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Optimal pressure sensor placement and assessment for leak location using a relaxed isolation index: Application to the Barcelona water network☆

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ABSTRACT

Water distribution networks are large complex systems affected by leaks, which often entail high costs and may severely jeopardise the overall water distribution performance. Successful leak location is paramount in order to minimize the impact of these leaks when occurring. Sensor placement is a key issue in the leak location process, since the overall performance and success of this process highly depends on the choice of the sensors gathering data from the network. Common problems when isolating leaks in large scale highly gridded real water distribution networks include leak mislabelling and the obtention of large number of possible leak locations. This is due to similarity of leak effect in the measurements, which may be caused by topological issues and led to incomplete coverage of the whole network. The sensor placement strategy may minimize these undesired effects by setting the sensor placement optimisation problem with the appropriate assumptions (e.g. geographically cluster alike leak behaviors) and by taking into account real aspects of the practical application, such as the acceptable leak location distance. In this paper, a sensor placement methodology considering these aspects and a general sensor distribution assessment method for leak diagnosis in water distribution systems is presented and exemplified with a small illustrative case study. Finally, the proposed method is applied to two real District Metered Areas (DMAs) located within the Barcelona water distribution network.

1. Introduction

An issue of great concern in water drinking networks is the existence of leaks at the distribution stage, highly related with water resource savings and management costs. The classical approach to leak control is passive, i.e. a leak is repaired when it becomes visible. Recently developed acoustic instruments also allow non-visible leak location (Khulief, Khalifa, Mansour, & Habib, 2012), but the use of such instrumentation in large-scale water networks is expensive and time-consuming. An acceptable approach is to divide the network into District Metered Areas (DMAs), where the *flow* and the *pressure* are measured (Lambert, Simpson, Vitkovsky, Wang, & Lee, 2003; Puust, Kapelan, Savic, & Koppel, 2010), and use a leak control-system on a permanent basis. Concretely, leaks affecting DMAs increase the flow and decrease the pressure magnitudes at the DMA inputs. Several empirical studies propose mathematical models to characterise the leak flow magnitude with respect to the pressure magnitude at the leak location point (Lambert, 2000, Thornton & Lambert, 2005). Best practice in the analysis of DMA flows consists in estimating the leak magnitude when the flow is minimum. This typically occurs at night time, when customers' demand is low and hence the leak magnitude over the total DMA flow is at its highest rate (Puust et al., 2010). Therefore, an accepted approach by the practitioners is to monitor the minimum DMA night flow in order to detect and repair the leaks when occurring, while also employing techniques to estimate the corresponding leak magnitude (Puust et al., 2010). However, the leak detection may not be straightforward, since different kind of phenomena e.g. unpredictable variations in the customers' demand or measurements' noise, long-term trends or seasonal effects, may occur.

Several works in the literature have addressed the leak location problem in DMAs. In Colombo, Lee, and Karney (2009), a review of transient-based leak detection methods is summarized. In the seminal work (Pudar & Liggett, 1992), a model-based leak detection and location is solved by means of a least-squares estimation problem. However, the latter problem is challenging when considering the non-linear models involved. Alternatively, a method based on pressure measurements and leak sensitivity analysis is proposed in Pérez et al. (2011), where a set of residuals—generated as the difference between

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pressure measurements provided by several sensors installed within the DMA and their estimations by the network hydraulic model—is analysed considering a certain threshold, which takes into account practical factors e.g. the model uncertainty and the measurement noise. This approach shows satisfactory results under ideal conditions, but its performance degrades when considering nodal demand uncertainty and measurement noise. This technique is improved in Casillas, Garza-Castañón, and Puig (2014), where an extended time horizon analysis is considered and a comparison of the performance using different metrics is presented.

The performance of the leak location approach is highly dependent on the sensor number and placement within the DMA. Hence, the sensor placement strategy is a key issue to consider in the overall leak location process. There is an important trade-off between the number of sensors and the subsequent cost preventing the use of a high number of sensors for leak location purposes. Consequently, this number should be optimised at the sensor placement stage, in order to produce the maximum benefit i.e. maximize the leak location performance at the minimum cost. According to these constraints, the sensors considered are pressure sensors since they are a cheaper alternative to flow meters for the company managing the network. However, the methodology presented here may also be used for alternative sensor placement setups e.g. combining pressure and flow meters as in Pérez, Cugueró, Cugueró, and Sanz (2014), or chlorine meters for water quality fault diagnosis. Hence, the methodology may be arranged with minor modifications to the placement of other type of sensors.

Regarding sensor placement for fault detection and isolation (FDI) purposes, several works concerning this subject may be found in the literature. Some approaches consider the study of structural matrices in order to locate sensors based on isolability criteria (Yassine, Ploix, & Flaus, 2008). In Rosich, Sarrate, and Nejjari (2009), an optimal set of sensors for model-based FDI is sought by means of an optimisation method based on binary linear programming. These works are embraced in the general framework of FDI of dynamic systems. However, they are not specially suited to consider the non-explicit non-linear set of equations describing a water distribution network. Alternatively, several works treated the sensor placement problem when applied to water distribution networks, most of them addressing the water contamination monitoring (e.g. Krause, Leskovec, Guestrin, Vanbriesen, & Faloutsos, 2008; Aral, Guan, & Maslia, 2010), where sensor placement is considered in a large water distribution network in order to detect malicious introduction of contaminants. Regarding leak location, less contributions addressed the problem of sensor placement. This problem is studied in Sarrate, Nejjari, and Rosich (2012), where an strategy based on the leak isolability maximization is considered to optimally place the sensors based on the water network structural model, and in Pérez et al. (2011), where an optimal sensor placement is formulated as an integer programming problem, similarly as presented here. Also, an entropy-based approach for efficient water loss incident detection is introduced in Christodoulou et al. (2013).

Furthermore, leak location in real water networks involves discrimination among a high number of possible leak locations—typically, the DMA nodes—which often leads to mislabel the actual leak location due to the limited number of sensors available. However, in practical situations there is no need to locate the leak at the exact point where is produced, since final on-the-ground leak location techniques—e.g. ground-penetrating radar, acoustic listening devices (Farley & Trow, 2003)—may precisely locate them starting from a close area where the actual leak is occurring. Hence, this calls for a methodology of sensor placement trying to cluster similar leak behaviors geographically, in order to minimize the number of installed sensors and locate the leak within a certain cluster distance precision.

Having this into account, in this paper a new approach for sensor placement focused on leak location in DMAs is proposed, based on the method introduced in Quevedo et al. (2011). Alternatively to Pérez et al. (2011), the approach presented here does not binarize the sensitivity matrix, but instead use the complete numerical information of this matrix, leading to better leak location performance as pointed out in Quevedo et al. (2011) and Casillas et al. (2014). The use of the numerical sensitivity matrix in the sensor placement problem requires the reformulation of the optimisation problem introduced in Pérez et al. (2011), since even both approaches are formulated as an integer optimization problem, isolability conditions considered in the former do not apply here. This reformulation leads to a non-linear integer optimization problem of large dimension that cannot be tackled with deterministic solvers, but with heuristic approaches. Here the use of Genetic Algorithms (GAs) is proposed, since they are a well suited approach to handle problems of this nature (Reeves, 1995, Koza, 1995). The novel aspects of the sensor placement methodology are, first, to reduce the effect of the leak mislabelling at the sensor placement stage, trying to geographically cluster nodes with similar leak signature. Hence, the sensor distribution favouring this clustering is selected, and the rest are discarded. The second novel aspect of the paper is the proposal of an assessment methodology, using new figures of merit in order to provide the goodness of a certain sensor set from the leak location point of view after the sensors are placed. The assessment indices proposed assume that the leak location algorithm will be based on the correlation between leak signatures, but are independent of the methodology used to place the sensors. Hence, the intrinsic leak mislabelling that may occur in real DMAs with a low ratio between sensors and network nodes is taken into account. To the knowledge of the authors, the use of a general assessment in terms of potential number of isolated leaks is not present in the literature. In Pérez et al. (2014), an assessment based on the isolation distance is presented in a real DMA, but this do not include the goodness of the sensor distribution regarding the number of isolable leaks for the whole network. The methodology presented is first illustrated in a small example network and then evaluated in several DMAs, located within the Barcelona water network.

The paper is organized as follows: the leak location methodology used as the basis for this work is introduced in Section 2. The sensor placement methodology is presented in Section 3, and the isolability assessment used to evaluate the goodness of the sensor set proposed is introduced in Section 4. The application case studies, based on several DMAs, and the results obtained applying the methodology proposed are shown in Section 5. Finally, in Section 6, some concluding remarks and future work are given.

2. Leak location problem

The leak location problem may be divided in two different levels: the sensor placement stage and the leak location stage, given a set of sensors. The leak location approach is summarised in this section, since it is the basis of the sensor placement algorithm formulation proposed in this work.

The leak location methodology considered here aims to locate leaks within a DMA by means of some pressure measurements gathered from the network and their estimations, obtained by a network hydraulic model. For a given DMA with N demand nodes and M pressure sensors, the leak detection methodology relies on the computation of the residuals $\mathbf{r} = [r_1 \dots r_M]^T$, where $r_i \in \mathbf{r}$ is the difference between the pressure measurement p_i and its corresponding estimation $\hat{p}_i$ obtained from a leakless simulation using the corresponding network hydraulic model as follows:

$$r_i = p_i - \hat{p}_i, \quad i = 1, \dots, M, \tag{1}$$

having one residual per each available pressure measurement within the DMA. The number and placement of the sensors is a key issue in the performance of the leak location method and is the target of this paper.

On the other hand, the leak location method relies on the study of the residual vector in (1) by means of sensitivity analysis, aiming to