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Online leak diagnosis in pipelines using an EKF-based and steady-state mixed approach

I. Santos-Ruiz [a], J.R. Bermúdez [a], F.R. López-Estrada [a,*], V. Puig [b], L. Torres [c,d], J.A. Delgado-Aguiñaga [e]

[a] Tecnológico Nacional de México/Instituto Tecnológico de Tuxtla Gutiérrez, TURIX-Dynamics Diagnosis and Control Group., Carretera Panamericana km 1080 SN, Tuxtla Gutiérrez, México, CP 29050, Mexico

[b] Department of Automatic Control (ESAII), Universitat Politècnica de Catalunya (UPC), Rambla de Sant Nebridi 10, 08222 Terrassa, Spain

[c] Universidad Nacional Autónoma de México, Instituto de Ingeniería, Ciudad de México, Mexico

[d] Cátedras CONACyT, Mexico

[e] Universidad del Valle de México, Campus Guadalajara Sur, CIIDETEC, 45601 San Pedro Tlaquepaque, Jalisco, Mexico

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ABSTRACT

This paper proposes a methodology for leak detection and isolation (LDI) in pipelines based on data fusion from two approaches: a steady-state estimation and an Extended Kalman Filter (EKF). The proposed method considers only pressure head and flow rate measurements at the pipeline ends, which contain intrinsic sensor and process noise. The LDI system is tested in real-time by using an USB data acquisition device that is implemented in MATLAB environment. The effectiveness of the method is analyzed by considering: online detection, location as well as quantification of non-concurrent leaks at different positions. The leak estimation error average is less than 1% of the flow rate and less than 3% in the leakage position. Furthermore, the incorporation of a steady-state estimation shows that the solution of the LDI problem has improved significantly with respect to the one that only considers the EKF estimation. An experimental analysis was also performed on the effectiveness of the proposed approach for different sampling rates and for different leakage positions.

1. Introduction

In fluid distribution systems, automatic fault monitoring and diagnosis are of great relevance worldwide. The primary purpose of an automatic pipeline monitoring system is to detect leaks, obstructions or sensor faults as quickly as possible, with a minimum of instrumentation and cost (Verde & Torres, 2017). In the case of leaks, these can cause substantial economic losses, damage to the environment and health risks. To size the problem, in water distribution networks the worldwide percentage of volumetric leakage losses has been estimated at around 21%, although in countries such as Mexico it reaches an average value of 40% (OECD, 2016). Also in Mexico, the state-owned oil company Pemex loses about two billion US dollars per year due to leaks in pipelines caused by clandestine outlets of the so-called "huachicoleros", which also pollute the environment and have caused explosions with the loss of human lives (Hernández, 2017; Oswald, 2017).

There are several methods for the direct detection of leaks, which are based on visual or palpable physical detection of the fluid such as hardware-based or Computational Pipeline Monitoring (CPM) methods. Hardware-based methods depend heavily on the physical equipment installed along the pipeline. On the other hand, CPM refers to software-based systems that operate with limited instrumentation and provide algorithmic tools that expand the possibilities of pipeline operators to recognize anomalies that can help to detect the leaks (API, 2002). The CPM tools are based on mathematical models of the pipeline and are complemented with measurement data of some physical variables associated with the flow process e.g. pressure, flow rate, and temperature, among others.

Although it is unavoidable that a leak detection technique depends on both, the mathematical models and the data processing, in the literature usually distinguish two approaches. On the one hand, data-driven detection methods that focus on the digital processing of signals prioritizing the statistical analysis of measurements and can be consulted in Mashford, Silva, Marney, and Burn (2009), Arifin, Li, Shah, Meyer, and Colin (2018), Camacho-Navarro, Ruiz, Perez, Villamizar, and Mujica (2015), Soldevila, Fernandez-Canti, Blesa, Tornil-Sin, and Puig (2017). On the other hand, model-based methods incorporate

* Corresponding author.
E-mail address: frlopez@ittg.edu.mx (F.R. López-Estrada).

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Fig. 1. Experimental pipeline.

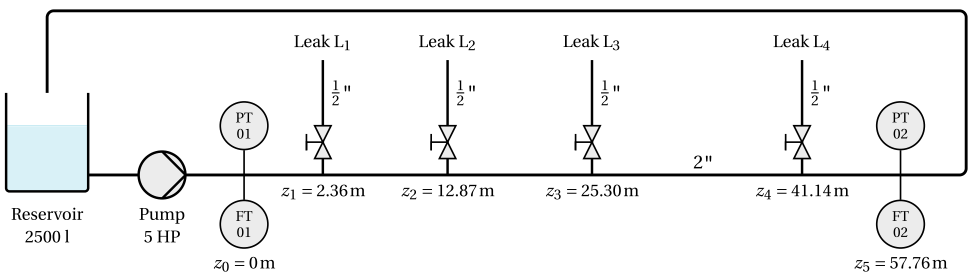

Fig. 2. P&I diagram of experimental pipeline.

dynamic equations based on physical principles (Delgado-Aguiñaga, Besançcon, Begovich, & Carvajal, 2016; Torres, Verde, Besançon, & González, 2014; Verde, 2001, 2004). There are also proposals for mixed methods that combine intensive data processing and mathematical flow models (Soldevila et al., 2016). Recently, comprehensive taxonomies of leak detection systems were presented in Henrie, Carpenter, and Nicholas (2016), Murvay and Silea (2012). According to these classifications, our proposal is included within the model-based techniques.

In the leak diagnosis, not only it is important to detect the leak and quantify it, but it is a priority to locate it as accurately as possible. So, it is necessary to have algorithms that precisely determine the location of the leak because it is not always visible from outside the pipe. An error of a few meters in locating a leak in an underground pipeline results in a significant cost for digging in a wrong area to repair it (Delgado-Aguiñaga & Begovich, 2017). In practice, one circumstance that limits the precise location of leakage using approaches based on the deterministic dynamic models of the pipeline flow is the presence of variable parameters in the mathematical model, which show a nonlinear dependence on the flow rate and other physical factors such as temperature (Dulhoste, Guillén, Besançon, & Santos, 2017). Other complications occur because the signals obtained from the pressure and flow sensors are generally noisy (Billmann & Isermann, 1987).

This paper proposes a methodology for detection, location, and estimation of fluid leaks in a straight pipeline (without branchings) by considering pressure and flow measurements at the pipeline ends. This set-up is justified because many hydraulic and fuel transport networks are instrumented in this way (Verde, Gentil, & Morales-Mené, 2013). Considering the noisy characteristic of the available measurements, this work is based on the proposal of Delgado-Aguiñaga, Besançon, and Begovich (2015), when using an EKF estimator, but also it incorporates the steady-state solution of the pipeline dynamic model to refine the solution and it proposes a strategy to accelerate the convergence of the iterative process. These added features are not only desirable but necessary since real-time implementation requires fast and accurate LDI methods. A feature that is highlighted is the live implementation using conventional hardware and software, unlike most other works referred in the literature that are limited to presenting simulation results or offline calculations. A deep analysis concerning the sensitivity of the system, its reliability and its accuracy in the location of the leaks are commented. An exhaustive experimental analysis was performed with 96 different leak scenarios, which illustrates the effectiveness and applicability of the proposed method.

Regarding the delimitation of the conditions where the proposal is applicable, only pipelines with pressurized flow are considered. Furthermore, the topic of LDI in biphasic flows has not been considered in this work, because the mathematical model used by the EKF would change due to phase transitions, so the current proposal does not include this possibility.

2. Materials and methods

2.1. Description and modeling of experimental pipeline

The experimental tests of the proposed method for leak detection and localization that is presented in this work were carried out on a pilot pipeline plant located at Laboratory of Hydraulics in the Tuxtla Gutiérrez Institute of Technology. This experimental pipeline is serpentine-shaped (Fig. 1) with an equivalent length of 57.76 m and it is made of 2-inch diameter PVC; the water is driven with a centrifugal pump whose power is controlled by a frequency inverter. A more detailed description of this pipeline setup is presented in Bermúdez, Santos-Ruiz, López-Estrada, Torres, and Puig (2017).

A P&I diagram of the pipeline setup used is shown in Fig. 2. Industrial pressure and flow-rate sensors/transmitters are located at the ends of the system. These sensors provide the information that will be used as inputs and outputs for the EKF estimator. Four manual gate valves in half-inch tees are located at arbitrary positions to simulate leakages, which are modeled as orifice outlets.

The signals from the pressure and flow transmitters are received through 4–20 mA current loops connected to a 14-bit data acquisition system (DAQ) with USB interface to MATLAB. As shown in Fig. 3, the current signals are read in voltage form through 470 Ω resistors at the