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Burst detection and location in water transmission pipelines

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Abstract

This paper presents results from testing of a burst detection and location technique on a water transmission pipeline. The primary targets of the method are medium and large bursts that are the result of a sudden rupture of a pipe wall or other physical element in the pipeline system. The technique is based on the continuous monitoring of the pressure in the pipeline combined with a hydraulic transient modeling. Analysis of a burst–induced pressure transient wave and its reflections from the pipeline boundaries is used to derive the location and size of the burst. The method has earlier demonstrated promising results on a laboratory pipeline and a dead-end branch of a real water distribution network. Results presented here show that the approach has a potential to be used for burst detection and location in long transmission pipelines. Bursts of different sizes, locations and opening times were successfully detected and located. Different operational regimes of the pipeline were considered. The technique could help to minimize the response time to the pipe failure and therefore reduce the losses associated with a burst and improve reliability of the pipeline operation.

Introduction

Water transmission pipelines are built with the purpose of transporting large volumes of water over long distances. A burst is a common failure of pipelines and can have very serious consequences. The large volume of lost water is only one part of the total loss associated with the burst. Burst might cause unacceptably long outage of the pipeline, surrounding property might be flooded and water might damage other infrastructure around the burst site. Thus, the costs of the burst can become considerable. In order to minimize losses caused by the burst, it is essential to isolate the damaged section of the pipeline as quickly as possible. Although most bursts in transmission pipelines are visually obvious, not all will be detected in a short period of time. In many cases, pipelines are running through remote rural areas and it can take a long time to detect, locate and isolate a burst.

A number of different techniques for pipe burst detection have been applied in the gas and oil industries (Schlattman 1991; Wang *et al.* 1993; Liou and Tian 1995; Silva *et al.* 1996; Rajtar and Muthiah 1997; Zhang 2001). Most of them combine continuous monitoring of the physical parameters with some form of mathematical modelling. Usually the techniques using more measurements have better performance. However, in case of water transmission pipelines, the budget is often restricted and systems requiring the least amount of hardware installation are likely to be of the most interest.

This paper presents the testing of the burst detection and location technique on a large-diameter water transmission pipeline. The approach combines the continuous pressure monitoring at one point along the pipeline and time domain reflectometry (TDR) theory (Jönsson and Larson 1992). A detailed description of the method can be found in Misiunas *et al.* (2005) along with validation on both a laboratory pipeline and a dead-end branch of the real water distribution network.

Methods

Background. The location of a burst in a pipeline can be determined based on the timing of the pressure transient wave reflections (Misiunas *et al.* 2003; Misiunas *et al.* 2005). Consider the simplified example pipeline in Figure 1a where a break occurs at point B and the pressure is measured at point M, $x_{B,1}$ and $x_{B,2}$ are the distances from the burst point to the boundaries 1 and 2 respectively and $x_{M,1}$ and $x_{M,2}$ are the distances from the measurement point to the boundaries 1 and 2 respectively. Figure 1b shows the idealized transient pressure trace at point M after the break has occurred.

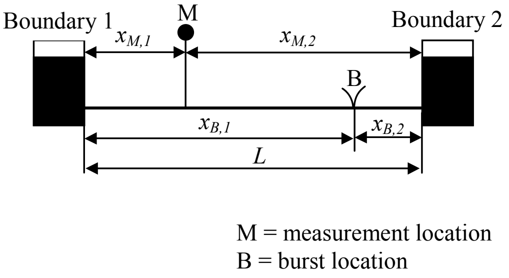


Figure 1a. The example pipeline system

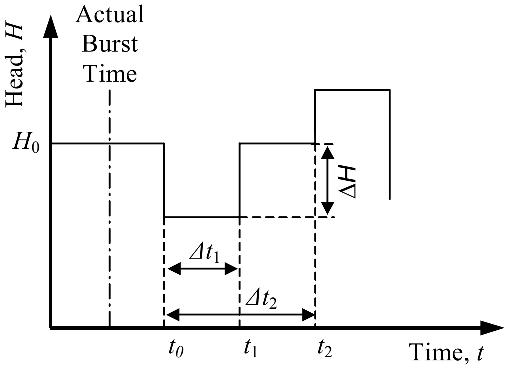


Figure 1b. The idealized burst transient trace for the example pipeline system

If the example trace is considered, the position of the break can be estimated using time differences $\Delta t_1 = (t_1 - t_0)$ and $\Delta t_2 = (t_2 - t_0)$ and following rules:

$$
\begin{aligned}
&\text{if } \Delta t_1 = \frac{2\cdot x_{M,1}}{a} \quad \text{then} \quad x_{B,2} = \frac{a\Delta t_2}{2}\\
&\text{if } \Delta t_1 = \frac{2\cdot x_{M,2}}{a} \quad \text{then} \quad x_{B,1} = \frac{a\Delta t_2}{2}\\
&\text{if } \Delta t_2 = \frac{2\cdot x_{M,1}}{a} \quad \text{then} \quad x_{B,2} = \frac{a\Delta t_1}{2}\\
&\text{if } \Delta t_2 = \frac{2\cdot x_{M,2}}{a} \quad \text{then} \quad x_{B,1} = \frac{a\Delta t_1}{2}
\end{aligned} \tag{1}
$$

where a is a wave speed of the pipe. Due to the uncertainty of the wave speed and the detected pressure change times t_0, t_1 and t_2 the conditions in Equation (1) may not hold exactly. Thus, the case having the best fit should be used to determine the break location.

Burst monitoring, detection and location. The continuous burst monitoring algorithm is illustrated in Figure 2 and can be divided into three parts: (1) the continuous on-line monitoring of measured pressure for a burst event (burst-induced transient wave), (2) gathering of the data window necessary to estimate burst parameters, and (3) analysis of the gathered data and burst parameter estimation.

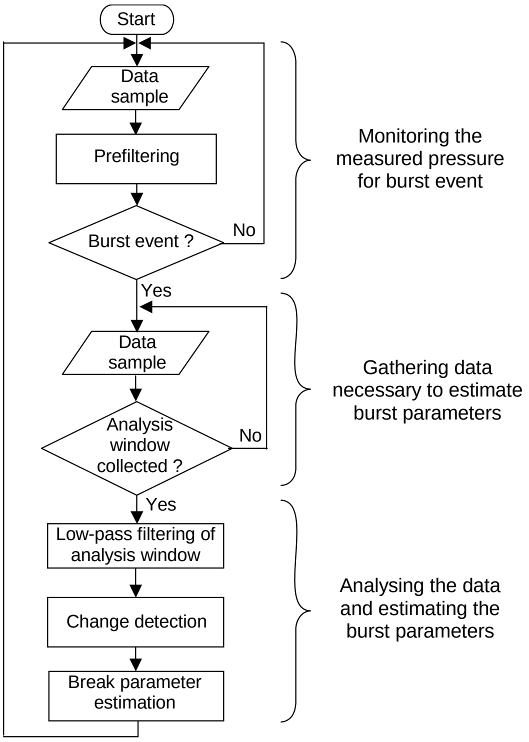


Figure 2. Continuous burst monitoring algorithm structure

(1) *Monitoring for a break event*. The cumulative sum (CUSUM) test (Page 1954) is used to detect the negative burst-induced transient wave in the pressure measurement. In case of a measurement noise, the data can be pre-filtered using the Recursive Least Squares (RLS) filter that estimates the signal θ_t from the

measurement y_t (containing noise) as $\theta_t = \lambda\theta_{t-1} + (1-\lambda)y_t$ The parameter $\lambda \in [0,1)$ is the forgetting factor limiting the smoothing effect of the filter. Residuals $\varepsilon_t = \theta_t - \theta_{t-1}$ are fed into a CUSUM change detection test:

$$
\begin{aligned}
&S_0 = 0, \quad S_t = \max\left(S_{t-1} - \varepsilon_t - \nu, 0\right) \\
&\text{if } S_t > h \text{ then issue alarm and set } t_a = t,\ S_t = 0
\end{aligned}
\tag{2}
$$

where S is the cumulative sum value, h and ν are threshold and drift parameters respectively. Threshold and drift parameters must be tuned for a particular pipeline based on typical fluctuations in the measured operational pressure.

(2) *Analysis window*. After the burst event is detected, a window of data $[t_a : t_a + T_w]$ that is sufficient for deriving the location of the break is collected for further analysis. T_W is a window length in time units:

$$
T_W = \frac{2 \cdot \max\left(x_{M,1}, x_{M,2}\right)}{a}
\tag{3}
$$

(3) *Burst parameter estimation*. Further analysis of the data window is performed offline. To remove the high frequency noise, the data is filtered using a Butterworth low-pass filter. An example of analysis window selection and the effect of filtering are illustrated in Figure 3a.

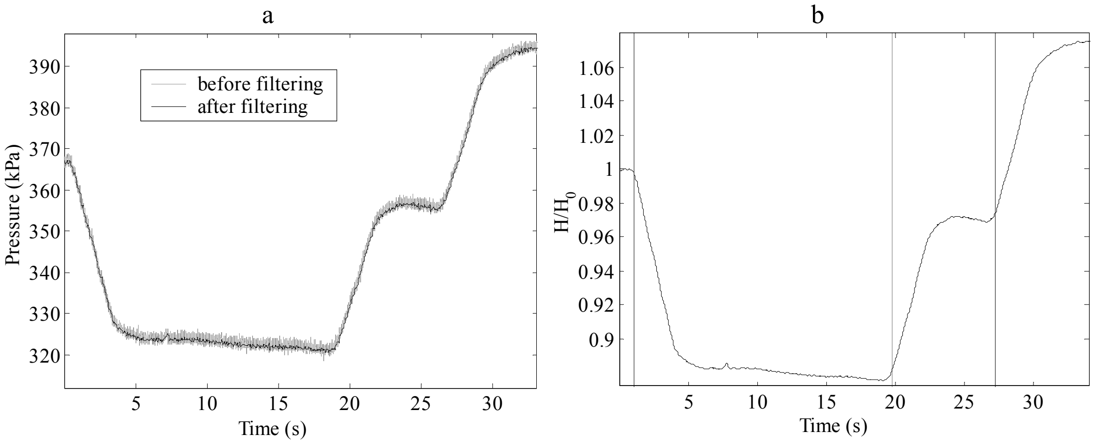


Figure 3. (a) The analysis window before and after low-pass filtering. (b) The instances of burst-induced transient trace (vertical lines) that have to be identified.

The timing of changes in the pressure data (vertical lines in Figure 3b) that corresponds to a burst-induced transient wave and its reflections from the boundaries are detected by a two-sided CUSUM change detection test:

$$
\begin{aligned}
&S_0^1 = 0 \quad \text{and} \quad S_0^2 = 0 \\
&\varepsilon_t = y_t - y_{t-1} \\
&S_t^1 = \max\left(S_{t-1}^1 + \varepsilon_t - \nu, 0\right) \quad \text{and} \quad S_t^2 = \max\left(S_{t-1}^2 - \varepsilon_t - \nu, 0\right) \\
&\text{if } \left(S_t^1 > h \text{ or } S_t^2 > h\right) \text{ then } \left(\text{issue alarm and set } t_a = t,\ S_t^1 = S_t^2 = 0\right)
\end{aligned}
\tag{4}
$$

For better performance of the change detection algorithm, an adaptive tuning of the threshold and drift parameters is implemented. After the magnitude of the burst transient wave has been identified (ΔH in Figure 1b), the threshold h is adjusted specifically to detect the reflections of the wave from the pipeline boundaries. The drift ν is tuned to account for the variation of the filtered pressure trace (dH/dt) prior to the first transient wave arrival (Figure 3b).

After the changes in pressure data have been detected and the time differences Δt_1 and Δt_2 calculated, the break position can be derived from Equation (1). Once the break is located, the section of the pipeline that contains the break can be isolated and then repaired.

Field validation results

An operational water transmission pipeline was used for testing the burst detection and location technique. The 26 km long pipeline is a part of the larger system and conveys water between the treatment plant pumping station on the upstream end and two large water tanks on the downstream end. A schematic view of the pipeline is shown in Figure 4.

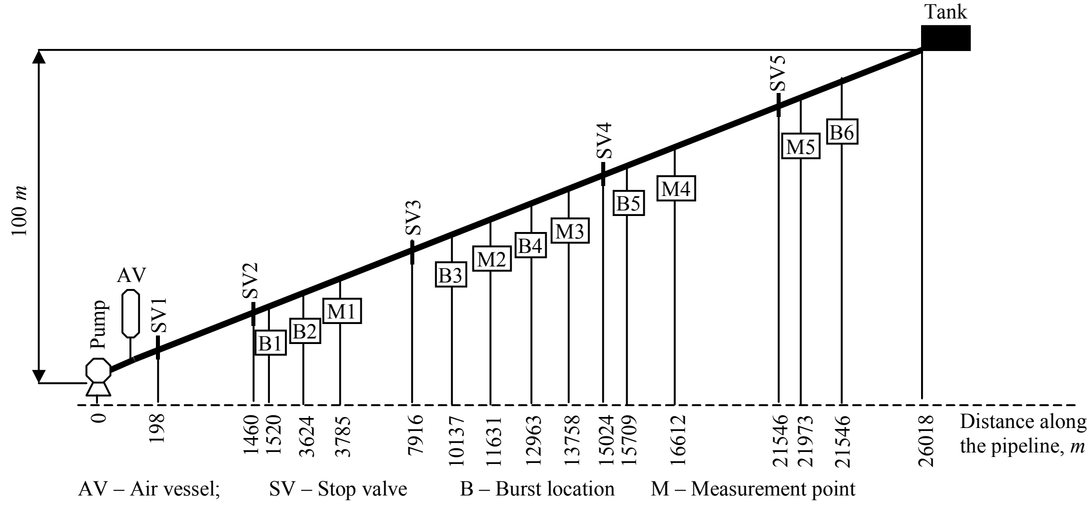


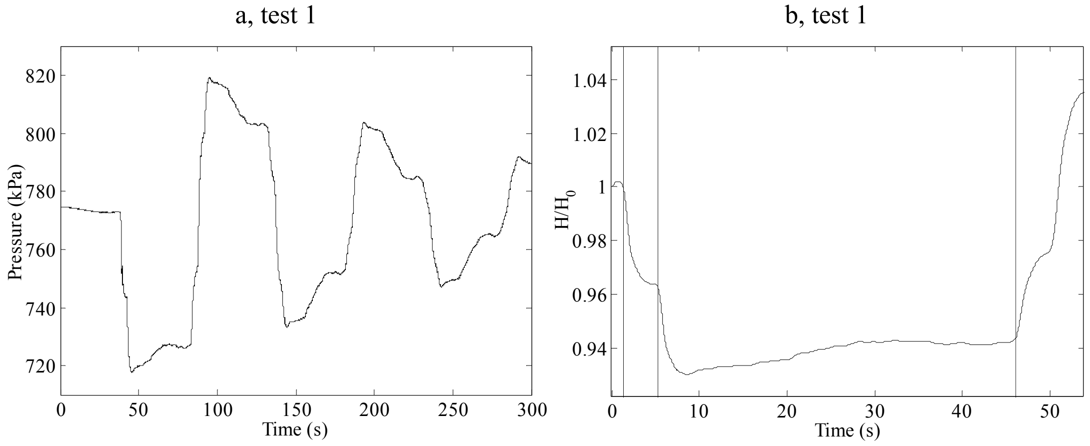
Figure 4. The layout of the pipeline

The MSCL (mild steel concrete lined) pipeline has a diameter of 750 mm and consists of three segments with different wall thicknesses (starting from the upstream end) - 5614 m of 7.94 mm, 6126 m of 6.35 mm, and 14278 m of 4.76 mm. This is quite an unusual design and makes the derivation of the wave speed value more complex. The wave speeds of 1100 m/s, 1030 m/s and 950 m/s were estimated for the three segments respectively (starting from the upstream boundary). The bursts were simulated using the opening of the side-discharge valve (with diameters of 40 mm and 50 mm) or the fire hydrant (with diameter of 30 mm). The pressure was measured at a sampling frequency of 2000 Hz using a Druck 810 pressure transducer and recorded to a notebook computer using 12-bit data acquisition card and Visual

Designer software. The following parameters were used in the three parts of the burst monitoring, detection and location algorithm:

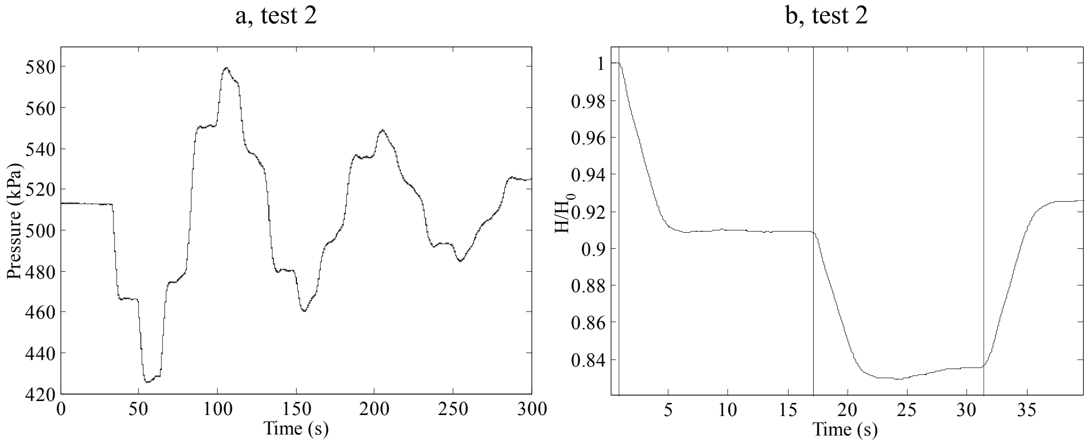
Monitoring for a burst event	λ	0.999
	h	0.5
	ν	0.0007
Butterworth filter for analysis window	order	2
	f_{cutoff}	10 Hz
Burst parameter estimation	h	Automatically tuned to 0.2 ΔH
	ν	Automatically tuned to dH/dt

A total of 11 tests were performed. For the first 9 tests there was no flow in the pipeline to represent the situation when no pumping is performed. A closed inline valve was acting as an upstream boundary. Burst locations and measurement point that were used in tests 1 to 9 are shown in Figure 4 and listed in Table 1. Different burst locations, sizes and opening times as well as measurement positions were used to evaluate the performance of the burst detection and location. Different inline valves were closed for different tests to alternate the length of the pipeline and extend the range of tested burst locations. As an example, measured pressure traces, analysis windows and CUSUM test results are shown in Figure 5 and Figure 6 for tests 1, 2 and 7, 8 respectively. The detailed results for all tests are given in Table 1.



a, test 1

b, test 1



a, test 2

b, test 2

Figure 5. Test 1 (burst at B2) and Test 2 (burst at B3). (a) Measurement point at M1.

Measured burst traces and (b) filtered data windows. Vertical lines indicate the changes detected by CUSUM.

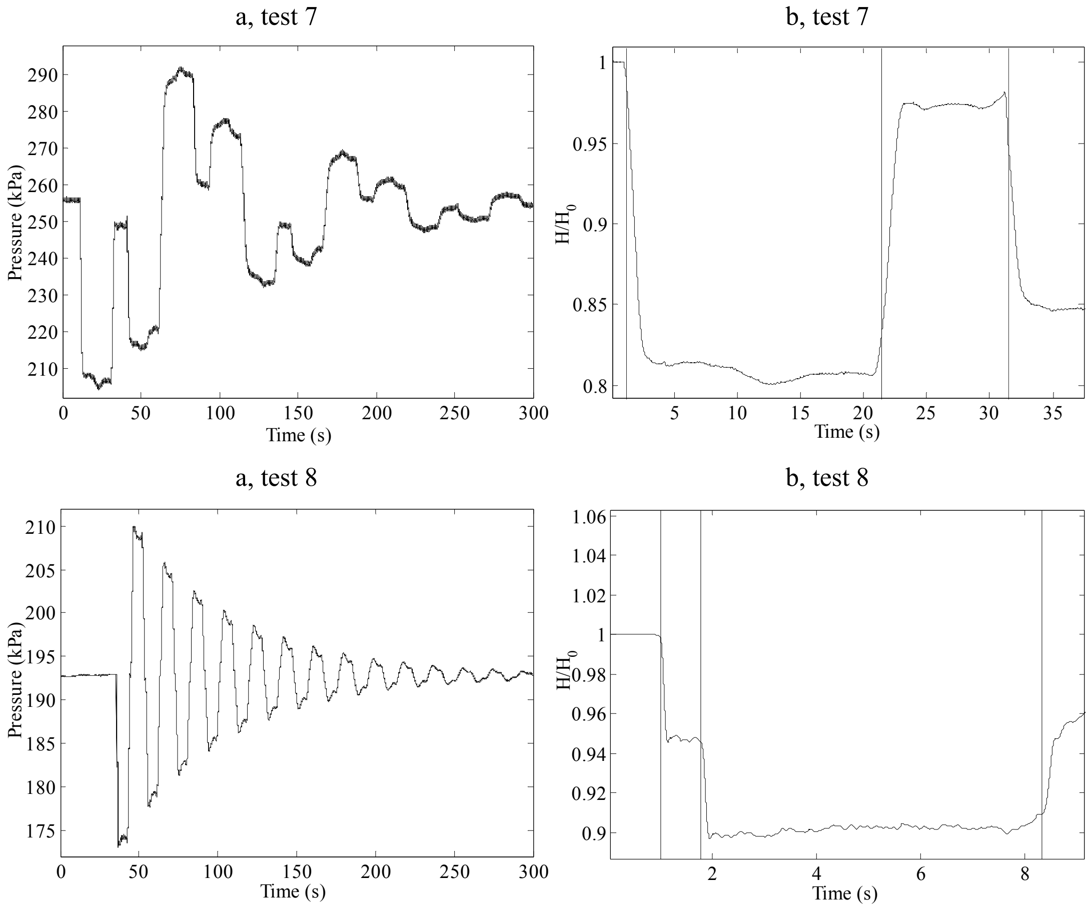


Figure 6. Test 7 (measurement at M4 and burst at B5) and Test 8 (measurement at M5 and burst at B6). (a) Measured pressure traces and (b) the filtered analysis windows. Vertical lines indicate changes in pressure detected by CUSUM.

The transient wave reflection from the valve has the same sign as the wave itself, whereas the reflection from the tank has the opposite sign. In Figure 5 and Figure 6 the influence of the burst location on the timing and the arrival order of the transient wave reflections from the tank and the valve can be observed.

Table 1. Summary of burst detection and location tests.

Test No.	Upstream boundary	Measured at, *m*	Burst size[*], *L/s*	Burst opening, *s*	Burst location, *m*		
					Actual	Found	Error
1	SV2[**]	M1	19.3	1.25	3624 (B2)	3638	14
2	SV2	M2	35.5	3.22	10137 (B3)	10143	6
3	SV1	M2	40.8	1.56	10137 (B3)	10217	80
4	SV2	M3	43.0	4.20	15709 (B5)	15614	94
5	SV3	M3	43.0	6.74	15709 (B5)	15619	90
6	SV2	M4	44.5	2.84	12936 (B4)	13026	90
7	SV1	M4	37.5	1.23	15709 (B5)	15674	35
8	SV5	M5	8.8	0.13	22622 (B6)	22618	4
9	SV2	M2	19.9	0.86	1520 (B1)	1460	60

All locations are given as a distance from the upstream pump station.
[*] Burst size was calculated from the measured change in pressure. [**] SV = stop valve.

Two tests were conducted with the pump running. Two locations of the bursts were tested for the same measurement point (tests 10 and 11). The nominal flow in the pipeline was 496 L/s. As an example, the measured burst pressure trace, analysis window and results of CUSUM for test 10 are shown in Figure 7. More details for both tests are given in Table 2.

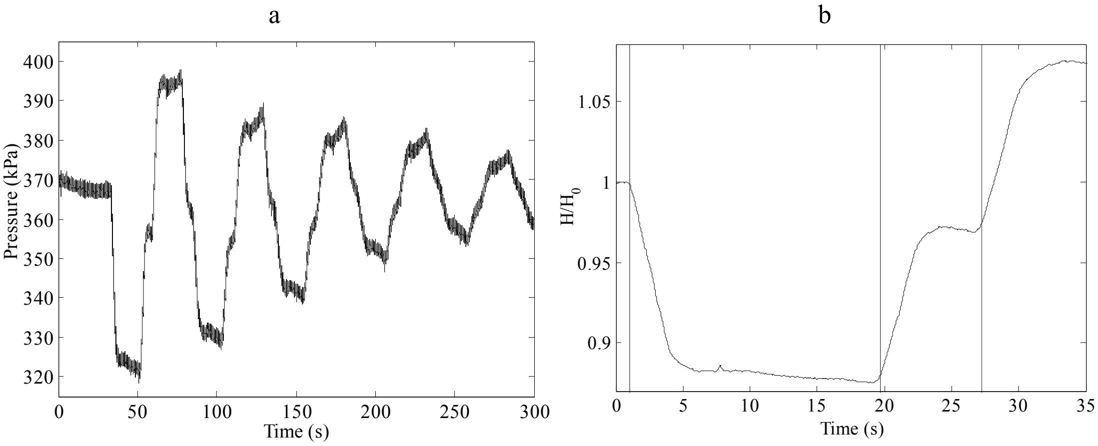


Figure 7. Test 10, measurement at M3 and burst at B3. (a) Measured burst trace and (b) filtered data window. Vertical lines indicate changes detected by CUSUM.

Since the pump was running the air vessels adjacent to the pump station were acting as an upstream boundary condition for a burst–induced wave. Therefore reflections from both boundaries have the same sign as shown in Figure 7a.

Table 2. Summary of burst detection and location tests.

Test No.	Upstream boundary	Measured at, *m*	Burst size[*], *L/s*	Burst opening, *s*	Burst location, *m*		
					Actual	Found	Error
10	Pump	M3	34.6	3.07	10137 (B3)	10193	56
11	Pump	M3	45.1	6.63	15709 (B5)	15566	143

All locations are given as a distance from the upstream pump station.
[*] Burst size was calculated from the measured change in pressure.

Discussion

The overall performance of the burst detection and location technique is very promising. Different burst sizes between 8 and 50 L/s and burst opening times from 0.1 s up to 6.8 s were tested. Six different burst locations and five measurement points were used. Most of bursts were successfully detected and located. As shown in Table 1 and Table 2, the error of in the burst location varies between 4 and 143 m, which is sufficiently small to be able to identify the section of the pipeline that has to be isolated. There are few issues that must be given special attention when evaluating the performance of the approach: (1) the minimum detectable burst size limit, (2) the burst located close to the boundary, (3) measurement position, (4) bursts caused by the pump operation.

(1) *The minimum detectable burst size limit.* The success of burst detection depends on the combination of two burst parameters – the size and the opening time. The shorter the opening time, the smaller the burst that can be detected and the larger the burst, the slower it can be. For instance, with parameters that were used during the tests, the technique would detect an abrupt burst with the size of 2 L/s as well as a 100 L/s burst having the opening time of 10 s. It has to be noted that only the detection of the burst event is considered when deriving the size of the smallest burst that can be detected. Even if the burst was successfully detected, the precision of its location derived by the technique is influenced by the distance from the burst to the closest boundary.

(2) *The burst located close to the boundary.* Test 9 is an example of the burst that occurs close (60 m) to the boundary. The measured pressure trace and the changes detected by CUSUM are shown in Figure 8.

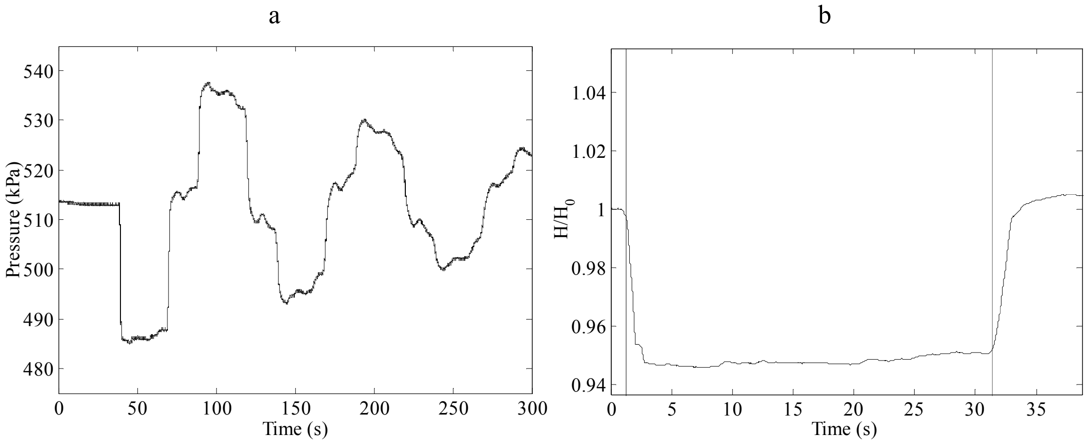
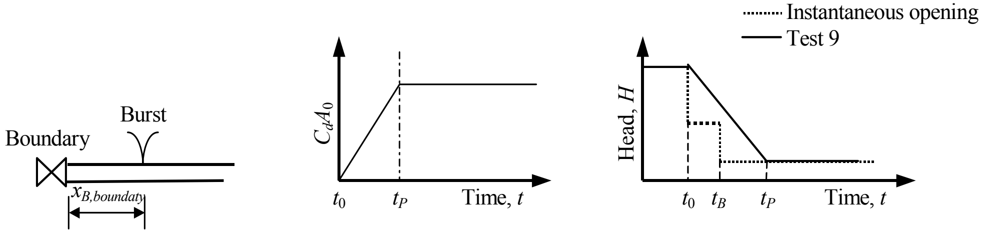


Figure 8. Test 9, measurement at M2 and burst at B1. (a) Burst trace and (b) the filtered analysis window. Vertical lines indicate changes detected by CUSUM.

The burst location was not found since only two changes in pressure were detected (Figure 8b). The more detail explanation of the situation is given in Figure 9. Assume that t_p is burst opening time and t_B is the time it takes for the burst-induced wave to travel to the boundary and back. Figure 9c shows the comparison of the pressure trace measured during test 9 with the theoretical pressure trace for the same burst that occurs instantaneously (t_p=0).



(a) Break near Boundary (b) Break Opening Profile (c) Head Response at Break

Figure 9. The occurrence of a break near a pipeline boundary

If $t_p > t_B$, the initial burst wave is still being generated when its reflection from the boundary reaches the burst point. In other words, the arrival of the burst wave reflection cannot be identified if the following condition is true:

$$x_{B,boundary} < \frac{t_P \cdot a}{2} \tag{5}$$

If the analysis window for test 9 is extended (Figure 10) it appears that the third change in pressure corresponds to the distance $2L/a$ where L is the length of the pipeline. This together with the fact that the second detected change indicated the reflection from tanks (sign opposite to the initial wave) suggests that the reflection from the valve has not been detected. Thus, the burst is assumed to be located within the distance of $0.5(t_p\ a)$ from the valve (Equation (5)). To verify this assumption, the burst was simulated 50 m away from the valve using the pipeline model. The transient pressure is solved by the method of characteristics (MOC) (Wylie and Streeter 1993). A good match between simulated and measured pressure traces is shown in Figure 10b and proves that burst was located close to the valve.

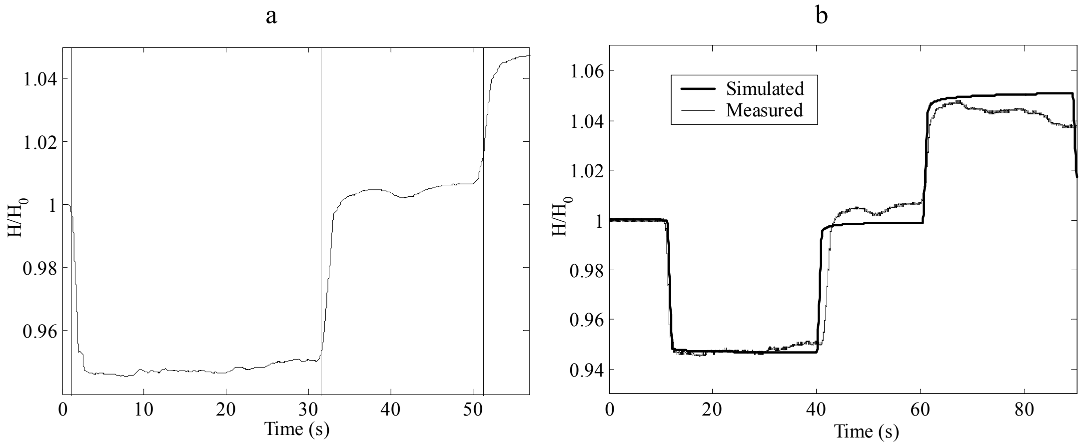


Figure 10. (a). The extended analysis window for test 9. Vertical lines indicate pressure changes detected by CUSUM. (b) The comparison between simulated and measured pressure traces for test 9.

(3) *The measurement position*. The measurement position can cause an error in the derived burst location when (a) the burst and the measurement positions are symmetrical with respect to the boundaries ($x_{M,1} = x_{B,2}$) – waves induced by a burst

reach the measurement point at the same (or almost the same) time and (b) the pressure is measured at the centre of the pipeline ($x_{M,1} = x_{M,2}$) – the arrival times of the pressure reflections coincide making determination of the true burst location difficult.

(4) *Bursts caused by the pump operation*. Two operational regimes of the pipeline have been considered so far – the pump being off and the pump being on. The third regime is transition between two abovementioned ones, i.e. pump start-up and shutdown. Figure 11 shows typical pump start-up and shutdown traces (no burst) measured at M4. In certain situations, a pipeline break can occur during a pressure transient that is caused by a pump start-up/shutdown. Dealing with bursts that are initiated by the pump operation requires special attention. One option is to model the pressure response of a transient initiated by the pump and compare the simulated trace to the measured one. The discrepancy between modelled and actual pressure traces would indicate a burst event.

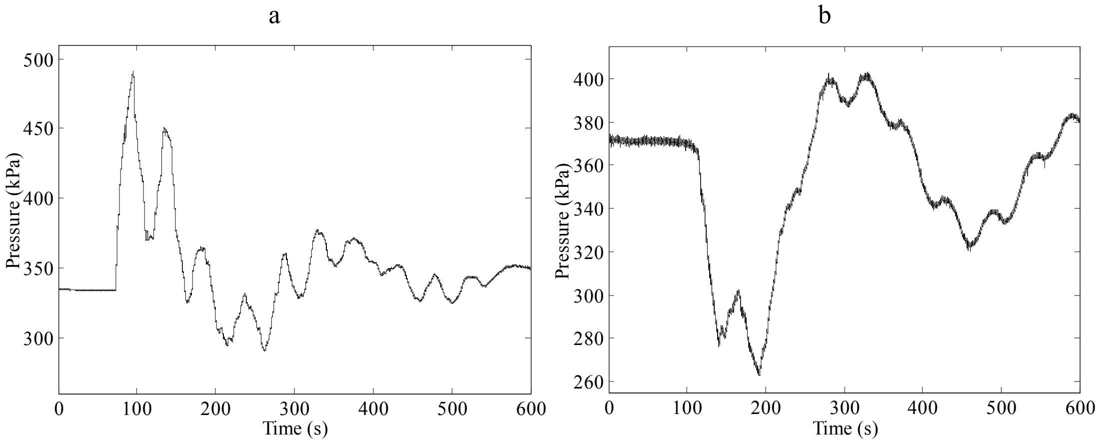


Figure 11. The pressure traces of (a) pump start-up and (b) pump shutdown

Since there is a standard procedure for pump operation and the hydraulic environment of the pipeline does not vary considerably, is it likely that the traces of pump start-up/shutdown will be similar each time. Thus, the historical measurements of pump start-up/shutdown can be used as a reference instead of the model. Due to the complexity of the experimental setup, testing for bursts that are initiated by the pump start-up/shutdown was not conducted.

Conclusions

Overall results of validation of the burst detection and location technique on a real water transmission pipeline are very promising. The method was tested using artificially induced medium and large bursts with opening times in a range of seconds. Bursts having different sizes, burst opening times and locations were successfully detected and located. The observed error in the location is sufficiently small to identify the section of the pipeline where the burst has occurred. The approach can be applied in three different regimes of the pipeline operation – offline, online and transient. An offline regime represents the situation when water is not being pumped and the upstream boundary of the pipeline is a dead-end. An online regime corresponds to the time when the pump is on and the downstream reservoir is being filled. The start-up and shutdown of the pump represent the transient regime of operation. The performance of the burst detection and location technique depends on the combination of three main factors: the size of the burst to be detected, its opening time and location (the distance to the closest boundary). There are two main performance indicators – the failure rate (number of bursts that are not detected) and the precision of the derived burst location. As far as the failure rate is concerned, the technique has a lower limit of the ratio between burst size and opening time and bursts that are smaller/slower will not be detected. The limit of detectable burst size can be controlled by tuning parameters of the burst monitoring algorithm, however, trying to detect very small bursts can lead to the high false alarm rate. Once detected, some bursts might not be precisely located. The example of such a situation is a burst that occurs close to the boundary of the pipeline. In case of uncertainty, a transient model can be used to verify the derived location or size of the burst.

Due to the fact that only a single point pressure measurement is required, the cost of installation of the burst detection and location system is quite low. If implemented, the approach would allow extremely quick reaction to the pipe failure. Consequentially, the damaged section of the pipeline could be isolated soon after the burst event minimising the volume of lost water and repair costs.

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References

Jönsson, L., and Larson, M. (1992). "Leak Detection through Hydraulic Transient Analysis." *Pipeline Systems*, B. Coulbeck and E. P. Evans, eds., Kluwer Academic Publishers, 273-286.

Liou, J. C. P., and Tian, J. (1995). "Leak Detection - Transient Flow Simulation Approaches." *Journal of Energy Resources Technology*, 117(September), 243-248.

Misiunas, D., Vitkovsky, J., Olsson, G., Simpson, A. R., and Lambert, M. F. (2005). "Pipeline Break Detection Using the Transient Monitoring." *Journal of Water Resources Planning and Management*, ASCE (to appear July 2005).

Misiunas, D., Vítkovský, J. P., Olsson, G., Simpson, A. R., and Lambert, M. F. (2003). "Pipeline Burst Detection and Location Using a Continuous Monitoring Technique." *International Conference on Advances in Water Supply Management, CCWI*, Imperial College London, UK.

Page, E. S. (1954). "Continuous Inspection Schemes." *Biometrika*, 41, 100-115.

Rajtar, J. M., and Muthiah, R. (1997). "Pipeline Leak Detection System for Oil and Gas Flowlines." *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, 19(February), 105-109.

Schlattman, D. T. (1991). "Pressure Analysis Improves Lines' Leak Detection Capabilities." *Oil and Gas Journal*, 89(52), 98-101.

Silva, R. A., Buiatti, C. M., Cruz, S. L., and Pereira, J. A. F. R. (1996). "Pressure Wave Behaviour and Leak Detection in Pipelines." *Computers & Chemical Engineering*, 20(Supplement 6. Part A), S491-S496.

Wang, G., Dong, D., and Fang, C. (1993). "Leak Detection for Transport Pipelines Based on Autoregressive Modeling." *IEEE Transactions on Instrumentation and Measurement*, 42(1), 68-71.

Wylie, E. B., and Streeter, V. L. (1993). *Fluid Transients in Systems*, Prentice-Hall Inc., Englewood Cliffs, New Jersey, USA.

Zhang, J. (2001). "Statistical Pipeline Leak Detection for All Operating Conditions." *Pipeline & Gas Journal*, 42-45.