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SENSITIVITY ANALYSIS OF END PRESSURES AND FLOWS WITH RESPECT TO A BLOCKAGE INSIDE A PIPELINE.

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Abstract. *The present paper is based on the sensitivity analysis of input and output pressures and flows of a pipeline for the detection and location of a blockage in a pipeline. To that end, three ways of modeling a blockage in a pipe have been designed. The first model assumes that the blockage is punctual like an orifice plate placed online in the pipeline. For the second and third model, a longitudinal blockage is assumed along the pipeline. In the second model, it is only considered a reduction of the pipeline cross-section in a particular stretch of the pipeline. In the third model, the blocked segment is modeled by considering two orifice plates and between the plates there is a blocked pipe stretch. These models have four different outputs, pressure and flow rate at the input and pressure and flow rate at the output. The aim of this work is to determine which pair of outputs have the highest sensitivity to the change of blockage position in order to improve the detection and location of the blockage. In this study, the energy for each output and for each position is calculated and the magnitude of the energy variation with respect to blockage position is then obtained. Numerical simulations are presented for the different models.*

Key words: Pipeline, Sensitivity analysis, Blockage, Modeling

1 INTRODUCTION

Fluid transportation by pipeline is really cheap and efficient, but faults, such as leaks or blockages, can generate a loss in money and repairing time if there are not detected in short time. A lot of work has been done on leaks detection and location but not so much on blockages detection and location (Wang et al. [1] and Guillén et al. [2]). Particularly, in this work, a sensitivity analysis is done to show how detectable is the position of a blockage when the input and output flows and pressures are measured.

The paper is organized as follows: section 2 presents the different models considered and section 3 explains the sensibility analysis done. Section 4 then shows the results in simulation, and section 5 concludes the paper.

2 DIFFERENT PIPELINE MODELS WITH LUMPED BLOCKAGE

As mentioned in Chaudry [3], if convective changes in velocity and constant liquid density could be considered, then the dynamics of the fluid in a pipeline can be described by the Water Hammer partial differential equations:

$$\begin{aligned} \frac{\partial H}{\partial t} + \frac{c^2}{gA} \frac{\partial Q}{\partial z} &= 0 \\ \frac{\partial Q}{\partial t} + Ag \frac{\partial H}{\partial z} + \frac{fQ|Q|}{2DA} &= 0 \end{aligned} \tag{1}$$

where H means the pressure head (m) and Q the flow rate in the pipeline (m^3/s), both varying in time t (s) and space z (m). In addition, the wave speed in the fluid (m/s), the gravitational acceleration (m/s^2), the cross-sectional area of the pipe (m^2), the diameter of the pipe (m), the friction coefficient, and the pipe length (m) are represented by the constant parameters c , g , A , D , f and L respectively. The boundary conditions on Q, H , for $z \in \{0, L\}$ and the initial conditions for the fluid dynamics must be fixed at $Q(z, 0)$, $H(z, 0)$ for $z \in [0, L]$. The partial differential equations Eq.(1) must be discretized in space in order to solve them numerically by using a finite-difference approximation of the spatial differential operators. If the boundary conditions on $Q(0, t)$ and $H(L, t)$ are imposed, then the equations for each section (i) are:

$$\begin{aligned} \dot{H}_i &= -\frac{c^2}{gA} \frac{Q_{i+1} - Q_i}{z_{i+1} - z_i} \\ \dot{Q}_i &= -Ag \frac{H_i - H_{i-1}}{z_i - z_{i-1}} - \frac{f_i Q_i |Q_i|}{2DA} \end{aligned} \tag{2}$$

where the H_i 's and Q_i 's refer to the approximate values of H, Q at z_i 's and Fig. 1 illustrates the discretization.

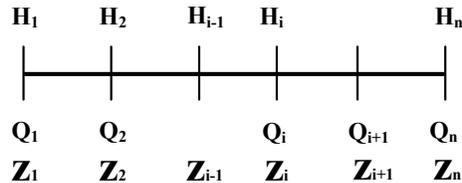


Figure 1: Pipeline discretized in n sections.

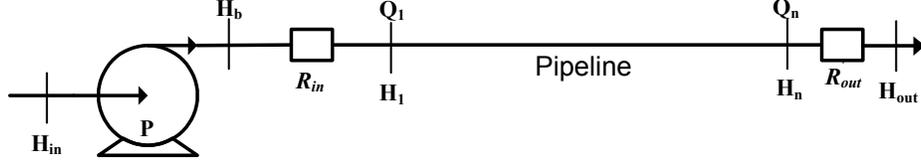


Figure 2: Pump-Restriction-Pipeline-Restriction configuration.

The boundary conditions will be given by a pump and a restriction that are connected at the beginning of the pipeline and at a restriction the end of it, as shown by Fig. 2. As the dynamics of the pump and the restrictions are much faster than the pipeline the static equations could be used, for the pump and the first restriction the equation are:

$$\begin{aligned} H_b - H_{in} &= A_P Q_1^2 + B_P Q_1 + C \\ H_b - H_1 &= R_{in} Q_1^2 \end{aligned} \quad (3)$$

and for the second restriction:

$$H_N - H_{out} = R_{out} Q_N^2 \quad (4)$$

where H_{in} and H_b are the pressure in the input and output of the pump, H_{out} is the output pressure of the second restriction and the constants parameters A_P , B_P , C_P are the pump parameters and R_{in} and R_{out} are the input and output restriction values respectively.

2.1 Blockage considered as punctual

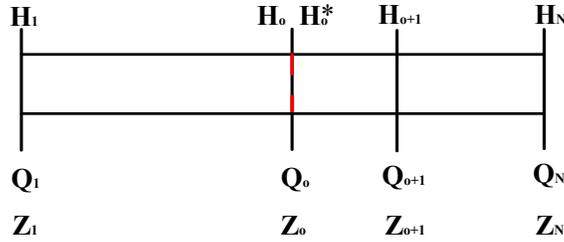


Figure 3: Pipeline with a punctual blockage at z_o .

The first model is based on the hypothesis that the blockage is punctual at position z_o (see Besançon et al. [4]), as shown by Fig. 3, the relation between the pressure before the blockage (H_o) and after (H_o^*) could be described as an orifice plate, so by using Bernoulli's equation the flows on the blockage is modified as follows:

$$\begin{aligned} \dot{Q}_o &= -Ag \frac{H_{o+1} - H_o^*}{z_{o+1} - z_o} - \frac{f_o Q_o |Q_o|}{2DA_o} \\ H_o^* &= H_o - \frac{Q_o^2}{2gA^2} \left[\left(\frac{A}{A_o} \right)^2 - 1 \right] - h_L \end{aligned} \quad (5)$$

In the second equation of (5) h_L represents the pressure losses due to the blockage, if the worst case of $h_L = 0$ is considered (its geometry is unknown), then the blockage modeled is bigger than the real one. Equations 2 describes the dynamics of the other pressures and flows.

2.2 Blockage considered as a section with a reduced cross section area

For the second model the blockage is modeled as a piece of pipeline (with length l_o) which its cross section area is reduced (from A to A_o), Fig. 4 illustrates the blockage.

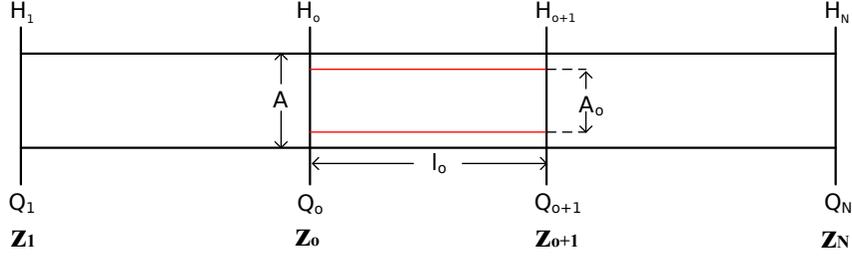


Figure 4: Pipeline with a cross section reduction between z_o and z_{o+1} .

The equations describing the pressure (H_o) at the beginning and the flow (Q_{o+1}) at the end of reduced part of the pipeline are modified (with respect to Eq. 2):

$$\begin{aligned} \dot{H}_o &= -\frac{c^2}{gA_o} \frac{Q_{o+1} - Q_o}{l_o} \\ \dot{Q}_{o+1} &= -A_o g \frac{H_{o+1} - H_o}{l_o} - \frac{f_{o+1} Q_{o+1} |Q_{o+1}|}{2DA_o} \end{aligned} \quad (6)$$

2.3 Blockage considered as a reduced section with both sides geometry

The last model is based on the second one, but it also takes into account the phenomena that occurs in the borders of the longitudinal blockage where first exists a contraction in the cross section of the pipe (from A to A_o) and then occurs an expansion of it (from A_o to A), shown in Fig. 5.

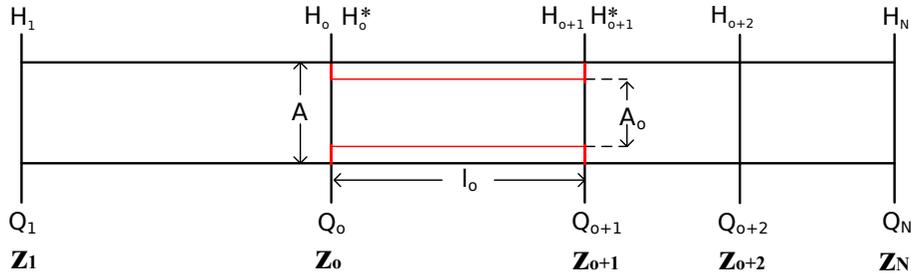


Figure 5: Pipeline with a cross section reduction between z_o and z_{o+1} and the sides effects.

Equation (7) describes the dynamics of the pressures and the flows before (H_o and Q_{o+1}) and after the blockage (H_{o+1} and Q_{o+2}).

$$\begin{aligned}
\dot{H}_o &= -\frac{c^2}{gA_o} \frac{Q_{o+1} - Q_o}{l_o} \\
\dot{Q}_{o+1} &= -A_o g \frac{H_{o+1} - H_o^*}{l_o} - \frac{f_{o+1} Q_{o+1} |Q_{o+1}|}{2DA_o} \\
\dot{H}_{o+1} &= -\frac{c^2}{gA} \frac{Q_{o+2} - Q_{o+1}}{z_{o+2} - z_{o+1}} \\
\dot{Q}_{o+2} &= -Ag \frac{H_{o+2} - H_{o+1}^*}{z_{o+2} - z_{o+1}} - \frac{f_{o+2} Q_{o+2} |Q_{o+2}|}{2DA}
\end{aligned} \tag{7}$$

The pressures just after the beginning and the end of the blockage are H_o^* and H_{o+1}^* , are modified using Bernoulli's in order to represent the change in the cross section area of the pipe.

$$H_o^* = H_o - \frac{Q_o^2}{2gA^2} \left[\left(\frac{A}{A_o} \right)^2 - 1 \right] \quad \text{and} \quad H_{o+1}^* = H_{o+1} - \frac{Q_{o+1}^2}{2gA_o^2} \left[\left(\frac{A_o}{A} \right)^2 - 1 \right] \tag{8}$$

Three different ways of modeling a blockage are shown in this section, next section gives a methodology for comparing the sensibility of the different outputs respect to the blockage's position.

3 SENSITIVITY ANALISYS

In order to quantify the effects of different blockage's positions in the measured variables, the sensibility (S) of one output (y) respect to the position (z) is introduced as the variation of the energy (E) of that output respect to the position (z):

$$S_z^y = \frac{\partial E_y}{\partial z} = \frac{\partial}{\partial z} \left(\int_0^T y(z)^2 dt \right) \tag{9}$$

The sensibility increases with the change of the energy of an output when the position moves, what implies that, the bigger this function is, the easier is to distinguish two different locations from that output. Sensibility analysis is also useful for parameter identifiability analysis (see Dötsch et al. [5]). In the next section, the three models will be simulated with the same inputs conditions and the sensibility analysis will be done for each measured variable.

4 NUMERICAL RESULTS

Using a simulation software (Simulink from MathWorks ©) the three models are simulated with the same inputs, $H_{in} = 1 + 0.5 \sin(2\pi t)$ (m) and $H_{out} = 1$ (m). Then defining the measured variables as H_1 , H_N , Q_1 and Q_N the eq. (9) is calculated for each model and each output. The time windows used is $T = 2s$ and 83 different positions are simulated taking 85 sections for the discretization of the pipeline. Table 1 shows the numerical values of the average of the absolute values of the sensibility. In order to understand this table, the values of the pressures H_1 and H_N are around 6.5 (m) and 3.5 (m) and the flows are near $4.3 \cdot 10^{-3}$

Table 1: Energy variation average for each output and each model.

Output	Model 1	Model 2	Model 3
H_{in}	$2.31 \cdot 10^{-05}$	$1.42 \cdot 10^{-04}$	$1.43 \cdot 10^{-04}$
H_{out}	$8.27 \cdot 10^{-07}$	$1.31 \cdot 10^{-05}$	$1.35 \cdot 10^{-05}$
Q_{in}	$8.52 \cdot 10^{-12}$	$9.35 \cdot 10^{-12}$	$9.46 \cdot 10^{-12}$
Q_{out}	$1.31 \cdot 10^{-12}$	$2.27 \cdot 10^{-11}$	$2.33 \cdot 10^{-11}$

(m^3/s) The second and third model have a similar sensibility but the first model has a minor sensibility than last two. The best pair of measures with bigger sensibility are H_{in} and Q_{out} , but it is still very low and if noise around 1% is injected in the outputs then two different positions will be indistinguishable.

5 CONCLUSIONS

In this work a sensibility analysis respect to the position of a blockage in a pipeline has been done for three different way of modeling a blockage. The numerical results shows that there are two model which are more sensible and in all the models there is a pair of outputs that show a bigger sensibility over the other two. In all the cases the values of sensibility founded are very low and to distinguish between two different positions is very difficult. In the future this sensitivity analysis will be done to more complex models to increase the value of this sensibility and guarantee a strong distinguishability between two different blockage positions.

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