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Diameter influence in real-time leak detection and isolation algorithms for plastic pipelines

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***Abstract*— This paper shows the influence of pipeline diameters, on Leak Detection and Isolation. Nowdays, there are many publications, which deal with leak isolation, by using Model-Based approach. Those methods require accurate parameters to isolate the leak. In general, if the parameters are not correctly known, the leak isolation fails, and using parameter values provided by the supplier may be misleading. In the present paper, it is pointed out how a small variation on the diameter parameter can cause considerable variations in the so-called Equivalent Straight Length, and consequently lead to bad leak isolation. Difference between nominal diameter and internal diameter is presented as well as its impact on the LDI algorithm. In this case, a LDI system based on an Extended Kalman Filter is implemented in real-time to illustrate the performance results using both diameters. Finally, the results are discussed.**

Keywords—fault diagnosis; leak isolation; pipeline diameter; extended kalman filter; realtime.

I. INTRODUCTION

The use of the ducts to transport water, gasoline, gas, etc. motivates to design algorithms for pipeline monitoring, and be able to detect and isolate quickly leakage. Nowadays, there are many publications on this topic, based on Fault Model Approach (FMA) algorithms [1]-[3], and Fault Sensitive Approach (FSA) [4]-[6]. These techniques use a nonlinear model deduced from Water Hammer Equations (WHE) [7], which describes the fluid dynamics in pipelines. The nonlinear model is used to design an observer to estimate dynamics of a liquid. This observer is in general the core of a Leak Detection and Isolation (LDI) system. These dynamics are analyzed and compared with measured signals, if a leak is present, the LDI algorithm begins to determine its magnitude and location. Unfortunately, if the nonlinear model, used in the LDI algorithm, does not represent adequately the system dynamics, the isolation can fail. Then uncertainty on pipeline parameters can be the cause of wrong isolation. Apropos of this, in [1], [8] the friction coefficient and its influence in LDI efficient algorithms have been studied. Another parameter, which is not given much attention, is the diameter, but we may emphasize that the use of the nominal diameter (D_N) instead of the real internal diameter (D_I) affects the leak isolation. Both diameters are not equal, they depend on the manufacturing standards. In general, it is used the D_N to design a LDI system regardless of the real D_I. But, it is necessary to be careful in determining this parameter, due to its impact on the accuracy of the LDI system, as it will be seen later. To our knowledge, a work analyzing this aspect is not available in literature.

In this paper, to show the importance of the diameter value, real-time experiments are performed by implementing the LDI system presented in [1] and, by using real data from a pilot prototype, which is equipped with flow rate and head pressure sensors at the ends of the pipeline. First, we will show how an uncertain diameter impacts the Equivalent Straight Length (ESL) [9], [10]. The ESL is the length of an equivalent straight pipeline obtained from a virtual substitution of each fitting (elbow, coupling, etc.) by a segment of straight pipeline presenting the same head loss as those fittings. In the present work, two ESL are calculated using the Darcy-Weisbach equation [7], [11] the first one using D_N, and a second one D_I. Both are then used in a LDI algorithm, which is tested in real-time and both results are compared, showing an important difference between the leak positions. Obviously, as it will be seen later, the leak isolation will be better when the real internal diameter is used. For this reason, to avoid incorrect leak isolation, it is important to measure the internal diameter before designing LDI systems based on a Model Approach.

The paper goes as follows: In Section 2, the nonlinear dynamic model, assuming only one leak in the pipeline, is presented. Section 3, discusses the ESL and its variation with respect to use the nominal diameter and internal diameter. To show influence of diameter variation in the leak isolation, in Section 4, real-time experiments are performed. Finally in Section 5, conclusions and future work are stated.

II. MODEL

This section presents the nonlinear model derived from the WHE, which describes the fluid dynamics in a pipeline.

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A. Modelling equations

Assuming the fluid to be slightly compressible and the duct wall slightly deformable; the convective changes in velocity to be negligible; the cross section area of the pipe and the fluid density to be constant, then the dynamics of the pipeline fluid can be described by the following Partial Differential Equations (PDE) named the WHE [12]:

Momentum Equation

$$\frac{\partial Q(z,t)}{\partial t} + gA\frac{\partial H(z,t)}{\partial z} + \mu Q(z,t)|Q(z,t)| = 0 \quad (1)$$

Continuity Equation

$$\frac{\partial H(z,t)}{\partial t} + \frac{b^2}{gA}\frac{\partial Q(z,t)}{\partial z} = 0 \quad (2)$$

where Q is the flow rate [m^3/s], H is the pressure head [m], z the length coordinate [m], t the time coordinate [s], g the gravity acceleration [m/s^2], A the cross-section area [m^2], b the speed of the pressure wave in the fluid [m/s], $\mu = f/2DA$, D the diameter [m] and f the friction factor.

Friction model: In the present work, the friction factor is calculated by using the Swamee-Jain equation, presented in [1], [8], [13]. In this formula the friction factor is function of the Reynolds number, which is in turn function of the flow:

$$f(Q) = \frac{0.25}{\left[\log_{10}\left(\frac{\varepsilon}{3.7} + \frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^2} \quad (3)$$

where ε [m] is the roughness and *Re* the Reynolds number given by:

$$\mathrm{Re} = \frac{QD}{\nu A} \quad (4)$$

and ν is the kinematic viscosity [m^2/s].

Leak model: One leak arbitrarily located at point z_1 (see Fig. 1) in a pipeline can be modeled as follows [3], [14]:

$$Q_L = \lambda\sqrt{H_L} \quad (5)$$

where the constant λ is a function, among others things, of the orifice area and the discharge coefficient, Q_L is the flow through the leak and H_L is the pressure head at the leak point.

B. Spatial Discretization of the WHE

In order to obtain a state space representation of model (1) and (2), the PDE are discretized with respect to the spatial variable z, as in [11], by using the following relations:

$$\frac{\partial H}{\partial z} \approx \frac{H_j - H_{j+1}}{z_j} \quad (6)$$

$$\frac{\partial Q}{\partial z} \approx \frac{Q_j - Q_{j+1}}{z_j} \quad (7)$$

By dividing the pipeline in only one partition, (see Fig. 1), then $z_j\,(j=[1,2])$, becomes the distance from the beginning of the pipeline to point of the leak and from the point of the leak to the end of the pipeline, respectively.

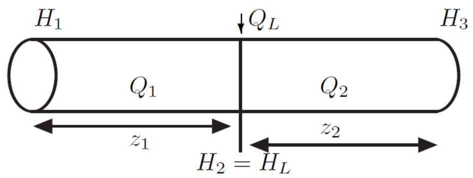

Fig. 1. Discretization of the pipeline with a leak Q_L

Notice that $z_2 = L_{ESL} - z_1$ where L_{ESL} is the ESL of the equivalent straight pipeline. Applying approximations (6) and (7) to equations (1) and (2) together with (5) and (3), and then incorporating as additional states z_1 and λ, we get [1]:

$$\begin{bmatrix} \dot{Q}_1 \\ \dot{H}_2 \\ \dot{Q}_2 \\ \dot{z}_1 \\ \dot{\lambda} \end{bmatrix} = \begin{bmatrix} \frac{-gA}{z_1}(H_2 - u_1) - \mu_1 Q_1|Q_1| \\ \frac{-b^2}{gAz_1}(Q_2 - Q_1 + \lambda\sqrt{H_2} \\ \frac{-gA}{L_{ESL} - z_1}(u_2 - H_2) - \mu_2 Q_2|Q_2| \\ 0 \\ 0 \end{bmatrix} \quad (8)$$

where:

$\mu_1 = f_1/2DA$

$\mu_2 = f_2/2DA$

with:

f_1 = friction factor calculated with Q_1

f_2 = friction factor calculated with Q_2

Note that in [1] it is used only one value for μ

Here, the input driving vector is $u = [H_1 \quad H_3]^T = [u_1 \quad u_2]^T$, and the output measured vector is $y = [Q_1 \quad Q_2]^T$.

Implemented LDI: To perform the next experiments, the LDI system presented in [1] is used. Briefly, this LDI system uses an EKF based on the nonlinear model (8). The main mission of this filter is to estimate the leak position z_1 and parameter λ related with its magnitude.

III. NOMINAL AND INTERNAL DIAMETERS

This section presents an analysis of the impact on the ESL when is used the D_N and D_I, individually. As well as the difference between both diameters.

A. Nominal Diameter vs Internal Diameter

When measuring the internal diameter of a pipeline, it may appear that its real value do not coincide with the nominal diameter reported in the pipe datasheet. To try to explain this discrepancy, the reader can refer to Table I which shows various pipelines with the same D_N, in this case equal to 50 mm. It can be noticed in this Table I, that the real D_I is not equal to D_N, it depends on manufacturing standards ASTM, D_E is the external diameter [15].

In LDI systems, this diameter uncertainty affects the leak isolation, via the ESL, which is calculated with the Darcy Weisbach equation, as discussed in next subsection.

TABLE I. MANUFACTURING STANDARDS ASTM

Manufacturing Standard ASTM	D_N (mm)	D_I (mm)	D_E (mm)
D 1785 Sch 40	50	52.50 ± 0.15	60.32 ± 0.15
D 1785 Sch 80	50	49.24 ± 0.15	60.32 ± 0.15
D 1785 Sch 120	50	47.62 ± 0.15	60.32 ± 0.15

B. ESL with Nominal Diameter and Internal Diameter

In this section, the Darcy-Weisbach equation is used to calculate the ESL with D_N and real D_I. In the datasheet of our pipes, D_N, is equal to $2.5in = 0.0635m$. Then the ESL is calculated for this value. Likewise, the real D_I is obtained directly by measuring the real internal diameter of the pipe, which is equal to $2.47in = 0.06271m$ and again the ESL is calculated, as follows:

$$L_{ESL} = \frac{\Delta H(D^5 \pi^2 g)}{f(Q)Q^2 8} \quad (9)$$

where:
ΔH = pressure drop in m.
g = acceleration due to gravity in m/s^2
D = diameter in m.
$f(Q)$ = friction factor *dimensionless*.
Q = flow rate in m^3/s.
with:
$Q = 7.7x10^{-3}\ m^3/s$
$v = 9.95x10^{-7}\ m^2/s$
$\Delta H = 7.1132\ m$

Note that the power of diameter is equal to 5. It means that the ESL is significantly affected with small variations of the diameter.

The ESL with $D_N = 0.0635m$, is equal to $87.4174m$. Moreover, by using D_I the ESL is equal to $82.1132m$.In Table II the obtained ESL's are compared.

TABLE II. ESL WITH NOMINAL AND INTERNAL DIAMETER

Diameter		ESL
Nominal diameter	0.06350 m	87.4174 m
Internal diameter	0.06271 m	82.1132 m
Percentage change	-1.2597 %	-6.4596 %

The effect of the difference on the isolation is illustrated in next section.

IV. EXPERIMENTAL RESULTS

In this section, we present real-time results in order to evaluate the performance of the chosen LDI system when using the D_N and the D_I. For the present work, we consider the pilot water pipeline built at the Center for Research and Advanced Studies in Guadalajara, México (CINVESTAV-Guadalajara), whose main parameters are given in Table III.

TABLE III. PROTOTYPE PIPELINE PARAMETERS

Parameter	Symbol	Value	Units
Length between sensors	L	68.147	m
Real internal diameter	D_I	$6.271x10^{-2}$	m
Nominal Diameter	D_N	$6.35x10^{-2}$	m
External diameter	D_E	$0.9x10^{-2}$	m
Wall thickness	ϵ	$13.095x10^{-2}$	m

The pipeline prototype is composed by Polipropileno Copolimero Random (PP-R) pipes, under standards manufacturing $NMX - E - 226/2 - 1998 - SCFI$, and it is equipped with: Two water-flow and two pressure-head sensors at inlet and outlet of the pipeline; a *5 HP* centrifugal pump and three valves at 17.045, 33.470 and 49.905 meters, in real length, respectively. Fig. 2 depicts a schematic diagram of the pipeline prototype, for more details see [6].

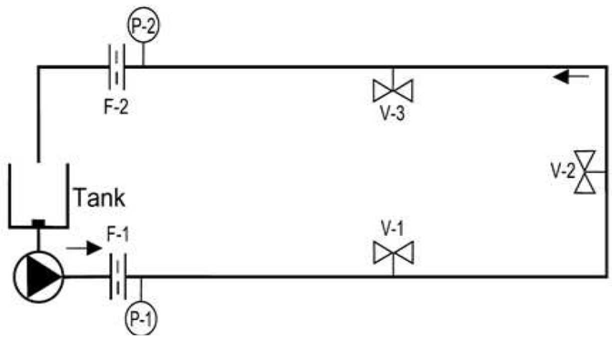

Fig. 2. Schematic Diagram

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To implement the chosen LDI, real data from prototype are used: The inflow and the outflow are shown in Fig 3. The corresponding input and the output pressure heads are shown in Fig 4. In both figures, t_L denotes the time when a leak appears (leak time).

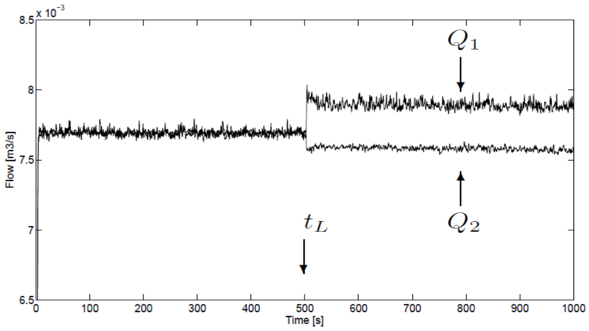

Fig. 3. Inflow rate Q_1 and outflow rate Q_2 of the pipeline

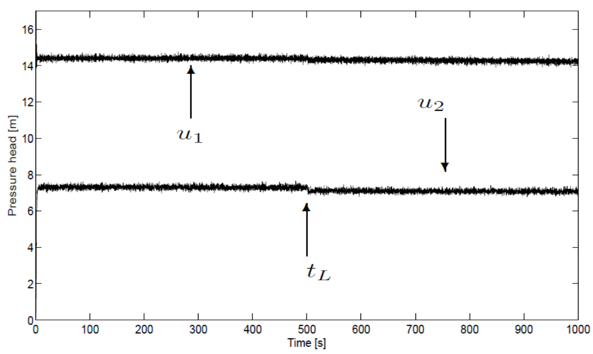

Fig. 4. Input pressure head u_1 output pressure head u_2 of the pipeline (observer inputs)

The friction factor is calculated online by using equation (3), and the ESL is calculated online by using both diameters in the equation (9), D_N in the first case and D_I in the second case. In both cases, the temperature was quasi-constant $T \approx 20^{\circ} C$. As a result, water density, kinematic viscosity and friction losses are quasi-constants. By using Darcy-Weisbach equation, the ESL between initial sensors and the valve $V-2$, which emulates a leak, is calculated in advance, and is $z_{L(ESL)} = 40.98m$. At $t_L = 500s$ the valve $V-2$ is opened to emulate the leak. The following simplest leak alarm is implemented as $|Q_{in} - Q_{out}| > \delta = 1.3x10^{-4}$ where δ is a threshold, which takes into account the magnitude of the noise in our pipeline to avoid false alarms. When alarm is activated at time t_L, the LDI observer is started and leak isolation begins. The initial conditions for the EKF before the leak are fixed as follows: $\hat{Q}_1^{\,0}$ and $\hat{Q}_2^{\,0}$ are equal to the mean values of the input and output flows in the operating point, $\hat{z}_1^{\,0}$ is set equal to $L_{ESL}/2$, and $\hat{H}_2^{\,0}$ is the pressure head calculated at distance $\hat{z}_1^{\,0}$ in absence of leak with the Darcy-Weisbach equation (9), and $\hat{\lambda}^0 = 0$ since the pipeline is not leaking. It is important to note that these initial conditions are kept constant until the leak is detected. The sampling time was chosen as 0.1181 *s*.

The process *(F)* and measurement noise *(R)* covariance matrices of EKF were experimentally tuned with the following values:

$$F = diag\lfloor 1x10^{-6} \quad 1x10^{-2} \quad 1x10^{-6} \quad 1x10^{-5} \quad 1x10^{5} \rfloor \quad (10)$$

$$R = diag\lfloor 1x10^{-2} \quad 1x10^{-3} \rfloor \quad (11)$$

The LDI system performance, is different in each case. In Fig. 5, where the nominal diameter is used in LDI design, the leak position is not accurate, the error is near *10%* with respect to the value $82.1132m$ calculated with real D_I.

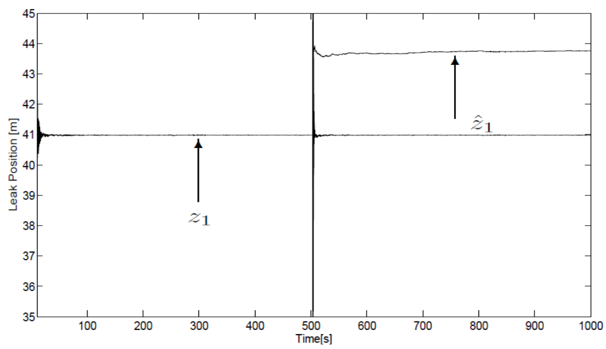

Fig. 5. Leak position using Nominal Diameter

Moreover, in Fig. 6, where the D_I is used in LDI design, the leak position is accurate, the error is near 2.5% with respect to the value $82.1132m$ calculated with real D_I.

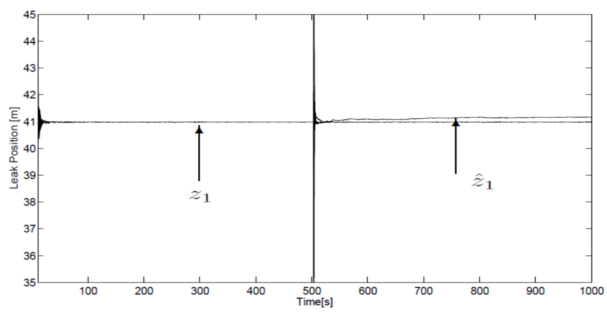

Fig. 6. Leak position using Internal Diameter

Finally in Fig. (7) the estimation of the pressure head in leak point $\hat{H}_2$ is shown.

V. CONCLUSIONS

When designing LDI system, the designer must be careful about the diameter of the pipeline, since nominal diameter may introduce errors leading to bad isolation. As future work,

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the effect of other parameters in LDI systems performance will be analyzed, such as: viscosity and density.

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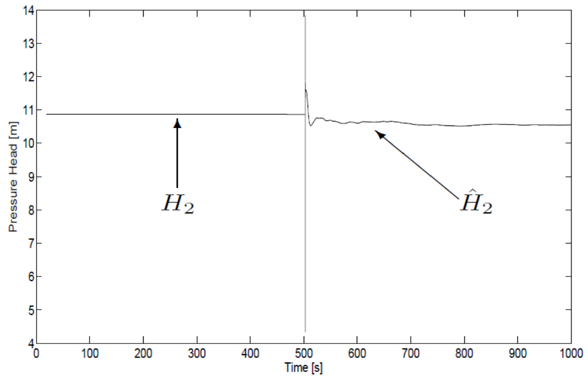

Fig. 7. Pressure head at leak point H_2 and its estimation $\hat{H}_2$

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