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Robust leak detection and its localization using interval estimation for water distribution network

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ABSTRACT

Water distribution network in cities is complicated and damage to pipes can occur in the form of leakage causing economic losses. Early detection of abnormalities and accurate determination of damage location are required. Cumulative sum (CUSUM) test, wavelet-based method, and point localization have been used. However, low accuracy in noisy situation, loss of time information, and absence of mathematical reliability remain unsolved issues. In this paper, we propose a new robust algorithm that detects leakage in water network addressing these issues using pressure measurements. This method consists of cumulative integral of shifted pressure data, floor function with three parameters followed by curvature function, and localization based on statistical estimation. Verification was performed using two different field leakage data sets and normal data sets. The detection scheme exhibits much fewer false alarms and localization is more practical to implement in real networks than the previous methods.

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1. Introduction

Water supply networks are complex and the pipelines are constructed underground. The problems such as leakage are difficult to detect and usually solved after large losses. When the fault detection and troubleshooting are delayed, water loss and damage to surrounding facilities increase (Berardi et al., 2008). The World Bank estimates that the volume of real losses in the world is 32.7 billion m^3 and the value of real and apparent losses amounts to 14.6 billion U.S. dollars per year (Thornton et al., 2008). For these reasons, developing a proactive management system is needed to minimize economic losses (Kishawy and Gabbar, 2010).

The methods for monitoring and managing water distribution system are classified into two categories based on the approach: model-based methods (Wu et al., 2010; Perez et al., 2014; Casillas et al., 2013; Mpesha et al., 2001) and measurement-based methods (Covas and Ramos, 2010; Mulholland et al., 2014; Aksela et al., 2009; Mounce and Machell, 2006).

Jung and Lansey (2014) propose a model-based method using flow rate. Whether the burst occurs or not is determined based on the difference between the actual measurement and the flow rate estimated by the hydraulic model and Kalman filter (KF). It is found by Ragot and Maquin (2006) that a burst can be detected using the residual between the measured flow rate and the predicted one by model and fuzzy analysis.

However, the diversity and complexity of the water distribution network makes developing an accurate and robust model impossible in real cases (Mounce and Machell, 2006). Because the pipe network structure, sensor positions, flow rate, and pressure can vary in each case, building a perfect model for all cases is impossible.

To overcome this limitation, measurement-based methods have been suggested. Loureiro et al. (2015) propose an algorithm for fault detection using the measured flow rate data. However, it is costly to install and maintain the flow meters and the number of flow meters installed is much smaller than that of the pressure gauges in a complex water distribution network. Therefore, leak detection algorithms using pressure data have been suggested as an alternative (Ponce et al., 2014).

Misiunas et al. (2006) use the cumulative sum (CUSUM) to detect a burst based on the measured pressure, which can represent abrupt pressure changes as peaks. If these peaks exceed a

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Nomenclature

I	the number of estimated leakage points based on the 2-combinations of sensors
$P_{burst,e}$	actual burst pressure data filtered by Kalman filter
$P_{burst,e}(0)$	the initial value of actual burst pressure data filtered by Kalman filter
P_{CI}	cumulative integral value of filtered leakage pressure data
P_{floor}	value of floor function defined in this paper
P_m	average of pressure value for data shifting
P_{shift}	shifted leak pressure data
s_i	ith estimated leakage point based on the 2-combinations of sensors

user-defined threshold, the algorithm indicates that a burst has occurred. Srirangarajan et al. (2013) propose an algorithm using pressure measurement and multiscale wavelet analysis (MWA), where pressure measurement is decomposed into 4-level coefficients for the burst detection.

However, it is possible to detect only the burst cases where sudden and large pressure changes occur by these two representative algorithms, CUSUM and MWA. It is reported that burst flow over 20% of the average flow can be detected easily while it is difficult to detect the leakage flow, smaller than the burst flow, except in extremely rare cases where there are few disturbances such as leakage at night (Bakker et al., 2014). CUSUM test has a robustness issue owing to the ambiguity of the threshold set by the user. In case of MWA, the loss of time information in estimating the arrival time of the leak effect in each sensor may cause significant error when continuous disturbances exist. Furthermore, the localization method applied in both studies uses a point estimation, which is impractical for real applications.

In this study, we propose a new robust method to overcome these three problems in detection of small leakage: lack of robustness under the noisy conditions, low accuracy caused by loss of time information, and absence of confidence bound. Our method uses only the pressure without the flow rate. First, the measured pressure is filtered by KF and it is shifted by subtracting the pressure average followed by the cumulative integral of the shifted one. Second, the floor function with three parameters and the curvature function are applied. After the occurrence time is obtained, statistical techniques are applied to find the segment that contains the leak point with confidence bound.

The proposed algorithm is validated using the leak detection tests and false alarm tests compared with CUSUM test and MWA. An actual burst occurred in Yeongwol, South Korea and burst experiment was conducted by opening a hydrant connected to real pipeline in Yangsan, South Korea. These data were used for the leak detection tests. The false alarm tests used the normal state data in these two cities.

The result shows that the proposed algorithm has better performances than the previous methods in two aspects: low occurrence of false alarms and high accuracy in leakage position determination.

2. Proposed algorithm

2.1. Data modification

The burst flow rate that occurred in Yeongwol, South Korea was not accurately measured, because it was an actual burst in a complex water network. The burst flow rate by opening a hydrant connected to real water network in Yangsan, South Korea was 3 L/s and the maximum normal flow rate was 9.4 L/s with 32% of burst size shown in Fig. 1. On the basis of these burst data, the leakage data were generated. The shape of the burst pressure data is similar to that of the leakage pressure data, but the size of the pressure change for the leakage is smaller than that of the pressure change for the burst. In order to obtain the leakage case data, following process was suggested.

$$P_{leak} = K_{factor} \times P_{burst,e} + (1 - K_{factor}) \times P_{burst,e}(0) + noise \quad (1)$$

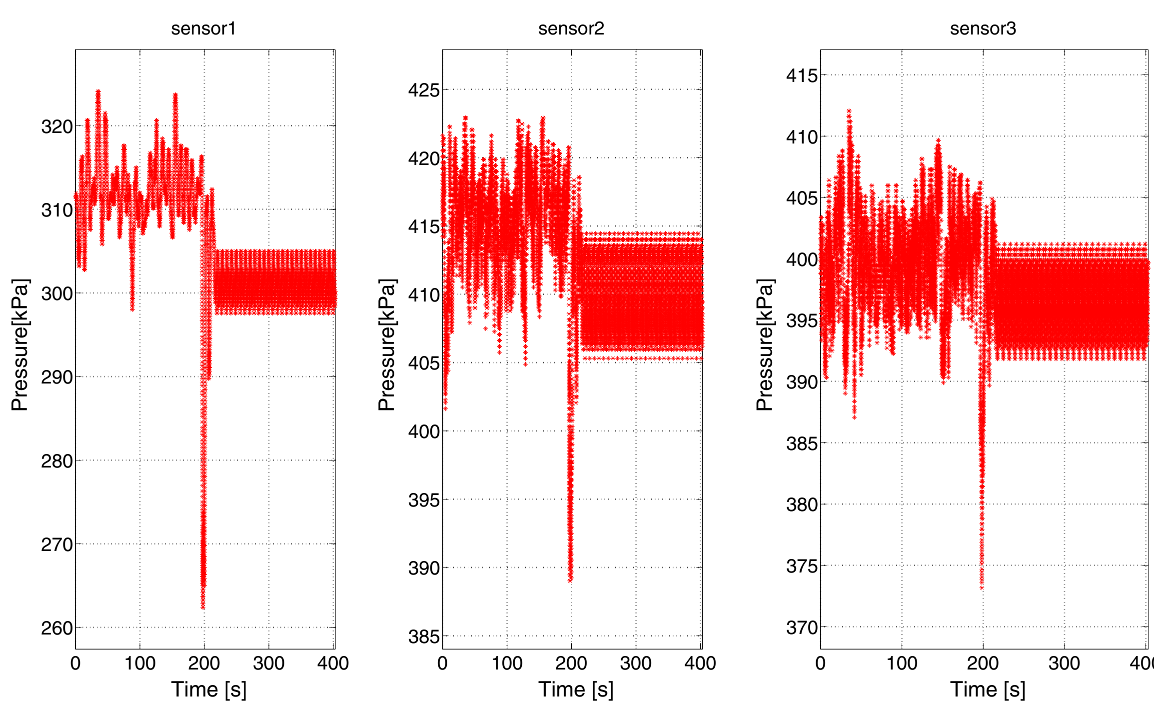

Fig. 1. The measured burst pressure data in Yangsan.

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