TRANSIENT ANALYSIS FOR LEAK DETECTION IN PIPE WITH FLUID-STRUCTURE INTERACTION

Lamjed Hadj TAÏEB*, Ezzeddine Hadj TAÏEB**

*UR Mécanique des Fluides Appliquée et Modélisation, Ecole Nationale d'Ingénieurs de Sfax, B. P. W 3038 Sfax, Tunisia, lamjed@quebecemail.com

**UR Mécanique des Fluides Appliquée et Modélisation, Ecole Nationale d'Ingénieurs de Sfax, B. P. W 3038 Sfax, Tunisia, Ezed.Hadj@enis.run.tn

Summary

The use of fluid transients has the potential to provide insight into effect of leaks in pipeline systems and hence provide leak detection method. This paper presents a technique for detection and location of leaks in a single pipe by means of transient analysis. The method uses transient pressure waves initiated by the sudden closure of an upstream valve. The presence of a leak in a pipe partially reflects these pressure waves and allows for the location and magnitude of leaks. The two constitutive equations of continuity and momentum yield a set of two partial differential equations of hyperbolic type. The computed results obtained by the method of characteristics describe the influence of the leak on head and discharge time-histories. To put in evidence the fluid-structure, interaction the influence of friction and Young modulus of the pipe wall on the leak detection and sizing is also discussed.

Keywords: leak detection, transient analysis , fluid-structure interaction, method of characteristics pipe.

1. INTRODUCTION

The detection and location of leaks in pipeline systems are major problems and leakage control has become high priorities for water supply utilities and authorities [1]. This is not only because there is a greater understanding of the economic and social costs associated with water losses, but there is also an imperative to make best possible use of the natural source that is water.

Several techniques for leak detection in pipe have been presented in the literature using different methods include acoustic technology [2], ground penetration radar or infrared spectroscope [3], transmission and reflection of pressure waves [4, 5], sequential statistical analysis [6], and transient analysis methods [7, 8, 9, 10, 11].

Some of the current numerical methods for locating and identifying leaks are either complicated or imprecise; most of them are time consuming. These methods usually used the acquisition and the analysis of extensive real-time data. Often, these data are either not available or costly to obtain.

The ideal technology for leak detection and location should be non-intrusive, faster and cheaper and should not require cessation of pipeline operations for long period of time. Since transient test data can give more information about a pipe system than steady state measurements, leak detection methodologies based on transient analysis can achieve this goal.

The purpose of this paper is to detect leaks in a single pipe system using transient event (water hammer signals) generated by the sudden closure of a downstream valve. A pressure wave travels along the system at high speed and is modified by the system during its travel. Leaks within a pipe partially reflect these pressure signals and allow for the accurate location and sizing of a leak by measuring the period of time which the pressure wave takes to travel from the measurement section to the leak and vice-versa.

To apply the procedure of leak detection with confidence and success, special attention has to be given to the dynamic effects related to the energy dissipation, namely the friction and the mechanical behaviour of the pipe wall [12].

The focus here is mainly to study the fluid-structure interaction by analysing the influence of the friction and the Young modulus of the pipe wall on the leak detection and sizing.

2. WATER HAMMER MODEL

2.1. Basic equations

The simplified one-dimensional continuity and momentum equations that describe transient flow in elastic pipe are [13]:

$$\frac{\partial H}{\partial t} + \frac{C^2}{gA}\frac{\partial Q}{\partial x} = 0 \qquad (1)$$

$$\frac{\partial H}{\partial x} + \frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{\lambda Q|Q|}{2gDA^2} = 0 \qquad (2)$$

where H is the piezometric head, Q is the discharge, C is the pressure wave speed, g is the gravitational acceleration, A is the pipe cross-sectional area, D is the internal pipe diameter, λ is the coefficient of friction, x is the special coordinate and t is the time.

The elastic wave speed, C, is a parameter that depends on the fluid compressibility and on the physical properties and external constraints of the pipe. Assuming linear-elastic behaviour of the pipe wall (described by Hooke's law), wave speed can be estimated by [13]:

$$C = \sqrt{\frac{K/\rho}{1+\frac{cD}{eE}K}} \tag{3}$$

where E is the Young's modulus of elasticity of the pipe, K is the fluid bulk modulus, ρ is the fluid density, e is the pipe wall thickness and c is a pipe constraint factor.

2.2. Leak modelling

A leak represents a flow loss without head loss. A leak is modelled as an orifice and the discharge, Q_ℓ, through it is assumed to be given by the following equation [7]:

$$Q_\ell = C_d A_\ell \sqrt{2gH_\ell} \tag{4}$$

where C_d is a discharge coefficient, A_ℓ is the orifice area and H_ℓ is the head on either side of the orifice assumed to be equivalent.

3. NUMERICAL RESOLUTION

Equations (1) and (2) can be transformed into a system of ordinary differential equations and solved by the method of characteristics (MOC). The compatibility equations are [3]:

$$Q_{Pi} - Q_{i-1} + \frac{gA}{C}\left(H_{Pi} - H_{i-1}\right) + \frac{\lambda}{2DA} Q_{i-1}\left|Q_{i-1}\right|\Delta t = 0 \tag{5}$$

along the positive characteristic line ($\Delta x/\Delta t = +C$), and

$$Q_{Pi} - Q_{i+1} - \frac{gA}{C}\left(H_{Pi} - H_{i+1}\right) + \frac{\lambda}{2DA} Q_{i+1}\left|Q_{i+1}\right|\Delta t = 0 \tag{6}$$

along the negative characteristic line ($\Delta x/\Delta t = -C$) where i is the node number, Δx and Δt are the distance ant the time steps respectively (figure 1).

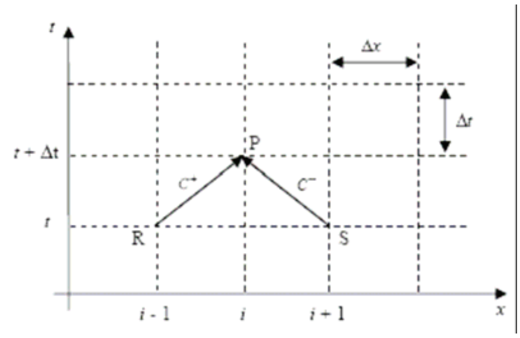

Fig. 1. Characteristic lines: Regular grid

3.1. Initial conditions

In this paper, attention is focused mainly on transients occurring in a single elastic pipe with a constant level reservoir at the upstream end and a rapid closure valve at the downstream end (figure 2). A single leak is supposed to exist at an intermediate section of the pipe located at a distance X from the valve. The pipe with a length L is subdivided in tow segments: pipe 1 from the reservoir to the leak and pipe 2 from the leak to the valve.

Initial conditions must be provided at the time 0 in order to solve the problem. These conditions can be determined by computing the solution of the following system of ordinary differential equations deduced from equations (1) and (2):

$$\begin{cases} \frac{dQ_J}{dx} = 0 \\ \frac{dH_J}{dx} = -\frac{\lambda Q_J^2}{2gDA^2} \end{cases} \tag{7}$$

where J refers to the pipe number.

The solution of this system is:

$$\begin{cases} Q_J(0,x) = Q_J(0,0) \\ H_J(0,x) = H_J(0,0) - \frac{\lambda Q_J^2}{2gDA^2} x \end{cases} \tag{8}$$

At the leak:

$$Q_1(0, L-X) = Q_2(0,0) + Q_{\ell 0} \tag{9}$$

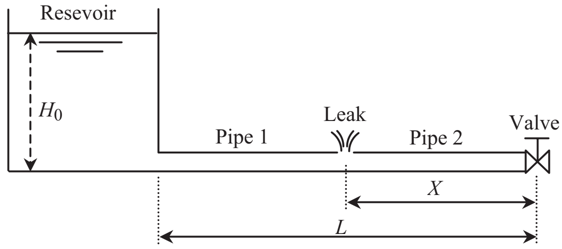

Fig. 2. Reservoir-pipe-valve system with a leak

3.2. Boundary conditions

Transient flow is created by the fast closure of the valve at the downstream end ($x = L$). At this section $Q_2(t, X) = 0$. At the upstream end, $x = 0$ and $t > 0$, the condition is given by the reservoir at fixed level $H_1(t,0) = H_0$.

At a leak, equation (4) is implemented in the MOC as an internal boundary condition (figure 3). The tow relationships that relate the upstream head and flow to the downstream head and flow are:

$$H_{1P,N_1+1} = H_{2P,1} = H_P \quad (10)$$

$$Q_{1P,N_1+1} = Q_{2P,1} + Q_\ell = Q_{2P,1} + C_d A_\ell \sqrt{2gH_P} \quad (11)$$

The compatibility equations either side of the leak are given by equations (5) and (6):

$$Q_{1P,N_1+1} - Q_{1,N_1} + \frac{gA}{C}\left(H_{1P,N_1+1} - H_{1,N_1}\right) + \frac{\lambda}{2DA} Q_{1,N_1}\left|Q_{1,N_1}\right|\Delta t = 0 \quad (12)$$

$$Q_{2P,1} - Q_{2,2} - \frac{gA}{C}\left(H_{2P,1} - H_{2,2}\right) + \frac{\lambda}{2DA} Q_{2,2}\left|Q_{2,2}\right|\Delta t = 0 \quad (13)$$

Equations (10) to (13) form a set of quadratic equation in $\sqrt{H_P}$ that is solved using the quadratic formula:

$$H_P = \left[\left(-C_d A_\ell \sqrt{2g} + \sqrt{\Delta}\right) \Big/ \left(4\frac{gA}{C}\right)\right]^2 \quad (14)$$

where

$$\Delta = \left(C_d A_\ell \sqrt{2g}\right)^2 - 8\frac{gA}{C}\left[\left(Q_{2,2} - Q_{1,N_1}\right) - \frac{\lambda \Delta t}{2DA}\left(Q_{2,2}\left|Q_{2,2}\right| - Q_{1,N_1}\left|Q_{1,N_1}\right|\right) - \frac{gA}{C}\left(H_{2,2} + H_{1,N_1}\right)\right] \quad (15)$$

Once H_P is determined the upstream and downstream flows are calculated using the positive and negative compatibility equations (5) and (6) respectively.

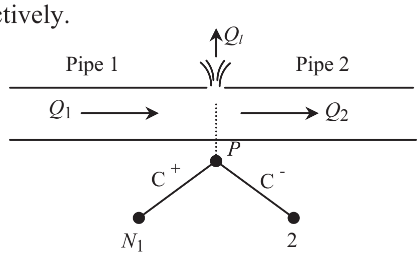

Fig. 3. Leak implementation in the MOC

4. APPLICATION AND RESULTS

4.1. Leak location and sizing

As an example, considering the reservoir-pipe-valve system represented by figure 1 with a leak at an intermediate section and the following characteristics: $D = 0.3048\ m$, $L = 1600\ m$, $C = 1200\ m/s$, $H_0 = 50\ m$ and $Q_0 = 0.02\ m^3/s$. The mean leak discharge $Q_{\ell 0}$ is $0.002\ m^3/s$ which is 10 % of the total mean flow at the upstream end.

Figures 4 (a, b and c) show the head history at the valve obtained by the numerical simulation for leaks located at various positions along the pipe ($X = L/3$, $X = L/2$ and $X = 2L/3$). Figure 5 shows the discharge history at leaks located at the previous positions.

Friction effects are ignored ($\lambda = 0$) to highlight the impact of the leak on the head of pressure evolution.

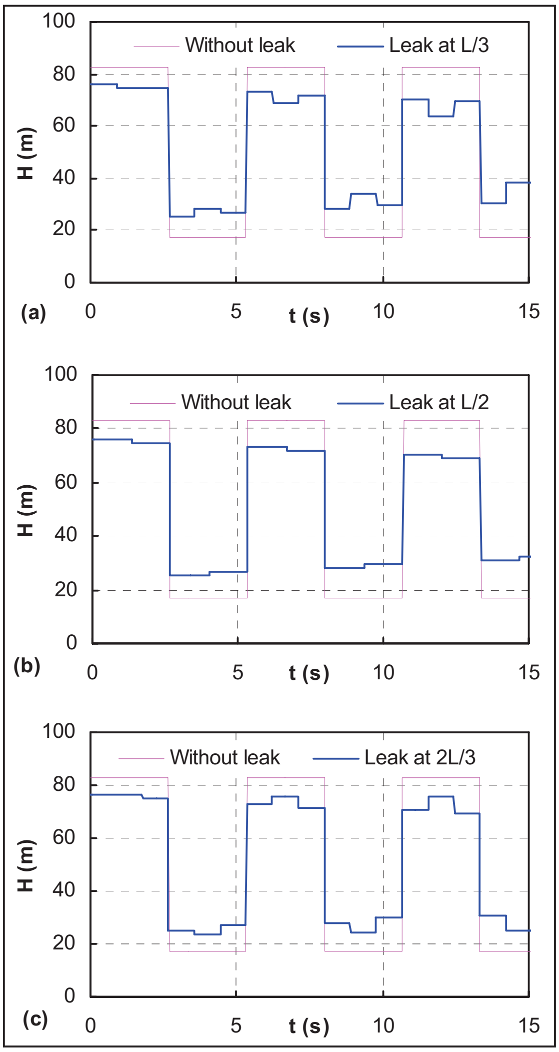

Fig. 4. Comparison of head history at the valve with different leak locations

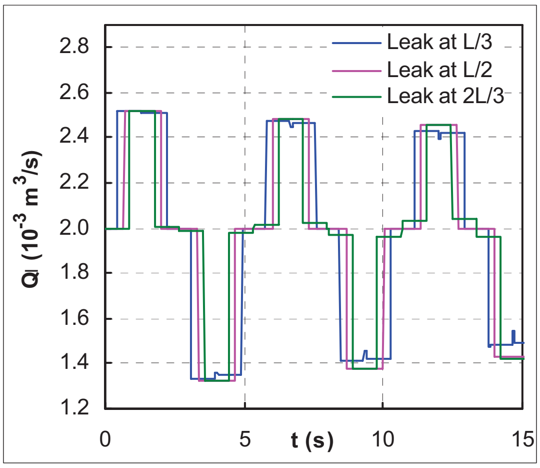

Fig. 5. Discharge history at the leak

The transient event is damped much more rapidly than in the system where the leak does not exist. It can be interpreted by the effect of the leak on the features of the pressure wave propagating along the pipe. Indeed, the leak causes partial reflections of wave fronts that became small pressure discontinuities in the original pressure trace and increase the damping of the overall pressure signal. Hence, through correctly interpreting the head-time history at the valve it is possible to extract information on leak location and leak discharge.

Figure 6, which is an enlargement of the results of figure 4, shows that the location of leak is given by:

$$X = \frac{t_f}{t_0} L \quad \text{and} \quad \frac{X}{L} = \frac{t_f}{t_0} \tag{16}$$

where t_f is the time difference between the initial transient wave and the reflected wave at the leak section (time corresponding to the sudden change of head from ΔH_1 to ΔH_2) and $t_0 = 2L/C$ is the pipe characteristic time. Table 1 summarizes values of t_f for the considered leak locations.

By analysing the head-time transient in figure 5, the leak discharge may be obtained by:

$$Q_{\ell_0} = \frac{gA}{C}\left(\Delta H_0 - \Delta H_1\right) \tag{17}$$

ΔH_0 and ΔH_1 are head rises provoked by the sudden closure of the valve when there is or there is no leak respectively.

Table 1. Leak location ($t_0 = 2.666\ s$)

Leak location	$L/3$	$L/2$	$2L/3$
$t_f\ (s)$	0.888	1.333	1.777
$X/L = t_f/t_0$	0.333	0.5	0.666

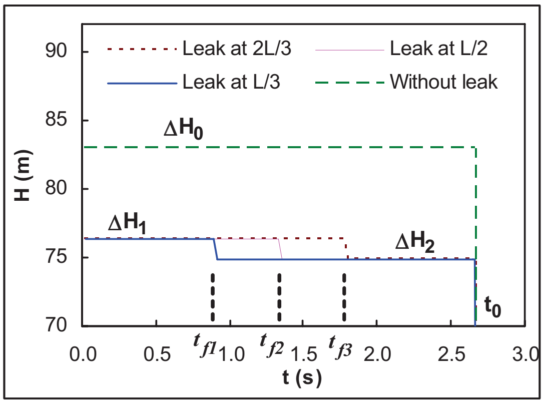

Fig. 6. Head history at the valve with different leak locations

4.2. Influence of the friction

The previous example of reservoir-pipe-valve system is numerically simulated taking in consideration the friction term ($\lambda \neq 0$). Figure 7 shows the effect of friction and leak on the pressure response at the valve.

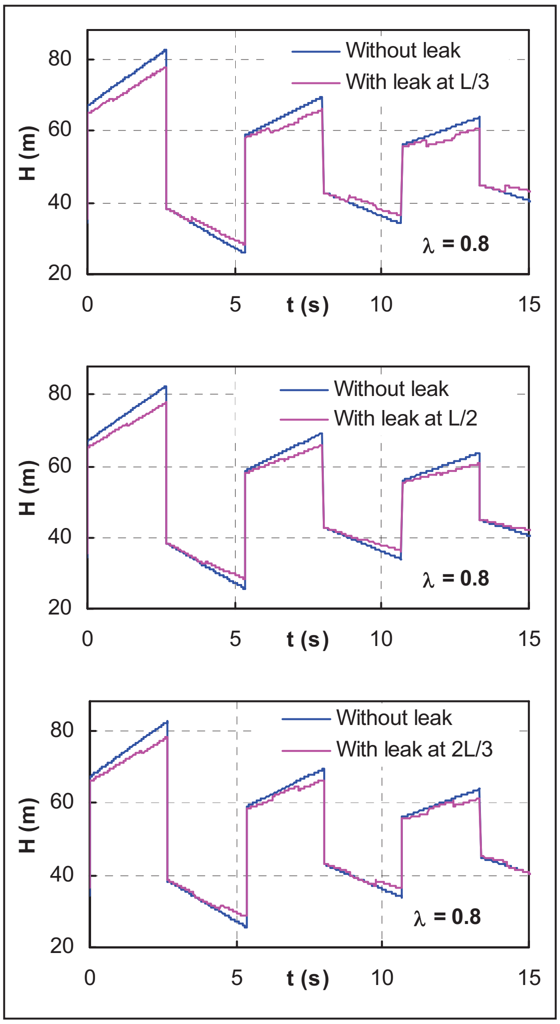

Fig. 7. Head history at the valve ($\lambda = 0.8$)

The friction damps and reduces the overall magnitude of the pressure response. The presence of leak serves to increase the damping in the system. Additionally, the pressure response is more complicated due to the reflection from the leak.

4.3. Influence of Young modulus

Figure 8 represents pressure head at the valve obtained for different values of Young modulus. When the pipe wall elasticity increases the pressure amplitude is reduced and the period increases (the pressure fluctuations are damped more rapidly). This can be interpreted by the effect of the pipe wall deformation on the features of the pressure wave propagating along the pipe. Indeed, the reduction of Young modulus generates a reduction of the celerity (Eq. 3) and consequently the amplitude of this wave is decreased.

Figure 7 shows also that the times t_0 and t_f increases when the Young modulus increases, but the quotient t_f/t_0 remains constant and equal to L/C. Consequently the leak location given by equation (16) is not affected by the change of Young modulus.

Figure 8 represents the fluctuations of the leak discharge for different values of Young modulus. The amplitude of leak discharge fluctuations is reduced when the Young modulus decreases.

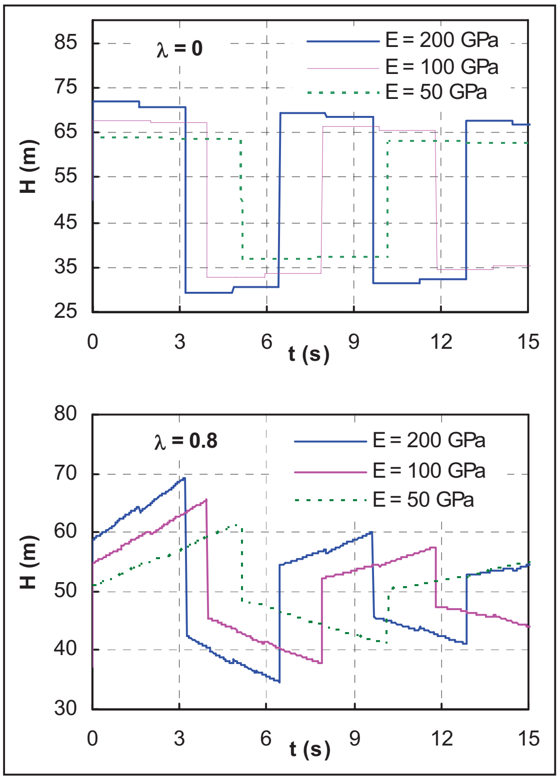

Fig. 8. Head history at the valve for different values of Young modulus
(Leak at $L/2$, $Q_{\ell_0} = 0.004\, m^3/s$)

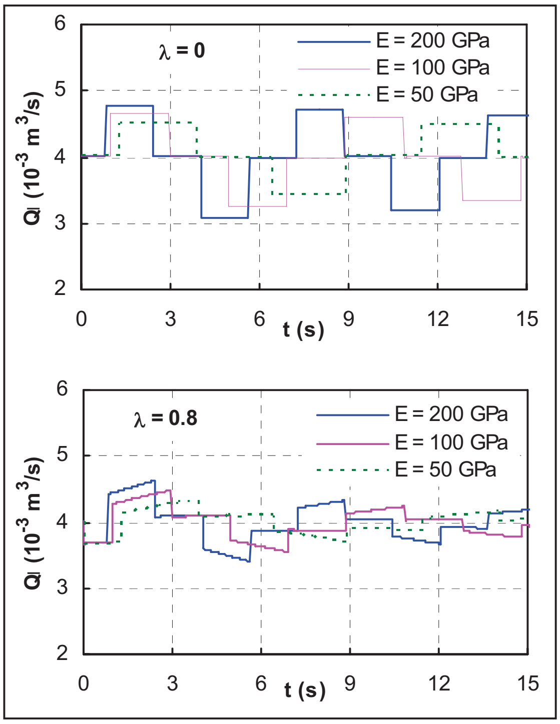

Fig. 9. Leak discharge for different values of Young modulus

(Leak at $L/2$, $Q_{\ell_0} = 0.004\ m^3/s$)

5. CONCLUSIONS

In this paper, a technique based on the analysis of pressure wave in a single pipe system to locate and size leaks was investigated. The method of characteristics, which requires less computer cost, is directly used to determine the magnitude of leaks by developing relations between the location and amplitude of the reflected wave at the leak section.

Furthermore, it is necessary to register the pressure time-history in just one section of the pipe (for example the downstream end) and then the proposed technique can strongly reduce leak detection survey costs in safe conditions.

This study shows that pipe-wall elasticity and steady friction affect the leak detection. Further work is needed in order to investigate the effect of the unsteady friction and pipe-wall viscoelasticity.

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