, solutions can be completed at any desired time with appropriate boundary conditions.

2.2 Unsteady friction factor

Usually the steady friction terms are used for the transient analysis. However, the modeled pressure and the experimental pressure data show lack of agreement after early time. In laminar flow, frequency-dependent frictional losses were demonstrated to be a major reason for additional losses and for dispersion of sharp pressure wave patterns [4]. Several models for unsteady friction factor have been proposed. The Brunone model relates unsteady part f_u to the instantaneous acceleration $\partial V/\partial t$ and instantaneous convective acceleration $\partial V/\partial x$. Simpson and Vitkovsky [5] improved the Brunone model to perform all types of unsteady conditions.

$$f=f_s+\frac{kD}{V|V|}\left\{\frac{\partial V}{\partial t}+a\cdot sign(V)\left|\frac{\partial V}{\partial x}\right|\right\} \tag{6}$$

in which sign(V) = (+1 for $V \geq 0$ or -1 for $V \leq 0$), and Brunone's friction coefficient k is $k=\sqrt{C^*}/2$. The Vardy's shear decay coefficient C^* is:

$$C^*=\begin{cases}0.00476\\ 7.41/\mathrm{Re}^{\log(14.3/\mathrm{Re}^{0.05})}\end{cases}$$

2.3 Leak in pipeline

Leak in pipe contributes to damping of transient event, as can be seen in Fig. 1 which shows the damping effect. In the pressure wave with leak, leak discharge (C_dA_L/A) was 0.008, and leak location (x^*_L)

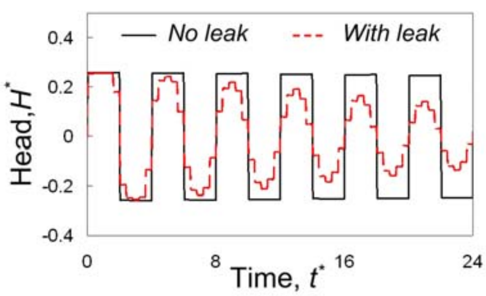


Fig. 1. Damping effect of leak on transient flow; x^*_{mea} −1.0, $x^*_L=0.2, C_dA_L/A=0.008$

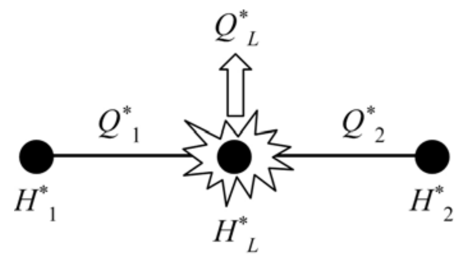


Fig. 2. Leak in pipe.

was 0.2. Location and discharge of leak affect transient event. Leak discharge in pipeline can be expressed by the orifice equation which is a function of pressure in a pipe and size of a leak:

$$Q_L^* = \frac{C_d A_L}{Q_0}\sqrt{2gH_0(H_L^*+1)} = \frac{C_d A_L}{Q_0}\sqrt{2gH_0}\sqrt{H_L^*+1} \tag{7}$$

Fig. 2 illustrates junctions with leak in pipeline. From the motion and continuity equations, we obtain the following equations for leak pressure and discharge

$$H_L^* = H_1^* - R\Delta x^* Q_1^* \left|Q_1^*\right| \tag{8}$$

$$Q_1^* = Q_L^* + Q_2^* \tag{9}$$

where, B=$f\Delta x/2gDA^2$.

Combining Eqs. (7) and (9) to (8) yields the following equation.

$$H_L^* = H_1^* - C_b\left\{\ C_a^2(H_L^*+1) + Q_2^{*2} + 2C_a Q_2^*\sqrt{H_L^*+1}\ \right\} \tag{10}$$

in which $C_a \equiv C_d A_L \sqrt{2gH_0}\,/Q_0$ and $C_b \equiv R\Delta x^*$. In the similar manner, the pressures at leak points and leak discharge with two leaks can be calculated.

2.4 Inverse transient method

The general purpose of the water distribution system problem is to obtain the pressure at node and flow rate between nodes with known outflow at node. In contrast, the inverse method finds outflow at node with known pressure at node and boundary condition.

Inverse transient method involves fitting a numerically modeled pressure trace to a reference pressure trace by minimizing the differences between calculated and reference values. With the information of leak location and leak discharge, we can calculate transient pressure event. To perform for leak detection in pipe by inverse transient analysis, an artificial transient event in the pipe was done by changing the flow at some location. Then observation of pressure at a number of locations in the system is need.

3. Genetic algorithm

The GA is an evolutionary computation paradigm inspired by biological evolution. In general, the fittest individuals of any population tend to reproduce and survive to the next generation, thus improving successive generations. However, inferior individuals can, by chance, survive and also reproduce [6].

The GA used in this study is a modified version of a Genetic Algorithm Optimization Toolbox for Matlab 5 developed by Christopher R. Houck [7]. MATLAB is used for the following reasons: it provides many built in auxiliary functions useful for the function optimization; it is completely portable; and it is efficient for numerical computations. The GA driver for a MATLAB version is free for public use and is available over the internet. Figure 3 shows the GA flow chart. A chromosome representation for GA is adapted real-valued type since it has been shown as more efficient.

4. Case study

Fig. 4 shows the schematic view of problem system with two leaks. Water passes through a reservoir – pipeline - valve hypothetical pipeline system with a constant head reservoir (H_0=25 m). For the pipeline of 1000 m (between x^*=0.0 and 1.0) in Fig. 4, a transient is initiated by closing the downstream valve. The initial steady flow in the pipeline is Q_0=2.0 L/s, which can be achieved by a partially opened downstream valve. The Reynolds number of the flow in the pipeline is 11,160. The Darcy-Weisbach friction factor is calculated as f=0.0302. The control valve executes a closure from a full-gate opening. The wave propagation speed is 1,300 m/s. Transient is introduced from the valve closure in 0.05 s. The fitness of each solution is estimated by employing an objective function. The objective function of the time series of pressure head can be expressed as

$$E = \sum_{i=1}^{end}(H_i^r - H_i^c)^2 \tag{11}$$

where, E : the objective function, H^r_i : time series of reference pressure head, H^c_i : time series of the calculated pressure head.

The number of leak was examined for one and two. Table 1 shows the detailed conditions of leak conditions. For the case with one leak, we set the GA parameters as leak location (x^*_L), leak discharge (C_dA_L/A), and friction factor (f). For the case with two leaks, we set GA parameters as leak location, leak discharge. The ranges of each GA parameters were $0 \leqq x^*_L \leqq 1$, $0 \leqq C_dA_L/A \leqq 0.1$, and $0 \leqq f \leqq 0.1$. In these ranges, the optimized values were obtained by changing these parameters. The reference pressure was calculated with true boundary condition and leak condition. And the effect of noise of the reference pressure was investigated.

5. Results of the case study

5.1 The effect of friction factor

Steady friction factor can be calculated by measuring pressures at some points in the pipeline. If we can reduce one parameter of friction factor, detecting efficiency can be improved. To investigate the effect of friction factor, we set the friction factor as wrong data from true value.

The cases with 10% larger value (0.0322) and 10% smaller value (0.0272) then true friction factor (0.0302) were investigated. The case with 10% larger friction factor detected leak location as 0.275, and the case with 10% smaller friction factor detected leak location as 0.225. Both case detected leak discharge as exact value.

These results confirmed that the effect of the friction factor was not serious for detecting leak, because the relation between the friction factor and leak location is linear.

Table 1. The conditions of leak.

No. of leak	GA parameters	True leak condition
One	x^*_L, C_dA_L/A, f	x^*_L=0.2, 0.4, 0.6, 0.8 C_dA_L/A=0.0001
Two	x^*_L, C_dA_L/A	$(x^*_L)_1$=0.3, $(C_dA_L/A)_1$=0.0004 $(x^*_L)_2$=0.7, $(C_dA_L/A)_2$=0.0006

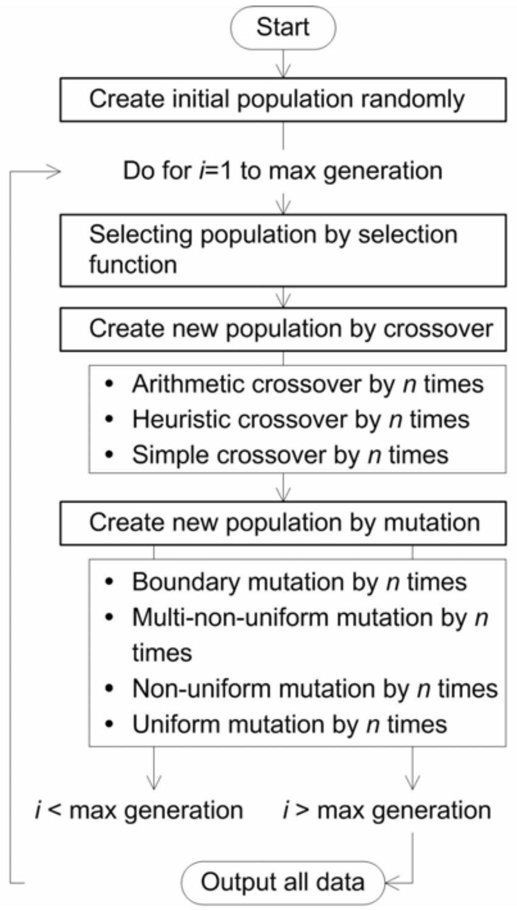


Fig. 3. GA flow chart.

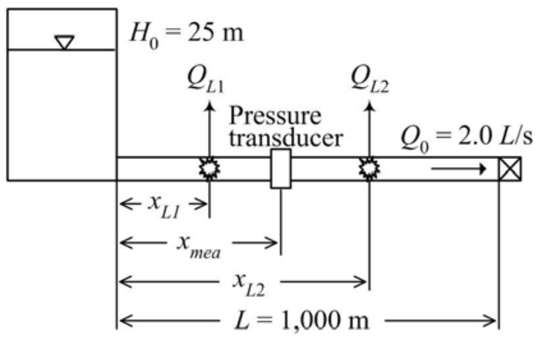
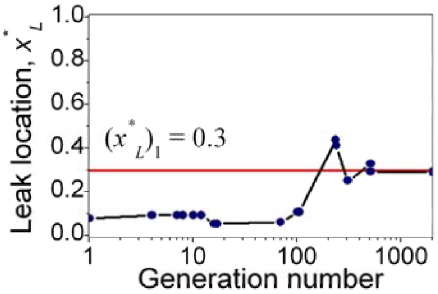
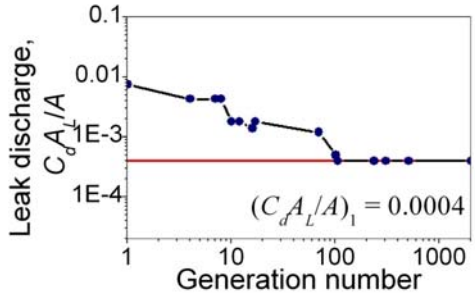


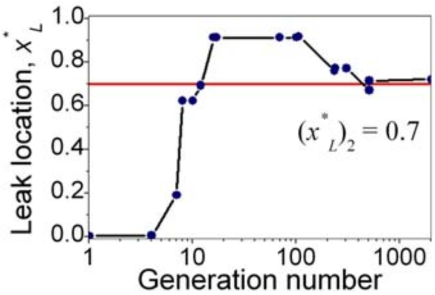
Fig. 4. Pipeline connecting an upstream reservoir and downstream valve.



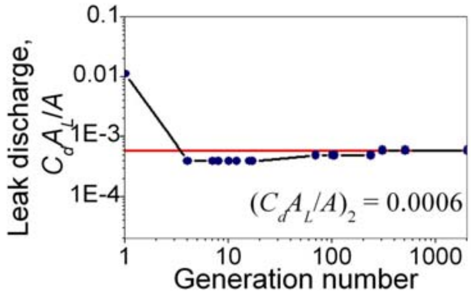
(a) Calculated leak location$(x^*_L)_1$



(b) Calculated leak discharge $(C_0A_\mathrm{L}/A)_1$

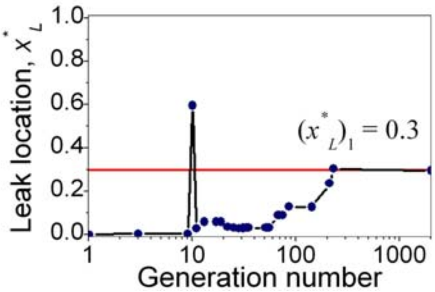


(c) Calculated leak location$(x^*_L)_2$

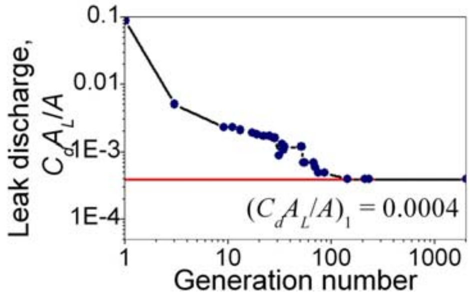


(d) Calculated leak discharge $(C_0A_\mathrm{L}/A)_2$

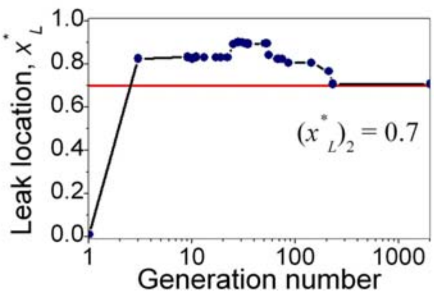
Fig. 5. Results of leak detection without noise.



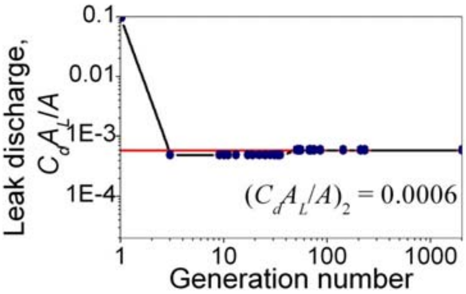
(a) Calculated leak location$(x^*_L)_1$



(b) Calculated leak discharge $(C_0A_\mathrm{L}/A)_1$

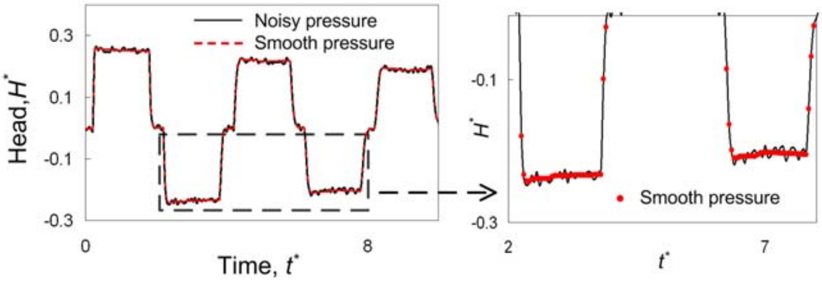


(c) Calculated leak location$(x^*_L)_2$



(d) Calculated leak discharge $(C_0A_\mathrm{L}/A)_2$

Fig. 6. Results of leak detection with noisy data.



Fig, 7. Compariso between noisy pressure and smooth pressure without noise.

5.2 Leak detection for the case with two leaks

The GA population number was 120, maximum generation was 2000, selection option (q) was 0.08, and iteration number of crossover and mutation was 3 for each generation. It takes about 608 seconds for one calculation by dell-8400 (Pentium 4 CPU 3.4GHz, 2G RAM). Fig. 5 shows the process of detecting leak. Although calculating time takes a lot compared to the case with one leak, we can detect leak location and leak discharge. In case with one leak, we can detect leak by 26 seconds. Calculating time with two leaks was about 23 times that of the case with one leak. The detected leak locations $(x^*_L)_1$ was 0.3, and $(x^*_L)_2$ was 0.7. The detected leak discharges were $(C_dA_L/A)_1 = 0.0004$, and $(C_dA_L/A)_2 = 0.0006$.

In the beginning of detection, the number of leak was determined by the post process. From this number of suspicious leak, GA parameters were decided.

5.3 Result of detection with noisy data

To make more realistic situation, noise with zero mean and random deviation of ±0.5 m is added to reference smooth pressure. The signals superimposed noises on the calculated pressures are compared to the signal without noise in Fig. 7. The leaks conditions and GA conditions are the same as the condition without noise. Fig. 6 shows the detecting process. Mean calculation time was 892 seconds. Detected leak locations and leak discharge are $(x^*_L)_1 = 0.2967$, $(x^*_L)_2 = 0.7067$, $(C_dA_L/A)_1 = 0.0004$, and $(C_dA_L/A)_2 = 0.0006$. The detected result using noisy data shows complicate but similar appearance to the case without noise.

6. Conclusion

In this study, the inverse transient method was used to detect leaks in the pipeline. Using pressure data, transient analysis with GA optimization was done for the leak detection. The leak location and leak discharge can be detected even for noisy data case using the present method.

Nomenclature

A	:	Area of pipe [m^2]
A_L	:	Leak area [m^2]
a	:	Wave speed [m/s]
C^*	:	Vardy's shear decay coefficient
C_d	:	Leak orifice discharge coefficient
D	:	Diameter of pipe [m]
f	:	Darcy-Weisbach friction factor
f_s	:	Steady friction factor
f_u	:	Unsteady friction factor
g	:	Gravitational acceleration [m/s^2]
H	:	Pressure head [m]
H_0	:	Pressure head at upstream reservoir [m]
k	:	Brunone's friction coefficient
L	:	Pipe length [m]
Q	:	Discharge of flow [m^3/s]
Q_0	:	Steady state discharge at downstream [m^3/s]
Re	:	Reynolds number
t	:	Time [s]
V	:	Velocity in the longitudinal direction [m/s]
x	:	Distance along pipe [m]
Δx	:	Distance between nodes [m]

Superscripts

*	:	Dimensionless unit

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