Journal of Loss Prevention in the Process Industries 43 (2016) 18–28

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

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

Decentralized scheme for leaks' location in a branched pipeline☆

C. Verde [a,*], L. Torres [a,b], O. González [a]

[a] Instituto de Ingeniería, Universidad Nacional Autónoma de México, Mexico City, Mexico
[b] Cátedras CONACYT, Mexico

ARTICLE INFO

Article history:
Received 28 December 2015
Received in revised form
17 March 2016
Accepted 18 March 2016
Available online 13 April 2016

Keywords:
Branched pipelines
Decentralized scheme for leaks' location
Parameter identification
Sensitivity function

ABSTRACT

This article presents a novel scheme for the detection and isolation of single leaks in a pipeline with a branch junction by measuring only the flow rate and pressure at the ends of the line. For the solution of this realistic issue, which commonly occurs in pipeline networks, the position of the branch junction and its flow rate are supposed to be known. The idea consists of deriving a model considering the branch junction as a known point in the pipeline such that the leak position is characterized by two possible orientations with respect to the branch (upstream and downstream of it). Thus, this model allows proposing a diagnosis scheme which includes a static selector and two identifiers designed by using a continuous extended Kalman filter with only one deviation parameter to be estimated. This framework reduces the identification task to one parameter which is associated with the deviation from a prescribed positive base position located between one of the pipeline ends and the branch. Simulation and experimental results with data of a hydraulic pilot pipeline of 200 $[m]$ show the promise of the novel scheme.

1. Introduction

Pipelines often pass through hazardous environmental areas from the point of view of natural disasters, such as landslides and earthquakes, as well as from the point of view of third-party influences, such as vandalism or obstruction. These hazards can significantly change the original structural functioning of the flowline, leading to damage, leakage and failure, with serious economic and ecologic consequences. Furthermore, the operational conditions of the pipeline *per se* can induce additional damage.

The leak detection task in pipelines can be tackled by using *fault detection and isolation* (FDI) tools based on a fluid model that represents the physical dynamics of a specific installation. These tools include, for instance, algorithms in frequency domain (Ferrante and Brunone, 2003) and time domain (Billman and Isermann, 1987; Kowalczuk and Gunawickrama, 2000; Torres et al., 2014; Moustafa et al., 2012), based on the model described by Chaudhry (1979), and Wylie and Streeter (1978). These algorithms were developed for a pipeline instrumented only with pressure and flow sensors at the ends and without branch junctions in between.

The more general scenario of multiple leaks with known pressure and flow at the ends of the pipeline has been studied with an equivalent input-output model for one leak, which achieves the detection and isolation task if (i) only sequential leaks appear (Verde and Rojas, 2015), or (ii) the location algorithm is implemented off-line by minimizing the $\mathscr{L}_2$ error (Verde et al., 2007, 2014). Therefore, there is a lack of satisfactory diagnosis algorithms for the general multiple leaks scenario, including the case of the branch junction with outflow in the pipeline.

A very common and realistic configuration in a pipeline's network is the presence of branch junctions with outflow from the main line which involves additional physical constraints in the fluid model. Fig. 1 describes this scenario in which the distances of the branch junction to the leak are z_2^u and z_2^d respectively. Note that a branch junction can be assumed to be a known and permitted outflow Q_b at a fixed position z_b of the pipeline. Thus, the leaks' detection problem in pipelines with outflow at the branch junctions can be considered as a particular problem of multiple leaks with multiple extractions. Thus, for the scenario of Fig. 1, one extraction can be considered part of the nominal behavior which is known, and the other which is unknown is undesirable. Since the structure of the dynamics' model varies if a leak is located upstream or downstream with respect to a branch junction, the above mentioned diagnosis algorithms cannot be simply applied to a

☆ Supported by II-UNAM and IT100414-DGAPA-UNAM, IT100716-DGAPA-UNAM.
* Corresponding author.
E-mail addresses: verde@unam.mx (C. Verde), ftorreso@iingen.unam.mx (L. Torres).

http://dx.doi.org/10.1016/j.jlp.2016.03.023
0950-4230/

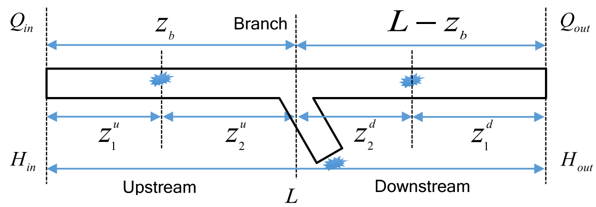

Fig. 1. Description of the leak's scenario with a branch junction.

pipeline with a branch in a section.

According to Wylie and Streeter (1978), each branch junction in a pipeline increases the number of boundary conditions, and as a consequence, the number of state variables in the dynamic models. As a result, new boundary conditions in each specific region of the pipeline with respect to the branch junction, along with an increment of the model order, must be considered. On the other hand, Visairo and Verde (2003) showed by a geometric approach that by assuming three possible leaks with known positions there is a lack of isolability for the leak located between the other two. As a consequence, the isolation task of two possible leaks —one located upstream and the other downstream of a branch junction— has no solution if the pressure and outflow at the branch point are unknown.

The above mentioned fact has motivated this work which proposes a reliable general scheme for detecting and locating a leak in a pipeline with a known branch junction considering the scenario described in Fig. 1. The key of the structure is the decentralization of the leaks' identification by reformulating the problem as two independent location tasks together with an orientation selector in which the orientation is referenced with respect to the branch junction. Fig. 2 describes the proposed decentralized scheme.

The selector determines the orientation of the leak with respect to the branch junction ($u \triangleq$ upstream or $d \triangleq$ downstream), and by considering the two feasible orientations, the identifiers estimate the distance between the branch junction and the leak. This means the leaks' location problem is reformulated as two independent tasks which can be solved by using diverse faults' algorithms. Thus, the parameters to be estimated are the distance with respect to a base point and the orientation. As usual, only the flow and head pressure at the ends of the pipeline are measured, and the outflow at the junction is known.

A benefit of the proposed scheme is that its implementation can be done without additional instrumentation in the pipeline. Moreover, its structure is very general; diverse FDI tools for nonlinear systems (Isermann, 2006) can then be used for each block. A preliminary version of the structure was published in Verde and Torres (2015) requiring a steady-state condition in the residuals for the implementation. However, this assumption generated a slow time response for the detection. Considering the practical point of view, one here improves the original idea by selecting the subsystems which require the minimal number of parameters to be adjusted and by using a dynamic estimator to achieve a fast response for the leak identification. Therefore, the decentralized scheme and its implementation with simple identification tools for dynamics' system' are the main contributions. The algorithms particulary used here include the following:

- a static residual between the real branch position z_b and its estimator on-line for the orientation selector;
- two decentralized continuous extended Kalman filters used as identifiers for the positions z_2^u and z_2^d (each one associated with its respectively orientation).

In this work, simulation and real data of a hydraulic pilot pipeline of $200\,[m]$ show the satisfactory performance of the scheme in the presence of changes in the boundary conditions, as well as branch outflows Q_b and leak positions.

The structure of the paper is the following. Section 2 defines the symbols and variables used in the work. Section 3 describes the fluid model divided into the four sections according to the scenario shown in Fig. 1 for which it is assumed that only one outflow can occur in addition to the known outflow Q_b at the branch point. Moreover, the specific parameters of the pilot water pipeline are given here. Section 4 talks about the advantages of the general decentralized scheme and introduces the specific design tools used in the work. In addition, a simple idea is presented for identifying on which side with respect to the branch junction is the leak. Section 5 introduces the derivation of two subsystems each one with only one parameter associated with a leak —upstream or downstream— obtained by linear transformations by assuming a base leak position with an unknown deviation. Furthermore, this section includes the observers' design for both subsystems with an additional state associated with its respective unknown parameter by using continuous extended Kalman filters. Section 6 describes the flow diagram of the scheme together with the block diagram implemented in MATLAB®, and Section 7 shows the good performance of the procedure with simulation and real data. Finally some conclusions are given in Section 8.

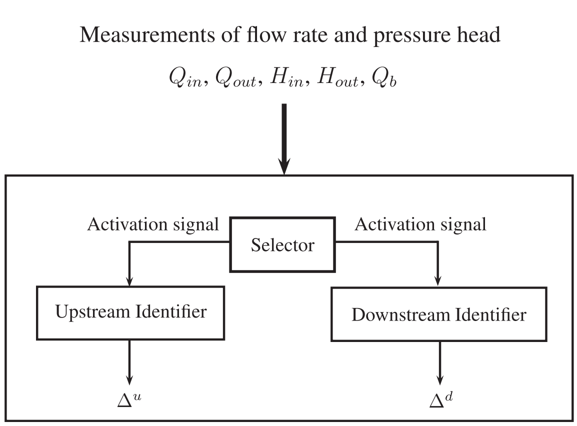

Fig. 2. General scheme with a selector of orientation and the two identifiers of the leaks.

2. Nomenclature

Table 1
Variables definition.

Symbol	Variable	Units
A_0^s	State linear matrix in model $\sum^s$	
B_0^s	Input matrix in model $\sum^s$	
a_1	$\frac{g\pi\phi^2}{4}$	$[m^3s^{-2}]$
a_2	$\frac{4b^2}{g\pi\phi^2}$	$[m^2s^{-2}]$
b	Wave speed in the fluid	$[ms^{-1}]$
f	Darcy-Weisbach friction factor	
g	Gravitational acceleration	$[ms^{-2}]$
$H(z,t)$	Pressure head at point z and time t	$[m]$
H_{in}	Pressure head at the upstream end of the pipeline	$[m]$
H_{out}	Pressure head at the downstream end of the pipeline	$[m]$
H_{j+1}	Pressure head at the end of section j	$[m^3s^{-1}]$

(continued on next page)