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Detección y localización de obstrucciones en una tubería utilizando observadores de estado (Kalman Extendido)

Pipeline blockage detection and location using state observers (extended Kalman)

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Resumen

En este trabajo se muestra el modelado matemático de un sistema de tuberías, para ser utilizado en la Detección y Localización de Obstrucciones mediante el uso de Observadores de Estado. Para llevar a cabo el modelado matemático de la tubería, se emplean las ecuaciones de Golpe de Ariete, las cuales son discretizadas utilizando el Método de Colocación. Posteriormente, se aborda la tarea de Detección y Localización de obstrucciones, donde se implementa un observador del tipo Kalman Extendido. Este observador tiene la capacidad de estimar simultáneamente la posición en la tubería ($\boldsymbol{z_c}$) donde se está presentando la obstrucción y el porcentaje de área de obstrucción ($\boldsymbol{A_o}$). El observador presenta un buen desempeño y es sometido a diversas pruebas, incluyendo su utilización en un modelo de tubería discretizado mediante el Método de Diferencias Finitas. Por último, se presentan las conclusiones y recomendaciones obtenidas del estudio realizado.

Palabras clave: Obstrucciones, detección, localización, observadores de estado, Kalman Extendido.

Abstract

This paper presents the mathematical modeling of a pipeline system that will be used in the detection and location blockages with state observers. The pipeline mathematical modeling is carried out with the Water Hammer Equations, which are discretized using the Collocation Method. Subsequently, the detection and location blockage tasks are addressed, where an extended Kalman observer is implemented. This observer has the ability to simultaneously estimate the pipe position (zc) where blockage is occurring and the blockage area percentage (Ao). The observer presents a good performance and is subjected to several tests, including its use in a pipeline model discretized by the Finite Difference Method. Finally, conclusions and recommendations obtained from the study are presented.

Keywords: Blockages, detection, localization, state observer, Extended Kalman.

1. Introduction

Pipelines are components used to transport fluids from one place to another. These pipelines can be individual, such as a gas pipeline or a polyduct (for transporting hydrocarbons products), or can also be pipelines networks found in industries and/or city water distribution systems. When a piping system is designed, it is designed under certain flow and pressure conditions. However, as time goes by, system faults occurs such as leaks and/o blockages that modify these flow and pressure conditions. In this work, we will study one of these faults, specifically blockages.

A blockage can occur due to an accidental valve closure (partial or total), formation of physical or chemical deposits. These can produce considerable energy losses (due to the pressure drop generated) and, therefore, increase the pumping needs of the fluid being transported, which means that the efficiency piping system decreases due to blockages. Blockages disturb the piping networks operation and can generate, an energy increase required for the operation system, a quality decrease of service and even a total or abrupt rupture due to an excessive increase pressure upstream of blockage. The early detection and location blockage is useful to carry out protection and maintenance activities. However, blockages are not easy to locate, since their presence is not visible from outside (as happens with a leak), unless there is a pipeline rupture; therefore, the Detection and Location of Blockages is vital in fluid transport industry through pipeline networks (Yang et al., 2019; Colombo et al., 2009; Souza et al., 2000).

Many research works address flow modeling in pipes to detect and locate these faults (leaks or blockages). Specifically for detection and location leak, some of many existing ones could be mentioned (Castro et al., 2009; Besançon et al., 2007; Billmann et al., 1984; Brunone et al., 2001; Wang et al., 2002). Regarding flow modeling in a pipeline for detection and location blockages, the following can be mentioned: (Wang et al., 2005; Lee et al., 2008; Ma et al., 2007; Sattar et al., 2008; Massari et al., 2014; Meniconi et al., 2012).

In present work, firstly, a pipe model is shown, which is obtained using collocation method. Secondly, the detection and localization blockages is presented, which an Extended Kalman observer type (EKF) performs. Initially, the observer is used on a discretized model by collocation method, where pipe is divided in two segments. Then, same observer is used on a model discretized by finite difference method, but using approach of the collocation method (divide pipeline in two segments). The observer achieves simultaneous estimation of blockage size (A_o) and position pipe (z_c) at which blockage occurring, in both pipe models.

2. Pipeline Modeling

2.1 Pipeline Model Equations

The classical water hammer equations are the used to develop the pipeline mathematical models (Chaudry, 2014). These equations are referred to as continuity equation and momentum equation. These, are a set nonlinear partial differential equations of hyperbolic type (Steven, 1988), and can be written as follows:

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

with $z \in [0, L]$ and $t \in [0, \infty)$, where z is independent length coordinate (*m*), t independent coordinate time (s). Dependent variables are: H pressure load (*m*) y Q pipeline flow (m^3/s). The other variables: c sound speed (m/s) which is considered constant, g gravity acceleration (m/s^2), D pipeline diameter (*m*), A pipe cross-sectional area (m^2), f dimensionless coefficient friction, are system parameters do not vary over time usually (Chaudry, 2014).

2.2 Flow (Q) and Pressure (H) Spatial Discretization

There are several methods to obtain a solution for this type equations (1). In the present paper use Collocation Method (Villadsen et al., 1967; Fletcher et al., 2006), since its simplicity makes it suitable for one-dimensional simulations. The Waterhammer Equations (1) discretization and solution by the Collocation Method is shown in detail in (Guillén., 2016).

3. Pipeline Models Designed

In previous papers (Guillén et al., 2012; Guillén et al., 2015) four different models have been shown to design the pipeline model. In those papers, it was shown that the closest model to real pipeline system is one that uses as boundary conditions inlet flow $Q_{in} = Q_1$ outlet pressure $H_{out} = H_n$ (Fig. 1). Based on this configuration, proceeded to design a pipeline model approximating the equations by Collocation Method. The pipeline models designed are shown below.

3.1 Pipeline Model by Collocation Method

In order to apply collocation method, pipe must divided into two segments, since method does not allow inclusion of discontinuities that which is happens when a blockage occurs. By dividing pipe into two segments, a first segment remains before the blockage and a second segment after it. These two pipe segments then connected by an equation that mathematically models the blockage. In turn, each segment has two pipe sections, with three collocation points for pressures (H_i) and three collocation points for flows (Q_i). A diagram of was described above can be seen in Fig. 1.

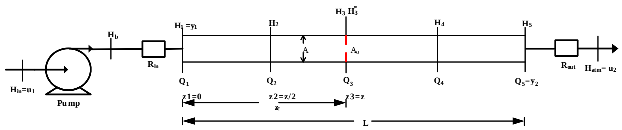

Fig.1. Collocation Method Pipeline Diagram.

The pipeline mathematical model was obtained using equations (1) as a basis. Then, a section approximation was made using a polynomial function $N_j(z_i)$, evaluated at collocation points (z_i) (Fletcher, 2006). After applying the Collocation Method, equations (1) are written as:

$$\dot{H}_i = -\frac{c^2}{gA}\sum_{j=1}^{n} Q_j N'_{ji}(z_i) \tag{2}$$

$$\dot{Q}_i = -Ag\sum_{j=1}^{n} H_j N'_{ji}(z_i) - \frac{f}{2DA}\left(\sum_{j=1}^{n} Q_j N_{ji}\right)^2 \tag{3}$$

By developing equations (2) and (3) for both the first two sections before blockage, as well as for the two sections that are after blockage, following mathematical model is obtained.

$$\begin{aligned}
\dot{H}_1 &= -\frac{c^2}{gAz}(-3u_1 + 4Q_2 - Q_3)\\
\dot{Q}_2 &= -\frac{Ag}{z}(-H_1 + H_3) - \frac{f}{2DA}Q_2^2\\
\dot{H}_2 &= -\frac{c^2}{gAz}(-u_1 + Q_3)\\
\dot{Q}_3 &= -\frac{Ag}{z}(H_1 - 4H_2 + 3H_3) - \frac{f}{2DA}Q_3^2\\
\dot{H}_3 &= -\frac{c^2}{gA(L-z)}(-3Q_3^* + 4Q_4 - Q_5)\\
\dot{Q}_4 &= -\frac{Ag}{(L-z)}(-H_3^* + u_2) - \frac{f}{2DA}Q_4^2\\
\dot{H}_4 &= -\frac{c^2}{gA(L-z)}(-Q_3^* + Q_5)\\
\dot{Q}_5 &= -\frac{Ag}{(L-z)}(H_3^* - 4H_4 + 3u_2) - \frac{f}{2DA}Q_5^2
\end{aligned} \tag{4}$$

Here:

Q_3^*, is flow Q_3 affected by blockage, H_3^* (pressure) is the equation that joins the two pipeline parts, and model mathematical the partial blockage that is occurring. Mathematical model of this partial blockage is as follows (Guillén, 2016):

$$H_3^* = H_3 - \frac{Q_3^2}{2gA_o^2}\left(1 - \left(\frac{A_o}{A}\right)^2\right) \tag{5}$$

Where: A is the cross sectional pipe area and A_o is blockage area (see Fig.1).

u_1 is:

$$u_1 = Q_1 = \frac{-C_1 + \sqrt{{C_1}^2 - 4(R_{ent} + C_0)(-C_2 + H_1 - H_{ent})}}{2(R_{ent} + C_0)} \tag{6}$$

In the same way, $u_2 = H_5$ (see Fig.1):

$$u_2 = R_{sal}Q_5^2 + H_{atm} \tag{7}$$

Pipeline model (4) was implemented and simulated with MatLab. The results is shows in Fig. 2. Here we can see how the outflow Q_{out} and the inflow Q_{in} decrease due to blockage (Fig. 2a), in turn, pressure H_{out} decreases and pressure H_{in} increases upstream of blockage (Fig. 2b). These behaviors in flows and pressures are that occur in a real piping system when a blockage is present.

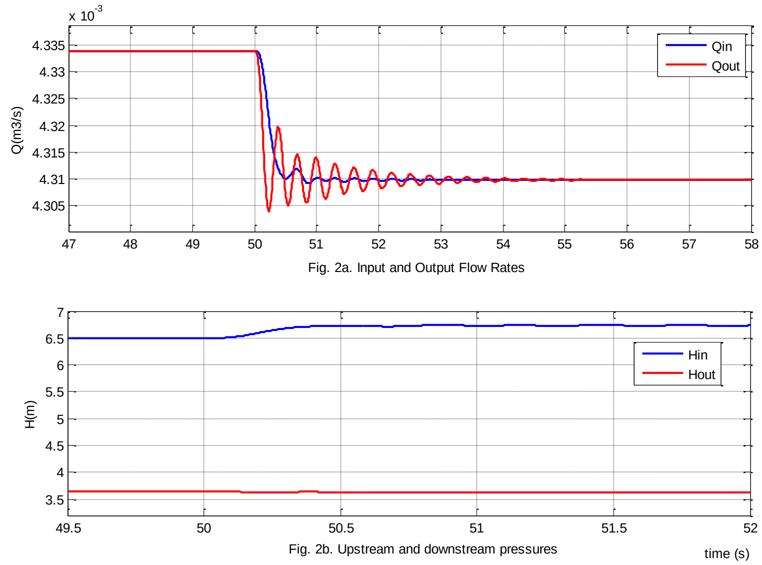

Fig. 2. An Blockage Simulation located in $z = 42.5\ m$ and $A_o = 0.5A$.

3.2 Pipeline Model developed by Difference Finite Method in two part

Here is a pipeline model where the equations (1) are discretized using the Finite Difference Method. In this second model, the pipeline is equally divided into two sections before and two sections after blockage, connected by equation (5) that models partial blockage being presented (as shown in Fig. 1), with the difference that pressures (H_i) and flow rates (Q_i) are calculated using the finite difference method (Chaudry et al., 2014; Pal et al., 2021). The obtained equations are shown in (8).

Where: H_3^* is represented by (5), u_1 is represented by (6) and u_2 by (7).

The model (8) was also implemented and simulated with MatLab, and the results shown in Fig. 3 were obtained. In this figure, it can be seen that this model (8) meets the requirements or behaviors of a pipeline when an blockage occurs: a decrease in Q_{out} and Q_{in} (Fig. 3a), a decrease in H_{out}, and an increase in H_{ent} (Fig. 3b).

$$
\begin{aligned}
\dot{H}_1 &= -\frac{c^2}{gA}\frac{Q_2 - u_1}{z_2 - z_1} \\
\dot{Q}_2 &= -Ag\frac{H_2 - H_1}{z_2 - z_1} - \frac{f_2}{2DA}Q_2^2 \\
\dot{H}_2 &= -\frac{c^2}{gA}\frac{Q_3 - Q_2}{z_3 - z_2} \\
\dot{Q}_3 &= -Ag\frac{H_3 - H_2}{z_3 - z_2} - \frac{f_3}{2DA}Q_3^2 \\
\dot{H}_3 &= -\frac{c^2}{gA}\frac{Q_4 - Q_3}{z_4 - z_3} \\
\dot{Q}_4 &= -Ag\frac{H_4 - H_3^*}{z_4 - z_3} - \frac{f_3}{2DA}Q_4^2 \\
\dot{H}_4 &= -\frac{c^2}{gA}\frac{Q_4 - Q_3}{z_4 - z_3} \\
\dot{Q}_5 &= -Ag\frac{u_2 - H_3}{z_4 - z_3} - \frac{f_3}{2DA}Q_5^2
\end{aligned} \tag{8}
$$

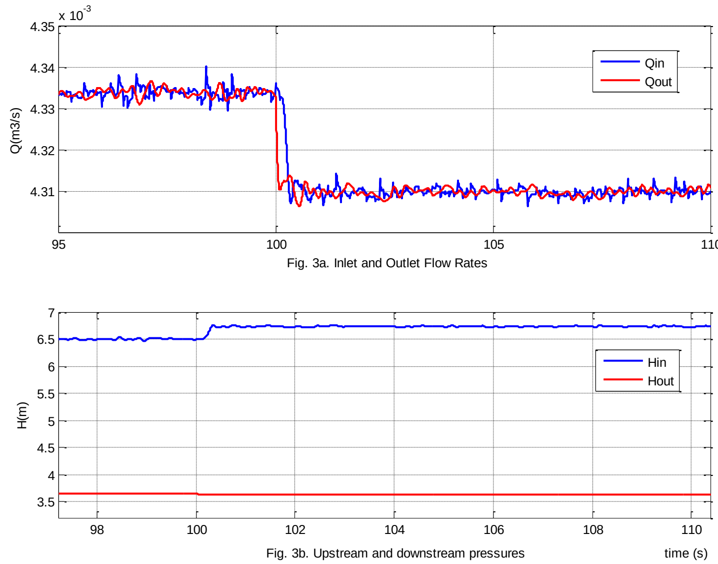

Fig. 3. Blockage simulation locate in $z = 70.83$ m and $A_o = 0.5A$.

4. Blockage Detection and Localization using an Extended Kalman Observer

In this section, we present the methodology for simultaneously estimating blockage percentage (A_o) and blockage position (z_c) where such blockage occurs. The methodology is based on an EKF. The system (1), after adding the pump and the two hydraulic constraints, was modified and resulted in the model described by (4), which can be written compactly as follows:

$$\dot{x} = f(x,u)\,;\; y = Cx \qquad (9)$$

Where function $f(x,u)$ and matrix C result from equations (4).

Depending on how model can be written, there are several solutions available for nonlinear systems (Besançon, 2007). A simple solution is to consider design of an EKF observer (Gelb, 1992). In order to improve stability, a version of EKF with a forgetting factor will be considered (Kalman et al., 1961; Reif et al., 1998), as follows.

$$\begin{aligned}
\dot{\hat{x}} &= f(\hat{x},u) - k(C\hat{x} - y)\\
k &= PC^TW^{-1}\\
\dot{P} &= PF^T + FP - PC^TW^{-1}CP + V + \delta P\\
F &= \frac{\partial f}{\partial x}(\hat{x},u)
\end{aligned} \qquad (10)$$

Where W (states noise) and V (outputs noise) are the covariance matrices, which are defined as positive.

It should be noted that in a typical piping system, $H_{ent} = u_1$ (pump inlet pressure) and $H_{atm} = u_2$ (atmospheric pressure at which the system discharges) can be treated as constants in a system with the configuration shown in Fig. 1. This implies that to detect and locate blockages, the observer will only need two measurements: $y_1 = H_1$ and $y_2 = Q_5$, while keeping u_1 and u_2 constant.

4.1 State Observer Design Based on a Pipeline Model Discretized by Collocation Method

In order to estimate the position and magnitude blockage in a pipeline, an observer was designed to detect and locate a blockage in some pipeline section. It is assumed that a blockage occurring at position z_c, where cross section pipe A is reduced to a blockage area A_o (marked in red in Fig. 1).

The equations of pipeline model were expressed in (4).

Specifically, an EKF observer was developed, for which following states were defined:

$$\begin{aligned}
x &= [H_1, Q_2, H_2, Q_3, H_3, Q_4, H_4, Q_5, z_c, A_o]^T\\
&= [x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}]^T
\end{aligned}$$

$$u = [Q_1, H_5]^T = [u_1, u_2]^T$$

$$y = [H_1, Q_5]^T = [y_1, y_2]^T$$

Where:

$x_9 = z_c$: position where blockage occurring (see Fig. 1).
$x_{10} = A_o$: blockage area.

If rewrite equations (4) in the defined states terms, observer's model would be as follows:

$$
\begin{aligned}
\dot{x}_1 &= -\frac{c^2}{gAx_9}(-3u_1 + 4x_2 - x_4)\\
\dot{x}_2 &= -\frac{Ag}{x_9}(-y_1 + x_5) - \frac{f}{2DA}x_2^2\\
\dot{x}_3 &= -\frac{c^2}{gAx_9}(-u_1 + x_4)\\
\dot{x}_4 &= -\frac{Ag}{x_9}(y_1 - 4x_3 + 3x_5) - \frac{f}{2DA}x_4^2\\
\dot{x}_5 &= -\frac{c^2}{gA(L-x_9)}(-3x_4^* + 4x_6 - y_2)\\
\dot{x}_6 &= -\frac{Ag}{(L-x_9)}(-x_5^* + u_2) - \frac{f}{2DA}x_6^2\\
\dot{x}_7 &= -\frac{c^2}{gA(L-x_9)}(-x_4^* + y_2)\\
\dot{x}_8 &= -\frac{Ag}{(L-x_9)}(x_5^* - 4x_7 + 3u_2) - \frac{f}{2DA}y_2^2\\
\dot{x}_9 &= 0\\
\dot{x}_{10} &= 0
\end{aligned} \tag{11}
$$

4.2 State Observer Design Based on a Pipe Model Developed by Finite Difference Method in Two Parts

In order to subject EKF observer presented in section 4.1 for further validation tests, it was test on pipeline model shown in (8). As mentioned earlier, this model includes two sections before and two sections after blockage (see Fig. 1); these two section is connect by equation (5), which represent partial blockage that is occurring, but pressures and flow rates calculation is done using Finite Difference Method.

To estimate the position z_c and magnitude A_o blockage that occurring in pipe, the EKF observer was used, which is designed based on pipe model calculated by collocation method. Here, are making a hybrid with both methods (finite differences and collocation). Finite Difference Method to model piping system (8) and Collocation Method to model the state observer (11).

Likewise, finite difference pipeline model was extended using $n = 6$ sections, specifically, three sections before and three sections after blockage. The nonlinear pipeline model has six sections and the observer has four sections.

5. Simulations and Results

Measured variables used by the observer ($y_1 = H_1$ and $y_2 = Q_5$) are contaminated with white noise. In Table 1 pipe parameters are shown. Normal operating conditions are: inlet flow $Q_1 = 0.0043\ m^3/s$ and outlet pressure $H_5 = 3.5m$.

Table 1. Pipeline Specifications

***g*(m/s²)**	***c*(m/s)**	***A*(m²)**	***f*(s⁻²)**	***L*(m)**
9.81	373	0.003	0.0223	85

5.1 Detection and Localization Blockage in the Pipeline Model discretized with Collocation Method

Pipe dynamics is represent to model (4), with $n = 4$ sections. A blockage $A_o = 0.95A$, and a blockage position $z_c = 42.5\ m$ were simulated. Fig. 4 shows estimation results. The state estimate $x_9 = z_c$ is shown in Fig. 4a. It is observed that z_c is estimated very quickly and quite accurately. The Fig. 4b shows estimate of $x_{10} = A_o$, which is also estimated quickly and accurately.

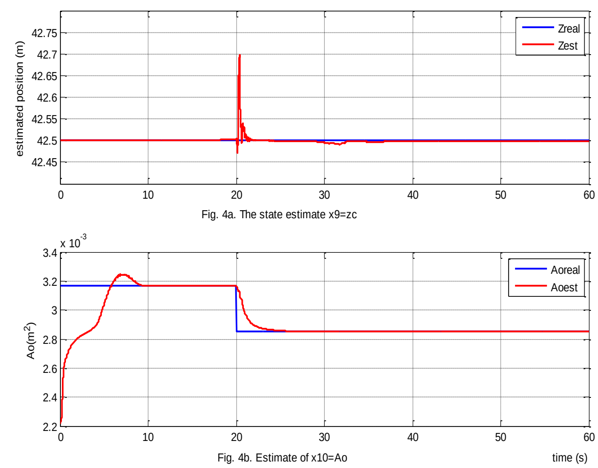

Fig. 4. Estimation of $z_c = 42.5\ m$ and $A_o = 0.7A$.

To assess the observer's ability to estimate different positions and blockage values, three different positions and three blockages percentages along pipe were simulated. At this point, is important to highlight that due to way the pipeline model is constructed (using the collocation method), when length z_c varies, the size pipe sections also changes. Specifically, when z_c is close to the pipeline inlet, lengths of the first two sections are reduced, as shown in Fig. 5a.

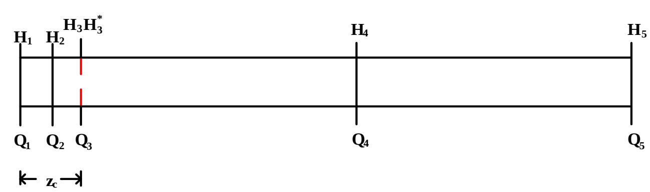

Fig. 5a. z_c is close to the pipeline inlet

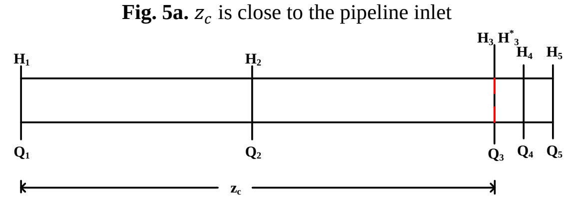

Fig. 5b. z_c is close to the pipeline outlet

Fig. 5. Variation in section size with changing z_c.

This reduction of z_c, allows a closer calculation of the pressures and flow rates, which are closer to the place where blockage is occurring, while the other pressures and flow rates are calculated more equidistant. Advantage here there is no need to increase number of pipeline sections (calculation time increase) to do a more accurate calculation of H_i and Q_i, since, with this pipeline modeling, the emphasis is made on the calculation of the H_i and Q_i that are closer to where blockage occurs. The same is true if blockage is close to pipeline outlet as shown in Fig. 5b.

Fig. 6 shows estimates for three different blockage positions (z_c), specifically 12, 36 y 63.75 m (remember $L = 85\ m$). Likewise, Fig. 7 shows estimate for three different blockage percentages (A_o), specifically 50, 70 y 90% of A.

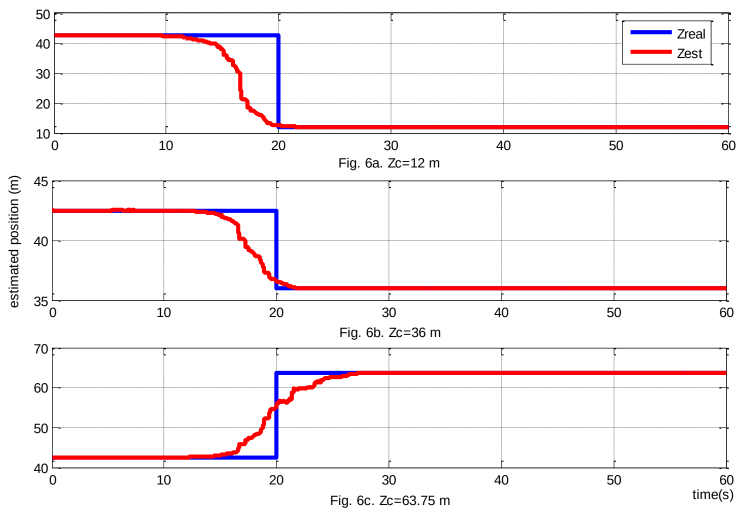

Fig. 6. Different positions of blockage location.

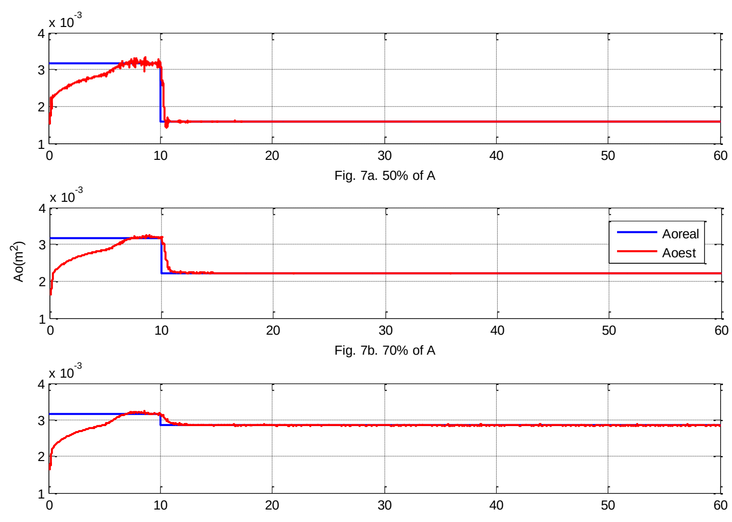

Fig. 7. Different blockage percentages.

In previous two figures can be seen (Fig. 6 and 7) that observer has ability to accurately estimate both different positions and different percentages of blockage. It highlight that three blockages positions, as well as the three percentages of it, do not occur simultaneously. However, observer does have ability to simultaneously estimate a position ($x_9 = z_c$) and a value for blockage percentage ($x_{10} = A_o$).

5.2 Detection and Localization Blockage in Pipeline Model Developed by Finite Difference Method in Two Parts

The equations governing observer for this case are those shown in (11). Likewise, finite difference pipeline model was extended using n=6 sections, i.e., three sections before and three sections after blockage. In other words: Nonlinear pipeline model has 6 sections and observer has 4 sections.

Fig. 8 shows estimates for three different blockage positions, specifically 16, 32 and 68 m ($L = 85\ m$). Likewise, Fig. 9 shows estimate for three different blockage percentages, specifically 50, 70 and 90% of A.

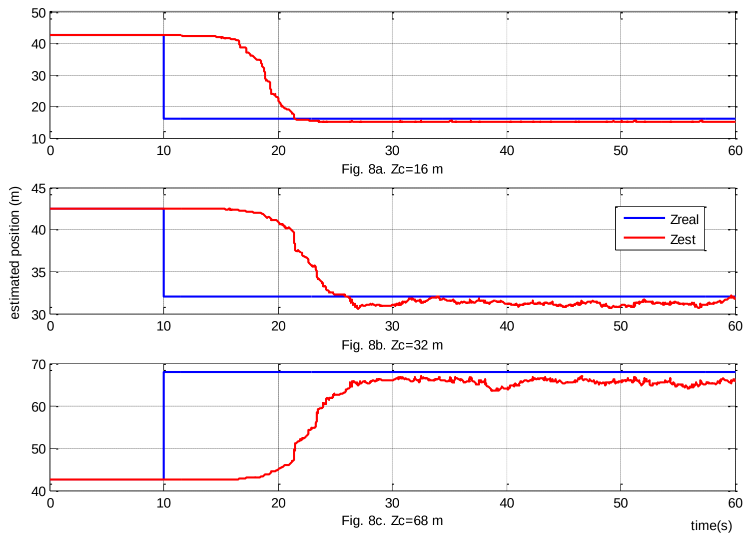

Fig. 8. Different positions of blockage location.

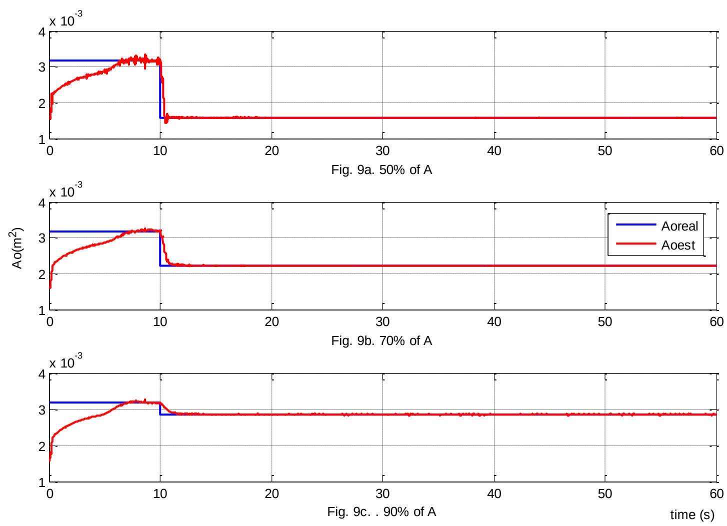

Fig. 9. Different blockage percentages.

In Fig. 8 and 9 can see that observer estimates both the different positions and the different percentages of blockage correctly, therefore the observer is able to re-estimate the two blockage parameters even though, it is subjected to a different pipeline model (finite differences).

6. Conclusions

In this paper, two models of a pipeline system for the detection and location blockage using a nonlinear Extended Kalman (EKF) type observer were presented. The first model, discretized using collocation method, was adapted to handle discontinuities by dividing pipe into two parts, allowing inclusion of an equation that model the blockage. This approach allowed EKF to simultaneously estimate position (z_c) and percentage (A_o) blockage, with satisfactory results in several simulations. Then a second model discretized by Finite Difference Method was used, maintaining division of pipeline (in two parts), and it was shown that EKF also manages to correctly estimate z_c and

A_o. Finally, can said that for the detection and location of a blockage, in a pipeline system such as one presented in this work, pipeline system model must be discretized with a sufficiently accurate method. Collocation method showed satisfactory results for this premise, and that by using an EKF based on this pipeline model, the two parameters that characterize a blockage (z_c and A_o) are satisfactorily estimated.

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