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Pipeline Leak Detection and Location based on Fuzzy Controller

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Abstract— Pipeline systems have been taken as one of the most important tools for transmission around the world. It will be important for the industrial society that pipeline systems function appropriately by taking into consideration the growing requirement for effective interconnecting fluid networks. Typically, there are various kinds of control systems or algorithms for pipeline leak detection. In this paper, a pipeline leak detection and location method is proposed based on fuzzy control. It is concluded that the response of the fuzzy controller is fast and has no oscillations and this is appropriate for numerous high- precision usages like robotics as well as weapon systems. The numerical results demonstrate that the suggested technique is simple, efficient, and has a high level of localization precision.

Keywords— **pipeline systems; fuzzy controller; pipeline leak detection**

I. INTRODUCTION

Piping systems are the safest and most efficient and cost-effective way for fluid transportation around the world. Pipelines act as the most important type of transport infrastructure to keep our country moving. They have been constructed for transporting several types of fluids. For example, liquid fertilizers can be traveled significant distances through pipe systems. Pipe systems are not only safer but need less energy to function than alternative transportation options. Apart from the industrial production processes, pipelines have been further used in aircraft hydraulic and fuel systems. Pipeline systems are among the safest and biggest transportation services, but that does not indicate that they are risk-free. Environmental threats might lead to damage, leakage, or blockage in pipe systems that consequently cause significant economic losses [1-4]. Thus, effective quality assurance is necessary for pipeline companies [5]. Pipeline operators employ several techniques for pipeline safety and also to detect faults in the pipelines [6].

There exist several different techniques recently utilized for the inspection of leakage and blockage faults in pipe networks [7-10]. In [11], a real-time transient modeling method has been utilised for leakage detection and localization in the pipeline systems. In [12] an extended version of a real-time transient modeling method to estimate two leaks simultaneously in a piping system is proposed. The authors in [13] focused on leakage reconstruction in pipe systems utilising sliding mode observer. In [14] a leak inspection device consisting of an adaptive Luenberger-type observer based upon a set of two-coupled partial differential equations governing the flow dynamics is proposed. The acoustic pulse reflectometry method has been used successfully to identify damage in pipelines utilising the time domain [15]. In [16] the cepstrum analysis technique is utilised to identify leaks in pipes. In [17] a new method based on auxiliary mass spatial probing by the stationary wavelet transform is suggested to detect damage in beams. In [18] the stationary wavelet transform technique is used to identify flaws in rotating motor bearings. In [19] a combination of the stationary wavelet transform, Kurtosis, and cross-correlation algorithms is proposed to effectively improve the ultrasonic signal detection ability.

Artificial intelligence has become the most effective approach which attracts many investigators to deeply research [20-25]. It has been successfully used for leak detection. In [26] and [27] neural network technique has been utilized to detect the leak in a pipeline and has been provided promising results. In [28] artificial neural network has been utilized to detect the leak in a pipeline such that the sound noise data has been gathered through several microphones placed within a specific distance from the damaged part. The fast Fourier transform algorithm has been performed on data and supplied to a feed-forward network for making a final decision. In [29] neural network technique has been used for pattern recognition in oil pipe networks.

In this paper, a new technique based on fuzzy decision-making is suggested to detect and locate leaks in a pipe. Two sensors are placed at the beginning and end points of a pipeline. The numerical results demonstrate that the proposed technique detects and estimates leaks accurately. The remainder part of this paper is organized as follows: in the next part, the pipeline model equations are described. Then the proposed new technique is explained. Next, the simulation results are demonstrated. Finally, conclusions are given.

II. PIPELINE MODELING

Usually, compressibility effects over the length of the pipe (L) and the convective change in speed can be neglected. The liquid density (ρ), the flow rate (Φ), and pressure ($\wp$) at the beginning and end points of the pipe can be easily calculated. Also, it is assumed that the cross-sectional area ($\mathring{A}$) of the pipe is constant along the pipe.

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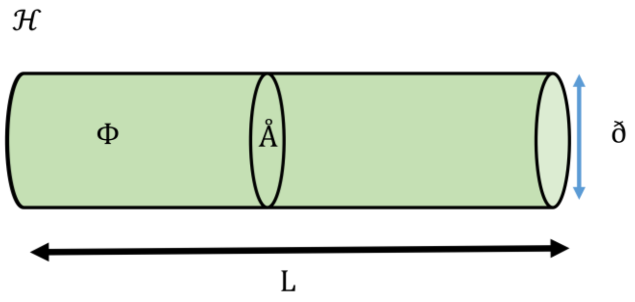

Fig. 1. The model of the suggested pipe

Consider the pipe shown in Fig. 1. The fundamental mathematical equation of fluid flow is based on the mass and momentum, and the conservation [30]. We obtain the momentum equation for the control volume using Newton's second law as follows:

$$\frac{\partial \upsilon}{\partial t}+\frac{1}{\rho}\frac{\partial \wp}{\partial x}+\frac{f}{2\eth}\upsilon^2=0 \qquad (1)$$

where $\eth$ is taken to be the diameter of the pipe, f is considered as the friction coefficient, x is taken to be the length coordinate, and t is taken to be the time coordinate. If we substitute $\upsilon=\frac{\Phi}{\mathring{A}}$ as well as $\wp=\rho g\mathcal{H}$ in equation (1) the following can be extracted:

$$\frac{\partial \Phi}{\mathring{A}\partial t}+g\frac{\partial}{\partial x}\mathcal{H}+\frac{f\Phi^2}{2\eth\mathring{A}^2}=0 \qquad (2)$$

Thus,

$$\frac{\partial \Phi}{\partial t}+\mathring{A}g\frac{\partial}{\partial x}\mathcal{H}+\frac{f\Phi^2}{2\eth\mathring{A}}=0 \qquad (3)$$

in which $\mathcal{H}$ is taken to be the pressure head, Φ is taken to be the flow rate, x is considered as the length coordinate, t is considered as the time coordinate, g is taken to be the gravity, $\mathring{A}$ is taken to be the section area, $\eth$ is considered as the diameter of the pipe, and f is taken to be the friction coefficient.

Normally, the friction coefficient depends not only on the Reynolds number (Re) but also on the roughness friction coefficient of the pipe (e) and is considered to be a constant. For a pipe that is circular in cross-section ($\mathring{A}$), the friction coefficient can be described using the Swamee-Jain equation as follows [31]:

$$\text{f}=\left(\frac{0.5}{\ln\left[0.27\left(\frac{e}{\mathring{A}}\right)+5.74\frac{1}{Re^{0.9}}\right]}\right)^2 \qquad (4)$$

in which the Reynolds number can be calculated as below,

$$Re=4\frac{\rho\Phi}{\pi\mathring{A}\mu}=\frac{\rho v\mathring{A}}{\mu} \qquad (5)$$

such that ρ is considered as the fluid density and μ is considered as the fluid viscosity. If $10^{-8}<\frac{e}{\mathring{A}}<0.01$ as well as $5000<Re<10^8$, then.

$$\frac{\partial p}{\partial t}+\rho a^2\frac{\partial v}{\partial x}=0 \qquad (6)$$

Utilizing the law of conservation of mass as well as the Reynolds transport theorem, the following continuity equation can be extracted,

$$\frac{\partial p}{\partial t}+\rho a^2\frac{\partial v}{\partial x}=0 \qquad (7)$$

If we substitute the pressure head ($\mathcal{H}$) as well as the flow rate (Φ) in (7), the following will be extracted,

$$\frac{\partial \mathcal{H}}{\partial t}+\frac{a^2}{g\mathring{A}}\frac{\partial \Phi}{\partial x}=0 \qquad (8)$$

in which a is considered as the wave speed in a fluid-filled elastic pipeline. The wave speed can be determined by the elasticity modulus of the liquid as well as the pipe.

Consider $\mathcal{H}(x,t)$ as well as $\Phi(x,t)$, where $\mathcal{H}$ denotes pressure head and Φ denotes flow rate, $x\in[0,\text{L}]$, where L is the length of the pipe. The momentum equation can be derived as follows when the flow rate has minor changes in the piping system,

$$\frac{\partial \Phi}{\partial t}+\mathring{A}g\frac{\partial}{\partial x}\mathcal{H}+\frac{f\Phi^2}{\eth\mathring{A}}=0 \qquad (9)$$

The piping system can be designed utilizing (8) and (9). As it is hard to find analytical solutions to these equations, therefore, numerical approaches can be used. Numerous approaches have been suggested to find the numerical solutions for these equations for instance characteristics as well as finite difference techniques. Here the finite difference approach is used. We have discretized equations (8) and (9) in the spatial variable in order to transform them into a system of ordinary differential equations. In order to discretize these equations, the finite difference method is utilized that divides the pipe into N parts

[32]. This technique is one of the most widely used techniques in model discretization. Due to the easy implementation and simple formulation of this technique we have used it in this paper. Here, we have defined this technique as follows:

$$\frac{\partial\Phi(s_{i-1},t)}{\partial s} \approx \frac{\Delta\Phi(s_{i-1},t)}{\Delta s} \approx \frac{\Phi_i - \Phi_{i-1}}{\Delta s} \tag{10}$$

$$\frac{\partial\mathcal{H}(s_{i-1},t)}{\partial s} \approx \frac{\Delta\mathcal{H}(s_{i-1},t)}{\Delta s} \approx \frac{\mathcal{H}_i - \mathcal{H}_{i-1}}{\Delta s} \tag{11}$$

$\forall i = 1,\cdots,n$, in which n is taken to be the number of sections also $\Delta s = s_{i+1} - s_i$ is the distance between two sequential location points. As shown in Figure 2, the continuous interval $z \in [0, \mathrm{L}]$ can be partitioned into three-point distinct sections $\{s_k\} \coloneqq \{0, s_{leak}, \mathrm{L}\}$, in which s_{leak} denotes the unknown leak location. The estimation of the leakage rate is made using $\Phi_{leak} = C_d \mathrm{A}_{leak}\sqrt{2g}\sqrt{\mathcal{H}(s_{leak},t)}$, in which C_d denotes the discharge coefficient, and A_{leak} is taken to be the cross-sectional area of the leakage. The leak rate can be calculated using $\Phi_{leak} = \Lambda\sqrt{\mathcal{H}(s_{leak},t)}$, in which $\Lambda = C_d \mathrm{A}_{leak}\sqrt{2g}$. The differential equations determining the structural dynamics of the piping system can be defined as follows:

$$\begin{aligned} \dot{\Phi}_1 &= \frac{g\mathrm{A}}{s}(\mathcal{H}_1 - \mathcal{H}_2) - \frac{f}{2\mathrm{A}\eth}\Phi^2{}_1 \\ \dot{\mathcal{H}}_{leak} &= \frac{c^2}{g\mathrm{A}s}\left(\Phi_1 - \Phi_2 - \Lambda\sqrt{\mathcal{H}_{leak}}\right) \\ \dot{\Phi}_2 &= \frac{g\mathrm{A}}{\mathrm{L} - s}(\mathcal{H}_2 - \mathcal{H}_3) - \frac{f}{2\mathrm{A}\eth}\Phi^2{}_2 \end{aligned} \tag{12}$$

We also suppose that the entering pressure $\mathcal{H}_1$ as well as the exit pressure $\mathcal{H}_3$ are known and have been determined using the pump power. Furthermore, pressure $\mathcal{H}_2$ near the leaking point and also the entering and exit flow rates (Φ_1 and Φ_2) are assumed to be unknown dynamic variables. Using the continuity equation, the following can be extracted,

$$\Phi_1 = \Phi_{leak} + \Phi_2 \tag{13}$$

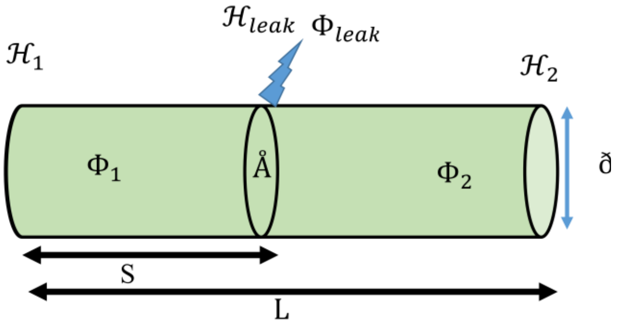

Fig. 2. The model of a leaking pipe

The inlet and outlet pressures $(\mathcal{H}_1, \mathcal{H}_2)$ as well as the inlet and outlet flow rates (Φ_1, Φ_2) at both the import and export terminals in the piping system are unvaried if there is no fault in the pipeline. As shown in Fig. 3, the pressure gradient alters after a leak is introduced to the pipeline.

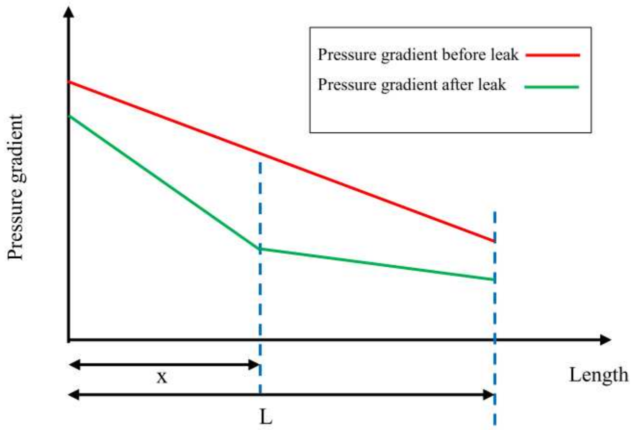

Fig. 3. changes of pressure gradient in the pipeline

III. FUZZY DECISION LOCALIZATION

The suggested fuzzy decision-making technique for detecting leaks is illustrated in Fig. 4.

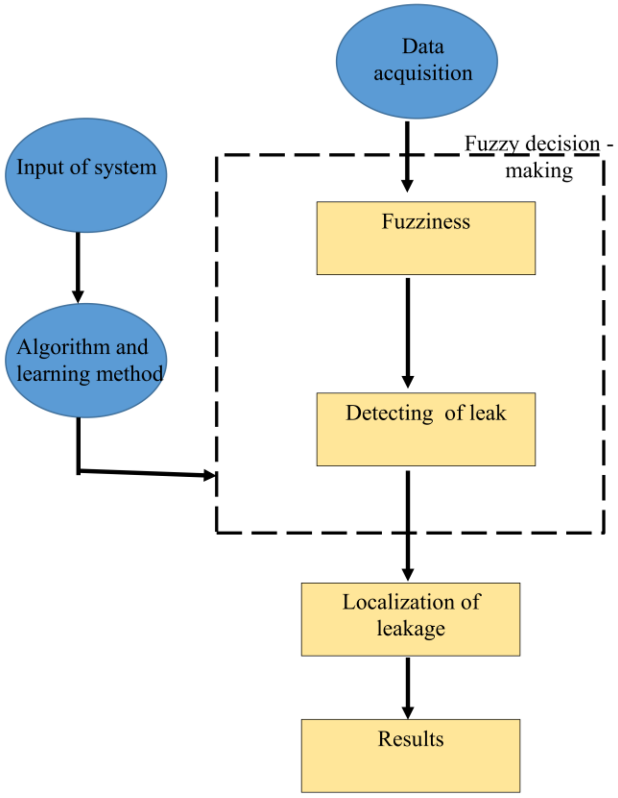

Fig. 4. Fuzzy decision-making framework for detecting leaks

In order to detect leaks in a pipeline, input data are fuzzified and their membership values are obtained. Generally, there are three common shapes of membership function: triangle membership function, Gaussian membership function, and exponential membership function. We can drive the rule base including all fuzzy rules for decision-making from a knowledge base that may be generated using learning algorithms. The rules are obtained from the rule base which is a specific type of knowledge base. Typically, a fuzzy diagnostic rule R_i can be defined as follows:

R_i: IF Operational condition of the shipping piping system,

THEN Reasoning outcome of the operation condition.

All of the work conditions in the assumption section establish decision status space $C = [c_1, c_1, \ldots, c_i, \ldots, c_m]$, in which c_i, is the $j-th$ type of work condition. All candidate reasoning causes the conclusion section to establish decision outcome space $D = [d_1, d_1, \ldots, d_i, \ldots, d_m]$, in which d_i is the $i-th$ candidate reasoning outcome. Each type of functioning condition is categorized into v degree fuzzy subset and the membership of the recent functioning condition that belongs to every subset is $E = [e_1, e_1, \ldots, e_k, \ldots, e_{v-1}]$ such that e_k denotes the $k-th$ degree of functioning condition deviation from the normal condition. Every type of candidate reasoning outcome is categorized into $\boldsymbol{U}$ degree fuzzy subset. The membership function associate with recent reasoning outcome which belongs to each subset can be defined as $F = [f_0, f_1, \ldots, f_k, \ldots, f_{u-1}]$, where f_k is the degree, wherein reasoning outcome of the recent functioning condition belongs to the $k-ih$ degree fuzzy subset.

It can be seen that uncertainty raises difficulties in modeling using deterministic techniques. Uncertainty often includes measurement uncertainty and uncertainty due to the stability/performance of the control system and data acquisition methodology. However, calculating measurement uncertainty is not easy. In this paper, the fuzzy logic decision-maker technique is utilized to detect leaks in a piping system. Various factors impact the pipeline network. The condition of the pipeline network is influenced by pipe type, pipe age, pumping system, pipe diameter, and fluid demand, see Fig. 5.

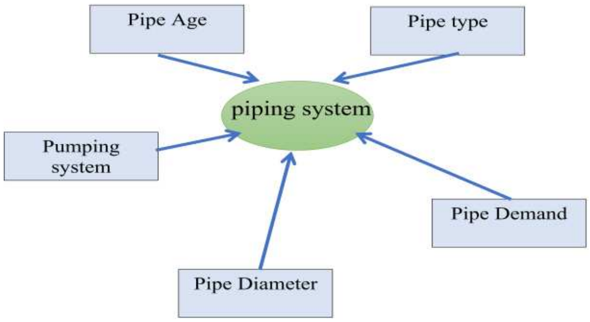

Fig. 5. A number of factors to affect the piping system

Leak localization can be defined using a membership value for the leak position in each of the evaluation categories, D_i that signifies a degree of fuzzy membership

– Leak (D_1)
– No leak (D_2)
– Potential leak (D_3)

Relation I. The deviations associated with the functioning condition c_j from regular conditions take on the deviation associated with all the candidate reasoning outcomes. The influence impact over the $i-th$ candidate reasoning outcome is defined by the measured matrix as below:

$$\vartheta_i = \begin{bmatrix} \vartheta_{i10} & \cdots & \vartheta_{i1(u-1)} \\ \vdots & \ddots & \vdots \\ \vartheta_{im0} & \cdots & \vartheta_{im(u-1)} \end{bmatrix}, \qquad i = 1,2, \ldots, n,$$

in which $\sum_{k=0}^{u-1} \vartheta_{ijk} = 1$, $i = 1,2, \ldots, n, j = 1,2, \ldots, m$ as well as $\vartheta_{ijk} \leq 1$.

Relation 2. The influence impact of all functioning conditions in decision status domain C is not the same for a supplied candidate reasoning outcome and is assessed by the following weight vector:

$$\gamma = \begin{bmatrix} \gamma_{1l} & \cdots & \gamma_{1m} \\ \vdots & \ddots & \vdots \\ \gamma_{nl} & \cdots & \gamma_{nm} \end{bmatrix}$$

in which $\sum_{j=0}^{m} \gamma_{ij} = 1$, $i = 1,2, \ldots, n, j = 1,2, \ldots, m$ as well as $\gamma_{ij} \leq 1$ ..

IV. EXAMPLE AND SIMULATION

The approach model is 140 m long and with an inner diameter of 65 mm and the input pressure head of 16m. To obtain pressure and flow rate, we have installed two high precision pressure sensors and one flow sensor at input and output of pipeline. There was a leak located at 87.15 m away from the initial of the pipeline.

In the model, the decision condition space consists of four operating status, C = { $\mathcal{H}_1, \mathcal{H}_2, \Phi_1, \Phi_2, \Phi_{leak}$). They denote pressure head of the Inlet, pressure head of the outlet, flow of the inlet flow of the outlet , and leakage flow respectively. Each operating status has three degree fuzzy subset, $E = [E_1, E_2, E_3]$. The decision result space introduce as $D = \{D_1, D_2, D_3\}$, The candidate reasoning result introduce as $F = \{f_0, f_1, f_2\}$.

Fig. 6 demonstrates the membership functions associated with functioning condition, such that the quantity of the fuzzy decision-making can be obtained as $3^5 = 243$

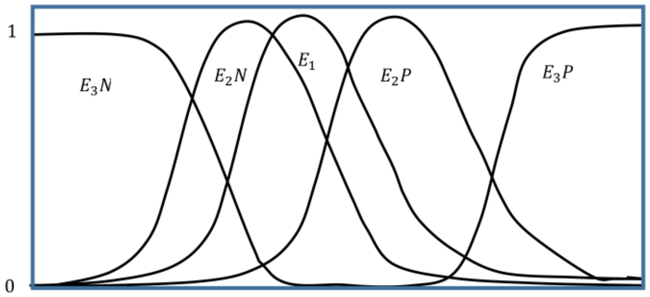

Fig.6. the membership functions associated

The fuzzy decision-making rules are demonstrated in Table 1

Table. 1. fuzzy decision-making rules

	Decision Condition					Decision results		
	$\mathcal{H}_1$	$\mathcal{H}_2$	Φ_1	Φ_2	Φ_{leak}	D_1	D_2	D_3
Rule 1	E_1	E_1	E_1	E_1	E_1	f_0	f_0	f_0
Rule 2	NE_2	NE_2	PE_2	NE_2	PE_2	f_1,f_2	f_1,f_2	f_0
Rule 3	PE_3	PE_3	PE_3	PE_3	PE_3	f_1,f_2	f_0	f_1,f_2
Rule 4	E_1	E_1	PE_2	PE_2	PE_2	f_1	f_0	f_1
Rule 5				PE_2		f_1,f_2	f_0	f_1,f_2

V. CONCLUSION

Leakage in the system of pipes that transport process fluids such as oil, industrial gas, water could result in crucial environmental, social, economic, health, and safety problems. Hence, pipe networks should be constructed with leakage inspection devices so that operators can be notified when the systems require detection. This paper proposes a new technique for pipeline leak detection and location on the basis of fuzzy logic. The proposed technique assist pipeline operators to locate the leak with good accuracy. Our results demonstrate that the fuzzy controller is simpler in design and generates positive outcomes that satisfy the performance requirements of a stable control system. The fuzzy controller generates a rapid response and has no oscillations that is highly appropriate for high-precision usages like robotics, nuclear as well as weapon systems.

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