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STUDY OF A FLOW MODEL FOR DETECTION AND LOCATION OF LEAKS AND OBSTRUCTIONS IN PIPES

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ABSTRACT: *This paper presents the development of a flow model for the final purpose to detect and locate leaks and obstructions in pipes. This model is based on one-dimensional water hammer partial differential equations, discretized with an explicit finite-difference method, to represent the unsteady incompressible flow in pipes, for a finite number of positions. First a study on the selection of boundary conditions for the best structure to represent a pipe system is proposed. This study intends to improve previous works based on some ‘simplified’ finite-difference scheme and basically using pressure boundary conditions at both sides of the pipe (at the beginning and at the end). In particular all configurations of boundary conditions are reviewed, alternating between pressure and flow at each end. Then substitution of those boundary conditions by pump and flow restriction equations is considered, in order to obtain a more realistic model and consider the possibility to measure less variables. Some simulations are finally presented and compared with real data, illustrating how the pipe behavior is better represented with the new boundary conditions, pumps and restriction equations. Those behaviors are considered in particular in the presence of leaks, making the model of interest for possible use in leak detection and isolation.*

KEYWORDS: *Water hammer model, finite differences, leak, obstruction.*

1 INTRODUCTION

Nowadays pipe networks are an essential part of the infrastructure of fluid transport systems in modern society. This is because it is the cheapest way to transport fluids. These networks cross populated areas, providing fluids to large populations, transporting water and chemicals (natural gas, oil and many other products). In all cases, a leak in pipe networks due to corrosion, the excessive stress by pressure increases, or another type of accident, cause loss of product but also serious environmental damage to be avoided or minimized by careful monitoring (A.L. Souza, et al, 2000). Therefore, the detection and location of leaks are very important to any industry that transports fluid through pipeline networks (Andrew F. Colombo, et al, 2009). On the other hand, the pipes may become obstructed, which also disrupts its operation, producing an increase of the energy required for system operation, decreased quality of service, or even a pipe complete break by excessive pressure.

In this paper we develop a flow model for the purpose of detection and isolation of such leaks or obstructions in pipes. This model is based on one-dimensional water hammer partial differential equations, which are discretized in space with an explicit finite-difference method,

and aims to represent the unsteady incompressible flow in pipes, for a finite number of positions.

This model also intends to improve previous studies in the same spirit as in (Verde, 2004), (Torres et al, 2008) (Dulhoste et al, 2011) for instance, which basically rely on pressure boundary conditions at both sides of the pipe (at the beginning and at the end). Those former models indeed appeared to be useful for leak detection and isolation purposes, by techniques of state observers (Besançon et al, 2007) (Torres et al, 2011), which means that improving the model can result in more accurate detection and isolation schemes. This type of application is left for future studies.

In the present paper, section 2 presents the basic model of the pipe, the considered discretization, and the study of associated boundary conditions with the purpose to obtain the best structure to represent a pipe system. Then section 3 presents the leaks and obstructions considerations, as well as the possible substitution of boundary conditions by pump and flow restriction equations, in order to obtain a more realistic model and to consider the possibility to measure less variables. Section 4 subsequently presents some corresponding simulation results, emphasizing that the model with new boundary conditions as well as pump and restriction equations can in-

deed give better results in reproducing the pipe behavior, particularly when comparing the simulated behavior with some real-data measurements. Finally section 5 proposes conclusions and some perspectives for future works.

2. MATHEMATICAL MODEL OF THE PIPING

2.1 Basic Equations to the Piping Model

Water hammer equations are used to develop the model of the pipe (Lucía Castro Burgos et al, 2009), those equations representing the generation, propagation, reflection and attenuation of pressure waves when changes occur in the piping system. A mass and energy balance in pipe section gives the following system of partial differential equations:

$$\begin{aligned} \frac{\partial H}{\partial t} &= -\frac{c^2}{gA} \frac{\partial Q}{\partial z} \\ \frac{\partial Q}{\partial t} &= -Ag \frac{\partial H}{\partial z} - \frac{fQ|Q|}{2DA} \end{aligned} \quad (1)$$

with:

- t : time coordinate [s]
- z : space coordinate [m],
- H : pressure head [m],
- c : speed of sound [m/s],
- g : acceleration of gravity [m/s^2],
- Q : flow rate in the pipe [m^3/s],
- D : pipe diameter [m],
- A : cross-sectional area of the pipe [m^2],
- f : coefficient of friction [non-dimensional].

Equations (1) correspond to a system of nonlinear hyperbolic partial differential equations in both Q and H , as functions of time t and space z (Jorge García-Serra, et al, 1995) (Steven C. Chapra, 2003).

2.2 Spatial discretization of Q and H :

With the purpose to use this model in schemes for detection and location of leaks and obstructions, it is convenient to discretize it in space. To that end, the pipe is divided into N sections, while upstream and downstream boundary conditions have to be considered, as presented in section 2.3. In addition, initial conditions corresponding to the values of $Q(z, t)$ and $H(z, t)$ along the pipe at time $t = 0$ have to be specified.

Let us consider here that the pipe length L is divided into N cells of uniform size $\Delta = L / N$ as shown in Figure 1.

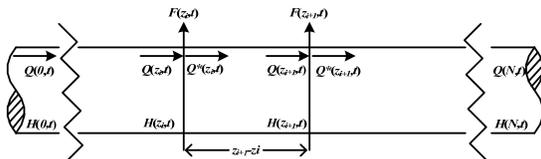


Figure 1. Pipe discretization in N sections.

Then the partial derivatives with respect to z can be approximated by the finite-difference method (Lucía Castro Burgos, et al, 2009) in a forward form for pressure head (H):

$$\frac{\partial H_i}{\partial t} = -\frac{c^2}{gA} \frac{Q_{i+1} - Q_i}{z_{i+1} - z_i} \quad \forall i = 1, \dots, n-1 \quad (2)$$

and in a backward form for the flow rate (Q):

$$\frac{\partial Q_i}{\partial t} = -Ag \frac{H_i - H_{i-1}}{z_i - z_{i-1}} - \frac{f_i Q_i |Q_i|}{2DA} \quad \forall i = 2, \dots, n \quad (3)$$

Index i in Eqs. (2) and (3) represents the index section of the pipeline for the variables under consideration.

2.3 Boundary Conditions

Two types of boundary conditions are considered in this paper, and thus two types of models are constructed accordingly as presented below.

2.3.1 Boundary Conditions 1 (Model 1): $Q_1 H_n$

The first model is obtained when using the following as boundary conditions:

- Upstream flow rate $Q_{in} = Q_1$
- Downstream pressure head $H_{out} = H_n$

In this case, some *outputs* for the model in a system sense can be:

$$H_{in} = H_1 \text{ and } Q_{out} = Q_n.$$

2.3.2 Boundary Conditions 2 (Model 2): $H_1 H_n$

The second model is constructed by considering the following as boundary conditions:

- Upstream pressure head $H_{in} = H_1$
- Downstream pressure head $H_{out} = H_n$

Here the model outputs can be:

$$Q_{in} = Q_1 \text{ and } Q_{out} = Q_n$$

Notice that this is the configuration more particularly considered in (L. Torres et al, 2008) for instance.

3. LEAK, OBSTRUCTION AND BOUNDARY EQUATIONS

This section presents some additional features of the developed models again with the purpose of possible use for fault detection. In that respect, the inclusion of leak or obstruction effects in the models is first considered.

Then, in order to make those models closer to a real system behavior, more precise boundary models are taken into account, by considering here some pump

equation, as well as hydraulic restrictions. Each of the corresponding additional equations is presented hereafter.

3.1 Leak Equation

In order to consider the possibility of a leak in the pipeline, it is necessary to take into account the corresponding flow balance as follows:

$$Q_i = Q_i^* + F_{(i)}\sqrt{H_i} \quad (4)$$

where Q_i is the flow at point i , Q_i^* the flow immediately after the leak considered to affect the flow at point i , and F_i a coefficient that determines the leakage rate as a function of internal pressure. Equation (2) is thus changed into the following one:

$$\frac{\partial H_i}{\partial t} = -\frac{c^2}{gA} \frac{Q_{i+1} - (Q_i - F_i\sqrt{H_i})}{z_{i+1} - z_i} \quad (5)$$

3.2 Obstruction Equation

In a similar way, to consider the possibility of an obstruction at some point i of the pipe, equations (2) and (3) should take into account the fact that the *area* will change at point (i) accordingly: an obstruction can indeed be simulated by reducing this area. Equations (2) and (3) then become:

$$\frac{\partial H_i}{\partial t} = -\frac{c^2}{gA_i} \frac{Q_{i+1} - Q_i}{z_{i+1} - z_i} \quad \forall i = 1, \dots, n-1 \quad (6)$$

$$\frac{\partial Q_i}{\partial t} = -A_i g \frac{H_i - H_{i-1}}{z_i - z_{i-1}} - \frac{f_i Q_i |Q_i|}{2DA_i} \quad \forall i = 2, \dots, n \quad (7)$$

where A_i is the area at point (i).

3.3 Model 3: Model $Q_1 H_n$ with pump and hydraulic restriction at piping entrance.

On the basis of the boundary conditions for the model named *model 1* two additional models can now be derived with the purpose to get a behavior closer to that of the real system. More precisely, a pump equation together with an input hydraulic restriction model are first added at the beginning of the pipe, and a second restriction is then added at the end of pipe, as shown in Figure 2.

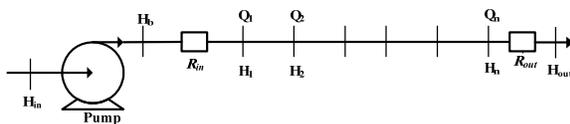


Figure 2. Pipe System.

3.3.1 Pump Equation

The equation of the considered centrifugal pump can be derived from the pump characteristics as follows:

$$H_b - H_{in} = C_2 Q_1^2 + C_1 Q_1 + C_0 \quad (8)$$

where:

$H_b - H_{in} = H_M$ is the manometric pressure height of the pump,
 Q_1 is the handled flow,
 C_0, C_1, C_2 are constant coefficients that depend on the pump.

3.3.2 Hydraulic Restriction Equation

The hydraulic restriction at the beginning of the pipe can be modeled by the following equation:

$$R_{in} Q_1^2 = H_b - H_1 \quad (9)$$

In this case R_{in} (restriction coefficient) depends on pressure losses occurring between the outlet pump and the beginning of pipe.

3.3.3 Equation for H_1 boundary condition

Adding the pump described by equation (8) as well as the hydraulic restriction represented by (9) to the model, boundary Q_1 now changes with the pressure, according to the following equation:

$$Q_1 = \frac{-C_1 + \sqrt{C_1^2 - 4(R_{in} + C_0)(-C_2 + H_1 - H_{in})}}{2(R_{in} + C_0)} \quad (10)$$

where H_{in} is a constant that depends on the tank suction conditions, supposed to be provided to the model at each simulation step. Consequently H_{in} becomes the boundary condition in equation:

$$\frac{\partial H_1}{\partial t} = -\frac{c^2}{gA} \frac{(Q_2 + F_{(1)}\sqrt{H_2}) - Q_1}{z_2 - z_1} \quad (11)$$

3.4 Model 4: Model $Q_1 H_n$ with pump and hydraulic restrictions both at entrance and exit of the pipe.

This model has the same boundary conditions and the same accessories as Model 3, but in addition takes into account another hydraulic restriction at the pipe exit, which can be modeled similarly to the hydraulic restriction at the entrance of pipe (equation (9)). Now H_n pressure is changing according to this restriction, and is estimated at each simulations step with the following expression:

$$R_{out}Q_n^2 = H_n - H_{out} \quad (12)$$

where R_{out} represents the pressure loss coefficient between the end of the test section and the discharge pipe. Therefore, H_{out} now becomes a boundary condition.

Finally, the full model taking into account leaks, obstructions, the pump equation and the two hydraulic restrictions can be written in *state space* variables. As a simple example of such a state space representation, a model for a pipe with a discretization for only *two* sections is presented. Notice that for this simple model, only one leak and one obstruction can be modeled, and it is possible to change the position of this leak or obstruction by the variation of the section sizes ($z_2 - z_1$ and $z_3 - z_2$ respectively, with $z_3 - z_1 = L$) but with the condition that leak and obstruction have the same position.

Obviously, models obtained with a discretization for a larger number of sections can take into account more leaks and obstructions, and in different positions.

For the two-section model we have:

- State variables given by:

$$x = [H_1, Q_2, H_2, Q_3]^T = [x_1, x_2, x_3, x_4]^T$$

- Model inputs given by:

$$u = [Q_1, H_3, z_2 - z_1, F, A_2]^T = [u_1, u_2, u_3, u_4, u_5]^T$$

- Considered outputs given by:

$$y = [H_1, Q_3]^T$$

which gives the following state space representation:

$$\begin{aligned} \dot{x}_1 &= -\frac{c^2}{gA_1} \frac{x_2 - u_1}{u_3} \\ \dot{x}_2 &= -u_5 g \frac{x_3 - x_1}{u_3} - \frac{f_1}{2Du_5} x_2 |x_2| \\ \dot{x}_3 &= -\frac{c^2}{gu_5} \frac{x_4 - (x_2 - u_4 \sqrt{x_3})}{L - u_3} \\ \dot{x}_4 &= -A_3 g \frac{u_2 - x_3}{L - u_3} - \frac{f_2}{2DA_3} x_4 |x_4| \end{aligned} \quad (13)$$

$$y = [H_1, Q_3]^T \quad (14)$$

where:

$A_2 = u_5$ represents de cross section at the obstruction point (an input for the model).

A_1 and A_3 represent the normal cross section at other points (model parameters).

4 SIMULATION AND ANALYSIS RESULTS

For each model, simulations were performed based on the operating conditions of a test-bed with the following physical parameters: PP-R pipe, $L = 85[m]$, $c = 407.75 [m/s]$, $D = 0.0635 [m]$.

This test-bed is located in CINVESTAV Guadalajara, Mexico, and its full technical characteristics can be found in (O. Begovich O, et al, 2008).

The behaviors obtained with the four models discussed above are presented for a configuration with three leakages in different points along the pipeline, and compared with the results of a real experiment on the mentioned test-bed under the same configuration. Additionally, the simulation of an obstruction in one point of the pipe is also reported.

The corresponding results are presented as follows: leaks simulation in Figure 3, this figure shows simultaneously the simulation data with the experimental measurements (these measurements were provided by the CINVESTAV), experimental measurements on the test-bed under leaks in Figure 4, and obstruction simulation in Figure 5.

Comments on those results can be as follows:

In Figure 3, H_{in} , H_{out} , Q_{in} and Q_{out} correspond to the simulations data while h_{in} , h_{out} , q_{in} and q_{out} are the experimental measurements.

- With Model 1 (Figure 3a), it can be seen how out flow Q_{out} decreases when each leak occurs: this is an expected result as a natural behavior. Similarly, one can observe that pressure H_{in} decreases as a result of the leaks.

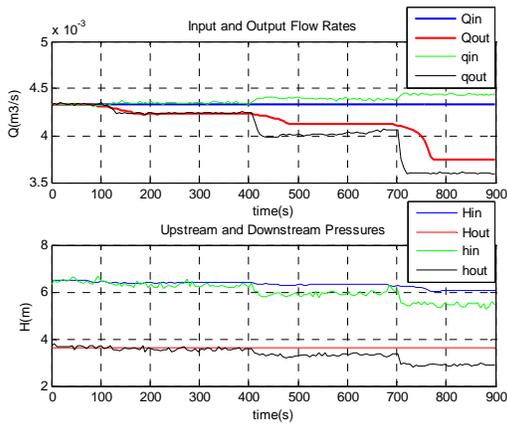
- The behavior of Model 2 can be seen in Figure 3b, where it appears again that Q_{out} decreases with each leak, but there is also an increase in flow Q_{in} , this probably because the boundary condition is the pressure H_1 . However, no change is observed in H_{in} and H_{out} , which is a behavior that is not consistent with that of a real pipe, because when a leak occurs in a real system, Q_{in} increases, H_{in} decreases, and Q_{out} , H_{out} decrease as well. This can be seen in Figure 4, where the behavior of a real system with the same leak tests as in Models 1 and 2 is represented.

- The case of Model 3 is considered in Figure 3c: here the addition of a pump and a hydraulic restriction makes it possible to simulate a loss pressure produced by some accessories (valves, elbows, etc.). The pump coefficients have been set to $C_0 = 27.27$ $C_1 = -274$ $C_2 = -415860$, obtained by curve fitting from a real pump graph. It can then be seen that in this case both Q_{in} and Q_{out} change as does the real system (Fig. 4). There is also a decrease in H_{in} as a result of leaks. However, H_{out} pressure remains constant while it should decrease as in Fig

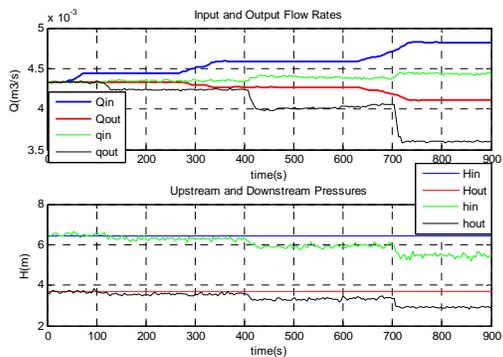
4. The addition of some hydraulic restriction at the exit of the pipe can solve for this problem: this is done in Model 4.

- Figure 3d presents the results obtained with Model 4. It is clear here how as a result of leakage flows, both Q and H at the input and output of pipe changed in a good accordance with what happens in as real system (Fig. 4).

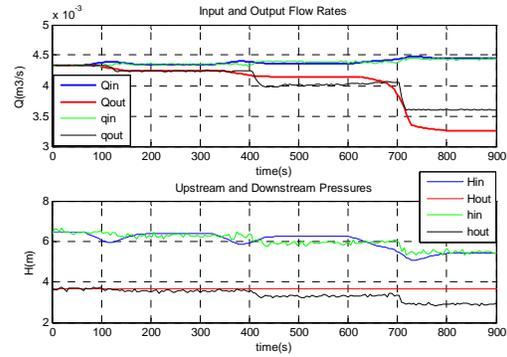
- Finally Figure 5 presents a simulation result with an obstruction in the pipe. This obstruction is simulated in Model 4 because it corresponds to the model that is closer to the real system behavior. An obstruction is characterized by a decrease in flow along the entire pipeline and increased of pressure above it. That is the reason why it is necessary to develop a methodology for the study of the differences in the behavior of flows and pressures between a leak and an obstruction with respect to different phenomena in the pipe, for example, changes in the operating point, disturbance in the process variables and/or some noise that it is causing an undesired output. Figure 5 shows how flows Q_{out} as well as Q_{in} decrease due to the obstruction, while the upstream pressure w.r.t. the obstruction increases. Unfortunately we do not have any similar obstruction test on a test-bed to validate further this simulation.



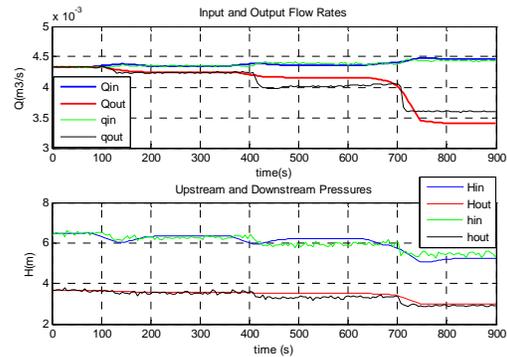
a. Model 1.



b. Model 2



c. Model 3.



d. Model 4.

Figure 3. Simulations of the four models in the presence of 3 successive leaks (at $t=100, 400, 700s$ resp.).

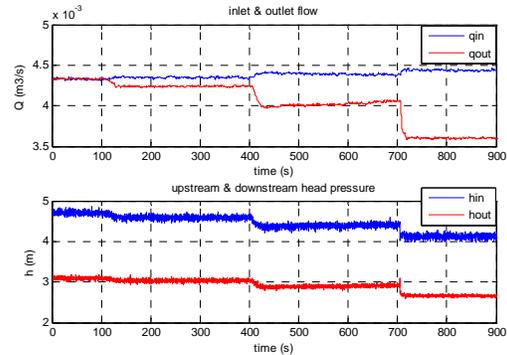


Figure 4. Leakage experiment conducted on a test-bed with 3 successive leaks (at $t=100, 400, 700s$ resp.).

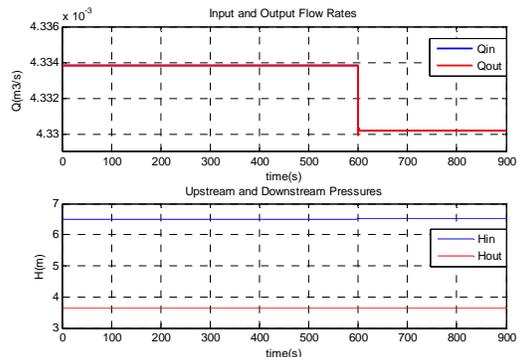


Figure 5. Simulation of an obstruction in the pipe.

5 CONCLUSIONS

In this paper we have studied the structure for a model which should help to detect leaks and obstructions in pipelines. Four model structures of a pipe were presented, to analyze which one of these can represent better the phenomena occurring in the pipeline. In these models we have considered two different types of boundary conditions: Q_1 , H_n used in Models 1, 3, 4 and H_n , H_1 used in Model 2. We considered them as direct boundary conditions for models 1 and 2, and through additional equations for boundary conditions, based on pump equation and flow restriction, for models 3 and 4.

Simulation results have shown that model 4, which includes all the studied equations for the boundary conditions, gives the behavior closer to that observed on a real system than other models, for the case of leak simulations. Additionally we illustrated the capacity to simulate obstructions in a pipe, but in this case without any validation so far.

As a consequence, a natural perspective is to obtain experimental data to validate the obstruction model. Our ultimate interest is also to use this modeling study for an application in fault detection and isolation in pipes (here clearly leaks or obstructions).

In particular this can be thought in the spirit of previous studies based on *nonlinear observers* approaches as in (L. Torres, et al, 2011) for instance, where such observers were developed for leak detection on the basis of a model similar to Model 2 in this paper. A direct perspective here is thus to improve those former results by at least relying on our improved Models 3 and 4, and extend them to some still unconsidered situations (with obstructions for instance).

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