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Accommodation of multi-leak location in a pipeline ☆

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Abstract

A novel model-based approach is proposed to detect leaks locations in a pipeline using only sensors of flow and pressure at the ends of the duct. The approach assumes a simple nonlinear model of the fluid in a pipeline with leaks, discretizing the spacial variable in nonuniform sections with unknown boundaries that depend on the leaks locations, z_1 and $z_1 + z_2$. The key to the detection and location algorithm is the use of a multi-task scheme: (1) the continuous monitoring and searching of the leak condition, sweeping all feasible leak positions of the duct, and (2) when a leak condition is detected, the scheme switches on and starts the accommodation of the unknown parameters (z_1, z_2) in the model, so that, an error signal is minimized satisfying physical constraints. Simulation examples with one and two leaks are given to show the effectiveness of the location procedure.

Keywords: Leak detection; Updating residual generator; Robust observer; Model-based approach for fault detection and isolation

1. Introduction

Leak detection in pipelines can be performed either through periodic surveillance or continuous monitoring. Surveillance techniques are based on observations from aircrafts or satellites. The continuous automatic monitoring considers physical effects by direct measurements or by calculation from the mathematical model of the pipeline. The tools used with the later technique are the principles of fluid dynamics (Chaudry, 1979) together with the theory of fault detection and isolation for dynamic process, FDI (Chen & Patton, 1999).

A considerable amount of work has been done to develop effective methods to detect and locate continuously small leaks using model-based methods in the last 20 years (Billman & Isermann, 1987; Kowalczuk & Gunawickrama, 2000; Shields, Ashton, & Daley, 2001; Verde, 2001). In all these contributions, a finite-dimensional model for the fluid with fix discretization of the spatial variable in the pipeline is assumed.

On the other hand, it has been recently shown (Visairo & Verde, 2003) that the existence conditions for a nonlinear residual generator robust to one leak and sensitive to the rest, with only sensors of flow and pressure at the ends of the duct, are satisfied only if the pipeline is divided in to three sections and at most two leaks positions are considered. This fact constrains the use of a bank of observers with fixed leaks positions and, moreover, a bias is produced in the residual when a leak deviates from the assumed fix location. These disadvantages explain why the simultaneous leaks isolation problem with unknown positions remains a challenge.

To solve the leak detection and location problem without extra measurements along the pipeline, a nonlinear model of the fluid is proposed here, discretizing the spatial variable in the pipeline into three nonuniform sections of unknown sizes (z_1, z_2, z_3), such that the existence condition for a residual generator satisfies. Thus, each leak or fault involves two unknown parameters in the fluid model, the outflow and its respective position. In spite of the increase of unknown

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parameters for each leak with this model, the setting up of static relations, which match with the physical leaks positions, can be used to reduce to one unknown parameter for each leak.

This reduced identification problem is tackled by coupling an estimator with a residual generator, such that an accommodation scheme with a double objective is proposed; in normal conditions, the monitoring system looks continuously for a leak, considering all the possible positions in the pipeline via a sweep signal. When the leak condition deviates from zero without regard to the position, an adaptive law is triggered to estimate the leak position considering physical constraints in steady state and minimizing the output error of a residual generator. In comparison with previous models and procedures for leak location, this way to address the position problem eliminates the deviation reported in Verde (2001) when a leak is not at the assumed fixed position, and the increase of sensors, as it is suggested in Shields et al. (2001). Thus, the main contribution of this paper is the reduction in the number of parameters that must be identified to isolate two leaks in a pipeline.

The paper is organized as follows. Section 2 introduces the nonlinear dynamic model assuming two leaks not uniformly distributed in the pipeline together with the statics relations, which satisfy the physical variables of the system. Section 3 proposes the accommodation scheme with a double objective: the monitoring task during normal conditions and the position location after the detection. This multi-task is achieved by coupling an estimator with residual generators. Section 4 indicates the design specifications for both the residual generators and estimation law. Simulation results for a water pilot pipeline are presented in Section 5, and finally the conclusions of the work are given in Section 6.

2. Nonlinear model

Assuming convective changes in velocity to be negligible in a pipeline of length L, and its cross-sectional area constant, the motion and continuity equations governing one-dimensional transient flow in a liquid pipeline are (Chaudry, 1979)

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

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

where H is the pressure head (m), Q the flow (m^3/s), z the length coordinate (m), t the time coordinate (s), g the acceleration of the gravity (m/s^2), A the cross-section area (m^2), D the pipeline diameter (m), b the speed of sound (m/s) and $\mu = f/2DA$ where f is the friction coefficient.

In the case of gas-flow, heat transfer dynamics must be considered in the PDE (1–2) and essentially, the ideas presented here can be applied. The extension for this case is reported in Pascual, Verde, and Casasola (2003).

Two leaks arbitrarily located at points p_1 and p_2 of the pipeline with outflow

$$Q|_{p_i} = \lambda_i\sqrt{H|_{pi}}, \quad i = 1,2, \tag{3}$$

respectively, produce a discontinuity in the system, where the constant $\lambda_i > 0$ is a function of the orifice area and discharge coefficient. As a consequence, the model with two leaks must be handled as a set of three PDE (1–2) with boundary conditions in between

$$Q^b|_{p_i-\varepsilon} = Q^a|_{p_i+\varepsilon} + Q|_{p_i} \quad \text{for } i = 1,2, \tag{4}$$

with $\varepsilon \to 0$ and $Q^b|_{p_i-\varepsilon}$ and $Q^a|_{p_i+\varepsilon}$ are the flows at the sections before and after each leak position, respectively.

Assuming a lumped parameters model for the fluid and measurements only at the ends of the duct, it has been recently shown (Visairo & Verde, 2003) that the isolation problem for two leaks in a pipeline has a solution only if the pressure $H|_{pi}$ at the leak position has a direct action in a measurable state. This important result constraints the approximations that can be used to discretize the PDE (1–2). Here, one approximates the partial derivative of the pressure with respect to the spatial variable z at the leak position by

$$\text{Section } i: \ \frac{\partial H}{\partial z} = \frac{H_i - H_{i+1}}{z_i},$$

with $p_1 = z_1$ and $p_2 = z_1 + z_2$. The flow is assumed constant in each one of the sections. The discretized variables according to these definitions are shown in Fig. 1, where the sections lengths satisfy

$$z_1 + z_2 + z_3 = L, \tag{5}$$

where L is the length of the line. One can see from Fig. 1, that the discretization depends on the leaks separation and as long as there is no leak, the sections sizes are arbitrary.

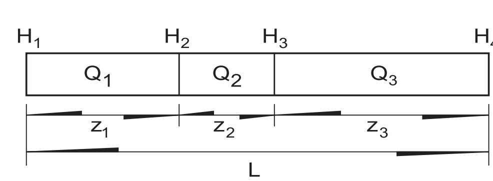

Fig. 1. Variables definition with nonuniform sections.