Journal of Process Control 42 (2016) 114–124

Contents lists available at ScienceDirect

Journal of Process Control

journal homepage: www.elsevier.com/locate/jprocont

Exact-differentiation-based leak detection and isolation in a plastic pipeline under temperature variations

J.A. Delgado-Aguiñaga [a,*], O. Begovich [a], G. Besançon [b,c]

[a] CINVESTAV IPN Unit Guadalajara, 45019 Zapopan, Jalisco, Mexico
[b] Control Systems Department, GIPSA-lab, Grenoble INP Saint Martin d'Hères, France
[c] Institut Universitaire de France

ARTICLE INFO

Article history:
Received 2 March 2015
Received in revised form 30 March 2016
Accepted 6 April 2016
Available online 27 April 2016

Keywords:
Fault detection and isolation
Nonlinear observer
Sliding modes
Leak
Pipeline

ABSTRACT

This paper presents an algorithm to detect and locate a leak in a plastic pipeline which carries pressurized water, *taking temperature variations into account*. The algorithm is based on an appropriate modeling, as well as a *Robust Exact Differentiation* method for state variables and leak parameters estimation. The model includes temperature dependence in several parameters (*friction factor* and *Equivalent Straight Length* typically), and the exact differentiation method is based on so-called *Higher-Order Sliding Modes*. The algorithm only considers measurements coming from pressure head and flow rate sensors located at the pipeline ends, while temperature variations are monitored via a sensor in the upstream tank feeding the pipeline. Experimental results finally illustrate the performance of this algorithm, and more particularly in comparison with the case when temperature variations are not considered.

1. Introduction

Over the years, many model-based methods have been developed with the aim of solving the problem of *Leak Detection and Isolation* (*LDI*). It is known indeed that leaking pipes have already caused serious accidents, mainly in pipelines carrying fuel and often due to illegal extraction, or that a high percentage of drinking water is lost due to pipeline leaks. For such reasons and related high social, environmental and economical impacts, this research topic has become increasingly important around the world. Two main model-based approaches have been used in the works on leak isolation: one called Fault Sensitive Approach [1–3], and the other one called Fault Model Approach [4–8]. But in many of these works, *friction* is assumed to be characterized by a *constant coefficient* in the pipeline. However, such a parameter typically depends upon the pipeline material, the flow rate and fluid temperature. In most of the previous works, this dependence has not been considered, assuming operation *under constant temperature*, and in a fully developed turbulent regime, which indeed results in a friction coefficient almost constant. But this mainly occurs in pipelines with high roughness, such as pipelines made of concrete, iron, steel, etc. In plastic pipelines, unfortunately, this is no longer true, because the plastic pipe roughness is too low, which means that fully turbulent flow is reached with difficulty, and that the flow regime remains in some transition zone, where the friction coefficient can vary a lot with the flow rate [9]. On the other hand, when the fluid undergoes temperature variations, its kinematic viscosity introduces a flow variation, and consequently the friction coefficient also varies. Moreover, if the friction coefficient changes, it impacts in turn the so-called Equivalent Straight Length (*ESL*) of the pipeline (discussed in more details later) which also affects the fluid dynamics. In some real situations, the pipeline is outdoors, and the fluid inside is exposed to temperature changes, for which a model with constant parameters may thus become inaccurate, making in turn model-based *LDI* algorithms inaccurate, as formally discussed in [10,11] on the basis of simulations. Therefore, studies on model-based *LDI* algorithms remain incomplete if they do not extend to tests on some *real* pipeline, *under critical situations*, such as significant fluid temperature variations.

On the other hand, the Sliding Modes have indeed been more and more used in the recent years for various problems of control and observation, motivated by their attractive properties of finite time convergence, robustness to uncertainty, or insensitivity to bounded external perturbations [12–14]. In particular, the combination with exact differentiation as proposed in the early work of [15] proved to be of particular interest for estimation issues. This is even more true in the case of so-called *Higher-Order Sliding Modes* (*HOSM*) version, as summarized in [16], and more and more observer application examples can be found in this context since [14] (see for instance [17–22] to cite a few recent examples).

* Corresponding author.
E-mail address: adelgado@gdl.cinvestav.mx (J.A. Delgado-Aguiñaga).

http://dx.doi.org/10.1016/j.jprocont.2016.04.005
0959-1524/

On this basis, the main contribution of the present work is to address the *LDI* problem on a real prototype, when considering that the pipeline fluid can undergo strong temperature changes. In this context a new temperature-dependent model, as well as a new estimation approach based on exact differentiation and *HOSM* are proposed. This *HOSM* technique comes in continuation of the former study of [5], where it has been successfully used in the case of constant temperature operation via simulation.

The real prototype corresponds to a plastic pipeline built at the Center for Research and Advanced Studies (*CINVESTAV*) in Guadalajara, México. With it, two cases are considered here: the first one with an *LDI* algorithm with temperature compensation, and a second one with a model with constant parameters. In the first case, the water temperature is measured continuously and used to calculate on-line the kinematic viscosity [23], from which the friction coefficient is adjusted on-line by using the so-called Swamee–Jain equation [24], as well as the *ESL* via the Darcy–Weisbach equation [25]. It is then shown how this improved pipeline modeling indeed allows to correctly track the fluid dynamics under temperature variations, and how in turn the *LDI* algorithm correctly locates the leak. Additionally, other two cases are presented, on the one hand, a case when the temperature compensation is not necessary, and, on the other hand, a case when the pump operation is variable, in order to evaluate a state-steady version of the *LDI* algorithm here proposed.

The paper continues as follows: Section 2 provides the mathematical model to be used for the *LDI* design scheme. Section 3 then presents the proposed exact-differentiation-based estimation scheme for the purpose of *LDI* and Section 4 illustrates the *LDI* performance on the considered real prototype. Section 5 finally concludes the paper.

2. Temperature-dependent modeling of pipeline dynamics

The effect of a leak in a pipeline can be modeled by using the Water Hammer Equations (*WHE*), which describe the transient response of water inside the pipeline. They consist of a pair of Partial Differential Equations (*PDE*). By considering any discretization method for this classical infinite-dimensional description, a finite-dimensional nonlinear state space model can be obtained. Here, a Finite Difference scheme is used, and the leak effect is added. In addition, the model is enhanced with temperature effect.

2.1. Classical pipeline dynamics and leak modeling

2.1.1. Water Hammer Equations

The equations describing the fluid transient response through a pipeline are known in the literature as the *Water Hammer Equations* [26]. They correspond to a pair of nonlinear hyperbolic *PDE's* which are obtained by mass and momentum balances. This model is classically derived under the following assumptions: the pipeline is considered as straight without any fitting, 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, and finally the temperature is constant. Then, the *PDE* governing the fluid transient response can be written as [25]:

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:

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

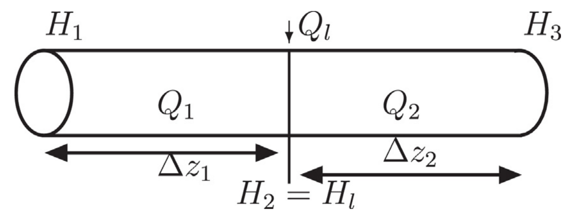

Fig. 1. Discretization of the pipeline with a leak Q_l.

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 local gravity acceleration [m/s^2], A the cross-section area [m^2], b the pressure wave speed in the fluid [m/s], $\mu = f/2DA$, with D the inner diameter [m] and f the friction factor.

Here, $z \in [0, L]$, and L is the pipeline length. In this work, the boundary conditions to be handled are the pressure heads at the ends of the pipeline. Those pressures will be respectively denoted by:

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

The boundary conditions are precisely obtained by the sensor measurements placed at the pipeline ends.

2.1.2. Leak model

The presence of a leak in a given position $z_l \in (0, L)$ can be handled as a new boundary condition in (1) and (2). The flow rate which flows through a hole (*leak*) in a pipeline may be modeled as: $Q_l = C_d A_l \sqrt{2g}\sqrt{H_l}$, 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 [23]:

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

in which Q_l is the flow rate through the leak, H_l is the pressure head at the leak point. $\mathcal{H}_{t_l}$ is the *Heaviside* unit step function associated to the leak occurrence at time t_l.

A closed-form solution of Eqs. (1) and (2) is not available. However, by neglecting or linearizing the nonlinear terms, various graphical and analytical methods have been developed. Some methods have been used for numerically integrating nonlinear, hyperbolic partial differential equations, for example: method of Characteristics and Finite-Difference method, among others. The method of characteristics is extensively used, for solutions of hydraulic transient problems, especially if the wave speed is constant [27]. In the present work, the pressure wave speed is not constant due to temperature variations, and for this reason, here the Finite-Difference method is used. With this method, and by considering boundary conditions (3), a finite-dimensional model can be obtained as follows [6]:

$$\dot{Q}_i = \frac{-gA}{\Delta z_i}(H_{i+1} - H_i) - \frac{f}{2DA}Q_i|Q_i|; \quad \forall i = 1, \ldots, n \tag{5}$$

$$\dot{H}_{i+1} = \frac{-b^2}{gA\Delta z_i}(Q_{i+1} - Q_i); \quad \forall i = 1, \ldots, n \tag{6}$$

in which $\Delta z_i = z_{i+1} - z_i$ denotes the ith section length between two successive points of positions z_{i+1} and z_i, with $z_1 = 0$, $z_{n+1} = L$ and z_i for $i \neq (1, n+1)$ corresponds to an interior discretization node (n = number of sections, and $n-1$ = number of interior discretization nodes). In the particular case $n = 2$, the boundary conditions are: $H_1 = H_{in}(t)$ and $H_{2+1} = H_{out}(t)$. Now, by using (5) and (6), and by introducing the presence of a leak precisely at the single interior