Analysis of Different Techniques for Locating Leaks in Pipes in Water Distribution System Using WSN

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***Abstract*—The most crucial part of the earth is water. Water is very much essential for survival of life on earth whether it is plant, animal or human being. Water distribution system takes care of distribution, generation of the quantity and quality of water in different parts of earth. One of the great hindrances for the water distribution system is leakage in the water pipelines. Lots of water gets wasted due to leaks. Localization of leaks through sensors is one of major issue of concern which has attracted the attention of the researchers. This paper deals with the various techniques of leakage detection used in past and recent years, their limitations, and the task about how to overcome those limitations.**

Keywords–water distribution system; leakage; sensors; hydraulic.

I. Introduction

Leakage of water in the pipelines through different distribution networks is a very important matter all over the world, which is affecting both supplier as well as customer in terms of cost and savings. The main task of water distribution system is to provide sufficient water both in quality and quantity to all its users. A significant amount of water is lost during the transit from supplier to consumer. Mostly all the water distribution system suffers from leakage. The measure of leaked water in water distribution networks differs from countries to countries and from regions to regions. Leakage also depends upon the maintenance system of water distribution networks.

Water Leakage not only affects costs and saving, but it is also issue of great concern in terms of health and environment. Lot of energy gets wasted as water suctioned from pumping is lost due to leakage. Leakage can also affect the quality of water by contaminating it with impurities at the leakage point.

The types of pipes in a distribution network largely determine the extent of losses [1], with older metallic pipes in corrosive soils generally being more prone to leaks than newer plastic pipes. While leakage rates specific to different pipe types have not been reported, a property described as the leakage parameter has been derived in an analysis of leakage control data. Water distribution network are continuously adapting and applying new technologies for reducing wastage of water due to leakage. There are basically three methods of leakage management [2]: (1) Method of leakage assessment focusing on amount of water lost; (2) Method of leakage detection concerned with the detection of leakage area and (3) Method of leakage control which effectively controls current and future leakage levels. We are concentrating on leakage detection method in this paper.

Leakage Detection Methods

Define Methods of identifying leak sites based on acoustic principles have been practiced from the inception of pressurized water distribution networks [1], However, over the past two decades, new detection techniques have been under development based on analysis of hydraulic characteristics of water within the pipe, ranging from measurement of hydraulic characteristics in the steady state, to measurements in the transient state [3], [4]. Although considerable research has been directed towards the development of techniques based on transient flow methods, the most commonly used method in the water distribution industry continues to be acoustic leak detection.

A. Acoustic Detection Methods

Acoustic leak detection is based on monitoring the noise and vibration generated by a fluid under pressure escaping through a leak site. While wooden listening sticks were utilized for this purpose in the early to mid 1900s, with the advent of microphones and the electronic age in the 1960s the accuracy of acoustic detection was enhanced. Further improvements followed with the development of correlators in the late 1970s [5] and the methods currently used by the water industry range from the electronic version of the listening stick [6] to advanced correlators with computerized signal analysis [7].

All these techniques are labour intensive; the listening sticks are manually operated whereas correlators and loggers require sensors to be placed directly on the pipe or fittings at street level. The sensors are usually installed at fittings via simple magnetic couplings, and they require minimal maintenance as they have built-in battery power. Signals from loggers monitored through a receiver module, hand-held or mounted in a patrolling vehicle, are used to identify the location of units indicating a leak condition, and hence the approximate position of a leak. More recent techniques deploy a tethered sensor inside the pipeline using special insertion equipment and monitor signals through the tethering 'umbilical' cord and surface probes. A free floating sensor has also been developed recently [8], [9]. These in-pipe sensors are more suited for large pipes (>300mm) such as trunk mains and require specialized deployment-retrieval equipment.

The disadvantages of the basic acoustic listening techniques have been well documented [10]. Some of these disadvantages include: interference through noise signals, variations in pipe pressure conditions due to varying pipe materials, leak characteristics and presence of multiple leaks.

Typically, leaks in cast iron, ductile iron and steel pipes can be detected at a maximum distance of 250 meters with accelerometers and up to 600 meters by hydrophones. However, acoustic techniques are not equally effective with every type of pipe as they have been primarily developed for metal pipelines and difficulties have been encountered with plastic [11] and with asbestos cement pipelines [12].

B. Transient Analysis (TA) Methods

Another technique for leakage detection is transient analysis methods. Because of the difficulties and expense associated with acoustic techniques, it is worth while investigating non-acoustic techniques of leak detection in pipe systems that include methods based on [13]:

1. Insertion of tracing substances into the fluid stream;
2. Electro-magnetic examination of the pipe from the inner side;
3. Study of quasi-static signals detected by sensors built into the pipe system such as pressure sensors, flow rate sensors and temperature sensors;
4. Analysis of transient signals detected by sensors built into the pipe system and study of leak generated temperature variations using infrared thermograph by sensors located outside the pipe system; and
5. Detection of radio frequencies emitted from transmitters situated inside the pipes and permeating outside through cracks.

As most leak detection methods had their inception in the oil and gas industry, only a few of these are suitable for potable water systems. Furthermore, some techniques are expensive (i.e. 2, 5 and 6) and in addition, others are intrusive into the water stream (i.e. 1, 2 and 6) increasing the risk of contamination. Techniques 3 and 4 seek to determine the pipe system state from the measured parameters of pressure, flow rate and sometimes temperature at various points in the pipeline system and at various times. In technique 4 when a transient pulse, such as a pressure wave, is introduced in a pressurized pipe system, a hydraulic transient event propagates through the system. The presence of leaks, variations in pipe diameter, pipe material, pipe geometry, elevation or air pockets, introduces changes in the hydraulic transient event propagation. A leak creates a pressure drop; a change in pipe size or geometry creates reflections; an air bubble creates a pressure drop followed by a pressure increase. Detection of these signals allows identification and location of the source that caused the change [14]. In the case of acoustic detection methods, a range of factors influence the transient analysis techniques. These include pipe characteristics, topography and leak characteristics.

Leakage control methods are designed to handle or repair the leaks only when they become visible. Many acoustic devices [15] have been developed that allow us to also locate invisible leaks, but, their implementation over a wide-area water distribution network is very expensive and time-consuming. Huge money got waste and the result is also not up to the mark. One solution is to separate the network into a district metered area (DMA). Rate of pressure and water flow is measured separately in each DMA so as to attain a permanent leakage control system [16]. The main task of leak detection system in the DMA is to monitor flow of water at night, when water requirement for the customer is low and the leakage can be easily detected from it. Mostly practitioners monitor the DMA or groups of DMAs at night for detecting and locating leaks as well as apply some methods to estimate the leakage level [2]. Technique of sensor placement strategy has become an important issue of research in recent years.

Generally a group of sensor is used to handle fault detection and leak localization. But we should not forget that it is obvious that only few sensors can be configured inside a DMA, considering the economic issue. The basic motto of sensor placement strategy are leak detection, leak isolation and leak localization. Few works have been done in sensor placement for fault detection and isolation.

II. LITERATURE SURVEY

During the last ten years the technique used for leak detection was based on detecting the edges of the pipe containing leaks depending on the different transient techniques. In recent research practitioners are focusing on genetic algorithm for leak detection. The techniques used past ten years as well as latest techniques have been discussed in this paper.

Leak Edge Detection Method

In 2001, leak detection in pipeline systems is performed using steady state pressure measurement in conjunction with acoustic methods [17]. These methods are generally expensive and time-consuming. Recently with the advent of high-speed computers, the focus of research has changed from steady state analysis to transient analysis. Leaks in pipelines affect the propagation of these transient waves; thus analysis of the behavior of this interaction can be used to form leak detection techniques. Three leading-edge leak detection algorithms [16] being developed at the University of Adelaide is presented in this paper includes: inverse transient method, transient damping approach and the inverse resonance method.

A. Inverse Transient Method

In the inverse transient method the pressure head is measured at a number of locations in a pipe network that is experiencing a transient event. Then, using a transient model that incorporates leakage, a number of leak candidates are checked at various locations in the network. A least-squares minimization is performed to fit the numerically modeled pressure heads to the measured pressure heads and determine if a suspected leak is a true leak. The least-squares minimization criterion (E) as shown in [16] is given by

$$\boldsymbol{E = \sum_{i=1}^{M} (Hi^{m} - Hi)^2} \tag{1}$$

where H_i^m = measured head, Hi = modeled head and M = total number of measurement data points. Inverse transient analysis requires the use of a transient model. For water transients, a transient simulation model based on the method of characteristics is used. The model includes unsteady frictional effects. The inverse transient method uses a transient model in which the leaks are fitted to the measured data using the shuffled complex evolution (SCE) algorithm [18].

B. Transient Damping Method

The inverse transient method requires accurate information about the boundary conditions and transient generation details for use in transient modeling. This can potentially complicate the implementation of the inverse transient method. An alternative idea is to use information from more easily measurable properties of transients for leak detection. One such property is the damping behavior of transients when leaks are present.

$$\boldsymbol{R_{nL} = \frac{C_d A_L}{A} \frac{a}{\sqrt{2gH_{L0}}} sin^2(n\pi X_L *)} \tag{2}$$

Where A = pipe diameter, a= wave speed, g= gravitational acceleration, H_{L0}= steady state head at leak and X_L* = dimensionless leak position. The ratio of any two damping rates gives an expression for the leak location that is independent of the leak size.

$$\frac{R_{n_2 L}}{R_{n_1 L}} = \frac{sin^2(n_2 \pi X_L *)}{sin^2(n_1 \pi X_L *)} \tag{3}$$

Therefore leaks may be detected and located using such ratios.

C. Inverse Resonance Method

The existence of a leak in a pipeline causes frequency-dependent behavior in the flow sand pressures during a transient event. For this type of behavior it is better to analyze in the *frequency-domain*. Therefore, an idea for a leak detection method may be based on how the pressure in a leaking pipeline responds to different frequency disturbances when a leak is present.

Leak Detection using Genetic algorithm

In recent years, the methodology used for detecting and localizing leak is based on measuring and calculating pressure using hydraulic network model [19] for a district metered area(DMA). A DMA consist of d demand nodes and e pressure sensors. The methodology used for leak detection was based on the computing the residual vector r = $[r_1 \ldots r_e]^T$, where the residual, $r_i \in$ r, is the difference between the pressure measurements p_i, and its corresponding estimation, $\widehat{pi}$, obtained from the simulation of the hydraulic model with no leak, i.e. ,

$$\boldsymbol{r_i = p_i - \widehat{p_i}} \tag{4}$$

For i = 1…e in DMA, one residual is available for each pressure measurement. The leak isolation method is based on analysis of the residual vector obtained from equation (4) using sensitivity analysis. Sensitivity analysis is obtained by measuring different effects on every pressure by each possible leak, taking one leak at a time as given below.

$$\boldsymbol{s_j} = \begin{bmatrix} \frac{\widehat{p_1}^{f_j} - \widehat{p_1}}{f_j} \\ \cdot \\ \cdot \\ \cdot \\ \frac{\widehat{p_e}^{f_j} - \widehat{p_e}}{f_j} \end{bmatrix} \tag{5}$$

For j = 1…d, where $\widehat{p_1}^{f_j}$ and $\widehat{p_1}$are the pressure measurement obtained from the hydraulic network model considering leak f_j case and the leak-free case. Leak detection is a scenario of injection of a leak of magnitude f_j in the j^{th} DMA network node and hence computing the sensitivity vector from equation (5). Assumption is that, there are d possible leaks, one for each node. The leak isolation criteria is based on the analyzing the residual vector, along with the sensitivity vectors, to determine which node has the greatest possibility of having a leakage. Several metrics can be used for performing isolability analysis [20]. But if the methods are based on projections between residual and sensitivity vectors then the result produced is best for the task of leak location [21].

Assume that r is the residual vector obtained from equation (4) according to the installation of the pressure sensors in the network. Finding the projections of residual vector j with each sensitivity vector is given by:

$$\boldsymbol{\varphi_j} = \frac{r^T s_j}{|r||s_j|} \tag{6}$$

for j = 1…d. Then, the largest projection will determine the candidate node that presents a leak, then a leak is located in node m , if -

$$\varphi_m = \max\left(\varphi_1, \varphi_2, \ldots, \varphi_e\right).$$

The main aim of this paper is to create a technique of placing optimal number of sensors, e, in water distribution networks (WDN) for a given DMA. It is clear that Equations (4) and (5) obtains the length of the sensitivity and residual vectors determining the number of sensors, e, installed in the network. A sensor configuration representing maximum isolability performance for all possible leak scenarios, the residual vectors can be calculated as

$$\boldsymbol{r_k} = \begin{bmatrix} \widehat{\boldsymbol{p_1}}^{f_k} - \widehat{\boldsymbol{p_1}} \\ . \\ . \\ . \\ \widehat{\boldsymbol{p_n}}^{f_k} - \widehat{\boldsymbol{p_n}} \end{bmatrix} \quad (7)$$

For k = 1…e , where $\widehat{p_1}^{f_k}$ and $\widehat{p_1}$ are the pressure estimation of leak scenario f_k and leak free scenario.

$\mathbf{F_j}$ used in Equation (5) is different from f_k in (7). The sensitivity matrix ***S***and residual matrix ***R***is obtained by concatenating all sensitivity and residual vectors.

$$\boldsymbol{S} = [\boldsymbol{S_1} \ldots \boldsymbol{S_d}] \quad (8)$$

$$\boldsymbol{R} = [\boldsymbol{r_1} \ldots \boldsymbol{r_d}] \quad (9)$$

The matrices S and R are calculated taking the assumption that all the nodes are used. In order to select a configuration with e sensors, the binary vector is defined as:

$$\boldsymbol{q} = [\boldsymbol{q_{1\ldots}} \boldsymbol{q_d}] \quad (10)$$

Where q_i = 1, if in the node i pressure is measured, otherwise q_i = 0. The diagonal matrix Q(q) can be obtained from vector q as:

$$\boldsymbol{Q(q)} = \boldsymbol{diag(q_{1\ldots} q_d)} \quad (11)$$

The sensitivity and residual vectors can be calculated as:

$$\boldsymbol{S_j(q)} = \boldsymbol{Q(q)S_j} \ , \ \boldsymbol{r_k(q)} = \boldsymbol{Q(q)r_k} \quad (12)$$

For j=1...d, Calculating the projections as Equation (6), on the basis of new sensitivity and residual vector, we get

$$\boldsymbol{\varphi_{kj}(q)} = \frac{\boldsymbol{r_k^T Q(q) S_j}}{|\boldsymbol{Q(q) r_k}||\boldsymbol{Q(q) S_j}|} \quad (13)$$

Where S_j and r_k are computed sensitivity and residual vectors considering all the nodes. To compute the projection matrix Ψ, using the above equation we get,

$$\boldsymbol{\Psi(q)} = \begin{bmatrix} \boldsymbol{\Psi_{11}(q)} \ldots\ldots\ldots. \boldsymbol{\Psi_{1d}(q)} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \\ \boldsymbol{\Psi_{d1}(q)} \ldots\ldots\ldots.. \boldsymbol{\Psi_{dd(q)}} \end{bmatrix} \quad (14)$$

Based on the above equation error index is calculated so as to obtain that the result calculated by above matrix is how much percentage correct.

III. CONCLUSION & FUTURE WORK

Leak detection is an important issue in terms of saving energy and resources. The two techniques used for leak detection since last ten years are acoustic and transient leak detection. Out of these two techniques, acoustic detection technique detects leaks either in plastic pipes or steel pipes. No method has been developed so far that can detect leaks in plastic as well as iron or steel pipes together using acoustic method. To overcome these limitation transient leak detection methods has been developed. The three edge leak detection algorithms based on transient method has been discussed, they are inverse transient method, transient damping method and transient resonance method.

All three methods discussed in this paper used different mathematical model for localization of leaks and concentrates on a characteristic behavior of transients when a leak is present in a pipe system. Much work has been done for finding and locating leaks but these works are still not up to the mark. The leak detection method based on genetic algorithms does not provide guarantee for obtaining the optimal solution as well as uncertainty factor such as nodes on demand and model parameters. The Genetic algorithm method also very complex and is difficult to implement. Further work to be carried out to handle the uncertainty problem and provide the optimal solution as well as to minimize the complexity.

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