A New Indicator for Real-Time Leak Detection in Water Distribution Networks: Design and Simulation Validation

Y. Ishido*, S. Takahashi

*Yokohama Research Laboratory, Hitachi, Ltd., 292, Yoshida-cho, Totsuka-ku, Yokohama, 244-0817, Japan

Abstract

This paper proposes a new algorithm for real-time leak detection in a water distribution network using real-time pressure measurements only. In particular, we newly introduce a Head Loss Ratio (HLR), a ratio of two differences of pressure measurements, as an indicator for burst leaks in a water distribution network. A detection algorithm based on HLRS is then developed. A theoretical justification is provided for a limited class of water distribution networks for the proposed algorithm. Simulation results are also given to demonstrate that the proposed algorithm can be successfully applied to a wider class of water distribution networks.

© 2014 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/3.0/).

Keywords: Water loss; leakage detection; pressure measurements; data analysis

1. Introduction

Early detection of invisible leaks in a water distribution network is of great significance to most water utilities. The delay in detection and repair of a failed water main can lead to a large amount of water loss and serious damage to infrastructure near the failure. In a densely populated city such as Yokohama, Japan, the total damage cost due to a pipe burst amounts to a few million US dollars in some case [1].

A growing attention has been paid in these decades to research on leak detection in which information from Supervisory Control And Data Acquisition (SCADA) is utilized (see e.g., [2 -8] and references therein). Since many highly-populated cities in the world have already been equipped with SCADA and some pressure sensors in their...
water distribution networks, a real-time leak detection system based on SCADA, especially flow and pressure data in the distribution network, has provided many water utilities another option to manage their water loss in addition to the traditional regular acoustic survey [9], night flow analysis [10], network calibration and simulation [11], transient analysis [12], and flow statistics [13, 14].

Many of the preceding works on leak detection based on SCADA are along the line of routine behavior estimation of flow and/or pressure sensors from the past measurement data. The system suggested in [2], for example, is supposed to detect new burst leaks in a water distribution network by detecting a statistically significant difference between actual measurements and expected "normal" values for pressure measurements. Various kinds of techniques in data analysis and artificial intelligence including Artificial Neural Networks [6], Bayesian Networks [7], Support Vector Machines [8], have been applied to improve the estimation of the routine behaviors of flow and pressure measurements so far.

This paper, in contrast, focuses on pre-processing of the available data from SCADA for a possible improved accuracy in leak detection in water distribution networks. In particular, we propose Head Loss Ratios (HLRs) as new leak-detection indicators, and will develop a new detection algorithm using HLRs. An HLR, which is defined as a ratio of two differences of pressure measurements, is expected to extract the effect of local anomalies such as leaks and unusual water consumption in a water distribution networks. We show by a theoretical result that the proposed detection algorithm is expected to be efficient in a particular class of water distribution networks. We then discuss the possible extension to a wider class of water distribution networks with simulation results.

The rest of this paper is organized as follows. Section 2 provides the definition of HLRs, a new algorithm for leak detection in a water distribution network, and a theoretical justification for the proposed algorithm. Section 3 provides the simulation results. Section 4 concludes the paper.

2. HLRs and A New Detection Algorithm

In this section, we provide the definition of HLRs and the leak detection algorithm using HLRs. A theoretical justification for the proposed algorithm is also given for a limited class of water distribution networks.

2.1. Head Loss Ratios (HLRs)

**Definition 1**

For a given measurement time \( t \), HLR for a triple of different pressure measurements \( (p_i, p_j, p_k) \) is given by

\[
HLR(p_i, p_j, p_k, t) = \frac{p_j(t) - p_i(t)}{p_j(t) - p_k(t)}
\]

if \( p_j(t) - p_k(t) \neq 0 \). \( HLR(p_i, p_j, p_k, t) := \infty \) when \( p_j(t) - p_k(t) = 0 \). Also, HLR for a quadruple of different pressure measurements \( (p_i, p_j, p_k, p_l) \) at time \( t \) is given by

\[
HLR(p_i, p_j, p_k, p_l, t) = \frac{p_j(t) - p_l(t)}{p_j(t) - p_k(t)}
\]

if \( p_k(t) - p_l(t) \neq 0 \). \( HLR(p_i, p_j, p_k, p_l, t) := \infty \) when \( p_k(t) - p_l(t) = 0 \).

When the pressures \( (p_i, p_j, p_k) \) are measured at three different locations with the same elevation and these measurement locations are connected by pipes, the right-hand side of (1) (or (2)) can be seen as the ratio of head losses of two different water flow paths: a path from the node for \( p_i \) to the node for \( p_j \), and a path from the node for \( p_j \) to the node for \( p_k \) (or a path from the node for \( p_k \) to the node for \( p_l \)).
2.2. A New Leak Detection Algorithm Using HLRs

We propose the following algorithm for real-time leak detection in a given water distribution network.

**STEP 1** Start Leak Detection System, and set the time \( t = 0 \).

**STEP 2** At every measurement time \( t = T \), calculate HLRs for all possible triples or quadruples of available pressure measurements. Then, plot the value for each HLR.

**STEP 3** For any fixed triple or quadruple of sensors, examine if there is a statistically significant diverge from a constant in the time-series plot of the HLR, i.e.,

\[
\{ \text{HLR}(p_i, p_j, p_k, t) | 0 \leq t \leq T \}
\]  

**STEP 4** If no HLR has a significant diverge, proceed to **STEP 2** for the next time instant \( t = T + 1 \). If a significant diverge is detected in one or more than one HLRs, the Leak Detection System warns the network supervisor of a possible leak and proceeds **STEP 2** for the next time instant \( t = T + 1 \).

2.3. Theoretical Justification for A Limited Class of Water Distribution Networks

For the leak detection algorithm proposed in the previous subsection, this subsection provides a theoretical justification when it is applied to a limited class of water distribution networks.

**Theorem 1**

For a given water distribution network and a given time span \([t_1, t_2]\), suppose that the following conditions hold true for all \( t \in [t_1, t_2] \).

i. The water distribution network has only one water source.

ii. The water distribution network has no water leak inside.

iii. The water distribution network has no pump working inside.

iv. There exists a function \( f(t) : R \rightarrow R \) such that any water consumption \( d_i(t) \) at node \( i \) in the water distribution network satisfies

\[
d_i(t) = a_i f(t)
\]  

for some non-negative constant \( a_i \).

Then, all HLRs that are computed by 3 or 4 pressures in the given water distribution network should be constant for all \( t \in [t_1, t_2] \).

The proof is omitted due to the space limitation.

**Theorem 1** implies that, for a class of water distribution networks in which water is consumed at all users in the same way, if the only one reservoir is working and all pumps inside the network are inactive for \( t \in [t_1, t_2] \), then a diverge in an HLR from a constant indicates leaks at some nodes in the given water distribution network. This implies that the proposed algorithm in the previous subsection is expected to be efficient for a class of water distribution networks in which water is consumed in a similar way (suppose e.g., a district which consists of totally residential areas), and that has little amount of existing water leaks.

3. Simulation

This section is devoted to simulations of the proposed algorithm. We show the simulated results when the proposed algorithm is applied to a wider class of water distribution networks in which water is consumed in a similar way, while in the previous section we assume exactly the same consumption patterns in (4). The hydraulic simulations in this section are performed by means of EPANET2 [15]. We performed simulations for a network
model with the total pipe length of 63,088[m] and the total demand of 2,630 [m$^3$/day]. The network model is produced from a real water distribution network with the same size.

For this network, we simulated two cases: Leak Incident 1 and Leak Incident 2. For all these cases, hydraulic simulation is sequentially performed for the duration 5 days, say, 13th to 17th, October 2013, with the simulation time step 4 [min]. For this 5-day simulation, we assume 4 demand patterns at consumers. The four demands patterns are all produced from a series of an actual 5-day water distribution data to a real water distribution network. Unlike some other hydraulic simulations, though, we develop four different demand patterns by adding white noises proportional to the pressures, to the original data. In other words, the four demand patterns are similar, but slightly different each other in order to express e.g., the variety in personal life styles of the users.

We describe the two cases in details below.

I. Leak Incident 1: There is no leak at the beginning time of simulation, i.e., 00:00 on 13th, October 2013. A leak happens at 22:40 on 14th, October 2013. The leak is modeled by an emitter in EPANET2 with an emitter coefficient $C = 1$ [m$^{2.5}$/hour]. The simulated pressures at three nodes $p_5$, $p_2$, and $p_4$ for the 5-days simulation are shown in Figs. 1, 2 and 3, respectively. The simulated normal pressures, i.e., pressures for the case of no leak during the whole simulation period, are also drawn in these figures with broken lines, for comparison. The $HLR(p_2, p_5, p_4, t)$ is given in Fig.4. The HLR for no-leak case is also shown by a broken line.

II. Leak Incident 2: There is no leak at the beginning time of simulation, i.e., 00:00 on 13th, October 2013. A leak happens at 08:00 on 16th, October 2013. The leak is modeled by an emitter in EPANET2 with an emitter coefficient $C = 1$ [m$^{2.5}$/hour]. The simulated pressures at three nodes $p_3$, $p_1$, and $p_4$ for the 5-days simulation are shown in Figs. 5, 6 and 7, respectively. The simulated normal pressures, i.e., pressures for the case of no leak during the whole simulation period, are also drawn in these figures with broken lines, for comparison. The $HLR(p_3, p_1, p_4, t)$ is given in Fig.4. The HLR for no-leak case is also shown by a broken line.

![Fig.1 Leak Incident1: $p_5(t)$ - (a) Zoom-out view; (b) Zoom-in view.](image1)

![Fig.2 Leak Incident1: $p_2(t)$ - (a) Zoom-out view; (b) Zoom-in view.](image2)
Fig. 3 Leak Incident 1: $p_3(t)$ – (a) Zoom-out view; (b) Zoom-in view;

$$HLR(p_2, p_3, p_4, t)$$

Fig. 4 Leak Incident 1: $HLR(p_2, p_3, p_4, t)$

Fig. 5 Leak Incident 2: $p_3(t)$ – (a) Zoom-out view; (b) Zoom-in view.
In either of the cases of Leak Incidents 1 and 2, we can observe that the selected HLR shows a clear divergence from a constant at the leak incident time. The usefulness of this type of indicator is well demonstrated at the observation that pressures themselves, in contrast, have only a very tiny pressure drop among many large noises. Because we cannot expect exactly the same routine behaviors in head measurements in most of real cases, this tiny pressure drop is indeed difficult to be detected without an appropriate data processing.
While we show in this section only two selected HLRs, many HLRs have similar significant deviations in these simulations. The localization of the leak incidents from an appropriately selected set of HLRs should be one of the future tasks in this research.

4. Conclusions

In this paper, we have provided a new algorithm for real-time leak detection in a water distribution network using pressure measurements data only. In particular, we have focused on an online pre-processing of the pressure measurements and have proposed a new type of indicator for leak detection. We have introduced HLRs as new leak incidents indicators, and have developed an anomaly detection algorithm using HLRs. We have provided a theoretical justification for the proposed algorithm for a limited class of water distribution networks. Simulation results are also given to demonstrate that the proposed algorithm can be successfully applied to a wider class of water distribution networks.

Future tasks in this research include possible applications of leaning intelligence such as Artificial Neural Networks, Bayesian Networks, and Support Vector Machines after the pre-processing proposed in this paper, and the localization of the leak incidents from an appropriately selected set of HLRs.

References