Fault Detection Using High Gain Observer: Application in Pipeline System

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Abstract: This paper proposes an high-gain observer design technique for fault detection in a hydraulic pipeline. A general nonlinear model of a pipeline is first derived based on general conditions. Then the observer is designed based on the general nonlinear model without linearisation. Simulation results show that the proposed technique can detect leaks quickly and accurately, compared with those Kalman-filter based methods.

1. INTRODUCTION

During the last few decades, complex pipeline networks have been designed in order to transmit natural substances from operation lines to consumption sites. Due to safety reasons, the construction of pipeline systems plays an important role to protect environment and to prevent product losses. Leakage may not only become a disaster to environment and production but also affect the normal operation of pipelines. Therefore fault detection has been an essential technology to running of pipeline systems.

There are a couple of techniques used to detect faults in a pipeline system. One of the most well-known schemes is the sampling method [J.L.Sperl,1991], which is usually done by carrying a detector along the pipeline or using a sensor tube buried in parallel to the pipeline. Normally, small leak volume can be detected using this method. But the response time is usually from several hours to days, and the cost of monitoring long pipelines is very high. Others include model-based fault detection schemes, of which the basic principle is to compare the time response of the actual system with that of the anticipated system generated using mathematical models. For example, [R.J.Patton *et al.* 1989] studied the difference between actual process measurements and estimated outputs and the divergence is used as a residual vector, which is used to compare with a threshold in order to detect faults.

The main aim of this paper is to use a particular class of nonlinear observers for fault detection in pipelines. A high-gain observer-based method for supervision and fault detection is introduced, which may lead to possible development of more effective solutions for fault detection in control systems. So far a few different methods for high-gain related observer design have been proposed. A typical observer design consists of two parts, a nonlinear system which can be transformed into a linear output mapped form and a linear observable dynamics that is driven by nonlinear output injection [A.J.Krener,1983].

State observers are dynamical systems that allow the outputs of the process to be estimated. An observer-based residual is a combination of the estimation error with the outputs. Their closed-loop structure makes these residuals more robust with respect to noise than Extended Kalman Filter (EKF).The residual approach is more suitable for the combined problem of fault where influence of a fault on the system is not perfectly known.

Fig.1 illustrates the implementation of the proposed fault detection scheme. The observer is used to estimate the system with the presence of fault, in this case its output differs with model output. By simply monitoring the residuals one can say that something is going wrong.

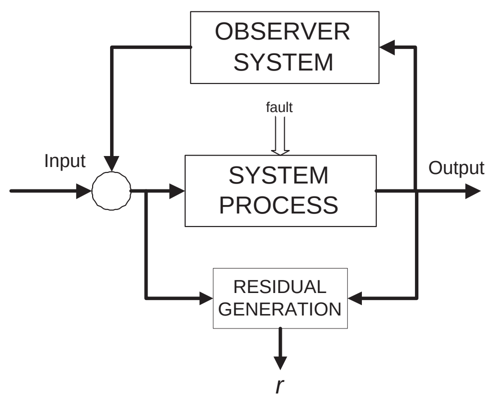

Fig. 1. Block Diagram Representation of Fault Detection Scheme via High Gain Observer Technique

The rest of this paper is organized as follows. Section 2 presents the nonlinear model of a pipeline and introduces some notations. Section 3 addresses the design of residuals using high gain observer. In Section 4, simulation results are provided to illustrate all the theory.

2. PIPELINE SYSTEM STRUCTURE

In this section, we introduce the pipeline model used for observer design. A pipeline data volume located between upstream and downstream in Fig. 2 is used for the derivation of the steady flow equation. Under the steady state condition and assuming that viscous effect and compressibility are negligible, the partial differential equation (PDE) of one-dimensional nonlinear pipeline model governing momentum and continuity is given by [Chaudry,1979], [F.M.White,1986],[C.Verde,2001]

$$\dot{Q}_i = a_1(P_i - P_{i+1}) - \mu Q_i|Q_i|, \quad i = 1, \cdots, n, \qquad (1)$$

$$\dot{P}_i = a_2(Q_{i-1} - Q_i - \lambda_{i-1}\sqrt{P_i}), \quad i = 2, \cdots, n \qquad (2)$$

where P is the pressure head (m), Q is the mass flow rate (Kg/s), t the time (s), and constant physical parameters a_1 and a_2 depending on the cell distribution w and distance $\Delta z = L/w$ of the pipeline such that

$$a_1 = \frac{gA}{\Delta m}, \qquad \text{and} \qquad a_2 = \frac{b^2}{\Delta mgA} \qquad (3)$$

where m the distance (m), A the pipeline cross-section (m^2), and $\mu = f/2DA$ with f being the Darcy-Weisbach friction coefficient and D the pipeline diameter (m), g the gravity (m/s^2). Generally, the effect of an orifice in pipeline can be expressed as the function of pressure where pressure $\Delta P_L = P_L - B_L$ at the leak with B_L representing the pipe elevation. If a leak $\lambda \geq 0$ occurs in pipeline with outflow which produces a discontinuity in system (1) and (2), then we have

$$Q_{leak} = \lambda\sqrt{(}P_L) \qquad (4)$$

which might progressively affect the system. Notice that if leak Q_{leak} developed at $x = x_k$ has no momentum in the x direction, Eq. (1) and (2) is still valid. Usually we define P_1 and P_{w+1} as the input and output of the system, respectively.

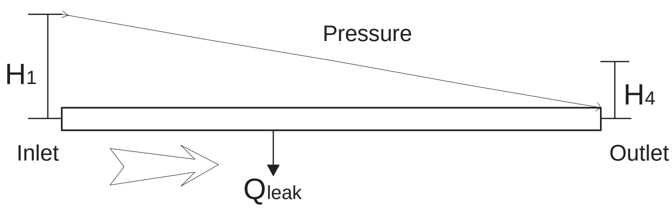

Fig. 2. Pipeline Diagram

Suitable initial and boundary conditions of this system need to be chosen in order to complete the description of the flow, which are specified below:

(1) Boundary condition

$$P(0,t) = f_P(t)$$
$$Q(L,t) = f_Q(t)$$

(2) Initial condition

$$P(x,0) = P_0(x)$$
$$Q(x,t) = Q_0(x)$$

In principle, the pipeline system consisting of (1) and (2) can be considered to be of the general nonlinear system form

$$\left.\begin{aligned} \dot{x} &= f(x,u) + g(x,u) \\ y &= h(x) \end{aligned}\right\} \qquad (5)$$

where $f(x) : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is the unknown continuous function, $g(x,u) : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is the unknown control gain, $x \in \mathbb{R}^n$ represents the state, $u \in \mathbb{R}^m$ stands for input and $y \in \mathbb{R}^p$ is the output of the dynamic system (5).

Assumption 1. Assuming that the system (5) is uniformly observable if and only if for every pair of initial state $(x_0, \bar{x}_0), x \neq 0$ and there exist transformation

$$x \rightarrow (h(x), L_f h(x), \ldots, L_f^{n-1}h(x))^{\mathrm{T}} \qquad (6)$$

is a diffeomorphism and has full rank, which transform system (5) into so-called observable canonical form [OCF] is given as

$$\left.\begin{aligned} \dot{x}_1 &= \varphi_1(x_1, x_2, u)x + u\gamma(x_1, x_2) \\ &\vdots \\ \dot{x}_{n-1} &= \varphi_{n-1}(x)x + u\gamma_{n-1}(x) \\ \dot{x}_n &= \varphi_n(x)x + u\gamma_n(x) \\ y &= h(x_1) \end{aligned}\right\} \qquad (7)$$

dh/dx nonzero means that we can replace the coordinate x_1 by $h(x_1)$.

Following the procedures in [J.P.Gauthier,1994], Eq (7) includes some unknown disturbances (4) affecting the system, assumed to be bounded. Therefore the system can be described as follows

$$\begin{aligned} x &= Ax + \Gamma(x,u) + \Phi(x,u) \\ y &= Cx \end{aligned} \qquad (8)$$

where the triangular form:

$$\Gamma(x) = \begin{bmatrix} \Gamma_1(x_1) \\ \Gamma_2(x_1, x_2) \\ \vdots \\ \Gamma_n(x_1, \ldots, x_n) \end{bmatrix} \qquad (9)$$

denotes the nonlinear terms, and the pair (A, C) is observable. $\Gamma(x, u, t)$ satisfies a uniform Lipschitz condition locally in x i.e.

$$||\Gamma(x_1, u, t) - \Gamma(x_2, u, t)|| \leq \alpha||x_1 - x_2|| \qquad (10)$$

and the function Φ can be considered as a disturbance which will be zero under disturbance-free condition.

2.1 *Observability for any input*

Observability describes the ability to infer the system states given output measurements in an interval.

The following result is proved in [J.P.Gauthier *et al.*,1992], [E.Bullinger,and F.Allgower,1997], [A.Isidori,1996]

Lemma 1. Suppose that in case of disturbance-free,

(1) the system (8) is complete for every bounded measurable input function with value in U.
(2) the nonlinearity Γ in (8) is bounded i.e. $||\Gamma(y, u, t)|| \leq \omega$ for all x, u.

Then there exists a coordinate transformation $\tilde{x} := T(x)$ that renders the system (8) into the following form:-

$$\begin{aligned} \dot{\tilde{x}} &= A\tilde{x} + \Psi(\tilde{x}) + \Gamma(\tilde{x}, u, t) \\ y &= C\tilde{x} \end{aligned} \qquad (11)$$

where

$$A = \begin{bmatrix} 0 & 1 & & 0 \\ & & \ddots & \\ & & & 1 \\ 0 & & & 0 \end{bmatrix}, \Psi(x) = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ \psi(\tilde{x}) \end{bmatrix}$$

$$\Gamma(\tilde{x}, u, t) = \begin{bmatrix} \Gamma_1(\tilde{x}_1) \\ \Gamma_2(\tilde{x}_1, \tilde{x}_2) \\ \vdots \\ \Gamma_{n-1}(\tilde{x}_1, \dots, \tilde{x}_n) \end{bmatrix}$$

where $\tilde{x} = [\tilde{x}_1, \dots, \tilde{x}_n]^T$, and $\Gamma(\tilde{x}, u, t)$ and $\Psi(\tilde{x}, u, t)$ are smooth function with locally Lipschitz with respect to $\tilde{x}$ and uniform with respect to u.

The approach presented in this paper is based on approximation of the flowrate and pressure transient theory, which has been successful in detecting leaks. It is assumed that the single pipeline has no pipe elevation $B_L = 0$ and is divided into $w = 3$ equally-spaced nodes. Then we have

$$x = [\, Q_1 \;\, P_2 \;\, Q_2 \;\, P_3 \;\, Q_3 \,]^{\mathrm{T}} \tag{12}$$

and the input vector

$$u = \begin{bmatrix} H_1 \\ H_4 \end{bmatrix} \tag{13}$$

and the output

$$y = \begin{bmatrix} Q_1 \\ Q_3 \end{bmatrix} \tag{14}$$

the matrix of the linear system part

$$A = \begin{bmatrix} 0 & -a_1 & 0 & 0 & 0 \\ a_2 & 0 & -a_1 & 0 & 0 \\ 0 & a_1 & 0 & -a_1 & 0 \\ 0 & 0 & a_2 & 0 & -a_2 \\ 0 & 0 & 0 & a_1 & 0 \end{bmatrix} \tag{15}$$

and the nonlinear term written in the following form

$$\Gamma(x, u) = \begin{pmatrix} -\mu y_1^2 + a_1 u_1 \\ 0 \\ -\mu x_3^2 \\ 0 \\ -\mu y_2^2 + a_1 u_2 \end{pmatrix} \tag{16}$$

and the output of the system $y_1 = x_1$ and $y_2 = x_5$, and the constant vector leak

$$\Phi(x, u) = \begin{pmatrix} 0 \\ a_2(\lambda\sqrt{x_2}) \\ 0 \\ a_2(\lambda\sqrt{x_4}) \\ 0 \end{pmatrix} \tag{17}$$

The presence of a leak within a section boundary imposes changes on the system response that is observed in the residual. The changes of system behaviour in the presence of leak will are discussed in next section. This paper presents an analytical solution that describes the pattern a leak induces on the resonance response for liquid flow in a frictionless pipeline system that can be used to detect, quantify and locate multiple leaks. Issues associated with the possible implementation of this technique, such as the influence of frequency-dependent friction, influence of the measurement position and the limitations of the technique, are also addressed herein.

Then, for the system (8) with disturbance-free condition, it is well-known that there exists a change of state coordinate $\tilde{x} = T(x)$ defined in a neighborhood of x_0 such that can be transformed into form:-

$$\Psi(\tilde{x}) = \begin{pmatrix} dh(\tilde{x}) \\ dL_f h(\tilde{x}) \\ dL_f^2 h(\tilde{x}) \\ dL_f^3 h(\tilde{x}) \\ dL_f^4 h(\tilde{x}) \end{pmatrix} = \begin{bmatrix} -\mu x_1^2 - a_1 x_2 \\ a_2 x_1 - a_2 x_3 \\ a_1 x_2 - \mu x_3^2 - a_1 x_4 \\ a_2 x_3 - a_2 x_5 \\ a_1 x_4 - \mu x_5^2 \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \end{bmatrix} \tag{18}$$

Applying the above coordinates transform to the system leads to

$$\begin{aligned} \tilde{x}_1 &= x_1 \\ \tilde{x}_2 &= -\mu x_1^2 - a_2 x_2 \\ \tilde{x}_3 &= -2\mu x_1 f_1 - a_2 f_2 \\ \tilde{x}_4 &= -2\mu f_1^2 + 4\mu x_1^2 f_1 - a_1 a_2 f_1 + 2\mu x_1 a_1 f_2 + a_2^2 f_3 \\ \tilde{x}_5 &= \{8\mu^2 x_1 f_1 + 8\mu x_1 f_1 - 8\mu^2 x_1^3 + 2\mu a_1 a_2 x_1\} f_1 \\ &\quad + \{4\mu a_1 f_1 - 4\mu a_1 x_1^2 + a_1^2 a_2 + a_1 a_2^2\} f_2 \\ &\quad + \{-2\mu a_1 a_2 x_1 - 2\mu a_2^2 x_3\} f_3 \\ &\quad + \{-a_1 a_2^2\} f_4 \end{aligned} \tag{19}$$

It can be seen that the condition given in Assumption (1) is satisfied and thus, the system is uniformly observable.With these properties there exists an asymptotic high-gain observer when no disturbance is taken into account. Therefore, residual generation can be performed by using either (5) or (11).

3. NONLINEAR OBSERVER DESIGN

In this section, two observer designs based on the OCF as well as the sliding mode approach will be introduced in order to have high accuracy and finite time convergence, which makes it one of key tools in robust state and fault estimation. The construction of observer will recall the approach presented in [J.P.Gauthier,1994] and [J.P.Gauthier *et al.*,1992]. The approaches mainly consider state estimation and fault detection by using residual generation.

3.1 Kalman-Like Observer

Once non-linear system (1) has been transformed into the non-linear observer canonical form (3) via local diffeomorphism $\tilde{x} = \Psi(x)$, then an observer system can be designed as

$$\dot{\hat{x}} = A\hat{x} + Bu + \Gamma(\hat{x}, u) + L(C\hat{x} - y) \tag{20}$$

which produces an error dynamic

$$\dot{e} = (A - KC)e + \Gamma(e, u) \tag{21}$$

where $e = \hat{x} - x$. Since the pair (A, C) is observable, then there exists a L such that $A - LC$ is a Hurwitz matrix, which means (20) is a state observer for (8). Note that the Lipschitz condition

$$||\Gamma(x_2, u) - \Gamma(x_1, u)|| \leq \varepsilon ||x_2 - x_1|| \tag{22}$$

with ε a constant, holds for the nonlinear function Γ.

3.2 Kalman-Like High Gain Observer

As an alternative to method in § 3.1, we introduce another approach to analyst frequency response. In this section, we will focus on high gain observer design

$$\dot{\hat{x}} = A\hat{x} + \Gamma(\hat{x}, u) + \Phi(\hat{x}, u) + K_\theta(C\hat{x} - y) \tag{23}$$

where the observer gain K_θ is chosen as

$$K_\theta = \begin{bmatrix} k_1/\theta^1 \\ k_2/\theta^2 \\ \vdots \\ k_{n-1}/\theta^{n-1} \\ k_n/\theta^n \end{bmatrix} \quad (24)$$

For any bounded $||u(t)||$ for all $t > 0$, there exist $0 < \theta < 1$, a constant to be specified later, such that the estimation error can be arbitrarily small.

Following the idea of [J.P.Gauthier,1994], let $S > 0$ a symmetric positive definite be the solution of the matrix equation

$$(A - KC)^{\mathrm{T}} S + S(A - KC) \leq -Q \quad (25)$$

One can notice that since the $\Gamma(x, u, t)$ is a locally Lipschitz, the estimation error $\hat{x} - x$ tends to zero exponentially fast when $t \rightarrow 0$. This leads to error dynamic

$$\dot{e} = (A - K_\theta C)e + \Gamma(\hat{x}, u) - \Gamma(x, u) + \Phi(\hat{x}, u) - \Phi(x, u) \quad (26)$$

The above result can be summarized in the following lemma.

Lemma 2. If the observer gain K_θ is chosen such that $(A - K_\theta C)$ is a Hurwitz matrix. Then for nonlinear terms $\Gamma(\cdot)$ and $\Phi(\cdot)$, there exist a constant $\omega > 0$ and constant K_θ such that the observer error e satisfies

$$||\hat{x} - x|| \leq \omega \quad (27)$$

By choosing an appropriate observer gain K, the dynamic error of e can be made arbitrarily small in an arbitrarily short time.

Proof of Lemma 1:

In order to prove the convergence of the observer, consider the constant vector gain K and the following Lyapunov candidate function:

$$V = e^{\mathrm{T}} P e \quad (28)$$

with P a positive definite matrix. Then,

$$\begin{aligned} \dot{V} &= \dot{e}^{\mathrm{T}} P e + e^{\mathrm{T}} P \dot{e} \\ &= e^{\mathrm{T}}[(A - \Delta^{-1} K C)^{\mathrm{T}} P + P(A - \Delta^{-1} K C)]e \\ &\quad 2(\hat{\gamma} - \gamma)^{\mathrm{T}} P e + 2(\hat{\omega} - \omega)^{\mathrm{T}} P e \end{aligned}$$

where

$$\hat{\gamma} - \gamma = \Gamma(\hat{x}, u) - \Gamma(x, u)$$
$$\hat{\omega} - \omega = \Psi(\hat{x}, u) - \Psi(x, u)$$

Provided that S satisfies Eq (25) and assuming that u is bounded together with

$$||\hat{\gamma} - \gamma|| \leq L_\gamma ||\hat{z} - z||$$
$$||\hat{\omega} - \omega|| \leq L_\omega ||\hat{z} - z||$$

where L_γ and L_ω are Lipschitz constant of the respective function, the following inequality can be obtained:

$$\dot{V} \leq (-q_m + 2p_M(L_\gamma + L_\omega U))||e||^2 \quad (29)$$

where q_m and p_M are the minimum and maximum eigenvalues of Q and S, respectively. Thus we can conclude that the origin of system (26) is exponentially stable such that $(-q_m + 2p_M(L_\gamma + L_\omega U)) < 0$ satisfied. As the estimation error $e = \hat{x} - x$ goes to zero as $t \rightarrow \infty$. Hence the convergence of the algorithm is guaranteed.

Theorem 1. [A.Uçar,1999] Given a system (8) satisfying the assumption that all states remain bounded, and the sliding condition $\dot{s}(t)s < 0$ holds, then the error dynamic (8) can be rewritten as

$$\frac{de_i}{d\tau} = \eta e_{(i+1)} - e_i \qquad \forall i = 1, \ldots, n \quad (30)$$

where $\tau = \frac{t}{\eta}$ and $\eta = \frac{1}{l_i}$.

Although e_{i+1} is nonzero, it satisfies the sliding condition. Hence, sliding motion always occurs for this system. Hence, the observation error has the structure

$$\dot{e}_i = e_{(i+1)} - l_i l_{(i-1)} e_i \quad (31)$$

The procedure of will be carried on until e_n and sliding motion occurs for all the component of the error system.

The idea is to carry the last term of Eq. (31) i.e. $e_i = e_1$ on every $\dot{e}_i$. We can use the property in Eq. (30) to simulate the first equation of the error dynamic system for example.

$$\begin{aligned} \dot{e}_1 &= 0 \\ e_2 &\rightarrow k_1 e_1 \end{aligned} \quad (32)$$

where $k_1 \rightarrow \infty$. Then, substitute Eq. (32) in the second equation of the error dynamic system and we have

$$\begin{aligned} \dot{e}_2 &= e_3 - k_2 e_2 \\ &= e_3 - k_2 k_1 e_1 \end{aligned} \quad (33)$$

Due to the special class of nonlinear systems in (8) together with sliding motion type observer gain, the observer system can be estimated and converges to zero as time goes to infinity.

4. SIMULATION RESULTS

A pipeline simulator is used to model a noise-corrupted pipe flow whose specification is give below.

- Length=100 km
- D=0.1 m
- b=1250
- λ=0.001

By using the parameters above and following the method in §3, the procedure was tested in a pipeline model divided into 3 section.

Because the leak estimate ($Q_{leak} = \lambda\sqrt{H}$) is for fluid in a steady state, we do not change the operation conditions. The data used in the measurement simulator are as follows:

$$\Delta m = 33.33km \quad (34)$$

and boundary conditions being constant

$$P(0, t) = 10bar, \qquad Q(L, t) = 0.0091kg/s \quad (35)$$

and the boundary conditions on every sections is assumed to be known exactly

$$p2 = 9.67, \qquad p3 = 9.12 \qquad p4 = 8.77$$

$$q1 = q2 = q3 = 0.0091$$

The simulations are accomplished with leaks of magnitude 0.001. The leak in the system is suddenly introduced at time $t = 2$s from the upstream end of the pipeline. A leak in a pipe causes partial reflections of wave fronts that become small pressure discontinuities in the original pressure trace and increases the damping of the overall pressure signal.

Simulation results are presented with residual signals and the outputs. For comparison we also present simulations result using Kalman filters and High-gain observer methods in Fig. 3 and Fig. 4.

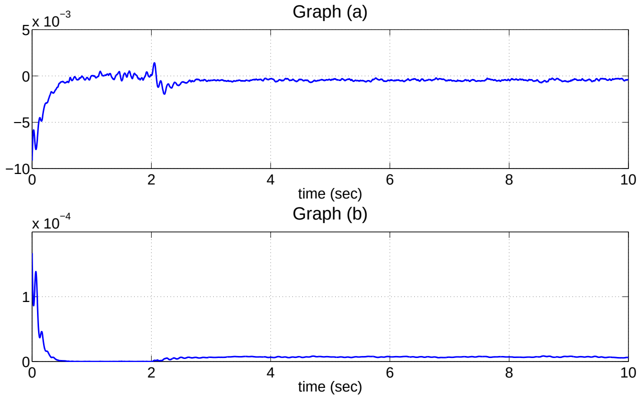

Fig. 3. Kalman-Like Result (a)residual response for leak (b) output error residual $\hat{y} - y$

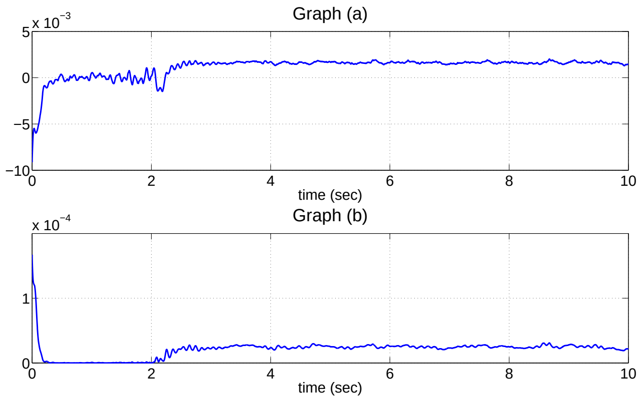

Fig. 4. High Gain Observer (a)residual response for leak (b)output error residual $\hat{y} - y$

The results shown are the comparison with EKF and high gain observer. It is obvious that the tracking of the high gain observer is much faster than that of the EKF.

This fault produces an approximated deviation of the steady flow in the system of 0.24 l/s.

In Fig. 3, we can see that when the variance of leak relatively small, Kalman-like observer cannot track the abrupt change quickly. Also, it constructs a weak response since it is close to zero. This will cause confusionfor monitoring purpose.

5. CONCLUSION

The speed and accuracy are very important performance factors of an fault detection method. For a flow in pipeline, fast leak detection can reduce the loss of leakage. This work presents an high gain observer to tackle the leak detection. Because it involves no linearization of the nonlinear pipeline model, its performance for parameter estimation is good. Furthermore, the proposed method is capable of detecting leaks quickly and accurately, even those relatively small ones.

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