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Computer implementation of a boundary feedback leak detector and estimator for pipelines II: Leak estimation ⋆

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Abstract: This paper is the second of a work in two parts describing the salient features of a computer system for continuous estimation of leaks in pipelines based on a Real-Time Transient Model (RTTM). While Part I is focused on a transient pipeline model based on current modeling techniques, in this Part II such model is complemented as a closed-loop Luenberger-type estimator for distributed-parameter models, referred throughout this work as *Aamo-Salvesen-Foss Estimator* (ASFE) after their designers in Aamo et al. (2006). Furthermore, along this paper, we sketch the design of a software architecture supporting a computer implementation of an industry-oriented, real-time, transient model-based, leak detection, localization and quantification system.

Keywords: Pipelines monitoring, process parameter estimation, pipelines leakage detection, nonlinear systems, distributed-parameter systems, boundary feedback estimation.

1. INTRODUCTION

The mass balancing method implemented on a *Real-Time Transient Model* (RTTM) is widely used in industry for the detection and (segment-) localization of leaks of transported product in networks of pipelines. Although this approach has been prevalent in industry since many years, from the viewpoint of automatic control theory, several objections can be raised with the purpose of increasing its reliability:

- The actual implementation of most *leak detection and localization systems* (LDLS) with the RTTM method consists of *open loop estimators* with finite-dimensional approximations of distributed-parameter systems.
- Therefore, it may take a rather long period of time before arriving to an appropriate initial condition with an *admissible* estimation error. Though, there is no reason to expect that the estimation error may converge to zero.
- In such open loop scheme, *instrumentation errors* and *modeling errors* propagate additively along the forward loop as *estimation errors* without any possibility of being compensated for, thereby affecting notoriously their overall predicting performance for leak diagnosis.

As an evidence of these statements, in Fukushima et al. (2000) is argued that unreliable data acquisition, unexpected low resolution of pressure sensors and uncontrolled fluctuations are common implementation problems which may lead to false alarms for leak detection systems based on (open-loop) transient models. See further arguments in van Reet and Skogman (1987) and Liou (1991).

In automatic control theory, the attenuation of estimation errors is achieved by feeding these errors back to the model under a scheme called closed-loop observer or estimator. One of the earliest closed-loop estimation schemes is known as the *Luenberger estimator*, where the output error is fed back to a model of the plant, such that the feedback loop guarantees by design asymptotic stability of a closed-loop error model, and thereby improves the observer estimated values. With their own distinctive variations, the adaptive state-observer of leaks by Billmann and Isermann (1987), the bank of unknown input state-observers by Verde (2001) and the nonlinear observers by Torres-Ortiz (2011) are all examples of this approach.

One type of feedback appropriate for the class of distributed systems in fluid dynamics, known as *boundary feedback*, is based on the *Riemann invariants* and other structural properties for hyperbolic partial differential equations (PDEs), see de Halleux et al. (2003). Boundary feedback has relevant implications for control and leak detection and localization for irrigation open-channels, Weyer and Bastin (2008); Bedjaoui et al. (2009), but also for pipelines. Recently, Aamo et al. (2006); Hauge et al. (2007, 2009), proposed a leak detection method using a Luenberger estimator for one-dimensional, one-phase distributed-parameter pipeline models.

Thus, based on the works previously mentioned and seemingly with the aim of increasing the precision and reliability of these diagnostic systems, the authors in Aamo et al. (2006), improved their estimates by feeding all the model inputs (pressures and flow-rates) back to their dynamic model and, –instead of considering a leak as an anomalous behavior to be discovered, as in the traditional approach–, they assumed that the *leaked flow-rate* and the *leak localization* are two parameters included in the dynamic model and *continuously estimated* throughout the pipeline operations. Though, the authors in Aamo et al. (2006) warn that exponential convergence is not provided with their boundary feedback setting and that leak parameters are estimated with *heuristic* adaptive laws.

The main purpose of this paper is to report our experiences on the computer implementation and test of this boundary feedback estimation scheme in combination with our model from

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the Part I (also reported in this congress). In particular we believe that the effect of instrumentation errors and modeling errors can be attenuated within the closed-loop system and with this the reliability of the leak diagnosis can be increased, being quantification and localization continuously estimated parameters.
Our approach is acceptedly a computer implementation of the methods presented previously by Aamo et al. (2006); Hauge et al. (2009), but with the following distinctive points:

- First of all, while they showed remarkable results of closed-loop estimation using the commercial simulation software OLGA (^{TM}SPT Group) as their transient pipeline model, in this paper we are using our own model which also includes the change of potential energy due to terrain topography, see Part I.
- Moreover, although continuous quantification and localization on the estimated leak can be used for detection with simple additions, all along their published work in Aamo et al. (2006); Hauge et al. (2009), the authors apparently left aside the problem of detection. In this work we expect to contribute to the improvement of the traditional balancing method as detection scheme by their boundary feedback methods. Therefore, for comparison, we have included some model-based packing-rate calculations.

Our computer implementation for the LDLS was written in C using LabWindows/CVI ($^{\mathrm{TM}}$National Instruments). Since the system is organized in *stages* and *modules*, this paper is organized accordingly: In particular, in Section 2 we sketch the necessary communications stage, which takes advantage of OPC (*OLE for Process Control*) technology in order to communicate with our *Distributed Control System* (DCS) or for a SCADA (*Supervisory Control and Data Acquisition*) system. In Section 3 we justify the need of a Module for Data Interpolation/Uniformization in order to eliminate the effect of several sources of data unreliability. Then the mass unbalance detection stage is introduced in Section 4. In Section 5 we present the closed-loop leak estimator in combination with the transient model presented in Part I. In Section 6 we present off-line simulation results based on real-time data obtained from our laboratory. We conclude with some final remarks.

2. THE COMMUNICATION MODULE

This section is concerned with the communication of the LDLS with the several data sources of pipeline data. Three possible sources of data are considered: data received from a Data Base (local or external), data collected from a DCS and data collected from a SCADA. For each of these sources was necessary to develop specific timer-based modules in order to acquire the necessary information. Also, this module must correct several problems in the data collected, like the size, format and units of data for each channel. With this module, it is possible to communicate our system with the DCS in our industry-oriented experimental facility: The IMP Multi leaks Pipeline Simulation Rig, see below in Section 6. Otherwise, the data source may be a SCADA from the control room operating some large pipeline network. In both submodules we may use OPC technology. The advantages of using OPC technology for LDLS has been discussed previously by Zhang et al. (2009).

3. THE STAGE OF DATA UNIFORMIZATION

SCADA is the data acquisition system most frequently used to poll data from field instruments/transmitters remotely located at the valve stations or the measuring stations from large pipeline networks. Unfortunately, as remarked in Fukushima et al. (2000), this scheme of telemetry is a source of unreliable data acquisition. There are several problems with the reliability and quality of the data collected, since such data may be polled with different sample times for each channel, and it is not always uniformly sampled. In particular, sometimes sampled data is not collected or it is collected with a considerable delay from the *Remote Terminal Units* (RTUs). According to the theory of non-uniform sampling, signals can be recovered from its non uniform samples if the *extended theorem for non-uniform sampling* is satisfied and a nonlinear interpolation is performed on the non-uniform samples, see *e.g.* Marvasti (1993). Therefore,

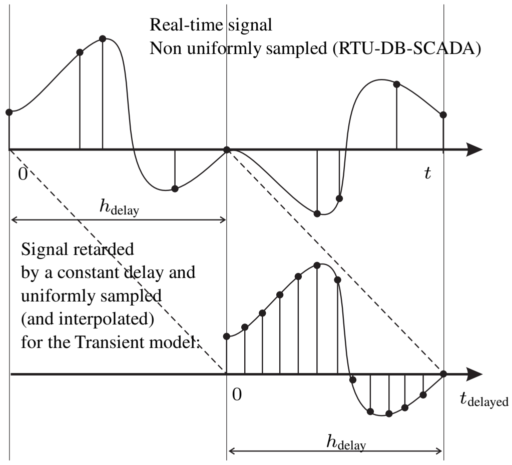

Fig. 1. Diagram for delayed data interpolation/uniformization.

three strategies for data processing were used in order to overcome all these problems: a delay in a horizon of time h_{delay} between the real-time and the time of execution of the transient model, a stage of data uniformization based on nonlinear interpolation, and in the event of a channel without fresh data, data replacement with the last value acquired.
In this stage, data is re-sampled at a higher frequency, appropriate for the solution of the transient model, excluding with this the possibility of a model out of order due to missing data, see Fig. 1. The price to pay for this strategy is that any diagnostic of leak detection will be reported with a delay h_{delay} and, in an event of absence of fresh data, the reliability of the LDLS will be reduced during such event.

4. THE STAGE OF MASS UNBALANCE DETECTION

In this section the method of volume/mass balance by Nicholas (1987) is restricted to one pipeline segment. For a complete description of the method see Wylie et al. (1993). Denote by m_{pipe} the mass inside a *control volume* $\forall$ in the pipeline with inflow and outflow flow rates w^{inflow} and w^{outflow} respectively. Let us consider the integral representation for the equation of mass preservation, including a leak with mass flow rate w^{ℓ} (superscript ℓ stands for *leak*) in some undetermined point along the pipeline segment. The mass balance equation in integral form is expressed by $\frac{dm_{\text{pipe}}}{dt} = w^{\text{inflow}} - w^{\text{outflow}} - w^{\ell}$, therefore the total leaked mass in the interval $[0, t]$ is given by $m^{\ell} = \int_0^t w^{\ell}\ dt$, where w^{ℓ} is obtained from the previous equation, and ordered as follows:

$$\underbrace{w^{\ell}}_{\text{balance rate}(W_B)} = \underbrace{(w^{\text{inflow}} - w^{\text{outflow}})}_{\text{flow balance}(Q_B)} - \underbrace{dm_{\text{pipe}}/dt.}_{\text{packing rate}(P_k)}$$

The *packing rate* P_k includes transient effects due to the fluid *volumetric compressibility* and the pipe *material elasticity* and can be determined from the transient model and additional parameters.

Remark 4.1. In the case of liquids, the packing rate P_k can be determined from the model by: $P_k = \frac{dm_{\text{pipe}}}{dt} = \sum_{i=1}^{n_n-1} \nabla^i \frac{\partial \rho^i}{\partial t} + \rho^i \frac{\partial \nabla^i}{\partial t}$, where ρ denotes density, $\frac{\partial \rho^i}{\partial t}$ models the change of fluid volumetric compressibility and $\frac{\partial \nabla^i}{\partial t}$ models the change in the pipeline volume due to the bulk modulus of elasticity, see details in Larock et al. (2000); Wylie et al. (1993).

Let $\Theta \in \mathbb{R}^+$ be a *detection threshold* in a time horizon defined by $[t_0, t_1]$, $\{t_1, t_0 \in \mathbb{R}^+ | t_1 > t_0\}$. Then a leak is diagnosed if the following is satisfied $\frac{1}{\Delta t}\int_{t_0}^{t_1} W_B \, dt > \Theta$, $\Delta t \overset{\text{def}}{=} t_1 - t_0$, see details in Wylie et al. (1993), pg 278.
Since the estimation of the packing rate depends, among others, on a precise calculation of the density profile $\hat{\rho}(x,t)$ (throughout hat accents denote estimated variables) for each volume-section of the transient model, a closed-loop model may provide a better estimation of density than the original open-loop approach.
For this reason we have implemented as detection scheme a closed boundary feedback estimator, including the packing rate calculation, see Fig. 2. Unfortunately, since the stage for leak estimation produces disturbances to the balance estimation stage, in our computer implementation we execute both estimators separately.
The following section discusses the closed-loop estimation stage that provides this improved estimation, including the estimated leak.

5. THE STAGE OF CLOSED-LOOP LEAK ESTIMATION

In Part I an algorithm to solve the transient model was provided in order to obtain an open-loop estimation of the pipeline profiles of $\hat{\rho}(x,t)$, $\hat{v}(x,t)$ and $\hat{p}(x,t)$, including the situation where multiple leaking points are present in discrete locations along the pipeline. Following Hauge et al. (2007) with slight variations, such model in Eqs. (1)-(2) from Part I, can be expressed as the following PDEs:

$$\frac{\partial \hat{v}}{\partial t} + \hat{v}\frac{\partial \hat{v}}{\partial x} + \frac{1}{\hat{\rho}}\frac{\partial \hat{p}}{\partial x} + g\frac{\partial z}{\partial x} + \frac{(1+\hat{\Delta})\hat{f}}{2D}\hat{v}|\hat{v}| + \frac{f_\ell(t,x_\ell)}{\hat{\rho}A} = 0, \quad (1)$$

$$\frac{\partial \hat{\rho}}{\partial t} + \hat{v}\frac{\partial \hat{\rho}}{\partial x} + \hat{\rho}\frac{\partial \hat{v}}{\partial x} + \frac{f_\ell(t,x_\ell)}{A} = 0, \quad (2)$$

where $f_\ell(t,x)$ is the leak functional (distribution), w_ℓ is the leak flow rate magnitude, x_ℓ is the leak position, t_ℓ time of the event of leak, $\delta(x)$ *Dirac delta function*, $H(t)$ is the *Heaviside's function*, $\hat{\Delta}$ is the correction factor of the Darcy-Weisbach factor f, $\hat{P}$ estimated pressure, $\hat{v}$ estimated velocity, see further details in Hauge et al. (2007); Hauge (2007)).

5.1 A model for the tie-in tapping point

Consider the event of a leak (w_ℓ, x_ℓ) in time $t = t_\ell$. Then the leak is defined after Hauge et al. (2007); Hauge (2007), by

$$f_\ell(t,x) \overset{\text{def}}{=} w_\ell \delta(x - x_\ell) H(t - t_\ell), \quad (3)$$

$$w_\ell \overset{\text{def}}{=} C_v \sqrt{\rho(t,x_\ell)\,(p(t,x_\ell) - p_{amb})}, \quad (4)$$

where the valve coefficient is defined by $C_v \overset{\text{def}}{=} \frac{\pi}{4}\hat{D}_\ell^2 \hat{C}_d \hat{u}_s$, where $\hat{D}_\ell$ is the (assumed) diameter of the leak, $\hat{C}_d$ is the estimated *discharge coefficient* associated to the leak point, p_{amb} is the ambient pressure, and $\hat{u}_s$ is the estimated *aperture of the valve*, $0 \le \hat{u}_s \le 1$.
Furthermore, we assume that for each leaking port or j-node in the Hamiltonian characteristics grid of Part I, there is one such tapping point model, defining a unique velocity v_ℓ^j, $j = 0, \ldots, n_n - 1$, where n_n is the number of nodes.

5.2 Boundary feedback

In this section we complement the model in Eqs. (1)-(2) with the closed-loop estimation scheme from Fig. 2, where the feedback boundary injection laws by Aamo et al. (2006):

$$\hat{v}_u = v_u + a_s \frac{1-k_0}{1+k_0} \ln\left(\frac{k + P_u}{k + \hat{P}_u}\right),$$
$$\hat{P}_d = (k + P_d)\exp\left(\frac{k_L - 1}{a_s(1+k_L)}(v_d - \hat{v}_d)\right) - k,$$

include two design constants $k_0 \in \mathbb{R}$, $|k_0| \le 1$ and $k_L \in \mathbb{R}$, $|k_L| \le 1$ see the block diagram in Fig. 2 and Aamo et al. (2006) for the tuning details. As claimed by their authors in Aamo et al. (2006), these equations assist the transient model to accelerate their convergence properties, though the authors also warn that exponential convergence is not shown with this boundary feedback setting.

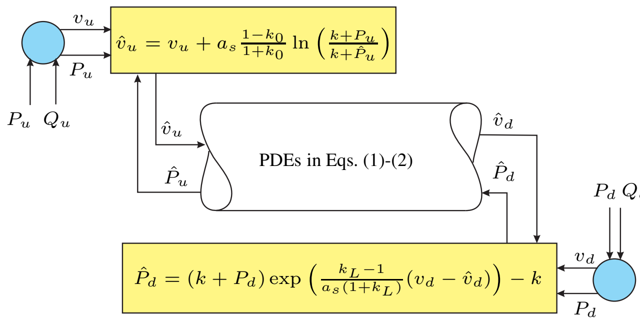

Fig. 2. The boundary feedback scheme for closed-loop estimation by Aamo et al. (2006).

5.3 The leak estimation stage

As discussed in Part I (Sec. 4), when an event of leak is present in a pipeline, there is a change in the normal behavior of the boundary variables at both extremes of the protected segment.
In the method called *Intersecting hydraulic grade-line*, such change has been used for leak localization with the implementation of two transient models, one based on *upstream boundary* data and the other with *downstream boundary* data, in such a way that the intersection of their hydraulic grade-lines (HGL), HGL $\overset{\text{def}}{=} \hat{p}(x,t)/\gamma + z(x)$, provides a sound approximation of the leak location, Al-Khomairi (1995).
In view of the previous discussion and the results from Part I, consider the following

Remark 5.1. (Localization by intersecting Hamiltonian profiles) Using the method of Hamiltonian characteristics in Part I, consider two *distributed port-Hamiltonian fluid* (DPHF) models, one based on their upstream boundary conditions (f_u^1, e_u^1) with specific Hamiltonian profile $h_{ub}(x,t) = \frac{1}{2}[v(t,x)]^2 + u(\rho(t,x)) + gz(x)$, and the other based on their downstream boundary conditions (f_d^2, e_d^2) with specific Hamiltonian profile $h_{db}(t,x) = \frac{1}{2}[v(t,x)]^2 + u(\rho(t,x)) + gz(x)$. An estimate of the leak localization $\hat{x}_\ell$ is given by the $\hat{x}_\ell \in [0, L]$ such that $h_{ub}(\hat{x}_\ell, t) = h_{db}(\hat{x}_\ell, t)$, *i.e.* the intersection of the specific Hamiltonian profiles.

Consider the following two functions defined by Aamo et al. (2006) associated to the protected segment of pipeline at the upstream boundary

$$\varphi_1 \stackrel{\text{def}}{=} v_u - \hat{v}_u + a_s \ln\left(\frac{k + P_u}{k + \hat{P}_u}\right) = v_u - \hat{v}_u + a_s \ln\left(\frac{\rho_u}{\hat{\rho}_u}\right),$$

and at the downstream boundary

$$\varphi_2 \stackrel{\text{def}}{=} v_d - \hat{v}_d + a_s \ln\left(\frac{k + P_d}{k + \hat{P}_d}\right) = v_d - \hat{v}_d + a_s \ln\left(\frac{\rho_d}{\hat{\rho}_d}\right).$$

These functions are useful for leak localization, in particular, because under a condition of perfect estimation at both boundaries $\varphi_1 = 0$ and $\varphi_2 = 0$, implying that the estimation error is zero. Otherwise in the event of a leaking port, both functions show discrepancies proportional to the estimation error.
Interestingly, the problem of leak estimation, as solved by Aamo et al. (2006), is another feedback loop consisting of a heuristic cycle of estimating (directly or indirectly) the leak flow rate $\hat{w}_\ell$ and leak position $\hat{x}_\ell$ and feeding such estimated values back to the closed-loop estimation scheme.
Although there is no proof of convergence, the leak magnitude $\hat{w}_\ell$, the leak localization $\hat{x}_\ell$, the valve constant $\hat{C}_v$, the correction factor $\hat{\Delta}$ of the Darcy-Weisbach dissipation coefficient, and even the valve aperture coefficient $\hat{u}_s$, are estimated with adaptive methods based on φ_1 and φ_2, as follows:

$$\dot{\hat{u}}_s(t) = \kappa_u(\varphi_1 - \varphi_2), \qquad 0 \le \hat{u}_s \le 1 \tag{5}$$

$$\dot{\hat{C}}_v(t) = \kappa_c(\varphi_1 - \varphi_2), \qquad \hat{C}_v > 0 \tag{6}$$

$$\dot{\hat{x}}_\ell(t) = -\kappa_x(\varphi_1 + \varphi_2)|\varphi_1 + \varphi_2|^{\frac{1}{\gamma}-1}, \qquad \hat{x}_\ell \in [0, L] \tag{7}$$

$$\dot{\hat{\Delta}}(t) = -\kappa_\Delta(\varphi_1 + \varphi_2)|\varphi_1 + \varphi_2|^{\frac{1}{\gamma}-1}, \tag{8}$$

$$\dot{\hat{w}}_\ell(t) = -\kappa_w(\varphi_1 - \varphi_2), \qquad \hat{w}_\ell \ge 0. \tag{9}$$

While $\hat{w}_\ell$ is originally proposed for direct estimation in Aamo et al. (2006), it has a rather poor performance for leak localization during time-varying conditions. With the purpose of improving the estimation of variable leaks, in Hauge et al. (2007) was proposed the use of $\hat{C}_v$. Finally in Hauge (2007) is proposed the adaptive estimation of $\hat{u}_s$.
Although we tested all of them, we certainly obtained a more robust estimation with the adaptive estimation of $\hat{u}_s$ and further processing with Eq. (4), to obtain $\hat{w}_\ell$.
In our implementation, the numerical solution of Eqs. (5)-(8) are part of a *Real-Time Integration Module* based on the Runge-Kutta method, which also serves to calculate other variables like the *total leaked mass/volume* (from the estimated leak flow-rate $\hat{w}_\ell$) and the total mass balance (from the mass balance flow-rate W_B).

5.4 Closing the loop for leak localization

In Part I, we presented a transient model with multiple *leaking ports* such that x_ℓ coincides with some j-node, in the Hamiltonian characteristics grid. Therefore, there are $n_n - 1$ different possible localizations.
Since the estimated leak position $\hat{x}_\ell$ from Eq. (7) is continuous in $[0, L]$, in order to include the estimated leak $(\hat{w}_\ell, \hat{x}_\ell)$ as a leaking port in the multi leaks transient model from Part I of this paper, it is necessary, as in the implementation by Hauge (2007), to distribute the leak over the spatial domain $[0, L]$ in two grid nodes in the Hamiltonian Characteristics method.
Consider the estimated values of aperture coefficient $\hat{u}_s$ and leak localization $\hat{x}_\ell$ resulting from the solutions of Eqs. (5) and (7). Let $\hat{x}_\ell \in [0, L]$ be such that $x_j \le \hat{x}_\ell \le x_{j+1}$ for some grid node points $x_j, x_{j+1} \in [0, L]$, and let some $0 \le \alpha \le 1$, $\alpha \in \mathbb{R}$ such that $\hat{x}_\ell = (1-\alpha)x_j + \alpha x_{j+1}$. In such conditions, let $\hat{p}_\ell$ and $\hat{\rho}_\ell$ be estimated from the grid-node approximations by $\hat{p}_\ell \stackrel{\text{def}}{=} (1-\alpha)p^j + \alpha p^{j+1}$ and $\hat{\rho}_\ell \stackrel{\text{def}}{=} (1-\alpha)\rho^j + \alpha\rho^{j+1}$ in order to estimate the mass rate $\hat{w}_\ell$ from the tie-in tapping point model (4). It can be verified that the equivalent apertures u_s^j, u_s^{j+1} such that the resulting mass rates $\hat{w}_\ell^j$ and $\hat{w}_\ell^{j+1}$ from Eq. (4) satisfy $\hat{w}_\ell = \hat{w}_\ell^j + \hat{w}_\ell^{j+1}$, are given by

$$u_s^j \stackrel{\text{def}}{=} (1-\alpha)\hat{u}_s, \tag{10}$$

$$u_s^{j+1} \stackrel{\text{def}}{=} \alpha\,\hat{u}_s. \tag{11}$$

The velocities v_j^ℓ, v_{j+1}^ℓ resulting from the mass rates $\hat{w}_\ell^j$ and $\hat{w}_\ell^{j+1}$ can be inserted in the vector of leak velocities $v^\ell = \left[v_0^\ell \; v_1^\ell \; \ldots \; v_{n_n-1}^\ell\right]^T$, used by the multiple *leaking ports* transient model of Part I, Section 4.
A similar approach about the use of α was taken when the estimation of $\hat{C}_v$ and $\hat{w}_\ell$ from the solutions of Eqs. (6) and (9) was considered.
At this point the scheme of leak estimation is complete and can be described by the block diagram of Fig. 3.

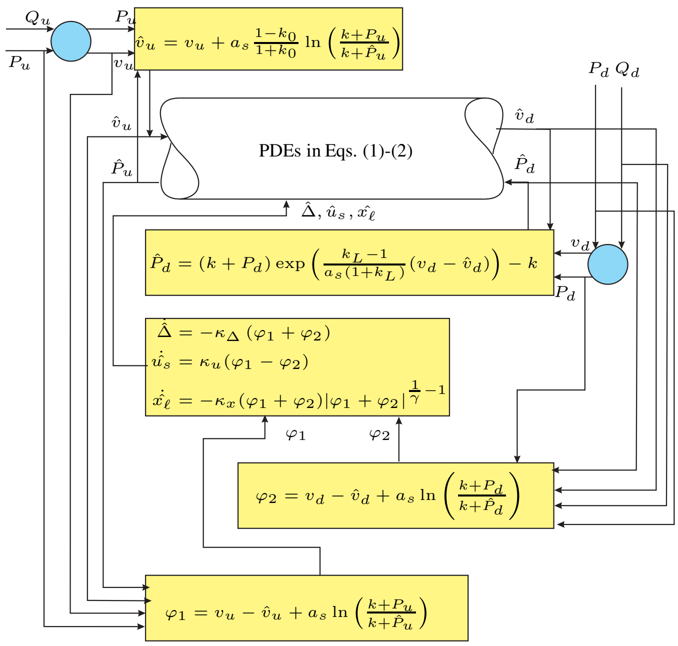

Fig. 3. A block diagram of the Aamo-Salvesen-Foss adaptive leak estimator, based on Hauge et al. (2009).

6. EXPERIMENTAL RESULTS

The leak detection, localization and quantification system described along this two-parts paper, is being home tested in our industry-oriented experimental facility.
The IMP Experimental Multi leaks Pipeline Simulation Rig (DESFM-IMP), consists of $176[m]$ of a copper pipeline with diameter $0.0508[m]$, that can be operated in different conditions of flow rate and pressure. It has 8 tapping points (leaks) remotely actuated with the DCS (an Emerson Delta-V). The

fluid transported may consist of gas, liquid or a two-phase combination of both. While the liquid (which may consist of the hydrocarbon Exxsol D80 or simple water) is propulsed by a standard pumping system, the gas (Nitrogen) is propulsed by an industrial compressor system. Both extremes of the experimental pipeline are terminated with pressure and temperature transmitters and Coriolis mass flow meters.
Additionally, with the purpose of quantifying the leaks, there are two flow meters, one for gas and one for liquid, collecting the flow from four tapping points for gas and four tapping points for liquid respectively. Each tapping point includes a pressure transmitter, see Table 1. For further characteristics and construction details, see Lopezlena et al. (2013).
Nevertheless, in this paper we restrict our results to individual leaks of liquid. In particular, in the first part of this section we test and tune the transient model without leaks. Then in the second part we test the closed-loop leak estimator with data collected from an essay of individual leaks using Exxsol D80.

Table 1. Localizations of tapping points with pressure transmitters in the DESFM-IMP

Leak flow meter FTF-G (gas tapping points)			Leak flow meter FTF-L (Liquid tapping points)		
Distance $[m]$	Elevation $[m]$	Transmit. Tag	Distance $[m]$	Elevation $[m]$	Transmit. Tag
0.0	0.4	Input	176.9	0.4	Output
19.37	4.2	PTF-7	156.6	3.95	PTF-8
44.27	4.7	PTF-5	131.7	4.45	PTF-6
56.77	5.2	PTF-3	119.0	4.95	PTF-4
81.67	5.7	PTF-1	94.1	5.45	PTF-2

6.1 Transient simulations without leaks using Exxsol D80

The pipeline transient model presented in Part I was tested with data acquired from our experimental rig where the profiles of pressure and flow-rate are presented using boundary feedback in two conditions: without any leak in Fig. 4 and in the presence of a leak in Fig. 5.
The computer system includes a user interface providing the

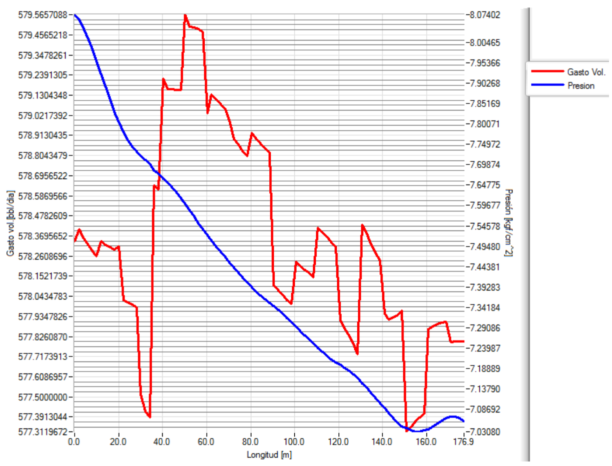

Fig. 4. Profiles of flow-rate (left in $[bpd]$) and pressure (right in $[\frac{kgf}{cm^2}]$) along the pipeline (length in $[m]$) without any leak.

estimation errors in open loop and closed-loop. Using boundary feedback (without leak estimation) the peak estimation errors of velocity v_d and pressure p_u were 1.6×10^{-7} and 6.7×10^{-2} respectively. After turning off the closed-loop (boundary feedback) the peak estimation errors of velocity v_d and pressure p_u turned to 5.7×10^{-2} and 0.36 respectively, showing the benefits of the closed loop (boundary feedback) estimation.

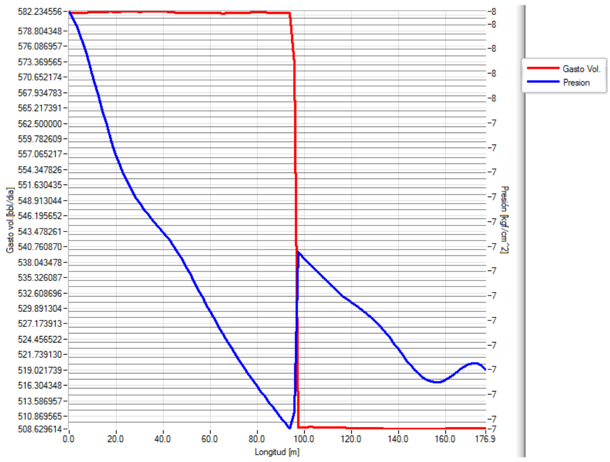

Fig. 5. Profiles of flow-rate (left, in $[bpd]$) and pressure (right, in $[\frac{kgf}{cm^2}]$) along the pipeline (length in $[m]$) with an estimated leak of 73.6 $[bpd]$ (12.6%) and location 95.4 $[m]$.

Table 2. Model and ASFE tuning parameters

n_n	δt $[s]$	Δx $[m]$	a_s $[m/s]$	k_0	k_L	κ_u	κ_x	γ
89	0.03	2.0	712.0	-0.001	-0.001	0.1	200	3.0

6.2 Essay of individual leaks using Exxsol D80:

The essay consisted in opening and closing sequentially each valve associated to one of the four localizations defined for liquid leaks in Table 1. In Table 3, we show the operating

Table 3. Essay of individual leaks using Exxsol D80 in DESFM-IMP, Nov. 27, 2012

Operating conditions		Leak localizations[1] in $[m]$				Leak condition		
Flow rate $[bpd]$	Pump Speed $[rpm]$	PTF-2 94.1	PTF-4 119.0	PTF-6 131.7	PTF-8 156.6	Time $[s]$	Flow rate [bpd]	Relative[4] %
575	500	(1)	(2)	(3)	(4)	10	68.57	12.0
1143	1000	(5)	(6)	(7)	(8)	15	51.43	4.5
1690	1500	(9)	(10)	(11)	(12)	20	34.29	2.0
2210	2000	(13)	(14)	(15)	(16)	25	17.14	0.78
575	500	(17)	(18)	(19)	(20)	25	17.14	3.0

[1] The number enclosed indicates the sequential order of execution. [4] Leak magnitude relative to the nominal flow rate.

conditions and the order of execution of individual leaks with Exxsol in the DESFM-IMP. The results obtained are shown in Figure 6, from acquired data from the DCS Delta-V. See tuning parameters for the Aamo-Salvesen-Foss Estimator in Table 2.
In Fig. 7 we show a detail of the historic trend of the estimated quantification and localization for the first four, 10 seconds, 12% leaks from Table 3. Although the closed-loop, boundary feedback estimator performs acceptably even with the disturbing influence of the inserted leaks, the precision of the estimated leak and the estimated localization do not perform very good during the simulations presented, see Fig. 7. One possible explanation is that the 10 seconds of duration of each leak may not be enough time for the estimator to arrive to its final value, implying that probably another set of data should be used, since higher values of κ_u, κ_x produce undesirable oscillations.
Nevertheless, we have observed that the estimated quantification is sensitive to the *assumed diameter of the leak*, which in real cases cannot be expected to be known with certainty. Furthermore, as already observed by Hauge (2007), the localization algorithm is sensitive to drift and/or bias by the pressure transmitters.

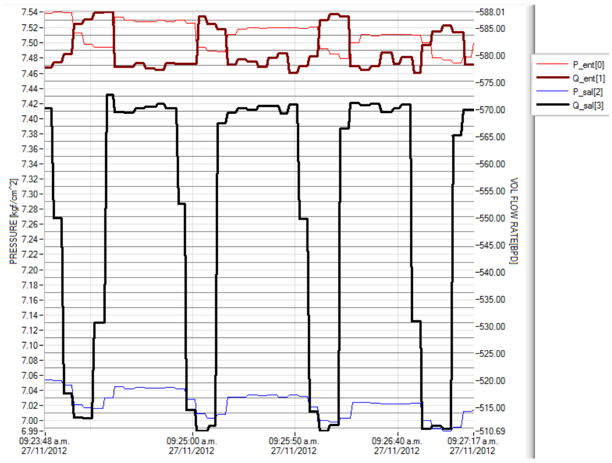

Fig. 6. Trends of input and output pressures (left, in $[\frac{kgf}{cm^2}]$) and input and output flow-rates (right, in $[bpd]$) due to the first four 12% leaks from the essay of leaks in Table 3.

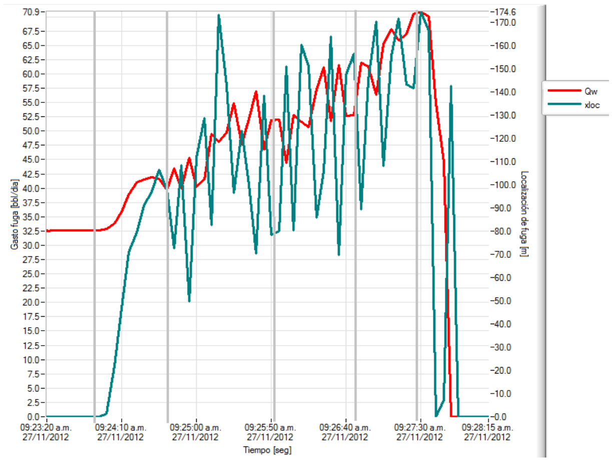

Fig. 7. Trends of leak quantification (red, left axis, flow-rates in $[bpd]$) and localization (green, right axis, length in $[m]$) versus time for the first four 12% leaks from Table 3 (gray vertical lines mark the start of each leak).

7. FINAL REMARKS

In this work divided in two parts, we presented preliminary results from our computer implementation of a boundary feedback closed-loop estimator of leaks based on the work by Hauge et al. (2009), using our own transient model. The implemented model performs quite well in real-time and its open loop estimation error can be improved greatly with the use of the closed-loop boundary feedback estimator by Aamo et al. (2006). Nevertheless, based on the data set obtained from our experimental tests rig, our preliminary results are not conclusive, since the transient behavior caused by leaks is apparently extremely fast for our implementation of the leak detection and localization scheme proposed in Hauge et al. (2009). In any case, objectives for our future research include further experimentation in our test rig and some improvements for our pipeline models to include unmodeled dynamic phenomena.
Furthermore, we intend to take advantage of the port-Hamiltonian model structure for the design of the feedback estimation loop and for the interconnection of pipelines in a network.
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REFERENCES

Aamo, O., Salvesen, J., and Foss, B.A. (2006). "Observer design using boundary injections for Pipeline Monitoring and Leak Detection". In *Int. Symp. on Adv. Control of Chemical Processes ADCHEM 2006*. Gramado, Brazil, April 2-5.
Al-Khomairi, A.M. (1995). *Improving leak detectability in long liquids pipelines*. Ph. D. Thesis, Colorado State Univ.
Bedjaoui, N., Weyer, E., and Bastin, G. (2009). "Methods for the localization of a leak in Open Water Channels". *Networks and Heterogeneous Media*, 4(2), 189–210.
Billmann, L. and Isermann, R. (1987). "Leak Detection Methods for Pipelines". *Automatica*, 23(3), 381–385.
de Halleux, J., Prieur, C., Coron, J.M., d'Andrea Novel, B., and Bastin, G. (2003). "Boundary Feedback Control in Networks of Open Channels". *Automatica*, 39, 1365–1376.
Fukushima, K., Maeshima, R., Kinoshita, A., Shiraishi, H., and Koshijima, I. (2000). "Gas pipeline leak detection system using the online simulation method". *Comp. Chem Engng.*, 24, 453–456.
Hauge, E. (2007). *Advanced leak detection in oil and gas pipelines using a nonlinear observer and OLGA models*. M.Sc. Thesis, Norwegian Univ. of Science and Tech., June.
Hauge, E., Aamo, O., and Godhavn, J.M. (2007). "Model based pipeline monitoring with leak detection". In 7^{th} *IFAC Symp. on Nonlinear Control Syst. NOLCOS'2007*. Pretoria, South Africa, August 22-24.
Hauge, E., Aamo, O., and Godhavn, J.M. (2009). "Model-based monitoring and leak detection in Oil and Gas Pipelines". *SPE Projects, Facilities & Construction, September*, 53–60. (SPE 114218).
Larock, B.E., Jeppson, R.W., and Watters, G.Z. (2000). *Hydraulics of Pipeline Systems*. CRC, USA.
Liou, J. (1991). "Leak detection and location by transient flow simulations". In *Proc. of The API Pipeline Conf.*, 268–281. Dallas, Texas USA, April 23-24.
Lopezlena, R., Mondragón, M., and Alamilla, J. (2013). "Instalación experimental para el ensayo de fugas múltiples en ductos de gas/líquido". In *Cong. Nacional de Control Automático*. Ensenada B. C., Mexico. (Oct. 16-18).
Marvasti, F. (1993). "4. Nonuniform Sampling". In R.J.M. II (ed.), *Advanced Topics in Shannon Sampling and Interpolation Theory*, (T. Elect. Eng.). Springer-Verlag. 121-156.
Nicholas, R. (1987). "Leak detection by model compensated volume balance". In *ASME Pipeline Engineering Symp.-ETCE 1987*, 13–20. Dallas, Texas USA, February 15-18.
Torres-Ortiz, F. (2011). *Modèles et observateurs pour les systèmes d'écoulement sous pression. Extension aux systèmes chaotiques*. Ph. D. Thesis, Univ. de Grenoble.
van Reet, J. and Skogman, K. (1987). "The effect of Measurement uncertainty on Real Time pipeline modeling applications". In *ASME Pipeline Engineering Symp.-ETCE 1987*, 29–33. Dallas, Texas USA, February 15-18.
Verde, C. (2001). "Multi-leak detection and isolation in fluid pipelines". *Control Engineering Practice*, 9, pp673–682.
Weyer, E. and Bastin, G. (2008). "Leak detection in open water channels". In *Proc.* 17^{th} *IFAC World Congress*, 7913–7918. Seoul, Korea. (July 6-11).
Wylie, E., Streeter, V., and Suo, L. (1993). *Fluid Transients in Systems*. Prentice Hall, Englewood Cliffs, N. J. USA.
Zhang, L., Qin, X., Wang, Z., and Liang, W. (2009). "Designing a reliable leak detection system for West Products Pipeline". *J. of Loss Prevention in the Process Industries*, 22, 981–989.