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Leak identification in a water distribution network using sparse flow measurements

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ABSTRACT

A linear programming technique is proposed to balance the flows in a network, matching flow measurements where available. Where necessary, a “leak-out” flow is invoked on a pipe section in order to achieve the balance. Usually, multiple solutions are possible, and these are sounded out by progressively increasing an integrity weight for each pipe section. A feature of the method is that it overlays “snapshots” of the network at a series of points in time, in order to progressively narrow down the part of the network which can commonly account for all observations.

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1. Introduction

Some 3.5 million people in the Durban metropolitan region receive drinking water through a system of 265 reservoirs. Most water is prepared in the Durban Heights and Wiggens plants, and is delivered to the reservoirs through an interconnected trunk main system comprising Northern, Southern and Western aqueducts. Downstream of the reservoirs are yet further vast consumer distribution networks.

Water losses in the trunk main system are estimated at 4%, whilst losses in the consumer distribution networks are somewhat higher than this. One cause of the water loss is aging piping. Another is water theft through illegal connections. As far as the consumer piping is concerned, a “pressure management” policy is presently being implemented and is showing immediate benefits, e.g. 23% reduction of losses in an example presented by Scruton, Bosboom, and Fijma (2011). They remark that a reduction of pressure by 10% typically reduces water loss by 10%. An additional benefit is that lower operating pressures lengthen the life of piping, albeit with some inconvenience to consumers.

The maintenance of the distribution network would obviously be aided by more accurate pin-pointing of leak locations. Troublesome spots could then be prioritised, rather than relying on the gradual replacement or lining of aging sections. The problem is that few measurements are available, so deduction of likely locations in this complex interconnected system is difficult.

A number of workers have addressed this problem of leak identification in flow networks, within the wider framework of FDI (fault detection and isolation). On the one extreme are the transient pressure methods of Casella, Bascetta, Maffezzoni, and Bodini (2003), Misiunas, Lambert, Simpson, and Olsson (2005) and Doney (2007). On the other extreme is the TaKaDu® approach of Scolnicov and Horowitz (2010). This latter method is not model-based, but is rather based on statistical correlations between flows and pressures, and the deviations from these correlations caused by a new leak.

Statistical techniques have also been used by other workers, but they have normally used a model to generate probability distributions to ascribe deviant measurements to either hydraulic parameter variation (e.g. roughness) or leaks. Poulakis, Valougeorgis, and Papadimitriou (2003) used probability distributions of the model parameters to obtain a measure of the probability that a set of measured flows and pressures could comply with any member of a range of modelled leak scenarios. Blesa, Puig, Saludes, and Vento (2010) used a Linear Parameter Varying (LPV) approach based on an EPANET hydraulic model of the network. A linearised model at the operating point allowed for an acceptable range of agreement (“zonotope”) based on confidence in the model parameters. Falling outside of that range triggered a leak alert.

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Some methods have relied on artificial intelligence techniques to recognise patterns indicating leaks. Gertler, Romera, Puig, and Quevedo (2010) used Principal Component Analysis based on pressure and flow deviations from a model, to associate such residuals with particular leak scenarios. As a test-case, a small network model was run in SIMULINK. de Silva, Mashford, and Burn (2011) trained a Support Vector Machine (SVM), similar to an artificial neural net, to classify leak situations in a water distribution network in Melbourne. An EPANET model of the network was used to provide a large enough training set embracing the possible leak situations. Xia and Guo-jin (2010) used a clustering approach to reduce the regions of the network that needed to be considered in respect of a leak. The clustering was based on the strength of inter-point pressure correlations (from hydrodynamic modelling). A fuzzy recognition algorithm then identified which cluster is associated with a leak by matching the pressure deviation pattern.

Several workers have focused on the sensitivity of pressure and/or flow measurements to new leaks, and have used the associated relational matrix to locate possible leaks. Ragot and Maquin (2006) proposed a model-based method where the model represented the mass-balance using flows (determined from pump switching) and reservoir accumulations. The model provided measurement sensitivity to the flows, which was then represented in a binary matrix. Measurement deviations from the model were then interpreted from this matrix using fuzzy logic. In similar work, Quevedo, Cugueró, Pérez, Nejjari, Puig and Mirats (2011) analysed the behaviour of a part of the Barcelona distribution network, using only pressure measurements. Residuals were defined by deviations from predicted pressures using a detailed hydrodynamic model based on EPANET. A sensitivity analysis of the model provided a matrix relating residuals to individual pipe flows, whence leaking pipe sections could be identified.

Wu and Sage (2006), followed by Sethaputra, Limanond, Wu, Thungkanapak, and Areekul (2009), describe software that has been developed to locate leaks in a defined water distribution network. An hydraulic model is initially set up, including leaks at potential locations. A genetic algorithm then performs an "optimal" fit of the model to a set of measured pressure and flow data, by randomly selecting from a range of parameters such as pipe roughness, but also possible leak values at all of the leak locations.

The present work parallels that of Wu and Sage (2006), in that a flow model, including potential leaks, is fitted optimally to measured flow data. In addition though, it explicitly seeks supporting evidence in the time variations of the system. Moreover, as in the work of Xia and Guo-jin (2010), candidate leak positions are found as a cluster.

In the application described below, a method is developed for more typical local conditions where the measurements available have poor temporal and spatial resolution. Measurements are always available for legal final consumers, because they have to be charged. But these are monthly (or even longer) consumptions. In this context, pressure measurements which vary quite rapidly are almost useless. Moreover, there are very few continuous pressure recordings, and pressures are in any case "interfered with" by in-line pressure-reducers. So the algorithm will be based entirely on the mass-balance. To allow for application of the same algorithm on the trunk-main system over shorter periods, the method will also provide for accumulations at nodes in the network (i.e. in reservoirs).

2. Theory

Consider the simple distribution system in Fig. 1. Of nodes V_1, V_2, V_3, V_4, V_5 and V_6, only V_1, V_4 and V_5 are cumulative (reservoirs). The rest are merely pipe junctions or delimiters of pipe sections. In this system, only three flow (or consumption) measurements (marked

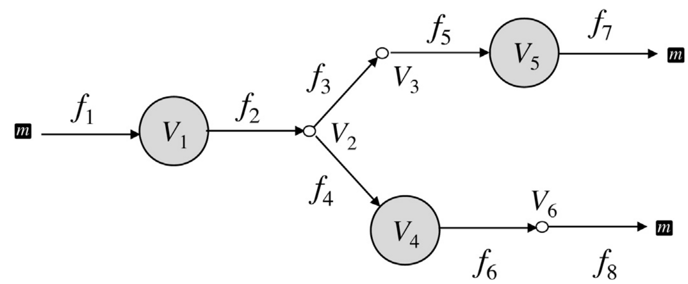

Fig. 1. Distribution system with N = 6 nodes and M = 8 pipes.

$\boldsymbol{m}$) are available: f_1, f_7 and f_8. Given that the accumulation rates dV_1/dt, dV_4/dt and dV_5/dt are also measureable, the basic problem is to ascribe water loss to the most likely of pipes j = 2, 3, 4, 5 or 6. There is obviously not enough information to do this, so, as shall be seen, the method attempts to enlist the help of time-variations in the system too (e.g. month-to-month consumptions).

Define a concept of pipe "leak-out" errors b_j and "leak-in" errors a_j, j = 1,. . .,M, as in Fig. 2.

So the node mass-balances are

$$\boldsymbol{A}[\boldsymbol{f}+\boldsymbol{a}]-\boldsymbol{B}[\boldsymbol{f}+\boldsymbol{b}] = \frac{d\boldsymbol{V}}{dt} \tag{1}$$

where

$$\boldsymbol{A}=\begin{bmatrix}1&0&0&0&0&0&0&0\\0&1&0&0&0&0&0&0\\0&0&1&0&0&0&0&0\\0&0&0&1&0&0&0&0\\0&0&0&0&1&0&0&0\\0&0&0&0&0&1&0&0\end{bmatrix}\quad \boldsymbol{B}=\begin{bmatrix}0&1&0&0&0&0&0&0\\0&0&1&1&0&0&0&0\\0&0&0&0&1&0&0&0\\0&0&0&0&0&1&0&0\\0&0&0&0&0&0&1&0\\0&0&0&0&0&0&0&1\end{bmatrix}$$

$$\boldsymbol{f}=\begin{pmatrix}f_1\\f_2\\f_3\\f_4\\f_5\\f_6\\f_7\\f_8\end{pmatrix}\quad \boldsymbol{a}=\begin{pmatrix}a_1\\a_2\\a_3\\a_4\\a_5\\a_6\\a_7\\a_8\end{pmatrix}\quad \boldsymbol{b}=\begin{pmatrix}b_1\\b_2\\b_3\\b_4\\b_5\\b_6\\b_7\\b_8\end{pmatrix}\quad \boldsymbol{V}=\begin{pmatrix}V_1\\V_2\\V_3\\V_4\\V_5\\V_6\end{pmatrix}$$

and measured values are inserted in Eq. (1) for dV_i/dt, i = 1,. . .,N (0 for non-accumulative nodes). Obviously one expects a_j = 0, but these terms are retained for an important balancing role which they

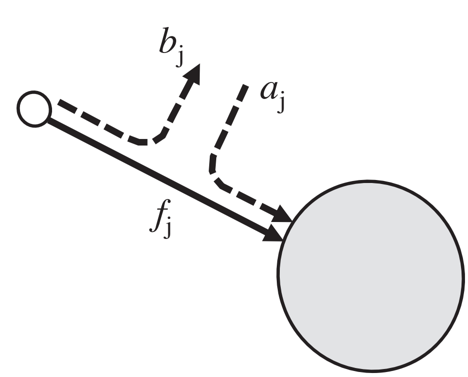

Fig. 2. Concept of "leak-out" and "leak-in" stream errors.

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