BURSTS IDENTIFICATION IN WATER DISTRIBUTION SYSTEMS

I. Borovik[1] , B. Ulanicki[2] and P. Skworcow[2]

[1]Bauman MSTU, 2-nd Baumanskaya, 5, 105005, Moscow, Russia; email: irencha11@rambler.ru
[2]De Montfort University, Process Control - Water Software Systems, De Montfort University, The Gateway, Leicester, LE1 9BH, UK; email: bul@dmu.ac.uk,

ABSTRACT

The leakage reduction problem as a whole is complex and requires co-ordinated actions in different areas of water network management, such as: direct detection and repair of existing bursts, general pipe rehabilitation programmes and operational pressure control. Water companies undertake a mixture of these complimentary actions. General pipe rehabilitation is the most costly and long term action, but is undertaken to improve a number of different factors including leakage and water quality. Operational pressure control is a cost-effective action for reducing leakage over whole sub-networks, and for reducing the risk of further leaks by smoothing pressure variations and is the subject of ongoing research. Detection and repair actions are targeted at sub-networks where bursts are present. Benefits of quick burst repair include reduced water losses, reduced disruption to traffic, reduced consequent losses (e.g. from flooding), and also reduced disruption to customers' supplies, which is an important water industry performance measure. The existing methods typically use passive identification approach whilst the presented approach is based on the active identification procedure.

The proposed burst location algorithm is based on comparing data by means of statistical analysis from a simple field experiment with results of water network simulation. An extended network hydraulic simulator is used to model pressure dependent leakage terms. The presence of a burst changes the flow pattern and also pressure at network nodes, which may be used to estimate the burst size and its location. The influence of such random factors as demand flows and background leakage on the process of burst detection is also considered. The field experiment is an extended fixed and variable orifice (e-FAVOR) test. During this test inlet pressure is being stepped up and down and the following variables are measured: inlet flow, inlet pressure (head) and pressure at a number of selected sensitive nodes. The method consists of three stages and uses two different models; one is inlet flow model (IFM) to represent the total inlet flow and another is the extended hydraulic model to simulate different burst locations. Initially the presence of a potential burst is investigated. If this is confirmed values of the demand, background leakage flow and burst flow in IFM are subsequently estimated. These are used to identify the burst site at the third stage of the method. The approach has been validated by solving a practical case study with correct diagnosis of the existing problems.

INTRODUCTION

The UK water industry is addressing the major challenge of reducing leakage in water distribution systems (WDS). Especially, unreported bursts are cause for concern with significant water losses and potential damage to urban infrastructure. Water distribution systems are complicated entities with thousands of interconnected pipes and other components. There is a need for developing efficient methods for identifying unreported bursts which remain invisible with the water draining away and never reaching the surface. Benefits of quick burst repair will also result in reduced disruption to customers, which is an important water industry performance measure.

Recently the UK water companies have heavily invested into restructuring water networks into smaller sub-networks known as District Metering Areas (DMAs). A DMA is a sub-network where the boundary flow is monitored in order to assess leakage. Its boundary is closed except for a low number of inputs and outputs with flow and pressure meters. This facilitates leakage management in terms of pressure control and bursts detection. When a new burst occurs it causes a noticeable increase in the minimum night flow (MNF) – and subsequently a burst location method can be applied. This research proposes such a method by exploiting different behaviour of background leakage and bursts under varying pressure (May 1994). John May proposed a pressure stepping experiment (FAVOR test) during which the inlet flow and inlet pressure were monitored. The authors of this paper observed that monitoring only the inlet variables is not sufficient even to estimate the size of the burst. Therefore, the test was extended to include additional measurements at a number of internal nodes in a DMA and is termed the extended FAVOR test (e-FAVOR test). The method comprises three steps: first performing the e-FAVOR test, subsequently estimating the size of the burst and finally identifying the burst location.

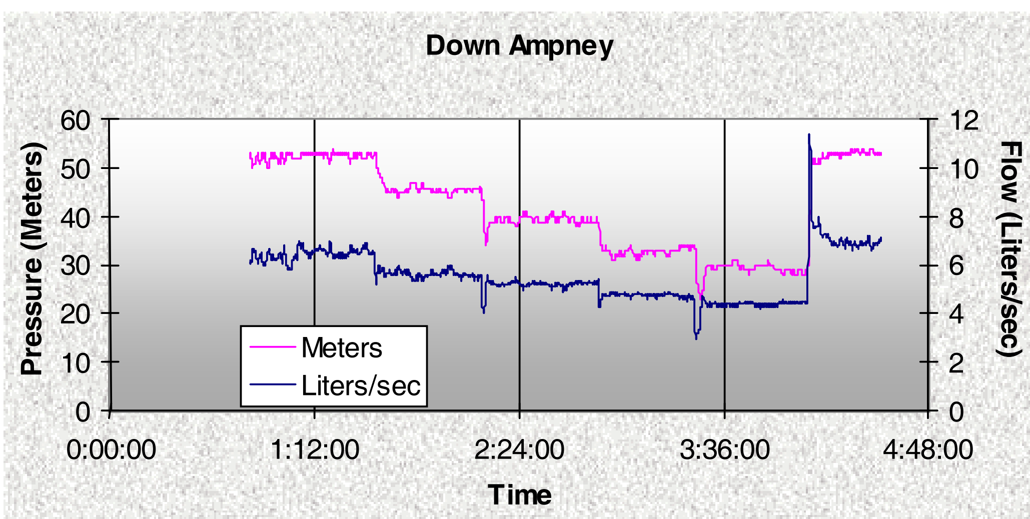

Figure 1. Typical results of the e-FAVOR Test – inlet flow and pressure

E-FAVOUR TEST

A typical e-FAVOR test is carried out during a night between 1 am and 5 am. The inlet pressure is changed stepwise over a typical range of values at 20-minute intervals during this period. Typical scenario of the inlet pressure and flow are depicted in Figure 1. It can be observed in Figure 1 that when the inlet pressure is changed stepwise, the flow changes in a similar manner. Note that only the steady-state data is considered and the data from the transient phase between steady states should be ignored.

It is not practical to measure internal pressure at all nodes in a DMA and therefore a small number of representative nodes (sensitive nodes) is selected for monitoring. The potential measurement points are hydrants and typically a water company is prepared to put 20 loggers for the experiment. The method of determining sensitive nodes has been developed by Prescott and Ulanicki (2006) and is related to that proposed by Bush and Uber (1998). The method uses the sensitivity matrix of the hydraulic model (Jacobian matrix) to determine how the pressure at each potential measurement node is affected by a burst at any node across the network. This matrix has dimension $m \times n$, where m is the number of potential pressure measurement points and n is the number of nodes in the network (possible burst location). The sensitivity matrix can be calculated from the network equations or extracted directly from a hydraulic simulator used in the method.

ESTIMATING THE BURST COEFFICIENT

The inlet flow can be represented by a three term inlet flow model (IFM):

$$q = d + c_1 p_i^{0.5} + c_2 p_{AZNP}^{1.5} \tag{1}$$

where d is an average total demand, p_i is pressure at a burst node, c_1 is the burst coefficient (related to the burst area), p_{AZNP} is average zonal night pressure and c_2 is the background leakage coefficient (related to the total area of the background leakage). The coefficients of the IMF can be estimated using least square method (LSM) from the available measurements for an assumed location of the burst.

It is assumed that the demand flow does not depend on pressure variations in a DMA and the average value of demand is constant over the considered period between 1 am – 5 am. The total background leakage flow represents the sum of all separate background leaks in a network and it is possible to use a single (common) coefficient of the background leakage c_2 and the Average Zonal Night Pressure p_{AZNP}.

The procedure is to assume the burst at a sensitive node and evaluate IFM model; this is carried out for each sensitive node using LSM. It is feasible because pressure p_i in model (1) is known from the e-FAVOR measurements. Note that number of obtained IFM models corresponds to number of sensitive nodes. Subsequently, the goodness of fit for each IFM model is tested using chi-square (χ^2) criterion and the best IMF model is selected to represent the burst flow and also the demand and the background leakage flow. In order to verify the hypothesis, i.e. the compliance of the measured and calculated values of the inlet flow, the following measure is used:

$$\chi^2 = \sum_{k \in time\_steps} \frac{\left(q'_k - q_k\right)^2}{q'_k} \tag{2}$$

where q'_k = model flow, q_k = measured flow.

The algorithm of burst size estimation in a DMA has been implemented in the MATLAB package and progresses through the following steps:

1. Read Excel files containing the experimental data.
2. Prepare the matrix of pressures at the sensitive nodes and calculate the values of the Average Zonal Night Pressure.
3. In a case of a network with many inlets, add all inlet flows together to form a total inlet flow.
4. Solve the least squares problem for each sensitive node $i \in S$ where S is a set of sensitive nodes.
5. Choose the solution which corresponds to the minimum value of the chi-squared criterion.

The outputs of the algorithm are values of the IFM coefficients and the resulting theoretical inlet flows and the vector of the χ^2 criterion values.

IDENTIFICATION OF BURST LOCATION

It was important to find a sensitive indicator of a burst location and the gradient of a pressure line was a very good candidate. A pressure line is a functional relationship between the inlet pressure and the pressure at a chosen node. In absence of leakage it is a straight line with gradient equal to 1. In the presence of a burst the gradient becomes smaller than 1 and the minimum value of the gradient is attained for the burst node. If a small background leakage is added the general rule does not change and the order in the gradient values is preserved with the smallest gradient for the burst node and the biggest gradient for the inlet node as depicted in Figure 2.

The gradients can be found by the least squares method to minimise deviations of the approximating straight line from the experimental data. The following information should be available for the burst location identification:

- inlet pressure which is stepped during the field experiment
- pressure measurements at the sensitive nodes
- gradients of the regression pressure lines for the sensitive nodes
- the IMF model estimated at the previous stage
- hydraulic model of the network

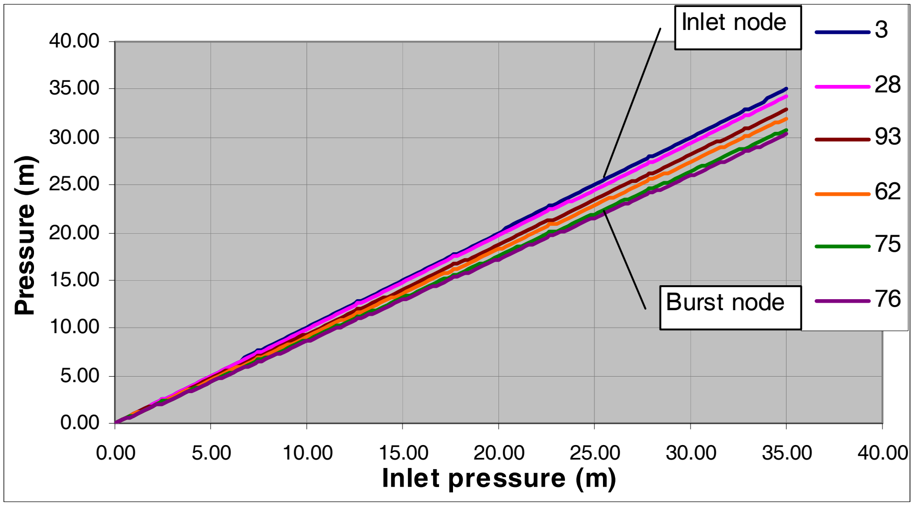

Figure 2. Pressure lines for a DMA nodes

The field measurements from the e-FAVOR test are used to estimate gradients of the measured pressure lines for sensitive nodes. A numerical experiments equivalent the e-FAVOR test is performed on the simulation model. The burst coefficient (calculated at the previous stage) is allocated to different nodes of the simulation model and the theoretical gradients of the pressure lines at the sensitive node are evaluated. For each burst location the value of the chi-squared criterion is calculated as:

$$\chi^2 = \sum_{i \in S} \frac{\left(b'_i - b_i\right)^2}{b'_i} \quad (3)$$

where b'_i = gradient estimated from measurements, b_i =gradient estimated from simulations. The allocation which gives the minimum value of the χ^2 criterion corresponds to the burst node.

SHENSTONE CASE STUDY

Shenstone DMA (illustrated in Figure 3) is fed through two PRV inlets and supplies 1008 consumers (917 domestic and 91 commercial). There are two 4 inch PRVs at inlet 1 and inlet 2, respectively, as shown in Figure 3. The recorded data from the e-FAVOR test are depicted in Figure 4.

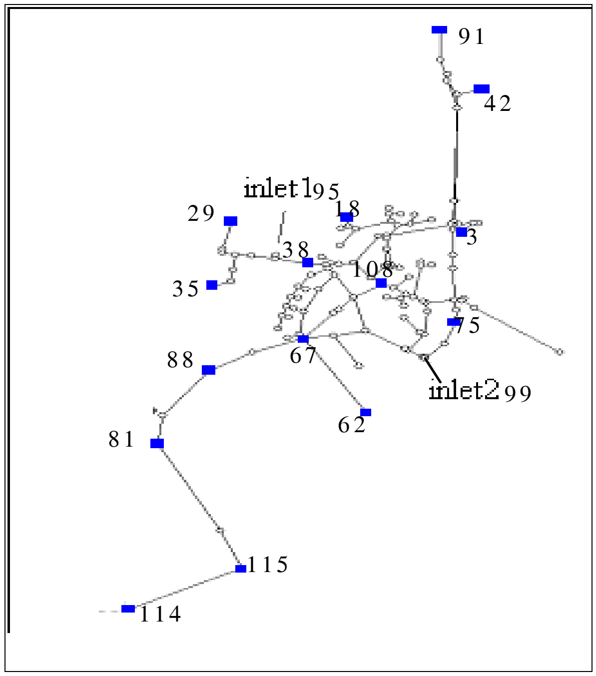

Figure 3. Shenstone DMA. Blue squares denote selected sensitive nodes.

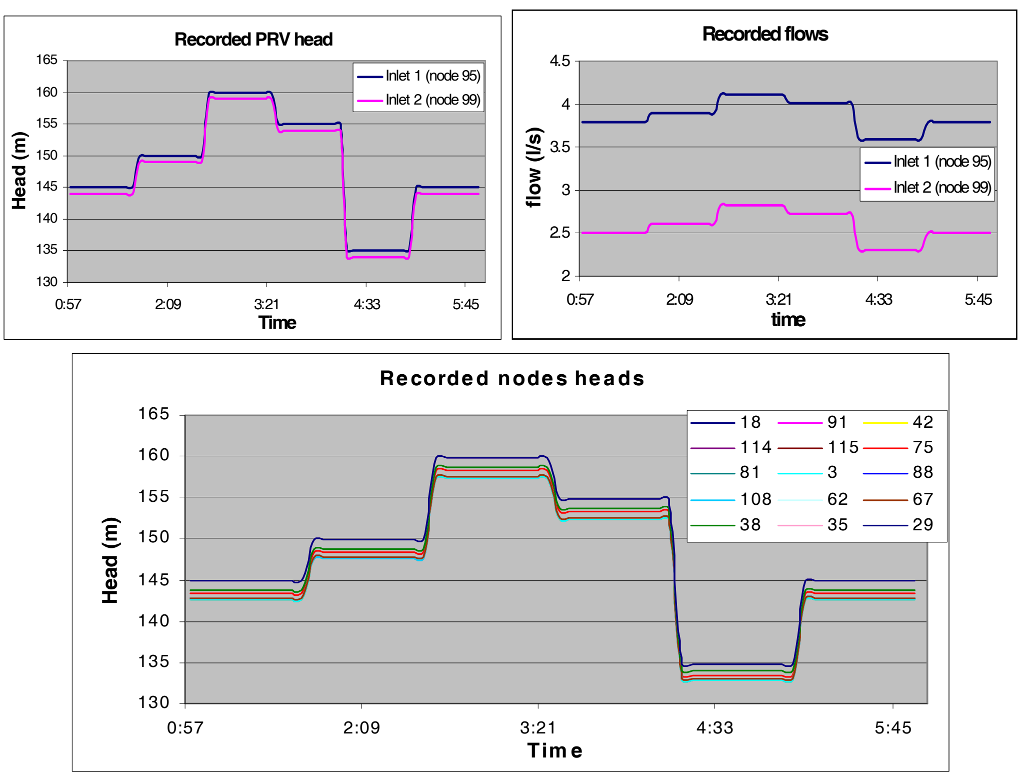

Figure 4. Recorded data

IFM models have been estimated by allocating a burst to different sensitive nodes. For each allocation a corresponding IFM model and the corresponding value of χ^2 have been calculated and are shown in Table 1. The IFM model corresponding to $\chi^2 = 9.31\times10^{-10}$ has been selected for estimating the size of the burst, therefore the coefficients of the model are $d = 4.0334$, $c_1 = 0.2429$ and $c_2 = 0.00227$.

Table 1.

Sensitive node	A demand factor (l/s)	A coefficient of the burst	A coefficient of the total background leakage	A value of χ^2 (the difference between calculated and recorded inlet flows)
The burst exponent = 0.512104				
95	3.643539	0.284718	0.002128	4.99E-08
99	4.033422	0.242887	0.002276	9.31E-10
18	3.709304	0.279806	0.002165	3.93E-08
91	3.876389	0.261679	0.002224	5.94E-08
42	3.873712	0.262168	0.002225	1.79E-08
3	3.55773	0.294989	0.002115	7.11E-08
114	4.333455	0.208249	0.002425	7.74E-08
115	4.305799	0.211826	0.00241	6.26E-08
81	4.032276	0.244776	0.002283	2.08E-08
88	4.117065	0.234884	0.00232	1.54E-08
108	4.360773	0.204427	0.002443	1.16E-07
62	3.922307	0.257142	0.002238	6.8E-08
67	3.950318	0.253477	0.002255	1.01E-08
38	3.803718	0.269449	0.002187	1.4E-07
75	3.972916	0.250807	0.002251	1.81E-08
35	3.766198	0.271833	0.002176	1.6E-08
29	3.735147	0.275068	0.002165	1.97E-08

The final stage was to find the burst location. The estimated burst coefficient $c_1 = 0.2429$ was allocated to each node of the hydraulic model one by one, simulated for each allocation and subsequently the model pressure regression lines were compared with the measured ones using χ^2 criterion. The best three allocation are shown in Table 2. The obtained results indicate a high degree of probability of the burst presence at node 80. The value of the total demand flow is 4 l/s, the value of the coefficient of the fixed area leakage (burst) is 0.2429. This finding was later confirmed by the water company following inspection of the area indicated by the proposed method.

Table 2.

Burst node	A value of χ^2 (reflects an error in prediction of burst location)
80	3.2E-06
69	1.44E-05
33	1.67E-05

CONCLUSIONS

The paper proposed a method for estimating burst flow and a burst location in a DMA. The method is based on an active identification procedure called e-FAVOR test which is carried out at night between 1 am and 5 am. The test requires deployment of pressure loggers to monitor pressure at sensitive nodes. The burst flow is estimated by comparing inlet measured flow and flow from the IFM model. The burst location is identified by comparing gradient of pressure lines from measurements and from hydraulic simulations. The method was formulated assuming presence of a single burst in a DMA, but can easily be generalised by application of genetic algorithms to search for the best flow and pressure line models. Findings were later confirmed by the water company following inspection of the area indicated by the proposed method. Another case study is currently under investigation.

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