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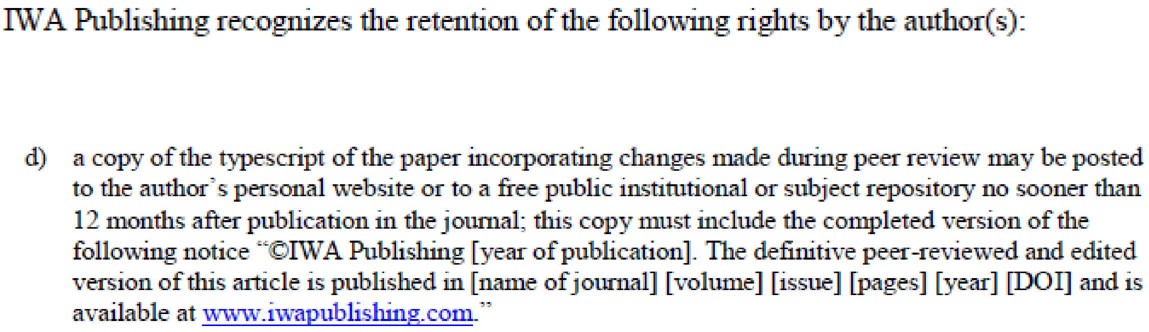

BURST DETECTION AND LOCATION IN WATER DISTRIBUTION NETWORKS

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Abstract. An algorithm for the detection and location of sudden bursts in water distribution networks combining both continuous monitoring of pressure and hydraulic transient computation is presented. The approach is designed for medium and large bursts that are the result of the sudden rupture of the pipe wall or other physical element in the network and are accompanied by the transient pressure wave that propagates throughout the network. The burst-induced transient wave arrival times and magnitudes measured at two or more points are used to find the location of a burst. The wave arrival times and magnitudes are detected using the modified cumulative sum (CUSUM) change detection test. Results of validation on a real network show the potential of the proposed burst detection and location technique to be used in water distribution systems.

Introduction

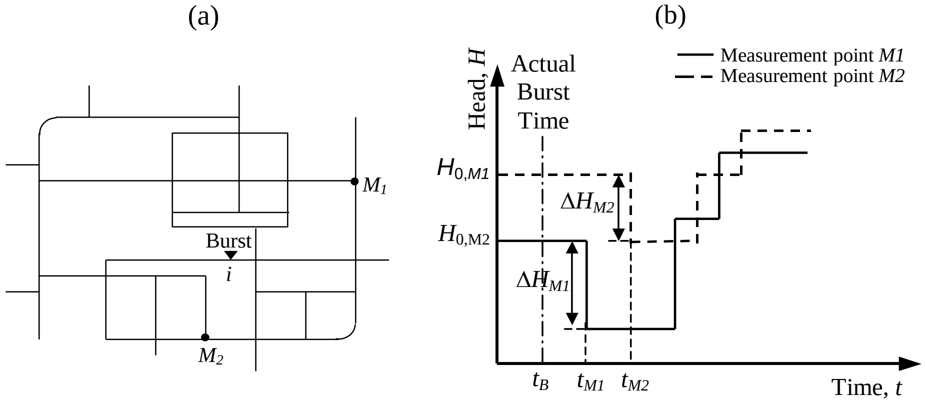
The losses in urban water supply system can be divided into two major parts - apparent losses and real losses (Lambert, 2003; Morrison, 2004). Apparent losses are due to the unauthorized consumption and meter inaccuracy, whereas real losses include leakage and overflows. Real losses can further be separated into bursts and background leakage. A pipe burst is the rupture of a pipe wall or other element in the network that is usually followed by a large discharge of water. Although the background leakage often is the main contributor to the volumetric loss, the overall costs associated with pipe bursts can be significantly larger and includes the cost of water that is lost, the repair of damaged surrounding infrastructure or flooded properties, customer complaints about interrupted supply, etc. Pipe bursts are relatively frequent in water distribution systems. Since many water supply systems are old and in poor condition, it is practically impossible to prevent pipe failures. Nevertheless, the losses associated with bursts can be reduced by minimising the time of burst detection and location. Although most bursts result in the appearance of water on the ground surface and are detected by customers or water company personnel (passive burst detection), the average location time can be quite long. In Morrison, (2004) the time for awareness and location of a 4 m^3/hour burst was estimated to be 5 days. Obradovic, (2000) reported burst location times of around 18 hours. Experience from the oil and gas industries shows that the determination of a burst location can be made more efficient and accurate by continuous monitoring of the system. Recent developments in instrumentation and data acquisition have reduced the cost of monitoring systems and made continuous monitoring of water supply systems feasible. However, most burst (leak) detection techniques described in the literature consider single pipelines and cannot be directly applied to a network situation (Misiunas et al., 2003; Silva et al., 1996; Zhang, 2001). In fact, the complicated topology found in water distribution networks requires special attention for burst detection and location methods to be successfully applied.

The majority of pipe network monitoring approaches found in the literature focus on the assessment of leakage that is present in the system. The most common and straightforward technique is the concept of district metering area (DMA) (WRc, 1994). By performing a simple mass balance analysis of the flow that is entering the DMA, the leakage level can be estimated and manual techniques are then used to locate the leak point. In this paper, sudden pipe bursts of medium to large size that have potentially dangerous consequences are considered. The proposed technique is based on a combination of continuous monitoring of the pressure at a number of points within the pipe network and hydraulic transient theory.

The basis of the method

The technique presented in this paper originates from the burst detection and location method proposed by the authors in Misiunas et al., (2004). In the case of a sudden pipe rupture a transient wave is generated and propagates throughout the network away from the burst point. If the pressure is continuously measured at two or more points within the network, the arrival times of the burst-induced wave at the measurement points can be used to derive the location of the burst. The schematic view of the burst monitoring system and the generalised pressure traces at two measurement points are shown in Figure 1.

Figure 1. (a) The schematic view of the burst monitoring system in a water distribution network and (b) generalized burst-affected pressure traces at measurement points.



The burst occurs at time t_B, which is assumed to be unknown. Two parameters can be obtained from the pressure trace at each monitoring point – transient wave arrival time t_M and the magnitude of the wave ΔH_M. Using the model of the network and the method of characteristics (MOC) (Wylie and Streeter, 1993) the shortest transient wave travel time between any two points within the network $\tau_{i,j}$ and the wave transmission coefficient between two points $T_{i,j} = \Delta H_j / \Delta H_i$ can be calculated (Misiunas et al., 2004). ΔH_j and ΔH_i are the burst-induced transient wave magnitudes at points j and i respectively. If the burst occurs at node i and the pressure is measured at nodes M_1 and M_2, the following equations should be true:

$$\left(t_{M_1} - t_{M_2}\right) - \left(\tau_{i,M_1} - \tau_{i,M_2}\right) = 0 \tag{1}$$

$$\frac{\Delta H_{M_1}}{\Delta H_{M_2}} - \frac{T_{i,M_1}}{T_{i,M_2}} \approx 0 \tag{2}$$

where t_{M1}, t_{M2} are the measured wave arrival times at points *M1* and *M2*; $\tau_{i,M1}$, $\tau_{i,M2}$ are the calculated wave travel times from point *i* to points *M1* and *M2* respectively; ΔH_{M1} and ΔH_{M2} are pressure wave magnitudes registered at measurement points *M1* and *M2*; $T_{i,M1}$, $T_{i,k}$ are transmission coefficients for the wave traveling from point *i* to points *M1* and *M2* respectively. The effect of friction along the pipe length and at the junctions has been neglected and therefore the left-hand-side of Equation (2) will be close, but not necessarily equal to zero. The burst orifice size is back-calculated using the Joukowsky pressure change relationship and the orifice equation (Misiunas et al., 2003).

Monitoring of the pressure for a burst event

To locate the burst, a transient wave has to be detected at two or more measurement points. The cumulative sum (CUSUM) change detection test (Page, 1954) may be used to monitor the measured pressure for a negative burst-induced pressure wave. The CUSUM test has been extensively applied for change detection in different time series analysis problems (Basseville and Nikiforov, 1993). If the measurement data contains a high level of noise pre-filtering is applied using the adaptive Recursive Least Squares (RLS) filter. The filter estimates the signal θ_t from the measurement H_t (containing noise) as

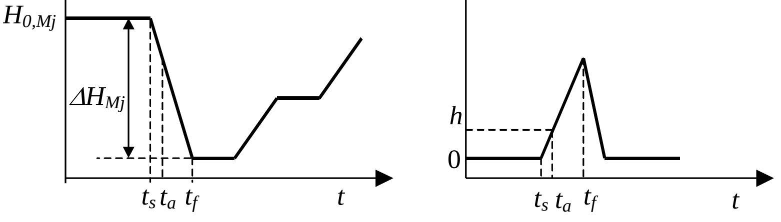
$$\theta_t = \lambda\theta_{t-1} + (1-\lambda)H_t \tag{3}$$

where the parameter $\lambda \in [0,1)$ is the forgetting factor that limits the smoothing effect of the filter. Depending on the noise level in the measured data, the forgetting factor is exponentially adjusted in real-time between selected minimum and maximum values. The residuals $\varepsilon_t = \theta_t - \theta_{t-1}$ are fed into a CUSUM test that is used to determine whether a change has occurred in the measured signal. Mathematically, the CUSUM test is formulated as the following time recursion

$$\begin{aligned} &G_0 = 0 \\ &G_t = \max(G_{t-1} - \varepsilon_t - \nu, 0) \\ &\text{if } G_t > h \text{ then issue alarm and set } t_a = t,\ G_t = 0 \end{aligned} \tag{4}$$

where G_t is the cumulative sum value at a time *t*, *h* and ν are threshold and drift parameters respectively. For every sample of data, the part of the change in signal ε_t that exceeds the drift value ν (the expected variation) is added to the cumulative sum G_t. When G_t reaches the threshold value *h*, the alarm is issued and the time of change t_a is recorded (Figure 2). To obtain the actual transient wave arrival time t_{Mj} and the transient wave magnitude at the measurement point ΔH_{Mj} times t_s and t_f have to be identified. As shown in Figure 2, time t_s corresponds to the time when the slope *dG/dt* becomes positive and time t_f corresponds to the time when *dG/dt* becomes zero or negative. Then $t_{Mj}=t_s$ and $\Delta H_{Mj}=H_{Mj}(t_s)-H_{Mj}(t_f)$.

Figure 2. The generalised traces of (a) head at burst point and (b) cumulative sum.

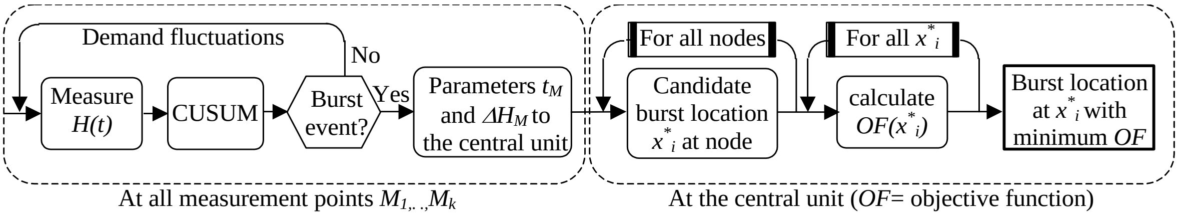


The choice of CUSUM parameters will influence the performance of the burst detection and location technique. The value of the drift ν sets the upper limit for the opening time of the burst that will be detected and the choice of the threshold *h* sets the lower limit for the size of the burst that will be detected. Although decreasing ν and *h* will expand the range of detectable bursts, both the drift and the threshold have to be large enough to avoid false alarm situations. Therefore, for optimal performance, the parameters have to be tuned specifically for a particular network. In this study the choice of the drift value is set to be equal to the average value of the observed pressure changes (*dH/dt*) in the filtered historical data. The threshold *h* is set to exceed calculated cumulative sum variations for the historic data. Since the hydraulic noise of the system is often dependent on the time of the day (diurnal demand variations), the variable CUSUM parameters may be chosen to further improve the performance of the burst detection and location.

Search for the burst location

A schematic view of the complete burst detection and location algorithm is shown in Figure 3. Once the burst event is detected in the pressure measurements at two or more monitoring points, identified wave arrival times and magnitudes are sent to the central unit where the search for the burst location is performed.

Figure 3.The structure of continuous burst monitoring algorithm



In this study, all the nodes in the network are nominated as burst candidate locations. Calculated transient wave travel times and transmission coefficients are used for calculating two objective functions that are based on the Equations (1) and (2):

$$OF1_i = \sum_{j=1}^{k-1}\sum_{p=2}^{k}\left[\left(t_{M_j}-t_{M_p}\right)-\left(\tau_{i,M_j}-\tau_{i,M_p}\right)\right]^2 \qquad \forall i \in [1,N] \qquad (5)$$

$$OF2_i = \sum_{j=1}^{k-1}\sum_{p=2}^{k}\left(\frac{\Delta H_{M_j}}{\Delta H_{M_p}}-\frac{T_{i,M_j}}{T_{i,M_p}}\right)^2 \qquad \forall i \in [1,N] \qquad (6)$$

where *k* is the number of measurement points and *N* is the number of nodes in the network. Both *OF1* and *OF2* have to be minimised in order to find the burst node. To combine the two objective functions (Equations (5) and (6)) a compromise programming approach is used. Compromise programming is a multi-criterion distance-based technique designed to identify compromise solutions. The following objective function is computed:

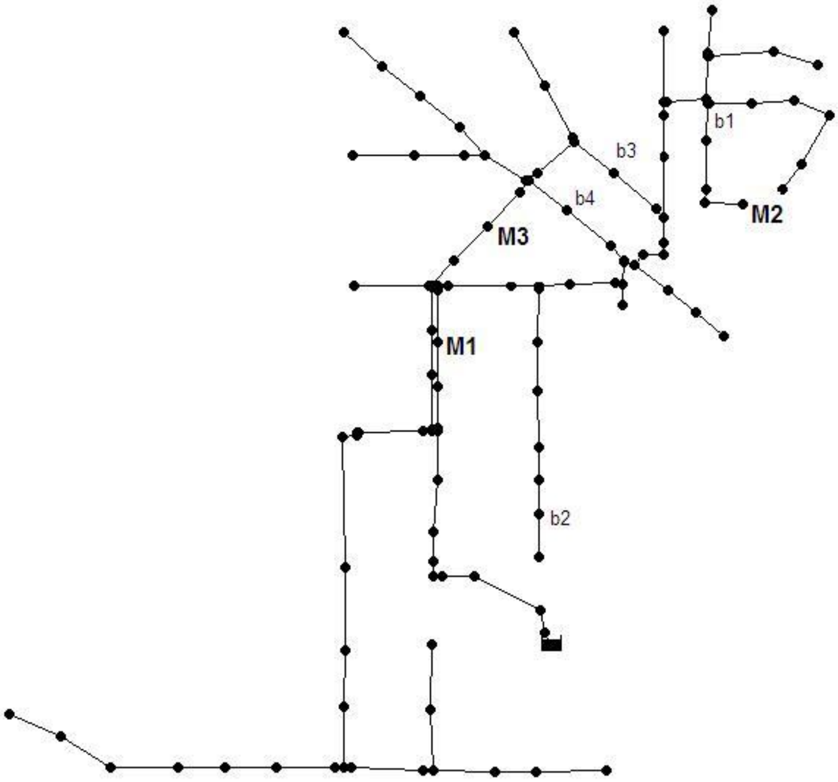
$$OF_i = \sqrt{\sum_{n=1}^{2} w_n\left(\frac{OFn_i - OFn_{\max}}{OFn_{\min}-OFn_{\max}}\right)^2} \qquad (7)$$

where w_1 and w_2 are the weights of *OF1* and *OF2* respectively. The objective function is calculated for all burst candidate locations and the node having the largest value of *OF* is declared to be the burst position.

Validation on a real network

A real water distribution network (Figure 4) was used to verify the proposed method for burst detection and location. Around 250 households are connected to the network that is fed from a fixed-head reservoir. To calculate theoretical transient wave travel times and transmission coefficients between different points in the system a network model has been built containing 108 pipes and 79 nodes. The pipes are mainly asbestos cement and have diameters between 100 and 250 mm, lengths between 70 and 210 m and a roughness height of 2 mm. The wave speed of 1120 m/s was used for all the pipes in the model. The node elevations are in the range of 140 to 160 m and the steady-state pressure at the nodes varies between 20 and 80 meters.

Figure 4. The layout of the pipe network.

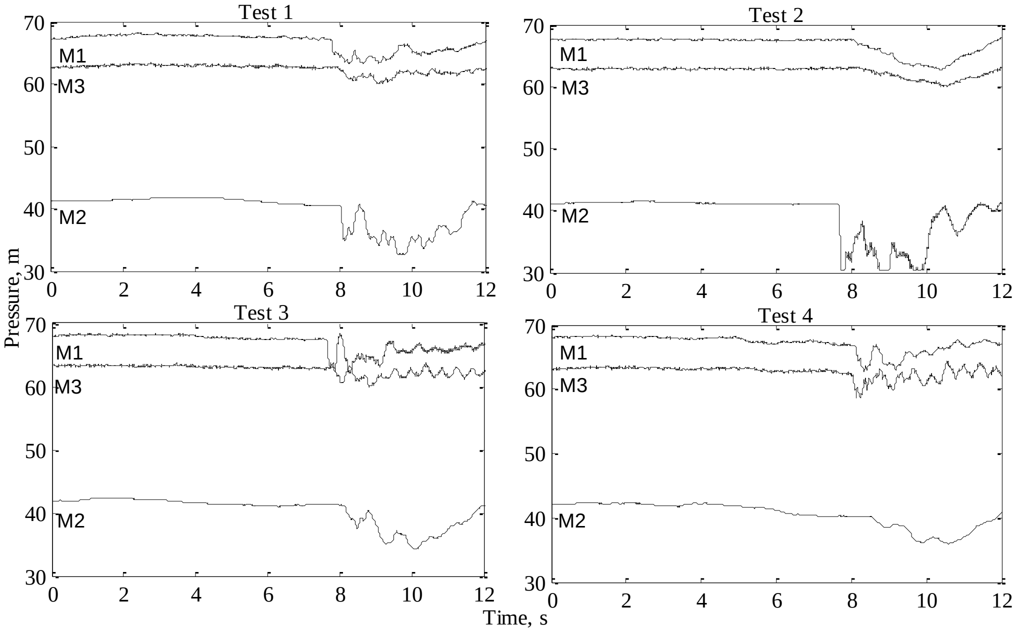


The pressure was continuously measured at three points (M1, M2 and M3 in Figure 4) at a sampling rate of 2000 Hz. The data acquisition system integrating variable-gain amplifiers and 16-bit A/D conversion cards enabled high-resolution (0.0023 m) pressure measurements. Four different burst positions were tested (b1 to b4 in Figure 4). The burst was simulated by opening a solenoid valve attached to a fire hydrant. The solenoid valve had a diameter of 10 mm, an opening time of approximately 40 ms and an estimated discharge coefficient $C_d A_o$=5.5 x 10^{-5}. All tests were conducted between 3:30 and 5:00pm on a summer day, thus relatively high demand variations were likely to be present in the system. The measured pressure traces from tests 1 to 4 are shown in Figure 5.

The time of transient wave arrival ($t_{s,Mj}$) and the wave magnitude ($\Delta H_{Mj}=H_{Mj}(t_f)-H_{Mj}(t_s)$) at the measurement points were detected using CUSUM test. Parameters of CUSUM test were selected based on the normal pressure variations recorded prior to the testing and were:

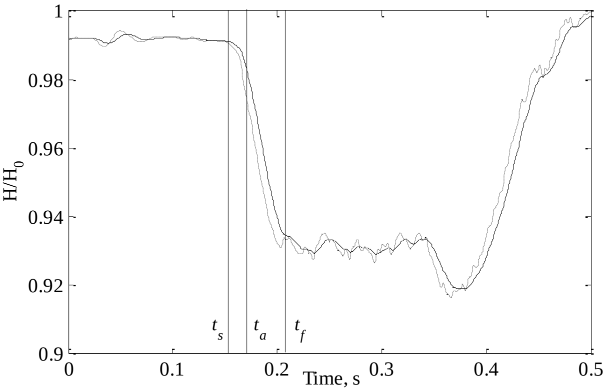
$$\lambda_{min}=0.75,\ \lambda_{max}=0.995,\ \nu = 0.002,\ h = 0.3$$

Figure 5. Measured pressure traces for tests 1 to 4



The example of CUSUM test results is shown in Figure 6. Burst-induced pressure waves were successfully detected in all measured traces except the one at point M1 during test 2. The change in pressure was too small to exceed the threshold value. Thus, only two measurement locations were utilized during test 2.

Figure 6. Test 3. The measured pressure trace at point M1 and the transient wave arrival times t_s, t_a and t_f detected by CUSUM test. The dotted line is data before filtering and the solid line is data after filtering.



The objective function (Equation (7)) was calculated for all burst candidate locations (all nodes in the network). Weights w_1=0.7 and w_2=0.3 were chosen to reduce the influence of a possible error in the measured transient wave magnitude due to secondary reflections from other parts of the network that arrive to the measurement point shortly after the burst-induced wave. Results for tests 1 to 4 are summarized in Table 1.

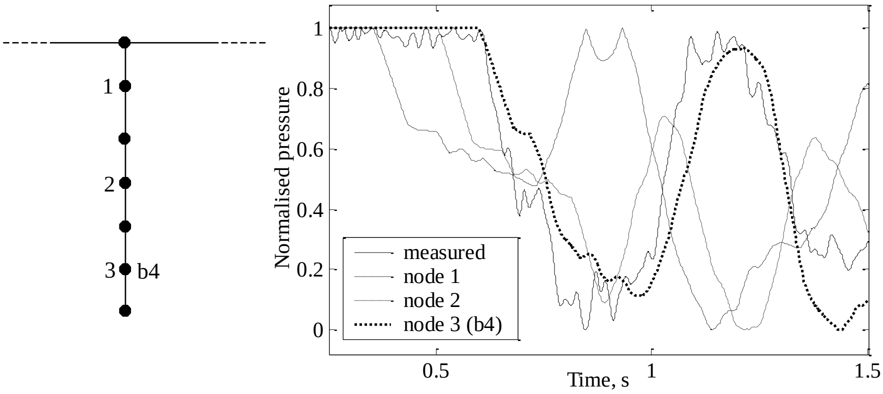
Table 1. Burst detection tests and results.

Test No.	Actual burst parameters			Detected burst parameters		
	Location	Opening, sec	C_dA_o	Location	Opening, sec	C_dA_o
1	b1	0.04	$5.5\cdot10^{-5}$	b1	0.068	$6.17\cdot10^{-5}$
2	b2	0.04	$5.5\cdot10^{-5}$	b2	0.055	$4.68\cdot10^{-5}$
3	b3	0.04	$5.5\cdot10^{-5}$	b3	0.047	$2.40\cdot10^{-5}$
4	b4	0.04	$5.5\cdot10^{-5}$	b4*	0.0335	$2.87\cdot10^{-5}$

*all nodes on the same branch as b4 had equal OF. Simulation was used to identify actual burst location.

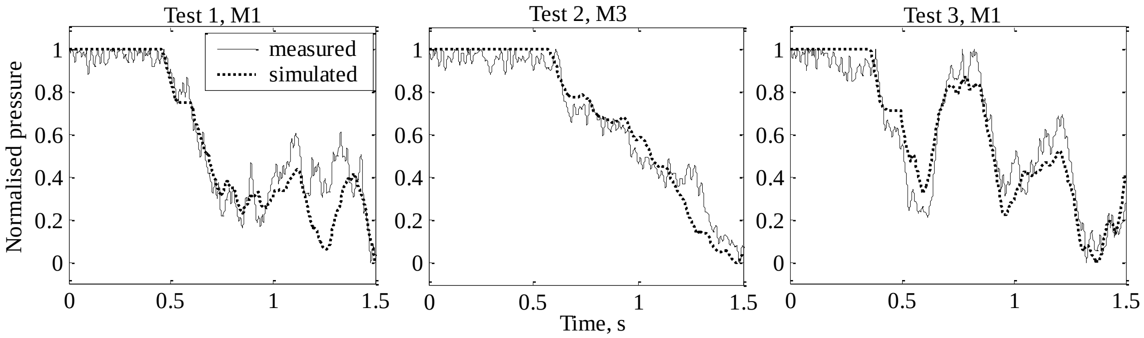
All bursts were successfully located including b2 (test 2) where the transient wave was detected at only two monitoring stations. For test 4 a non-unique burst location was found. All the nodes on the same branch as the actual burst position b4 had the same value of the objective function. This is due to the fact that the burst-induced transient wave would take the same path to the measurement points for all the possible burst locations on the branch. To find the actual location the burst was simulated using a transient model at three locations on the branch (nodes 1, 2 and 3 in Figure 7) and the resulting 1.5 sec pressure traces at the measurement point M3 were compared to the measured one. To eliminate the influence of the error in the burst size estimate, pressure traces were normalized. Node 3 (b4) had the closest fit and was selected as a burst location. As already mentioned, the transient wave magnitude detected in the measured pressure traces can be affected by secondary reflections and therefore the error in the estimated burst size is observed. However, the burst size estimate is only used to evaluate the extent of the event and the precision is not essential.

Figure 7. Test 4. The branch of the network where a non-unique burst location was found (left) and the comparison between measured and simulated pressure traces at point M3 (right). The burst was simulated at nodes 1,2 and 3.



The model was also used to verify the burst locations derived for tests 1 to 3. The comparison between measured and simulated pressure traces is shown in Figure 8. A relatively good fit between measured and simulated data was observed, especially considering the fact that the model has not been calibrated. If calibrated, the model is likely to mimic the real system substantially better.

Figure 8. Verification of burst locations for tests 1 to 3



Conclusions

Validation of a proposed burst detection and location technique on a real water distribution network has shown promising results. Bursts of relatively small sizes (the cross-section area of the burst equal to 0.99% of the cross-section area of the pipe) simulated at different locations within the network at the time of the day with high demand fluctuations were successfully detected. Three measurement points were used to locate the actual burst point from the 79 burst candidate nodes. In the case when the unique location of the burst was not found (for a burst on the dead-end branch of the network), the simulated burst traces were used to identify the actual location of the burst. Simulations were also performed to verify the locations of bursts that were successfully located by the technique. For optimal operation of the burst monitoring technique, the parameters have to be tuned for a particular pipe network. Network topology, demand characteristics and measurement accuracy, as well as the accuracy of the network's model are factors influencing the performance of the burst detection and location technique. The main performance indicators are: (a) the minimum burst size that can be detected, (b) the maximum burst opening time and (c) the false alarm rate. The proposed methodology could be implemented as a continuous monitoring system of the sudden pipe failure in the water distribution networks. The on-line monitoring enables the immediate response to the burst event. The failure isolation time can be minimized preventing large losses. If implemented, the proposed technique could increase the efficiency and reliability of the water supply. The cost of installation is relatively low and the investment return time is expected to be short.

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