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Parameterized transient model of a pipeline for multiple leaks location

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A B S T R A C T

This work deals with the location of multiple leaks in a pipeline when only the flows and pressures of the fluid at the extremes of the line are known. The key of the leaks' detector which should operate in quasi-real-time is the family $\mathcal{F}$ of parameterized transient models for all two leaks scenarios in the pipeline. The family $\mathcal{F}$ of dynamic models is obtained by considering the equivalence in the steady-state of a leak at position z_{eq} with two leaks. This equivalence reduces the dimension of the unknown parameters' vector in the dynamic model from four to two. To estimate the specific parameters of $\mathcal{F}$, an off-line identification process is suggested which minimizes the quadratic error between the pipeline data and the member of the family. Results of the leak detector with 12 scenarios offered estimation errors less than 1% in all the cases for a water pipeline of 200 $[m]$. This illustrates the potentiality of the parameterized transient model for the identification of multiple leaks.

1. Introduction

The reliability of pipeline networks is an important and constant concern in fluid transportation systems. Although pipelines are protected against damage, pressure surges in networks often induce leaks and line breaks. In the case of hazardous fluid transportation, leaks may have a severely damaging impact on the environment as well as considerable human and economic losses. In Mexico (López, 2013), illegal extractions and leaks represent a total loss of up to 6.15 billion of US dollars per year. Leaks are caused by natural catastrophes like earthquakes, failure of the mechanical integrity and excavation activities. Moreover, the automatic supervision systems report false positions if the supervisor supposes only one leak. Multiple leaks scenarios must be considered, since confidential reports declare that the illegal groups produce multiple extractions, keeping the outflows below the threshold of the detectability curve.

In recent decades a considerable amount of algorithms for the estimation of leaks has been proposed to allow the reduction of the number of sensors and to improve the security of the networks. Such algorithms are part of on-line computational pipelines' monitoring (Billman & Isermann, 1987; Ferrante & Brunone, 2003; Lee, Vítkovsky, Lambert, Simpson, & Liggett, 2005; Scott & Barrufet, 2003). Two frameworks in general have been used to tackle the problem of diagnosis and supervision of systems: the qualitative tools based on artificial intelligence (Venkatasubramanian, Rengaswamyd, Yin, & Kavuri, 2003b) and those based on an analytical dynamic model (Venkatasubramanian, Rengaswamyd, Yin, & Kavuri, 2003a). The latest algorithms have a specific objective: the supervision of general faults in the process including its sensors and actuators. In the case of pipelines the faults can correspond to leaks and clogs which can be identified using fault detection and isolation (FDI) tools for analytical systems and signal processing (Blanke, Kinnaert, Lunze, & Staroswiecki, 2006).

Torres, Besançon, and Georges (2009) have recently proposed an extended Kalman filter to detect both the outflows of the leaks and their locations by assuming data of flow and pressure heads at the ends of the pipeline. The filter is designed considering the positions of the leaks as additional states in the model; nevertheless, the estimation convergence depends strongly on its initial condition. Another proposition uses a second order sliding mode observer which assumes known leaks' positions for the reconstruction, which is not realistic (Angúlo & Verde, 2013).

Because the multiple leaks' models are equivalent to one leak case in the steady-state, two leaks are detectable but the isolability problem is not feasible without dynamic considerations (Verde, Bornard, & Gentil, 2003). Specifically, the two leaks location in a

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Nomenclature

A	Cross-sectional area [m^2]
a_1	Constant $= gA$ [$\mathrm{m}^3\ \mathrm{s}^{-2}$]
a_2	Constant $= b^2/2DA$ [$\mathrm{m}^2\ \mathrm{s}^{-2}$]
b	Wave speed in the fluid [$\mathrm{m\ s}^{-1}$]
$E(Q)$	Normalized quadratic error
$\mathcal{F}$	Family of equivalent dynamic models
g	Gravitational acceleration [$\mathrm{m\ s}^{-2}$]
$H(z,t)$	Pressure head at point z and time t [m]
$\dot{H}_j$	Temporal derivative of H at section j [$\mathrm{m\ s}^{-1}$]
H_{in}	Pipeline upstream pressure head [m]
H_{out}	Pipeline downstream pressure head [m]
H_{zj}	Pressure at $\tilde{z}_j$ [$\mathrm{m}^3\ \mathrm{s}^{-1}$]
h	Sampling time [s]
$J(\theta)$	Quadratic function
j	Section number
L	Pipeline length [m]
n	Number of leaks
n_p^*	Number of steps of p in the interval [0, 1]
$n_{\tilde{z}_2}^*$	Number of steps of $\tilde{z}_2$ in the interval [0, L]
p	Relative factor of the outflows
$Q(z,t)$	Flow at point z and time t [$\mathrm{m}^3\ \mathrm{s}^{-1}$]
$\dot{Q}_j$	Temporal derivative of Q at section j [$\mathrm{m}^3\ \mathrm{s}^{-2}$]
Q_{in}	Pipeline upstream flow [$\mathrm{m}^3\ \mathrm{s}^{-1}$]
Q_{out}	Pipeline downstream flow [$\mathrm{m}^3\ \mathrm{s}^{-1}$]
$\overline{Q}_{eq}$	Equivalent outflow with one leak [$\mathrm{m}^3\ \mathrm{s}^{-1}$]
Q_{zj}	Outflow at $\tilde{z}_j$ [$\mathrm{m}^3\ \mathrm{s}^{-1}$]
Q_e	$Q_{in} - Q_{out}$ for the algorithm [$\mathrm{m}^3\ \mathrm{s}^{-1}$]
t	Time [s]
t_w	Initial time for the criterium [s]
t_d	Final time for the criterium [s]
$T_{\overline{Q}e}$	Detection threshold [$\mathrm{m}^3\ \mathrm{s}^{-1}$]
Y	Data matrix for the algorithm
z	Absolute spatial coordinate [m]
$\tilde{z}$	Relative spatial position by section
$\tilde{z}_j$	Relative spatial position of the jth leak
z_{eq}	Position of equivalent leak [m]
μ	Friction parameter
λ_j	Leak coefficient at $\tilde{z}_j$ [$\mathrm{m}^{5/2}\ \mathrm{s}^{-1}$]
$\nu(\tilde{z},t)$	Variable $Q_j(\tilde{z},t)$ or $H_j(\tilde{z},t)$
$\overline{\nu}$	Variable ν at steady-state
$\widehat{\nu}$	Variable ν in the parameterized model
θ	Unknown parameters $[p, \tilde{z}_2]$
θ^*	Optimal value of θ
θ^0	Initial value of θ for the optimization

pipeline has been studied and discussed in the past by diverse authors, e.g. Korbicz, Koscielny, Kowalczuk, and Cholewa (2004, pp. 821–864) and Verde, Visairo, and Gentil (2007). This fact is graphically illustrated in Fig. 1 where the transient flows at the extremes for diverse pairs of simultaneous leaks are presented with similar behavior of flows in the steady-state. These scenarios define a family $\mathcal{F}$ of multiple leaks with an equivalent steady-state behavior.

Diverse methods have been suggested, including the consideration of test signals for the fluid. A procedure to identify the occurrence of one or two leaks considering the frequency response of the fluid is reported in Jimenez and Verde (2012); however, limitations in the sensors' bandwidth of flows and pressure made the method unfeasible. A further suggestion to identify the parameters is the excitation of the fluid with specific signals in the valve, given in Colombo, Lee, and Karney (2009) and more recently Gong et al. (2013) argue that leaks induced reflections which are

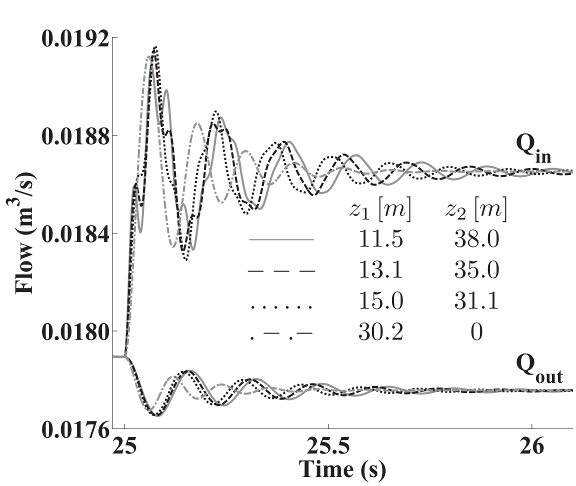

Fig. 1. Diverse flow transient responses with equivalent leak position at 30.23 m and outflow 0.0018 m^3/s for the pilot pipeline.

observed as discontinuities in the pressure traces. Unfortunately, field work and the verification of these techniques is lacking in most of the cases. The multiple leaks' location is then an open technological issue, where accuracy and bandwidth of measurements must be taken into account as well.

An alternative to detect the parameters without test signals is to extract leak information from the total transient response off-line instead of from only the arrival time of the pressure wave, as has been suggested in Liou (1990). Recently Moustafa, Kaik, Alda, and Omar (2012) tackle the location problem by searching the estimation model that minimizes the error between the measurements and their estimations using a Kalman filter. From an artificial intelligence (AI) perspective, Ni, Jiang, and Panigrahi (2013) proposed a support vector machine and a particle swarm optimization, both of which minimize the error between data and model to determine the leak positions. The last two optimization methods require a high consumption of computer time, and the training process is conducted by assuming similar leaks and known transients produced by simulations. Since each leak generates two unknown parameters in the models, if the outflow magnitude produced by a leak is not similar to the values used during the training, false leaks are detected which make these methods unfeasible in a real application.

Thus, as an effort to reduce mainly the illegal extractions from a pipeline, this work is oriented to the development of a new methodology for the localization of two simultaneous leaks in a single phase fluid with only sensors of flow and pressure at the inlet and outlet.

As shown in Korbicz et al. (2004, pp. 821–864) relations exist in steady-state between the parameters (position and outflow) associated with one leak and the parameters of a family $\mathcal{F}$ for the case of two leaks. These equivalent relations permit the simplification of the parameter identification problem of leaks, as shown here. As a result, one obtains a parameterization for the two leaks model, validated with the commercial simulator PipelineStudio (2013), with only two unknown parameters assuming as known the total outflow in steady-state and the equivalent position with one leak.