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EXAMPLES OF PIPELINE MONITORING WITH NONLINEAR OBSERVERS AND REAL-DATA VALIDATION

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ABSTRACT

This article shows how nonlinear observers can be used as tools for the monitoring of pipelines. In particular two observer approaches for two different applications are presented: a one-leak detection and isolation problem on the one the hand, and the same problem *with friction estimation* in addition on the other hand. In the first case, the system which represents the pipeline with a leak satisfies some uniform observability condition allowing for the design of a classical *high gain* observer (with a static Lyapunov equation). In the second case, the system is no longer uniformly observable, but still satisfies the observability rank condition, and an Extended Kalman Filter is proposed, under the use of exciting inputs. In both cases, experimental results are provided.

Index Terms— Leak detection, nonlinear systems, observer applications, high gain, EKF.

1. INTRODUCTION

Monitoring pipelines for the purpose of leak detection and isolation is a problem of obvious real interest, and the special topic of *algorithmic* methods to that end has already motivated various studies for a few years. Most of them are based on a frequency viewpoint and/or off line analysis (see e.g. [1, 2, 3, 4, 5, 6, 7, ...]) and the idea here is that using observer techniques can yield *on-line transient-based* new methods, in the spirit of preliminary studies of [8].

Such an approach in return strongly relies on some appropriate dynamical modeling which appears to be nonlinear, and at the same time nonlinear observers have already motivated various methodological developments (see e.g. [9] for a recent overview).

In the present paper, by considering a finite-dimension model resulting from the classical infinite-dimensional description of water dynamics in pipelines (so-called *Water Hammer* equations [10]) in the presence of possible leaks, a couple of nonlinear observers are proposed for the purpose of leak detection and isolation, either when all other parameters of the model are known, or when the friction coefficient in the model is unknown.

Some corresponding observability arguments are provided in each case, as well as the full observer design, and both observers are validated on the basis of real-time experiments on a prototype pipeline available at the Mexican Research Center Cinvestav.

The paper is organized as follows: in Section 2, the Water Hammer equations are recalled together with the obtention of finite-dimension models by means of the finite difference method. Section 3 then presents the two nonlinear observers which are proposed: the first one under the form of the classical *high gain observer* with a static Lyapunov equation, while the other one is based on an Extended Kalman Filter. In Section 4, some experimental results in order to show the performance of the observers are provided on the basis of the real pipeline of the Cinvestav used as a test-bed. Finally, Section 5 draws some conclusions about the contribution of this paper.

2. PIPELINE MODEL

Assuming convective changes in velocity to be negligible, and that the liquid density and pipe cross-sectional area are constant, the momentum and continuity equations governing the dynamics of the fluid in a pipeline can be expressed as [10]:

$$\frac{\partial Q(z,t)}{\partial t} + gA\frac{\partial H(z,t)}{\partial z} + \frac{\mathfrak{f}Q^2(z,t)}{2\phi A} = 0 \qquad (1)$$

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

where H is the pressure head (m), Q the flow rate in the pipeline (m^3/s), b the wave speed in the fluid (m/s), g the gravitational acceleration (m/s^2), A the cross-sectional area of the pipe (m^2), ϕ the diameter of the pipe, $\mathfrak{f}$ the

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friction coefficient, t and z the time (s) and space (m) coordinates respectively.
Here $z \in [0, L]$ where L is the length of the pipe.
Initial conditions as usual correspond to the values of $Q(z,t)$, $H(z,t)$ along the pipe at $t = 0$.

In this work, the boundary conditions to be handled are the pressure heads at the ends of the pipe. Those pressures will be respectively denoted by:

$$H(z=0,t) = H_{in}(t); \; H(z=L,t) = H_{out}(t) \tag{3}$$

On the other hand, the presence of a leak in a given position z_f must be handled as a new boundary condition for the system. This new condition is the value of the outflow caused by the leak given by:

$$Q_f(t) = \mathbb{H}_{t_f} \lambda_f \sqrt{H(z_f,t)} \tag{4}$$

where $\lambda_f = A_f C_f > 0$, A_f is the sectional area of the leak, C_f the discharge coefficient and $\mathbb{H}_{t_f}$ is the Heaviside unit step function associated to the occurrence of the leak at time t_f.

Closed-form solutions of these equations are not available. However, several methods have been used to numerically integrate them, such as the method of characteristics [10], the finite difference method [11] [12], the orthogonal collocation method [13][14], etc. In the present paper, we use the finite difference method because of its simplicity and because the structure of the resulting models appears to be appropriate for the conception of nonlinear observers.

By using the finite difference method, and by considering the imposed boundary conditions, the finite model with the presence of leaks is given by the following equations:

$$\dot{Q}_i = \frac{a_1}{\Delta z_i}(H_i - H_{i+1}) - \mathfrak{f}\mu Q_i|Q_i|; \quad \forall i = 1, \ldots, n \tag{5}$$

$$\dot{H}_{i+1} = \frac{a_2}{\Delta z_i}(Q_i - Q_{i+1}); \quad \forall i = 1, \ldots, n \tag{6}$$

where $a_1 = -gA$, $a_2 = -\frac{b^2}{gA}$, $\mu = \frac{1}{2\phi A}$ and with boundary conditions: $H_1 = H_{in}$ and $H_{n+1} = H_{out}$.

Now, using Eq. (5)-(6) with $n = 2$, we obtain the following system:

$$\begin{aligned} \dot{Q}_1 &= -\mathfrak{f}\mu Q_1|Q_1| + \frac{a_1}{\Delta z_f}(H_{in} - H_2) \\ \dot{H}_2 &= \frac{a_2}{\Delta z_f}(Q_1 - Q_2 - \lambda_f \sqrt{H_2}) \\ \dot{Q}_2 &= -\mathfrak{f}\mu Q_2|Q_2| + \frac{a_1}{L - \Delta z_f}(H_2 - H_{out}) \end{aligned} \tag{7}$$

where the two sections have been renamed as $\Delta z_1 = \Delta z_f$ and $\Delta z_2 = L - \Delta z_f$.

This system is a finite version of the water hammer equations, which in this case are spatially-discretized in two sections. This system can represent the presence of a single leak, whose position is given by the size of the first section Δz_f. The problem of model identification or leak detection is then discussed in next section.

3. OBSERVER APPROACHES

In order to estimate the parameters of a pipeline or some parameters related to a leak event from a limited number of measurements (typically located at each end of the pipeline), system (7) can be extended with the ”dynamics” of such parameters, and nonlinear observers can be designed for the resulting extended system (and the given ’output equation’ representing available measurements). Assuming that water flows at the pipe ends are directly measured, one gets an output equation as:

$$y = [Q_1 \; Q_2]^T. \tag{8}$$

Two situations will then be considered for detection purposes hereafter: leak detection and isolation while knowing full model parameters first, and then leak detection and isolation together with friction estimation.

3.1. One-leak detection

The problem of leak detection and isolation when knowing model (7) with output equation (8) can be addressed by direct estimation of leak coefficients, namely Δz_f and λ_f. To that end, consider the following additional equations:

$$\dot{\Delta} z_f = 0; \dot{\lambda}_f = 0 \tag{9}$$

such that, the state vector of system (7) becomes:

$$x = [\; Q_1 \quad H_2 \quad Q_2 \quad \Delta z_f \quad \lambda_f \;]^T \tag{10}$$

where x is composed by the elements x_i with $i = 1, ..., 5$.

By gathering the pressure heads of model (7) into some input vector $u := [H_{in}, H_{out}]^T$ the whole model takes the form of a nonlinear state-space representation of the following form:

$$\begin{aligned} \dot{x}(t) &= f(x(t)) + g(x(t))u(t) \\ y(t) &= [h_1(x), h_2(x)]^T = h(x(t)) \end{aligned} \tag{11}$$

In the case of operation with *constant* pressure heads $u(t) = u_0$, the state equation can be re-written as:

$$\dot{x}(t) = F_{u_0}(x(t))$$

for which observability can be checked to be satisfied as follows:
Define the following transformation:

$$\begin{aligned} \Phi : \Re^5 &\rightarrow \Re^5 \\ x &\mapsto \xi = \Phi(x) \end{aligned} \tag{12}$$

with $\Phi(x) =$

$$\begin{bmatrix} h_1(x) & L_{F_{u_0}} h_1(x) & h_2(x) & L_{F_{u_0}} h_2(x) & L^2_{F_{u_0}} h_2(x) \end{bmatrix}^T$$

where $L_{F_{u_0}} h(x)$ denotes the usual Lie derivative of function h along F_{u_0}.

Then the jacobian matrix of Φ has a determinant given by:

$$\Delta_\Phi = \frac{{a_1}^3 a_2 \sqrt{H_2}\,(\Delta z_f\,u_2 + u_1\,L - u_1\,\Delta z_f - H_2\,L)}{{\Delta z_f}^4\,(L-\Delta z_f)^2} \tag{13}$$

which only vanishes whenever:

$$\Delta z_f(H_{in} - H_{out}) = L(H_{in} - H_2).$$

This condition appears to be inconsistent with equations (7) in steady state in the presence of a leak, which means that for any constant input, Φ defines a change of coordinates.

With the following notations:

$$\Phi : x \mapsto \left\{ \begin{array}{l} \xi^1 = [h_1, L_{F_{u_0}} h_1]^T \\ \xi^2 = [h_2, L_{F_{u_0}} h_2, L^2_{F_{u_0}} h_2]^T \end{array} \right. \tag{14}$$

where ξ^1 and ξ^2 are composed by the elements ξ_{1i} and ξ_{2j} respectively, with $i = 1,2$ and $j = 1,2,3$,
the system in ξ coordinates becomes:

$$\begin{aligned} \dot{\xi}_{11} &= \xi_{12} \\ \dot{\xi}_{12} &= \varphi_{12}(\xi, u_0) \\ y_1 &= \xi_{11} \end{aligned} \tag{15}$$

$$\begin{aligned} \dot{\xi}_{21} &= \xi_{22} \\ \dot{\xi}_{22} &= \xi_{23} \\ \dot{\xi}_{23} &= \varphi_{23}(\xi, u_0) \\ y_2 &= \xi_{21} \end{aligned} \tag{16}$$

This system is under the form of a *uniformly observable* one, for which some *high gain* observer can be designed following the classical result of [15] for the single output case, or [16] for some multi-output extensions.

By considering two subsystems of the form:

$$\dot{\xi}^i = A_i \xi^i + \varphi_i(\xi, u_0),\ y_i = C_i \xi^i,$$

for $i = 1,2$ and appropriate A_i, C_i, φ_i resulting from (15)-(16), the observer design can for instance be done on the basis of two separate single-output designs as follows:

$$\dot{\hat{\xi}}^i = A_i \hat{\xi}^i + \varphi_i(\hat{\xi}, u_0) - S_i^{-1} C_i^T (C_i \hat{\xi}^i - y_i),\ i = 1,2$$

with S_i classically given by (see e.g. [9]):

$$S_1 = \left[\begin{array}{cc} \frac{1}{\lambda_1} & -\frac{1}{\lambda_1^2} \\ -\frac{1}{\lambda_1^2} & \frac{2}{\lambda_1^3} \end{array}\right];\ S_2 = \left[\begin{array}{ccc} \frac{1}{\lambda_2} & -\frac{1}{\lambda_2^2} & \frac{1}{\lambda_2^3} \\ -\frac{1}{\lambda_2^2} & \frac{2}{\lambda_2^3} & -\frac{3}{\lambda_2^4} \\ \frac{1}{\lambda_2^3} & -\frac{3}{\lambda_2^4} & \frac{6}{\lambda_2^5} \end{array}\right];$$

for $\lambda_1,\ \lambda_2 > 0$.

Notice that the observer can be implemented in original coordinates as follows:

$$\dot{\hat{x}} = f(\hat{x}) + g(\hat{x})u - \left(\frac{\partial \Phi(\hat{x})}{\partial x}\right)^{-1} \left[\begin{array}{c} S_1^{-1} C_1^T \\ S_2^{-1} C_2^T \end{array}\right] (h(\hat{x}) - y) \tag{17}$$

Remark. The same type of approach also holds when using varying pressure heads.

3.2. One-leak detection with friction estimation

In the previous example, the model parameters - except the *leak* parameters - have been assumed to be known and constant, including the friction coefficient ($\mathfrak{f}$), even when a leak occurs.

However, in practice, this coefficient is not easily known. In addition, it appears to vary under the effect of a leak. For those reasons, and under the simplifying assumption that the friction can be approximated by a single coefficient even after a leak appears, the estimation problem is here extended to that of the friction coefficient together with the leak parameters.

This means considering system (7) now with the following additional equations:

$$\dot{\Delta} z_f = 0; \quad \dot{\lambda}_f = 0; \quad \dot{\mathfrak{f}} = 0 \tag{18}$$

Thus, we are brought to a new extended state vector:

$$X = [Q_1, H_2, Q_2, \Delta z_f, \lambda_f, \mathfrak{f}]^T$$

yielding a new state space representation:

$$\dot{X}(t) = F(X(t)) + G(X(t))u(t);\ y(t) = H(X(t))$$

with the same input and output vectors u and y as before, and functions F, G, H accordingly.

Now following the same arguments as before with this new representation, it appears that the model is no longer uniformly observable for constant inputs.

Hence an actual state reconstruction here needs the use of *varying inputs*, providing enough excitation (in a sense of persistent inputs for instance as described in [9]), and a practical way to achieve such a reconstruction is to design some Extended Kalman Filter.

The observer then reads:

$$\dot{\hat{X}}(t) = F(\hat{X}(t)) + G(\hat{X}(t))u(t) + K(t)[y(t) - H(\hat{X}(t))] \tag{19}$$

where the observer gain K is a time-varying $q \times m$ matrix computed as:

$$K = S\bar{H}^T R^{-1} \tag{20}$$

for S solution of:

$$\dot{S} = (\bar{F} + \alpha I)S + S(\bar{F}^T + \alpha I) - S\bar{H}^T R^{-1} \bar{H} S + W \tag{21}$$

with:

$$\bar{F} = \frac{\partial F}{\partial x}(\hat{x}, u), \bar{H} = \frac{\partial H}{\partial x}(\hat{x})$$

$$S(0) = S(0)^T > 0, W = W^T \geq 0, R = R^T > 0$$

and a positive real number $\alpha > 0$.

4. EXPERIMENTAL RESULTS

In this section, we present some experimental results in order to illustrate the performances of the proposed observers w.r.t. the purpose of leak detection and isolation. The experiments have been realized in a pipeline with the following physical parameters:

Table 1. Test-bed parameters

g	L	b	D
9.81 (m/s^2)	85 (m)	407.75 (m/s)	0.0635 (m)

This pipeline is available at CINVESTAV (Research and Advanced Studies Center) in Guadalajara, Mexico.
It is equipped with water flow (F) and pressure head (P) sensors at some input and output points, as well as various valves allowing to simulate leaks, as shown in figure 1. More details about its physical composition can be found in [17].

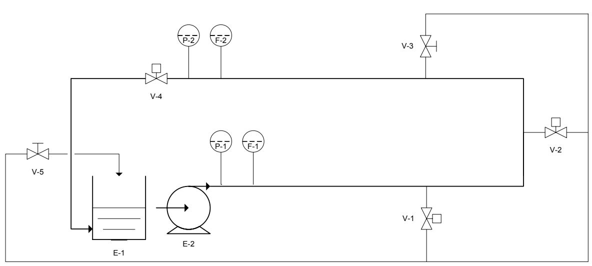

Figure 1. Pipeline experimental test-bed (Cinvestav)

4.1. One-leak detection

A leak has been generated at $\Delta z_f = 20$ (m) from the upstream. The friction coefficient, $\mathfrak{f} = 0.0226$, has been estimated in steady state before the leak event.

Figures 2-3 illustrate the pressure and flow measurement at the upstream and downstream of the pipeline. The pressure measurements (H_{in} H_{out}) are used as the inputs for observer (17), whereas the flow measurements (Q_{in} Q_{out}) are taken as the outputs.

From Figures 2-3, it can be noticed that a leak indeed appears at a time between 130 and 150 (s), and therefore, the leak coefficient estimation is started at time $t = 150$ (s) (remember that observer (17) can only work when a leak exists).

For the estimation, the observer was tuned with $\lambda = 2$ and initialized with $\hat{x}_{11} = 0.004256$ (m^2/s), $\hat{x}_{12} = 50$ (m), $\hat{x}_{21} = 0.004256$ (m^3/s), $\hat{x}_{22} = 5.4607$ (m) and $\hat{x}_{23} = 0$ (m^2).

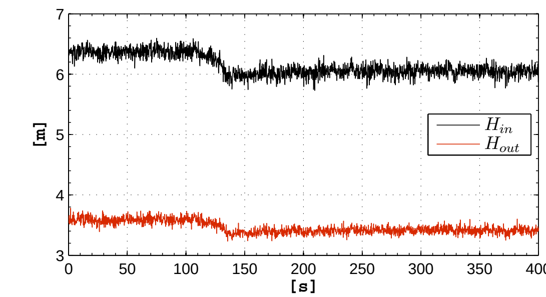

Figure 2. Measurements of pressures at the ends

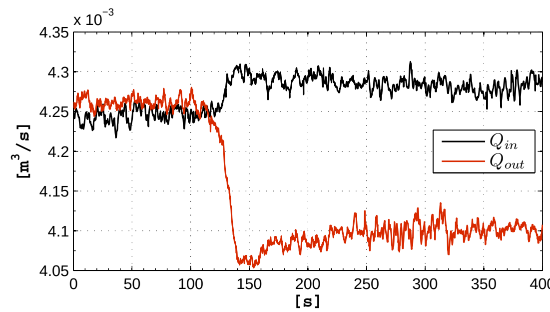

Figure 3. Measurements of flows at the ends

Figure 4 shows the corresponding estimation results. It can be seen on this figure how the position and leak coefficient are indeed well estimated.

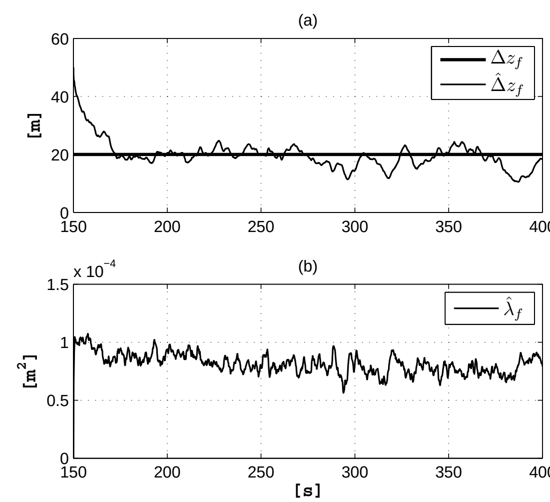

Figure 4. (a) Estimation of the leak position, (b) Estimation of the leak coefficient

4.2. One-leak detection with friction estimation

For this second estimation problem, a leak has been generated at position $\Delta z_f = 63m$.

Dealing with the Extended Kalman Filter, the pipeline dynamics have been excited with varying input variables.
In practice here, the upstream pressure head and the down-

stream water flow have been varied as the input variables, while the upstream water flow and downstream pressure head have been taken as output variables, all of them varying as shown in figures 5-6.

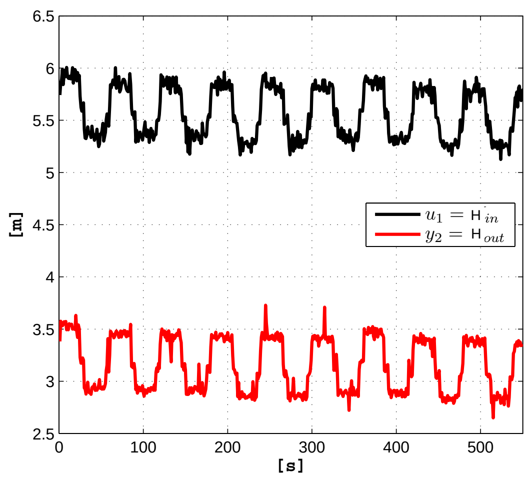

Figure 5. Pressures at the pipeline ends under excitation

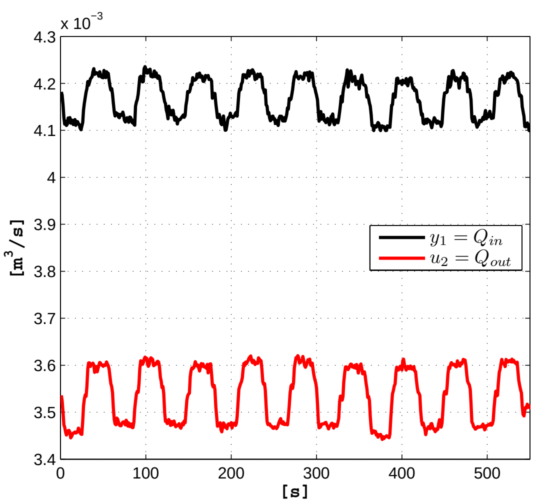

Figure 6. Flows at the pipeline ends under excitation

An observer of the form (19)-(21) has then been used, with:

$$\alpha = 0.05,\ W = 0.001I,\ R = I,\ S(0) = I$$

and initial values:

$$\hat{x}_1 = 0.004359\,(m^3/s);\ \hat{x}_2 = 4.5\,(m);\ \hat{x}_3 = 0.00435\,(m^3/s);$$
$$\hat{x}_4 = 35\,(m);\ \hat{x}_5 = 0\,(m^2);\ \hat{x}_6 = 0.01.$$

Corresponding estimation results are reported on figures 7 to 9.

It can be seen on figure 7 how the friction coefficient is indeed adapted, while figure 8 show how the leak magnitude is estimated as well.

Finally, it can be seen on figure 9 that the position is also quite well estimated, up to a 3%-error. This can be explained by the approximation made on the friction coefficient, by considering an average value for the whole pipeline. Refining this will be part of future studies.

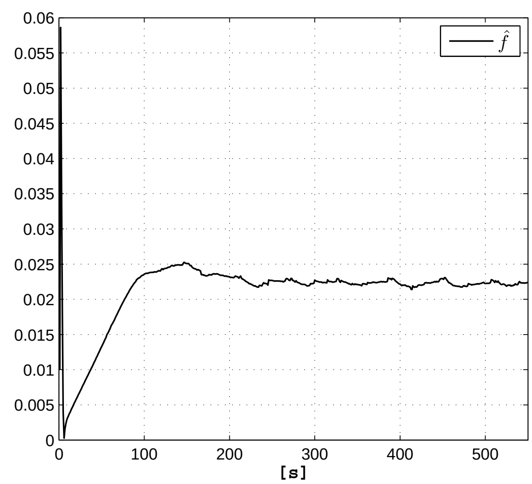

Figure 7. Friction estimation

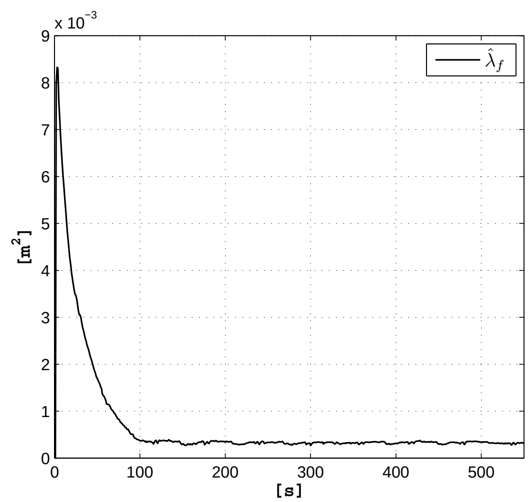

Figure 8. Leak coefficient estimation

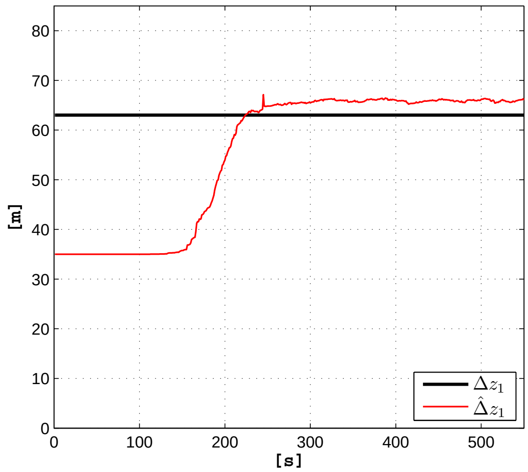

Figure 9. Leak position estimation

5. CONCLUSIONS

In this paper, observer approaches for parameter estimation related to leak occurrences in a pipeline have been proposed, and validated on real experiments. In particular it has been emphasized how the estimation of leak coefficients can be extended with the friction estimation. Improving the corresponding results will be part of future studies, as well as the extension of the here proposed approach to the case of multi-leak estimations.

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