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Leak Localization in Water Distribution Networks using Pressure Residuals and Classifiers

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Abstract: In order to take into account the scarcity of the water resource and the increasing of the population, the management of drinking water networks has to be improved with the use of new tools and actions that allows fighting against wasting water. The monitoring of drinking water networks is based on the use of sensors to locate malfunctions (leaks, quality/contamination events, etc.). Practical implementation has to be carried out by optimizing the placement of the number of sensors and improving the detection and localization of malfunctions. Techniques for the detection and localization of leaks have been proposed in the last years based on the evaluation of residuals obtained by means of the comparison between the measurements obtained by the sensors and the values obtained by simulating the water network in a leak free scenario. In this paper, a data-driven approach based on the use of statistical classifiers working in the residual space is proposed for leak localization. The classifiers are trained using leak data scenarios in all the nodes of the network considering uncertainty in demand distribution, additive noise in sensors and leak magnitude. Finally, the proposed approach is tested using the well-known Hanoi network benchmark.

Keywords: Fault diagnosis, classifiers, water distribution networks, leak localization, pressure sensors

1. INTRODUCTION

Water leaks in water distribution networks (WDN) can cause significant economic losses in fluid transportation leading to increase reparation costs that finally generate an extra cost for the final consumer. In many WDN, losses due to leaks are estimated to account up to 30% of the total amount of extracted water. This is a very important amount in a world struggling to satisfy water demands of a growing population.

Several works have been published on leak detection and isolation (localization) methods for WDN (see e.g. Wu et al. (2011)), Puust et al. (2010) and references therein). Model based leak detection and isolation techniques have also been studied starting with the seminal paper of Pudar and Liggett (1992) which formulates the leak detection and localization problem as a least-squares estimation problem. However, the parameter estimation of water network models is not an easy task (Savic et al. (2009)). The difficulty lies in the non-linear nature of water network model and the few measurements usually available with respect to the large number of parameters to be estimated that leads to an underdetermined problem. Alternatively, in Pérez et al. (2011, 2014), a model based method that relies on pressure measurements and leak sensitivity analysis is proposed. This methodology consists in analyzing the residuals (difference between the measurements and their estimation using the hydraulic network model) on-line regarding a given threshold that takes into account the modeling uncertainty and the noise. When some of the residuals violate their threshold, the residuals are compared against the leak sensitivity matrix in order to discover which of the possible leaks is present. Although this approach has good efficiency under ideal conditions, its performance decreases due to the nodal demand uncertainty and noise in the measurements. This methodology has been improved in Casillas et al. (2012) where an analysis along a time horizon has been taken into account and a comparison of several leak isolation methods is offered. In case where the flow measurements are available, leaks could be detected more easily since it is possible to establish simple mass balance in the pipes. See for example the work of Ragot et al. (2006) where a methodology to isolate leaks is proposed using fuzzy analysis of the residuals. This method finds the residuals between the measurements with and without leaks. However, although the use of flow measurements is viable in large water transport networks, this is not the case in water distribution networks where there is a dense mesh of pipes with only flow measurements at the entrance of each District Metering Area (DMA). In this situation, water companies consider as a feasible solution the possibility to installing some pressure sensors inside the DMAs, because they are cheaper and easy to install and maintain.

In this paper, a new approach for leak localization in WDN is presented. This approach combines the use of models and classifiers. Models are used to generate residuals while

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classifiers are used for analysing the residuals taking into account the residual leak sensitivity. Finally, the proposed approach is applied to a case study based on the Hanoi water network and compared against the angle method introduced in Casillas et al. (2012).

This paper is organized as follows: Section 2 presents an overview of the proposed approach. Section 3 describes the proposed methodology. Section 4 presents the results of the application of this methodology in Hanoi case study. Finally, Section 5 draws the main conclusions.

2. OVERVIEW OF THE PROPOSED APPROACH

2.1 Overview

The aim of the proposed methodology is to localize leaks in a water distribution network using pressure measurements and their estimation using the hydraulic network model. This methodology is complementary to the analysis of DMA night consumes that is used for detecting and estimating the leakage level (Puust et al. (2010)).

Model based leak localization method is based on comparing the monitored pressure disturbances caused by leaks at certain inner nodes of the DMA network with the theoretical pressure disturbances caused by all potential leaks obtained using the DMA network mathematical model. Thereby, the residual set, $\boldsymbol{r}\in\Re^{ns}$, is determined by the difference between the measured pressure at inner nodes, $\boldsymbol{p}\in\Re^{ns}$, and the estimated pressure at these nodes obtained using the network model considering a leak-free scenario, $\hat{\boldsymbol{p}}_0 \in\Re^{ns}$

$$\boldsymbol{r}(k) = \boldsymbol{p}(k) - \hat{\boldsymbol{p}}_{\boldsymbol{0}}(k) \quad (1)$$

The size of the residual vector $\boldsymbol{r}$, ns, depends on the number of inner pressure sensors of the DMA network. In (Pérez et al. (2011)), an optimal pressure sensor placement for leak localization was presented to achieve the minimum economical costs (number of sensors) keeping a suitable performance of the leak localization method. The number of potential leaks, $\boldsymbol{f}\in\Re^{nn}$, is considered to be equal to the number of network nodes n_n, since from the modeling point of view as proposed in Pudar and Liggett (1992) and Pérez et al. (2014) leaks were assumed to be in these locations.

The fault diagnosis approach proposed in this paper is depicted in Fig. 1. It is based on using pressure residuals (1) between available pressure measurements in the network and estimations of these magnitudes provided by a hydraulic simulator (Epanet) combined with a statistical classifier. This classifier determines the most probable leak that produces the mismatches between the measurements and the estimations.

The hydraulic model simulated by Epanet considers a known structure (pipes, nodes and valves) and network parameters: pipe coefficients and estimated water demands (using historical billing records) in the nodes ($\hat{d}_1,\ldots,\hat{d}_{n_n}$) since in general in real practice nodal demands $d_1,\ldots, d_{n_n}$ are not measured (except for some particular consumers where automatic metering readers (AMR) are available). On the other hand, pressure measurements are subject to the effect of sensor noise $\boldsymbol{n}$. Finally, when a leak f_i appears in the network the leak magnitude $|f_i|$ is not completely known.

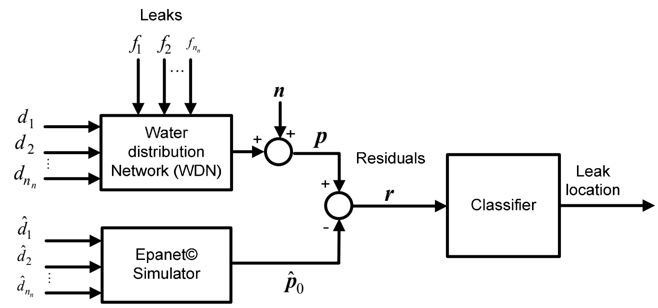

Fig. 1. Leak localization scheme

2.2 Motivation

The proposed approach summarized in Fig. 1 is an alternative to the sensitivity-to-leak analysis (Pérez et al., (2011, 2014)) where instead of using a classifier, the theoretical pressure disturbances caused by all potential leaks are stored in the sensitivity matrix $\boldsymbol{\Omega}\in\Re^{ns\times nn}$ (with as many rows as DMA inner pressure sensors, ns, and as many columns as potential leaks (DMA network nodes, n_n)) is obtained as

$$\boldsymbol{\Omega} = \begin{pmatrix} \frac{\partial p_1}{\partial f_1} & \cdots & \frac{\partial p_1}{\partial f_{n_n}} \\ \vdots & \ddots & \vdots \\ \frac{\partial p_{ns}}{\partial f_1} & \cdots & \frac{\partial p_{ns}}{\partial f_{n_n}} \end{pmatrix} \quad (2)$$

where each element s_{ij} measures the effect of the leak f_j in the pressure p_i of the node where the inner pressure sensor i is located. The leak isolation is based on matching the residual vector (1) against all the columns of the sensitivity matrix using some metrics (see Casillas et al. (2012) for details).

However, in practice, it is extremely difficult to calculate $\boldsymbol{\Omega}$ analytically in a real network because a water network is a large scale problem described by a multivariable non-linear system of equations which may also be non-explicit. Thereby, the sensitivity matrix is generated by simulation of the network model approximating the sensitivity s_{ij} by

$$s_{ij} = \frac{\hat{p}_{if_j} - \hat{p}_{i0}}{f_j} \quad (3)$$

where $\hat{p}_{if_j}$ is the predicted pressure in the node where the pressure sensor i is placed when a nominal leak f_j is forced in node j and $\hat{p}_{i0}$ is the predicted pressure associated with the sensor i under a scenario free of leaks (Pérez et al. (2011)). Then, repeating this process for all n_n potential faults the approximation of the sensitivity matrix is obtained.