BURST DETECTION IN WATER DISTRIBUTION SYSTEMS VIA ACTIVE IDENTIFICATION PROCEDURE

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Abstract

This paper considers an approach to detect unreported pipe bursts in water distribution systems via active identification procedure. The approach involves carrying out an e-FAVOR test; results of the test are used together with a hydraulic model of the network as the inputs to a software tool, which is under development. New bursts indicators are proposed, which are considered to be more resilient to modelling errors and to inaccurate reading of the pressure logger elevation. The methodology was tested in practice in a manual manner and proved to be effective, but time consuming. In this paper some automatic analysis algorithms, developed to speed up the burst detection process, are described and tested via simulations. Results to date indicate suitability of the proposed burst indicators and the developed algorithms.

Keywords
Leakage control, burst detection, e-FAVOR test, EPAnet

1. INTRODUCTION

Water distribution systems are complicated entities with thousands of interconnected pipes and other components. As a result, the leakage reduction problem is complex and requires co-ordinated actions in different areas of water network management, including direct detection and repair of existing bursts. Benefits of quick burst detection and repair include reduced water losses, reduced disruption to traffic, reduced consequent losses (e.g. from flooding), and also reduced disruption to customers' supplies. In particular, unreported bursts are cause for concern, since they lead to significant water losses and potential damage to urban infrastructure.

Recently the UK water companies have invested into restructuring water networks into smaller sub-networks known as District Metering Areas (DMAs). A DMA is a sub-network where each boundary flow is monitored; this facilitates leakage management in terms of pressure control and bursts detection. In particular, when a new burst occurs it causes a noticeable increase in the minimum night flow (MNF). Several methods for on-line detection of new bursts have been proposed. These methods are based on a near real-time monitoring and automatic analysis of inlet flows and pressures inside the DMA, employing different data analysis approaches e.g. Neural Networks [1] or Evidence Theory [2]. A typical method for detection of existing bursts used by the water companies involves the use of acoustic sensors [3]. However, a recent industrial project carried out by the authors and Veolia Water has shown that even a large burst causing losses of 6 Ml of water per day may remain unreported and be undetectable using standard acoustic sensors.

The approach to detect existing unreported bursts presented in this paper is based on the active identification procedure and exploits the behaviour of bursts under varying pressure. The method involves carrying out an extended fixed and variable orifice (e-FAVOR) test [4], where the DMA inlet pressure is being stepped up and down, while recording inlet flow, inlet pressure and pressure at selected locations inside the DMA using loggers. The results of the e-FAVOR test are used together with a hydraulic model of the DMA in EPANET format [5] as the inputs to a software tool, which performs series of simulations and facilitates data analysis. Existing methods for burst detection based on an active field test, including earlier work of the authors, are usually based on iterative placing of a burst in a simulation model and comparison of pressures from simulations with pressures obtained from field measurements. Such methods rely on an accurate hydraulic model of the DMA and accurate pressure measurements. The methodology presented in this paper is considered to be more resilient to modelling errors since it employs changes in head-loss as bursts indicators.

The paper is organised as follows: Section 2 describes the field test (e-FAVOR); Section 3 describes an overview and theoretical foundations of the methodology together with outcomes of some practical experiments; Section 4 concerns development of algorithms and a software tool for burst localisation; results of simulation studies are presented and discussed in Section 5 and final remarks can be found in Section 6.

2. E-FAVOR TEST

Typical e-FAVOR test is carried out during a night between 1 am and 5 am, when an average demand and also demand variations are low. During the test DMA inlet pressure is being stepped up and down by changing pressure reducing valve (PRV) setpoint, while recording inlet flow, inlet pressure and pressure at selected locations inside the DMA using loggers. Typically one pressure logger per 100-200 properties is installed. Locations of loggers can be chosen either:

- arbitrarily, e.g. one logger at the inlet to the DMA, then several loggers at the extremes of the DMA and then finally evenly scattered loggers within the centre of the DMA, or
- automatically, using nodes sensitivity matrix, which determines how the pressure at each potential measurement node is affected by a burst at any node across the network.

In both cases all loggers should be separated from each other by at least few (typically 4-5) other nodes.

The test needs to be carried out for at least two PRV setpoints: standard and reduced. However, to estimate the amount of leakage from the pressure and flow measurements, rather than only from MNF, the data should cover at least three inlet pressure levels (e.g. standard, reduced and intermediate). Note that only steady-state data are taken into account, i.e. periods of transients resulting from changing the PRV setpoint are ignored.

3. BURST DETECTION USING CHANGES IN HEAD-LOSS

3.1 Theoretical foundations

Burst detection methods based on comparison of pressures from simulation with pressures obtained from field measurements rely on an accurate hydraulic model of a DMA and accurate pressure measurements. Even small discrepancy in nodes elevation between the model and the actual water network may result in simulated pressures being inaccurate, and hence invalidate the results of the comparison. However, our past experience indicates that elevation of nodes in hydraulic models provided by water companies can be inaccurate. In this work, it is proposed to use changes in head-loss as bursts indicators to reduce the dependency on an accurate model, in particular accurate information about the nodes elevation, and to compensate for any offset in pressure measurement due to e.g. biased logger.

Consider measurement of pressure at two nodes, denoted *i* and *j*, which are connected hydraulically such that water flows from *i* to *j*. Two measurements are taken: one for standard and one for reduced PRV setpoint. Head-losses between *i* and *j* for standard and reduced PRV setpoint are given by equations (1) and (2), respectively:

$$\Delta h_{i,j}^{s} = p_i^s + e_i - \left(p_j^s + e_j\right) \tag{1}$$

$$\Delta h_{i,j}^{r} = p_i^r + e_i - \left(p_j^r + e_j\right) \tag{2}$$

where: $\Delta h_{i,j}^{s}$ and $\Delta h_{i,j}^{r}$ denote head-losses between *i* and *j* for standard and reduced PRV setpoint, respectively; p_i^s and p_i^r denote pressure measurement at node *i* for standard and reduced PRV setpoint, respectively; e_i denotes elevation of node *i*. Thus, change in head-loss between *i* and *j*, denoted $\Delta^2 h_{i,j}$, can be expressed as:

$$\Delta^2 h_{i,j} = \Delta h_{i,j}^{s} - \Delta h_{i,j}^{r} = p_i^s - p_j^s - \left(p_i^r - p_j^r\right) \tag{3}$$

Note that the elevation term does not appear in equation (3); hence, when a comparison of $\Delta^2 h$ obtained from measurements and from simulation is considered, accurate data on nodes elevation is not so important. Furthermore, although measurement of pressure should be precise, any offset due to biased logger (which may result e.g. from inaccurate reading of logger elevation) is automatically eliminated and thus does not affect the results. To obtain a normalized change in head-loss, denoted $\Delta^2 h_{i,j}^{\%}$, the following formula is used:

$$\Delta^2 h_{i,j}^{\%} = \frac{\Delta^2 h_{i,j}}{\Delta h_{i,j}^{s}} \cdot 100\% \tag{4}$$

Remark 1:

Non-zero $\Delta^2 h_{i,j}^{\%}$ is caused by change of flow in the pipes connecting nodes *i* and *j*. Assuming that the demand remains constant during the measurement, this change in flow is a result of change in leakage. Consequently, high $\Delta^2 h_{i,j}^{\%}$ indicates that the pipes connecting nodes *i* and *j* are carrying the flow feeding the burst.

3.2 Methodology overview

The proposed approach to detect existing bursts using data from e-FAVOR test has arisen from earlier joint project and discussions between the authors of this paper and the Asset Performance team of Veolia Water, UK. The methodology comprises three steps:

1. **Network skeletonisation.** A logic diagram of how loggers connect with each other (in terms of flow patterns) in the DMA is produced using network topological data. For every connection $\Delta^2 h$ is calculated from the pressure measurements.
2. **Determination of burst areas.** The logic diagram produced in step 1 is overlaid with $\Delta^2 h$ and $\Delta^2 h^{\%}$ calculated for each connection and is analysed (see *Remark 1*) to produce maps showing areas where a burst is suspected.
3. **Pinpointing an exact burst location.** Amount of leakage flow for standard and reduced PRV setpoint are estimated from measurements. Series of simulations are performed with the leakage allocated to different nodes in the suspected burst areas. $\Delta^2 h$ obtained from measurements and from each simulation are compared and statistical analysis of data is carried out to pinpoint an exact burst location.

3.3 Practical experiments

An e-FAVOR test has been carried out on three Veolia Water DMAs and the approach described above has been applied. In each case the method proved to be successful in determining burst location, which was confirmed by subsequent excavation. The experiments and data analysis led to discovery of over ten bursts, including a 6 Ml/d burst, which previously was undetected using standard leakage detection techniques such as acoustic sensing, visual inspection and trunk main walking. The experiments also resulted in an improved knowledge of the considered DMA (e.g. leaking boundary valve) and explanation of some suspected leaks. During the experiments described above all steps of the process were carried out manually and were found to be time consuming. Furthermore, for large networks and more than one burst location, steps 2 and 3 become difficult to be carried out manually. This prompted the development and implementation of algorithms that automate some of these steps, hence speeding-up the overall burst detection process.

4. DEVELOPMENT OF ALGORITHMS AND SOFTWARE TOOL

Use of appropriate algorithms can fully automate some of the steps listed in Section 3.2 and can support a human operator/modeller in other steps (i.e. automate some sub-steps). In this section development of such algorithms is described and their implementation in an integrated burst-detection tool is presented. The tool is under further development and uses an open-source package ScicosLab 4.4 [6] and EPANET 2 network simulator [5].

4.1 Location of loggers and skeletonisation of network

Given number of available loggers, model of the DMA in EPANET format and a list of hydrants where loggers can be placed, the algorithm proposes location of loggers, which can subsequently be modified by an operator. To calculate location of loggers the algorithm employs nodes sensitivity matrix, whilst ensuring that all loggers are separated from each other by *N* (an input parameter) other nodes and that there is some minimum (an input parameter) head-loss between neighbouring loggers.

Subsequently, a diagram of how loggers connect with each other is produced, via automatic analysis of flow patterns, produced by simulation of the DMA under normal conditions. Obtained diagram is a directed graph, whose vertices are network nodes where the loggers are located. A connection (directed edge) between logger *i* and *j* exists, if: (i) there is at least one continuous flow path from *i* (or its direct neighbour) to *j* (or its direct neighbour) and (ii) there are no other loggers on any flow path between *i* and i. Set of all connections in the diagram is further denoted as *K*. The tool allows to automatically highlight the pipes which form the flow paths of each connection. Note that this step requires simulation of a hydraulic model of the DMA; minimum required accuracy of the model is that the direction of flows obtained from the simulation has to match the reality.

4.2 Determination of suspected leak areas

For each connection of the DMA diagram $\Delta h^{s}_{i,j}$ and $\Delta h^{r}_{i,j}$ are calculated from the e-FAVOR test data. Subsequently, for each connection $\Delta^2 h_{i,j}$ and $\Delta^2 h^{\%}_{i,j}$ are calculated, according to equations (3) and (4), and displayed as a layer over the DMA model and the diagram. To identify suspected leak areas, patterns of $\Delta^2 h_{i,j}$ and $\Delta^2 h^{\%}_{i,j}$ are analysed. Consider vertex *i* with one upstream and one downstream connection (Figure 1). Based on *Remark 1*, if $\Delta^2 h^{\%}_{j,i}$ is large and $\Delta^2 h^{\%}_{i,k}$ is small, then there is a leak in the vicinity of vertex *i*.

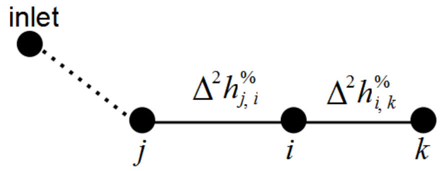

Figure 1. An abstract example of a diagram of logger connections

For simple DMA topology, such as illustrated in Figure 1, area of burst can easily be determined via manual analysis of all $\Delta^2 h^{\%}$. However, for a more complex topology with multiple connections between vertices, such manual analysis can be time consuming. To support a human operator and speed up the determination of suspected leak areas, it is proposed to calculate a total normalised head-loss change from the DMA inlet for each vertex of the diagram, denoted $\Delta^2 h^{\%}_{IN,i}$. *M* vertices (*M* is user-defined) with the highest $\Delta^2 h^{\%}_{IN,i}$ are then selected and highlighted on the diagram; the suspected burst areas are defined as the vicinity of these vertices. Note that this functionality does not use a simulation model and relies only on measurements.

4.3 Pinpointing an exact burst location

In the current stage of the developed tool a single-inlet DMA and a single burst are assumed. The amount of leakage flow for standard and reduced PRV setpoint, denoted l_s and l_r, respectively, can be estimated either from MNF or according to equation (5):

$$l_s = q_s - d\,; \qquad l_r = q_r - d \tag{5}$$

where q_s and q_r are measured PRV flows for standard and reduced PRV setpoint, respectively, and *d* represents total demand, estimated by finding a least-square solution of a two-term inlet flow model given by equation (6). Note that to find a solution of (6), the e-FAVOR test data needs to cover at least three PRV setpoints (e.g. standard, reduced and intermediate). To use a three-term inlet flow model including also background leakage [4], the e-FAVOR test data needs to cover at least five PRV setpoints.

$$q_{\{s,r,i\}} = d + c p^{\alpha}_{\{s,r,i\}} \tag{6}$$

In the above formula p_s, p_r and p_i are average measured DMA pressures for standard, reduced and intermediate PRV setpoints, respectively; *c* and *α* are burst coefficient and exponent, respectively; $\alpha \in \langle 0.5, 2 \rangle$.

Subsequently, series of simulations are performed with the leakage flows allocated to different nodes in the suspected burst areas. For each node *i* in the suspected burst area two simulations are performed: one for l_s allocated (as an additional demand) to the node *i* and with standard PRV setpoint, another with l_r allocated to the node *i* and with reduced PRV setpoint. Obtained simulation results are processed to calculate simulated changes in head-loss for each connection of the DMA diagram. For each node *i* the simulated and measured changes in head-loss are then compared and the goodness of fit, denoted B_i, is evaluated according to equation (7).

$$B_i = \sum_{k \in K} \Delta^2 h^{error}_k ; \quad \Delta^2 h^{error}_k = \begin{cases} \dfrac{\left(\Delta^2 h^{sim}_k - \Delta^2 h^{meas}_k\right)^2}{\Delta^2 h^{meas}_k} & if \quad \Delta^2 h^{meas}_k > 0 \\ \left|\Delta^2 h^{sim}_k\right| & otherwise \end{cases} \tag{7}$$

where $\Delta^2 h_k^{sim}$ and $\Delta^2 h_k^{meas}$ denote simulated and measured change in head-loss for *k*th connection in the diagram, respectively. The nodes with the lowest coefficient B_i are then highlighted in the DMA model to indicate the exact locations where the bursts are suspected.

5. SIMULATION STUDIES

Simulation studies presented in this section are based on the network model provided by United Utilities, UK. A burst was simulated by placing an emitter in the model and e-FAVOR test was simulated by changing PRV setpoint in the model. Number and location of loggers in the simulation reflects actual measurements carried out by United Utilities as a part of network calibration. The provided model consists of 922 nodes, 690 pipes and 289 valves, but the area subjected to e-FAVOR test (i.e. downstream of PRV) consisted of approx. 200 nodes. Diagram of connections was obtained automatically and is illustrated in Figure 2; note that $\Delta^2 h_{i,j}$ and $\Delta^2 h_{i,j}^{\%}$ for each connection are not displayed here for clarity.

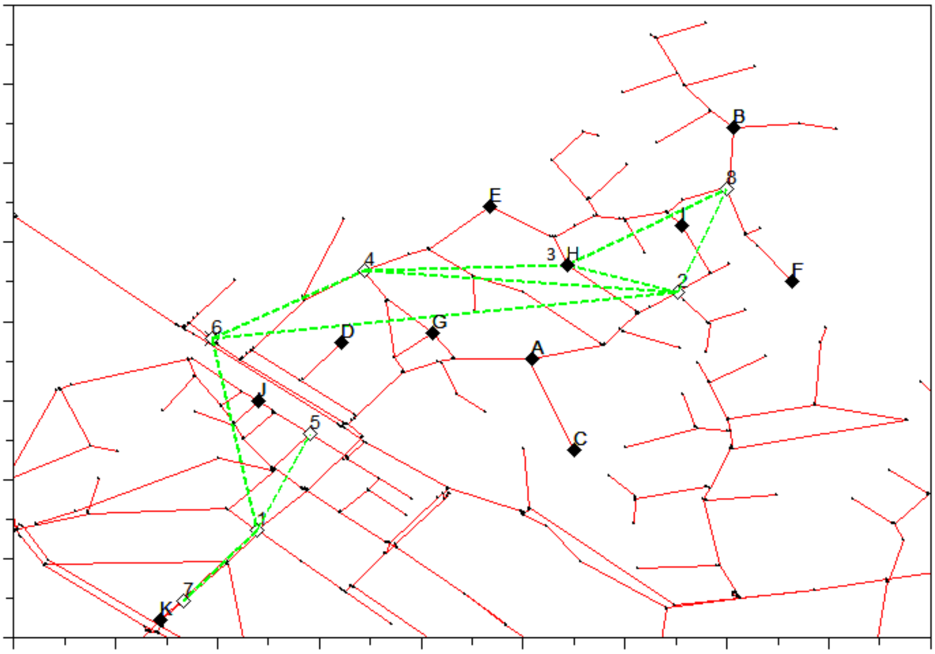

Figure 2. Network model and diagram of logger connections. Legend: small dots – network nodes, solid lines – pipes, dashed lines – diagram connections, white diamonds – loggers (1 – 8), black diamonds – locations where a burst was simulated (A – K). Logger 6 is at PRV outlet.

5.1 Suspected burst area

To test the approach described in Section 4.2 a burst was simulated in each (one at a time) of the arbitrarily chosen locations illustrated in Figure 2. In each simulation burst coefficient and burst exponent were randomly drawn from uniform distributions spanned over $\langle 0.04, 0.1 \rangle$ and $\langle 0.5, 1 \rangle$, respectively. Resulting burst flow for standard PRV setpoint was between 0.7 and 3.7 l/s. For each simulation total normalised head-loss change from the DMA inlet ($\Delta^2 h_{IN,i}^{\%}$) was automatically calculated for each logger location, see Table 1. It can be observed that in all cases the highest values in each row (marked with bold italic) have been obtained for the loggers that are close to the burst location, which confirms suitability of $\Delta^2 h_{IN,i}^{\%}$ to determine the area of burst.

5.2 Exact burst location

For each burst simulated in Section 5.1, the methodology described in Section 4.3 was applied; nodes to be tested (i.e. assumed to be in the suspected burst area) were these in the set A – K. Obtained values of B_i are summarised in Table 2. It can be observed that typically the closer the tested node to the actual burst location, the lower the value of B_i. However, since the distribution of loggers is sparse, values of B_i obtained for neighbouring nodes (e.g. node A and C) are practically indistinguishable from each other. Similarly, bursts at nodes B and F produce almost the same B_i in all cases, due to lack of information about changes in head-loss in the part of the network to the right of logger 8. Nevertheless, in all other cases there is substantial difference between obtained B_i, which indicates suitability of the proposed approach.

Table 1. Total normalised head-loss change from the DMA inlet.

Logger ID →	$\Delta^2 h^{\%}_{IN,i}$ [%]								Burst
Burst location ↓	1	2	3	4	5	6	7	8	flow [l/s]
A	9.69	***10.87***	***10.79***	10.48	9.14	0.00	9.63	10.51	0.83
B	9.13	10.48	10.38	9.91	8.64	0.00	9.09	***12.63***	0.93
C	10.81	***12.13***	***12.05***	11.72	10.18	0.00	10.75	11.72	1.01
D	5.08	5.06	5.07	***5.18***	4.77	0.00	5.05	4.91	0.57
E	27.55	***29.63***	***29.70***	29.00	26.77	0.00	27.47	29.30	2.90
F	34.50	37.85	37.62	36.36	33.42	0.00	34.40	***43.50***	3.66
G	31.55	***32.44***	***32.44***	***32.54***	30.80	0.00	31.48	32.08	3.58
H	14.42	***16.28***	***16.33***	15.55	13.70	0.00	14.34	15.88	1.28
I	33.65	36.61	36.35	35.25	32.79	0.00	33.57	***37.56***	3.65
J	7.09	6.59	6.60	6.73	***8.60***	0.00	7.09	6.41	0.72
K	20.79	19.60	19.63	19.86	20.08	0.00	***21.04***	19.26	2.25

Table 2. Coefficient B_i for different burst locations. Lowest values in each row are marked with bold italic.

Tested node →	B_i										
Burst location ↓	A	B	C	D	E	F	G	H	I	J	K
A	***0.0003***	1.3774	***0.0003***	0.0055	0.0008	1.3821	0.0018	0.0028	0.1027	43.9	0.0193
B	0.0269	***0.0002***	0.0269	0.0337	0.0271	***0.0002***	0.0294	0.0271	0.0138	0.0669	0.2259
C	***0.0010***	2.0927	***0.0010***	0.0054	0.0018	2.1005	0.0019	0.0054	0.1555	0.0466	0.2746
D	0.3002	9.3530	0.3002	***0.0001***	0.2556	9.3876	0.0375	0.5885	1.2314	0.0106	0.0377
E	0.0088	34.3	0.0088	0.0384	***0.0007***	34.4	0.0205	0.0135	1.5437	0.1346	0.0484
F	0.2580	***0.0666***	0.2580	0.2962	0.2620	***0.0672***	0.2812	0.2805	0.1445	0.9350	8.6289
G	0.0399	80.5	0.0399	0.0140	0.1056	80.9	***0.0006***	0.3198	5.0653	0.1510	0.0290
H	0.0028	0.0549	0.0028	0.0126	0.0014	0.0550	0.0063	***0.0011***	0.0151	0.0368	0.0159
I	0.0903	1.0639	0.0903	0.1499	0.0865	1.0708	0.1226	0.0948	***0.0051***	2471.3	19.7
J	0.3390	41.4	0.3370	0.0091	0.2798	41.6	0.0608	0.6532	3.4199	***0.0000***	0.0098
K	0.7630	490.9	0.7633	0.0042	1.2577	493.2	0.1424	2.9776	34.1	0.0518	***0.0009***

6. CONCLUSIONS

This paper described an approach to detect unreported pipe bursts via e-FAVOR test, analysis of network topology and a comparison of measurements vs. simulation. New bursts indicators were proposed, which are considered to be more resilient to modelling errors and inaccurate reading of pressure logger elevation. The methodology was tested in practice in a manual manner and proved to be effective. Automatic analysis algorithms, designed to speed up and facilitate the burst detection process, were described and tested via simulations. Results obtained so far indicate suitability of the proposed burst indicators and the developed algorithms. Further work is on-going and is focused mainly on extending the algorithms for multiple-burst case and on analysing the impact of measurement noise, modelling errors and density of loggers.

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