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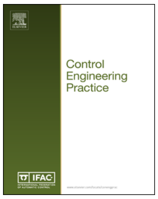

Multi-leak diagnosis in pipelines based on Extended Kalman Filter

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ABSTRACT

A model-based approach to detect and isolate non-concurrent multiple leaks in a pipeline is proposed, only using pressure and flow sensors placed at the pipeline ends. The approach relies on a nonlinear modeling derived from Water–Hammer equations, and related Extended Kalman Filters used to estimate leak coefficients. This extends former results developed for the single leak case, but with the difficulty that the model is modified at each new leak occurrence. A model adaptation strategy is thus proposed, allowing us to monitor indeed each new leak, and no matter where it appears. Experimental results illustrate the performance of the proposed algorithm.

1. Introduction

Pipeline monitoring has become an important issue around the world for its high environmental and economic interest. In general the main objective of a Leak Detection and Isolation (*LDI*) system is to detect and locate the smallest leaks as early as possible with minimal instrumentation. Usually, pressure and flow sensors are placed at pipeline ends, and are employed by the *LDI* system, that is used to locate them through mass balance and non-stationary calculations.

Several model-based procedures for leak isolation purpose have been developed in the last few years to improve the security of pipeline systems, often using strategies of *state observers* (algorithms aiming at recovering information on unmeasured variables via a measurement-based corrected mathematical model Besançon, 2007) (Begovich & Valdovinos-Villalobos, 2010; Begovich, Pizano, & Besançon, 2012; Billman & Isermann, 1987; Torres, Besançon, Georges, Navarro, & Begovich, 2011; Verde, 2001. In Billman & Isermann (1987), nonlinear adaptive observers are proposed for fault detection through a special correlation technique for a single leak, but the sensitivity of leak location to uncertainty is very high. On-line application results of such a technique for a plastic pipeline prototype have been reported in Begovich et al. (2012). This problem has been widely studied in the framework of *observation*, simply by considering the unknown parameters (*leak coefficients*) as constant state variables, where the state vector can be clearly extended by including the unknown parameters in itself, and can be even solved via parameter estimation (Besançon, 2007), and various works based on this philosophy can be found in Torres, Besanon, Georges, Navarro, & Begovich (2011), Torres, Besançon, & Georges (2012), Navarro, Begovich, Besançon, & Dulhoste (2011), and Navarro, Begovich, Sánchez-Torres, Besançon, & Patiño Murillo (2012). Notice that several alternative approaches also exist and are continuously developed, as discussed in the recent overview of Murvay & Silea (2012) for instance, or even more recent papers of Ostapkowicz (2014) about a pressure-wave-based approach, or wei Liu, xing Li, kun Yan, tao Fu, & qian Zhang (2015) on a methodology based on acoustic waves.

However, most of those studies are dedicated to the case of single leaks, and the multi-leak problem has not been studied that much. In particular, it becomes more and more difficult as the number of leaks increases, and even the two-leak case remains a challenge. Only a few works to solve the multi-leak problem have been reported. For instance Verde (2001) introduces a method based on residual evaluations of a bank of unknown input observers that are robust against one leak and sensitive to the rest, in the simultaneous leak case. The method consists of two steps, first the decoupling problem from a leak considered as disturbance is solved, and then, the residual generator design for each set of leaks is obtained using a Kalman Filter through a linearized model.

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However, the leak isolation with this method is satisfactory only for leaks which generate small variations from nominal value. In Verde & Visairo (2001) the former procedure is extended by considering a nonlinear model, and it is shown that the isolation problem for each leak is solved first by seeking a subsystem that is robust with respect to this leak and sensitive to the rest, and after a nonlinear observer for the subspace obtained in the first part is designed. It is shown that a linear transformation which generates a subsystem decoupled from a leak can be only applied in the nonlinear system if two leaks are considered. The main contribution in Verde (2005) is the reduction in the number of parameters that must be identified to isolate two non-concurrent leaks in a pipeline. To achieve that, a nonlinear model is considered, such that the existence condition for residual generator is satisfied, through the setting up of static relations which match with the physical leak position to reduce to one the unknown parameter for each leak. However, often two unknown parameters related with a leak occurrence are considered. In addition, these results are reported only in simulation, and this procedure is successful only if a new leak appears at the down side of the previous one, once that first one has been located (Verde, 2005; Verde et al., 2008). Very recently in Verde, Molina, & Torres (2014), the authors presented some results dealing with the simultaneous leak problem, and proposed the reduction of number of leak parameters to be determined, by considering a family $\mathcal{F}$ of parameterized transient models for all scenarios of two leaks. This family is obtained thanks to steady-state relations between the leak parameters (position and magnitude), and the parameters of a family $\mathcal{F}$ for the case of two leaks. However, this methodology is limited only to two-leak cases and it works in quasi-real-time.

On the other hand, the so-called Extended Kalman Filter (*EKF*) (Simon, 2006) has been widely applied in observation problems on nonlinear systems, specially when the measurements are corrupted by noise. Particularly, in the framework of leak isolation problem, the *EKF* has been studied (as in Torres et al., 2011, 2012 for instance), but it has even been considered to estimate other parameters besides leak coefficients, as friction factor, by using additional input excitation. In such an approach, the basic idea is to use the output error between measured output and the observer output as an estimator for leak occurrences. After a leak appears such a quantity called *residual* goes to zero, simultaneously giving the estimation of leak coefficients. With this idea, the present work is dedicated to face the multi-leak problem when leaks appear successively, starting from the single-leak case based on an *EKF*, and developing a multi-leak diagnosis scheme by expanding the pipeline model description at each new leak occurrence. To achieve this purpose, each time that a leak appears and it is identified, its information is saved and is taken as constant for all possible future leak occurrences while the pipeline model takes an appropriate form. Then, it is shown through experiments with real database how this approach can face the multi-leak problem even regardless if the newest leak appears after or before (in space) the latest one.

The paper continues as follows: Section 2 provides the mathematical model to be used for the *LDI* system. Section 3 then presents the proposed model-based methodology for multi-leak estimation and Section 4 illustrates the *LDI* performance on the considered real prototype. Section 5 finally concludes the paper.

2. Pipeline model

The pipeline model is classically derived under the following assumptions: the pipeline is considered to be straight without any fitting, and without slope, the fluid is slightly compressible, the duct wall is slightly deformable, the convective velocity changes are negligible, likewise, the pipeline cross section area and fluid density are constant. Then, the Partial Differential Equations (*PDE*) governing the fluid transient response, can be written as (Roberson, Cassidy, & Chaudhry, 1998)

Momentum equation

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

Continuity equation

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

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

Here, $z \in [0, L]$ denotes the position along the pipe, and L is the Equivalent Straight Length (Mataix, 1986). In this work, the boundary conditions to be handled in (1) and (2) are taken among the pressure heads and the flow rates at the ends of the pipeline, which are all given by sensor measurements. More precisely, boundary conditions for (1) and (2) are here considered to be

$$\begin{aligned} H(z=0,t) &= H_{in}(t) \\ H(z=L,t) &= H_{out}(t) \end{aligned} \tag{3}$$

The presence of a single leak arbitrarily located at position $z_l \in (0, L)$ can be handled as a new boundary condition in (1) and (2), with outflow $Q_l = C_d A_l \sqrt{2g}\sqrt{H_l}$, in which C_d is the discharge coefficient, and A_l is the leak cross section area. Now by defining $\lambda \equiv C_d A_l \sqrt{2g}$, Q_l can be expressed as (Crowe, Roberson, & Elger, 2000)

$$Q_l = \mathcal{H}_{t_l}\lambda\sqrt{H_l} \tag{4}$$

in which Q_l is the leak flow rate in (m^3/s), H_l is the pressure head at leak point in (m), λ is the leak coefficient in (m$^{5/2}$/s), $\mathcal{H}_{t_l}$ is the *Heaviside* unit step function associated to the leak occurrence at time t_l.

On the other hand, a simple way to obtain some more tractable model for simulation and estimation is to use some finite-dimensional description of *PDE*'s (1) and (2), and in this work the finite-difference method is used as follows (Verde, 2001):

$$\frac{\partial H(z_i,t)}{\partial z} \backsimeq \frac{H_{i+1} - H_i}{\Delta z_i} \quad \forall\, i = 1, \ldots, n \tag{5}$$

$$\frac{\partial Q(z_{i-1},t)}{\partial z} \backsimeq \frac{Q_i - Q_{i-1}}{\Delta z_{i-1}} \quad \forall\, i = 2, \ldots, n \tag{6}$$

where H_i and Q_i stand for $H(z_i,t)Q(z_i,t)$ and $\Delta z_i = z_{i+1} - z_i$ respectively. Thus, the *PDE*'s (1) and (2) can be approximated by a pair of nonlinear ordinary differential equations through (5) and (6) keeping time as a continuous variable. Now by considering boundary conditions (3) as well as assuming that one leak may occur at each section end, its influence can be included with (4), and assuming that the leaks are not uniformly distributed through the duct, the space $(0, L)$ can be divided into n sections of size Δz_i, $\forall\, i = 1, \ldots, n$ with $\sum_{i=1}^{n} \Delta z_i = L$, to represent $n-1$ leak occurrences. Finally, a finite-dimensional model for any number of sections can be obtained as follows (Verde, 2001):

$$\dot{Q}_i = \frac{-gA}{\Delta z_i}(H_{i+1} - H_i) - \frac{f(Q_i)}{2DA}Q_i|Q_i| \quad \forall\, i = 1, \ldots, n \tag{7}$$