TRANSIENT-BASED PERIODICAL PIPELINE LEAK DIAGNOSIS[1]

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Abstract

In this paper, a periodical pipeline leak diagnosis technique based on transient response difference monitoring is presented. During past two decades, a considerable amount of research effort has been dedicated to the application of controlled hydraulic transients for pipe leak detection and location. Leak reflection method (LRM) and inverse transient analysis (ITA) are the most popular techniques described in the literature. Significant improvements of the theoretical part of the two methods have been presented. However, available experimental results indicate that both LRM and ITA approaches suffer from model precision-related errors. As a result, only large leaks can be detected and located. The fundamental principle of the proposed methodology is the assumption that leak diagnosis will be performed periodically. Leakage detection is considered to be a repetitive procedure that is a part of the active failure monitoring system, which is permanently installed on the pipeline. The technique does not use the model of a pipeline to detect and locate leaks and, therefore, eliminates the model-related errors. A transient response of the pipeline system is measured periodically and the difference between transient responses is monitored to identify the presence of a leak/leaks. Leaks of relatively small size can be successfully detected and located. The performance of the proposed method was evaluated on the real large water transmission pipeline and positive results were observed. The lower limit of the detectable leak diameter was estimated to be as small as 0.31% of the pipeline diameter. The observed precision of the derived leak location was less than 0.3% of the total pipeline length. Proposed periodical leak diagnosis system allows for a quick and inexpensive leak detection and location in water transmission mains. The technique is also able to detect and locate other pipeline abnormalities, such as blockages and air pockets. The approach can be installed separately or be integrated with the continuous burst monitoring technique that was earlier developed by the authors to form a multi-type pipeline failure detection and location system.

Keywords
Pipelines, leakage, transient, detection, location, diagnosis

1. INTRODUCTION

Pipe failure is a frequent event in water supply systems. Pipe failure has different types depending on the size and the character; however, any failure results in a larger or smaller leak. Thus, leakage detection and location becomes an important issue. Depending on the application, leak detection can be associated with two different operations. In larger transmission pipelines, where larger failures are common, leak detection is usually associated with identifying discrete pipe failure events. Subsequent leak location involves the identification of the actual position of the leak. In distribution networks, leakage detection is often integrated with leakage assessment, where the amount of water that is lost due to leaks present in the

[1] Reference: **Misiunas, D., Lambert, M.F. and Simpson, A.R.** (2006). "Transient-based periodical pipeline leak diagnosis." 8th *Annual Symposium on Water Distribution Systems Analysis,* American Society of Civil Engineers, Cincinnati, Ohio, Utah, USA, 27–30 August.

system is estimated. Leakage is detected collectively and the identification of a particular leak is part of the location process. Generally, two leakage detection and location (sometimes also referred to as leakage control) strategies can be used for both pipelines and pipe networks: passive (manual) or active (automatic). If passive leak control is practiced, reaction to a leak incident is based on visual observations. For example, the appearance of water on the ground surface following pipe failure is visually detected by the staff or reported by costumers. Manual location techniques are then used to identify the actual location of the failure. Active leakage control includes management policies and processes that are used to locate and repair unreported leaks from the water supply system (Tripartite Group 2002). Active leakage control can involve systematic manual leak inspections or continuous monitoring for automatic detection of leaks. Manual leak location techniques are usually used; although some leak monitoring systems provide automatic location.

Passive leakage detection is straightforward, simple and does not involve any systematic action. Thus, it will not be discussed. Active leakage control techniques can further be divided into two groups: (i) inspection (survey) and (ii) monitoring. Inspection or survey leak detection is a planned action that is performed at discrete time instances. The inspection involves checking the whole or a part of the system to assess the level of leakage and find leaks that are already present. Continuous failure monitoring is used for detection of leak events in real-time. A monitoring system is installed on a pipeline or in the network permanently and is continuously checking for new leaks. A large number of leak detection and location techniques have been applied in real systems or have been described in the literature. The complete review can be found in (Misiunas 2005). In this paper only a brief overview will be given.

Commercially available leakage inspection methods can generally be divided into two large groups - acoustic inspection techniques and non-acoustic inspection techniques. In addition to these two groups, transient-based leak inspection methods are considered here due to high interest given to them by the research community. Acoustic inspection techniques, such as listening (Hunaidi and Chu 1999; Pilcher 2003; Chastain-Howley 2005), acoustic monitoring (Rajtar and Muthiah 1997; van der Kleij and Stephenson 2002) and Cross-correlation (Hunaidi and Wang 2004) are being used in water industry. Non-acoustic inspection techniques, such as tracer gas technique (Heim 1979; Heitbrink *et al.* 1999), thermography (Weil *et al.* 1994; Weil and Graf 1996), ground penetrating radar (GPR). (Hyun *et al.* 2003; Stampolidis *et al.* 2003; Nakhkash and Mahmood-Zadeh 2004) and pig-based methods (Anon 1997; Mergelas and Henrich 2005) are more common for gas and oil pipelines. All these methods have common drawbacks – short inspection range, sensitivity to noise, high time and labor demand. Hydraulic transient-based techniques can be seen as a cheaper and faster alternative. A number of hydraulic transient-based techniques for detecting and locating existing leaks are described in the literature: leak reflection method (LRM) (Jönsson and Larson 1992; Brunone 1999; Brunone and Ferrante 2001), inverse transient analysis (ITA) (Liggett and Chen 1994; Vitkovsky *et al.* 2000), impulse response analysis (IR) (Liou 1998), transient damping method (TD) (Wang *et al.* 2002), frequency domain response analysis (FDR) (Mpesha *et al.* 2001; Mpesha *et al.* 2002; Lee *et al.* 2005). The main objective of all transient leak detection methods is the same - extract information about the presence of a leak from the measured transient trace. Only LRM and ITA methods have been tested in field conditions (Brunone 1999; Jönsson 2001; Vítkovský *et al.* 2001; Stephens *et al.* 2004; Covas *et al.* 2005). Field results have showed that the performance of both techniques can be considerably enhanced by resolving model error-related problems. These problems will be illustrated in the next section, using a real example. In this paper, a periodical leak diagnosis system is presented that can be implemented on water transmission pipelines. The technique is based on the transient response difference monitoring. The approach does not use the transient model and therefore does not suffer from model-related problems observed while applying earlier methods. The technique is presented using test results from the real water transmission pipeline. The method is also shown to be effective for detecting and locating air pockets and blockages.

2. MODELLING LIMITATIONS WHEN APPLYING TRANSIENT-BASED LEAK DETECTION AND LOCATION TECHNIQUES

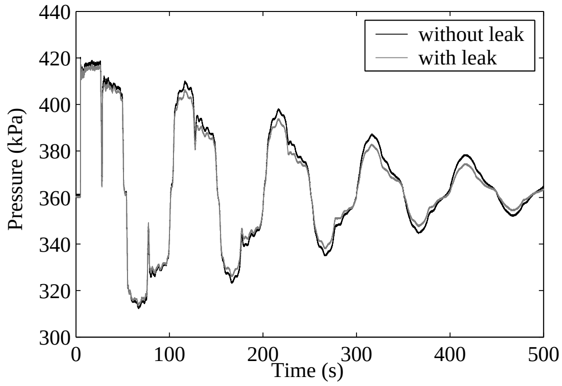

Figure 1. The comparison of pressure traces with and without leakage

In Figure 1, the transient response pressure traces from a real pipeline are shown. Parameters of the pipeline will be presented later in this paper. The transient was artificially generated by a sudden closure of the side-discharge valve and the response was measured for no leak and leak situations. Approximately 15 L/s leak was created artificially by opening a fire hydrant. The leak reflection method (LRM) and the inverse transient analysis (ITA), have been applied to detect the leak. To detect the leak and to derive its location, both LRM and ITA methods rely on the information that is concentrated mainly within the data window that corresponds to the first period of the transient wave (4L/a) starting from the first rise of the pressure in the measured trace. In fact, LRM only uses the data window from the first transient wave arrival to the arrival of its reflections from the boundaries (2L/a). An example of such window is shown in Figure 2.

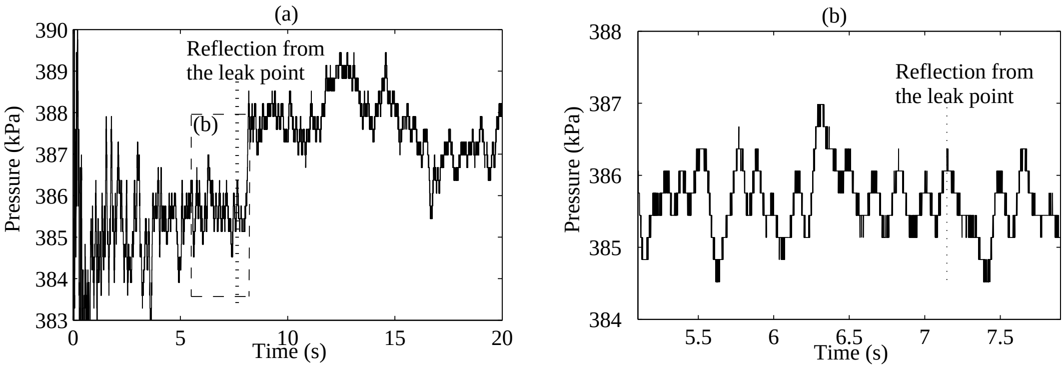

Figure 2. (a) Measured pressure response for a leak case with the vertical line indicating the reflection from the leak and (b) a closer view of the part of the trace showing the reflection from the leak

Traditionally, the LRM approach was based on timing of the transient wave reflection from the leak observed on the measured traces. From Figure 2 it is clear that the task becomes very difficult when a real pipeline is considered. The vertical dashed line indicates the time instance that corresponds to the actual location of the leak. It is unlikely that the reflection from the leak can be identified visually or by using data analysis techniques. The LRM method is designed assuming that the measured pressure trace in between the first rise and the reflection from the boundary will have a flat profile. In that case, the reflection of the generated wave from the leak point will cause a noticeable change on the measured trace. In the real pipeline, high frequency oscillations are present on the trace (Figure 2). Those oscillations is a composition of the measurement noise and reflections from different elements of the pipeline. Any change of the physical properties of the pipe will cause a reflection of the transient wave as it propagates along the length of the pipeline. Many of these reflections have similar character as the reflection from the leak, which makes the detection of the latter difficult and sometimes even impossible as demonstrated in Figure 2.

The ITA approach is based on minimizing the difference between measured and simulated traces. The leak is placed at different location in the model and the simulation results are compared to the actual measurement. An example is shown in Figure 3, where the leak is simulated at the actual location and the obtained trace is compared to the measured one.

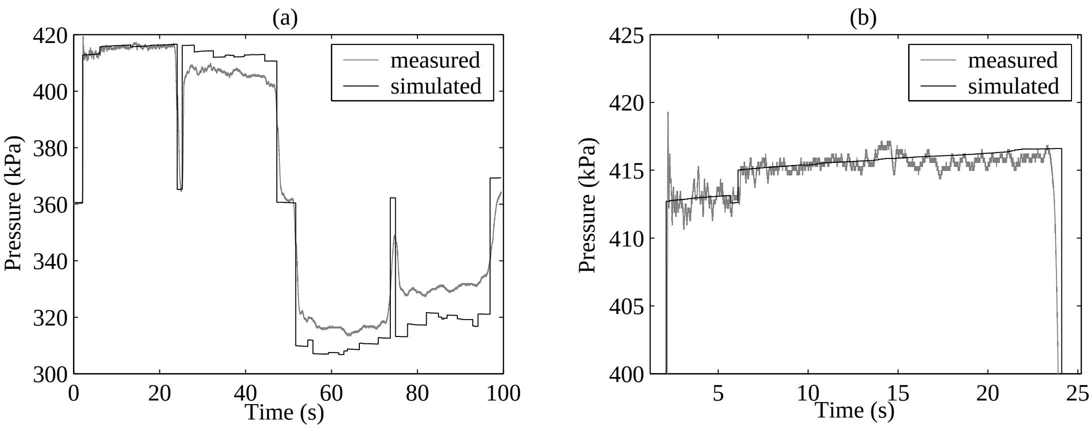

Figure 3. The comparison of simulated and measured traces with a leak

The length of the data window length that is used for inverse fitting is a subject of choice. In Figure 3, a data window with a length of one pipeline period ($4L/a$) is shown. The agreement between measured and simulated data is really poor. Figure 3b shows a shorter data window that includes data prior to the arrival of the transient wave reflections from the boundaries. The fit between measured and simulated traces is slightly better. The leak was simulated at six different locations, including the actual leak point. The square root of the sum of squared differences between the measured and simulated traces for all samples was used as the objective function. Results of the IT analysis are summarised in Table 1.

Simulated leak location (m)	Objective function	
	Long data window	Short data window
9656	42885	370.2783
11886	44633	361.5068
12076	44749	331.5617
12266	44856	360.6017
13026	45313	361.6719
13406	44380	361.5416

Table 1. Results of the IT analysis

The discrepancy between the simulated and measured responses is large for all tested leak locations as indicated by large values of the calculated objective function. To compare the results of the objective function for different leak locations, derived values were normalized applying the division by the optimal (minimum) objective function. The distribution of the normalized objective function at different points along the pipeline for both short and long data windows is shown in Figure 4.

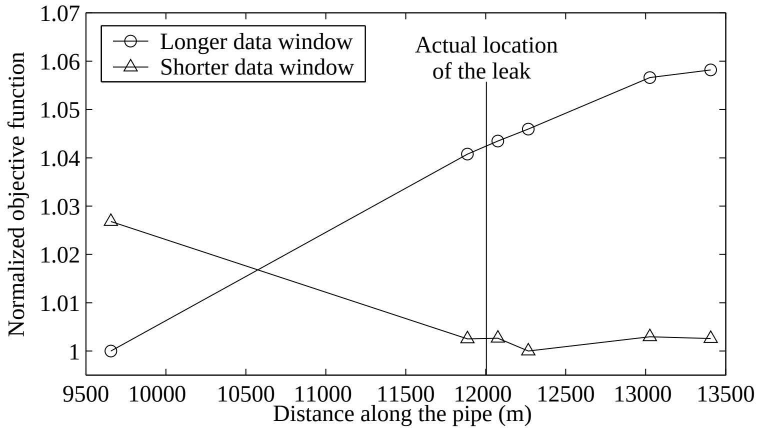

Figure 4. Distribution of the normalized objective function for different locations along the pipeline

The leak simulated closest to the actual leak location did not have the best fit when using both short and longer data windows. Actually, the difference between the outputs of the objective function for all three leak locations that were tested was less than 5%. The location having the best fit was 155 m away from the actual leak location when the shorter data window was used and 4130 m away from the actual leak location when the longer data window was used. As already mentioned, the error in the results is mainly due to lack of information about the physical state of the pipeline or, in other words, the low quality of the model. Increasing the complexity of the model might provide a better agreement between modeled and measured traces. However, often detailed information about the physical structure of the pipeline is not available. In cases when a more precise model of the system can be built, longer computational times are required. Higher computing power demands might become an issue due to the fact that the ITA method requires a large number of simulations.

There are two possible solutions to the problem described above. The first solution, as already suggested, is to increase the complexity and, consequently the precision, of the model. This is a rather difficult task. Alternatively, the methods have to be modified so that modelling is not required. In the following section, a leak detection and location approach that eliminates the influence of the modelling error is described.

3. METHODOLOGY

The fundamental principle of the proposed methodology is the assumption that leak diagnosis will be performed periodically. Leakage detection is considered to be a repetitive procedure that is a part of the active failure monitoring system, which is permanently installed on the pipeline. The initial pressure trace, i.e. the trace measured directly after the installation of the monitoring system, is considered to be leak-free and represents the transient response of the intact pipeline. This trace is used as a reference for the consequitive tests, substituting the modelled trace. Relative changes in the transient pressure response are used to detect and locate pipeline abnormalities. Any discrepancies between the last measured transient response and the reference trace are attributed to a change of the pipeline's physical properties, i.e. leakage. Figure 5 illustrates the way the proposed technique works.

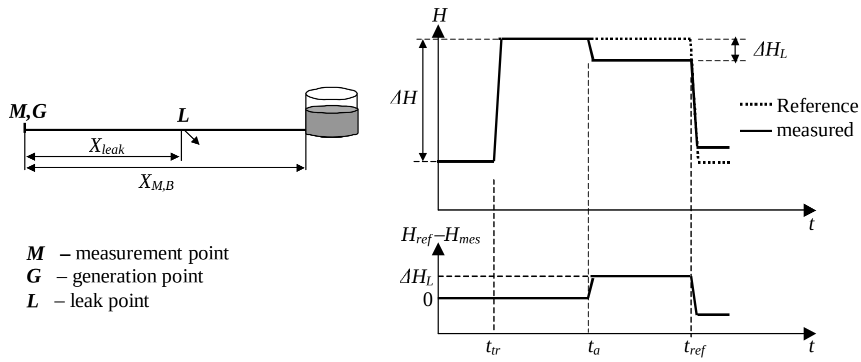

Figure 5. Difference between the reference and measured pressure traces caused by reflection from the leak point

A pipeline running between a dead-end and a tank is considered as an example. The transient is generated at point G and the pressure is measured at point M (Figure 5). Both G and M are placed at the dead-end boundary of the pipeline. The leak, L, is located along the pipe at a distance X_{leak} away from the measurement and generation point. Figure 5 also shows generalised pressure traces for leak-free and leak situations (upper plot) and the difference between the two traces (lower plot). The traces are adjusted to compensate for the difference in steady-state pressure (H_{noleak} - H_{leak} = 0 for $t<t_{tr}$).

To locate the leak, the classical theory of LRM is used. The transient wave is artificially generated at time t_{tr} and propagates along the pipeline. When the wave reaches the leak, part of it is reflected. The size of the reflection, ΔH_L, depends on the size of the leak, the size of the generated transient and frictional effects in the pipeline. When the reflection from the leak reaches the measurement point it will affect the difference between the reference trace and the measured trace. The time instance t_a when the difference $|H_{no\ leak} - H_{leak}|$ becomes greater than zero is used to derive the location of the leak:

$$X_{leak} = \frac{a(t_a - t_{tr})}{2} \tag{1}$$

3.1. Modifications for transmission pipelines

The measurement and generation setup shown in Figure 5 represents the ideal case. In reality, it might not be possible to generate the transient and measure the pressure at the dead-end boundary. It is preferable that the operation of the pipeline is not interrupted by the leak detection procedure. Furthermore, in some cases the generation and measurement equipment might have to be installed separately, at two different locations along the pipeline. Figure 6 shows the case where the generator and the measurement station are installed at different points along the pipeline.

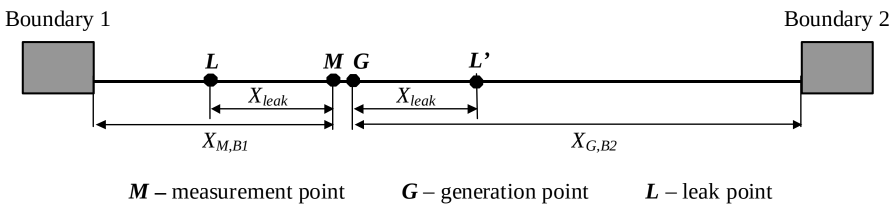

Figure 6. Two possible locations of the leak

The measured pressure trace will look similar to the one in Figure 5. The time t_{tr} will correspond to the arrival of the generated transient wave at the measurement station. The time of change in the difference $H_{no\ leak}$ - H_{leak} will correspond to the arrival of the transient wave reflection from the leak at the measurement station. Using t_{tr} and t_a, the distance X_{leak} can be calculated using Equation 1. However, since the transient generation point is placed along the pipeline, two waves will be generated and will propagate in opposite directions from the generation point. Thus, as indicated in Figure 6, there will be two possible locations of the leak: (a) location L, distance X_{leak} away from the transient generation point in the direction of boundary 2 or (b) location L', distance X_{leak} away from the measurement point in the direction of boundary 1. The timing of the transient reflection from the leak does not provide enough information to identify whether L or L' is the actual location of the leak.

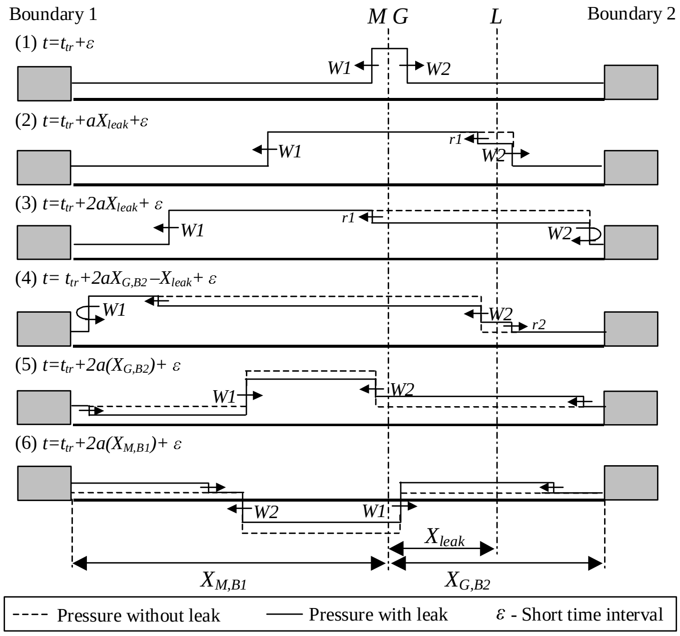

Figure 7. Transient wave propagation and reflections from leak and pipeline boundaries

The actual location of the leak can be identified from the analysis of transient wave reflections from the boundaries of the pipeline. In Figure 7, the transient wave propagation and its reflections from the leak and from pipeline boundaries are shown in sequential steps. The pipeline system from Figure 5 is considered and the leak is assumed to be located at L. Pressure profiles are shown for cases when there is no leak and when the leak is present at L. The transient generation and pressure measurement are assumed to be placed at the same point. To better visualise the pressure changes at the measurement point, pressure distributions are shown a short time interval ε after different waves have passed the measurement point. The following sequence of events can be identified:

- At time t_{tr} two transient waves ($W1$ and $W2$) are generated at point G and propagates in both directions along the pipe
- At time $t_{tr} + aX_{leak}$ the wave $W2$ is partially reflected at the leak. The magnitude of the reflection $r1$ is equal to ΔH_L.

- At time t_{tr} + $2aX_{leak}$ reflection *r1* reaches the measurement point. At this time instance, the difference between the pressure for no-leak and leak cases, i.e. H_{noleak} - H_{leak}, becomes equal to ΔH (neglecting frictional effects).
- The wave *W*2 reaches the boundary at the time t_{tr} + $aX_{G,B2}$ and is reflected from it. The reflection depends on the reflection coefficient of the pipeline boundary P_{B2}. At time t_{tr} + $2aX_{G,B2}$-X_{leak} the reflected wave reaches the leak point and a part of it is reflected (*r*2). The reflected *r*2 will have a magnitude slightly smaller than ΔH_L.
- At time t_{tr} + $2aX_{G,B2}$, the remaining part of *W*2 reaches the measurement point. Due to reflections *r*1 and *r*2 the change in the difference H_{noleak} - H_{leak} is observed at the time t_{tr} + $2aX_{G,B2}$. The size of the change is approximately equal to $P_{B2}(r1 + r2)$.
- Since there is no leak between the measurement point and boundary 1, the wave *W*1 reaches the measurement point at time t_{tr} + $2aX_{M,B1}$ (after it was reflected from the boundary) with the same magnitude as for the no-leak case. Thus, the arrival of *W*2 has no effect on the difference H_{noleak} - H_{leak}.

The following conclusions can be made after the sequence presented above is analysed: assuming that the leak is located between the measurement/genera\-tion point and one of the boundaries, the actual location of the leak can be identified by observing the effect of the transient wave reflections from the boundaries on the difference H_{noleak} - H_{leak}. If the reflection of the boundary causes the change in H_{noleak} - H_{leak}, the leak is located between the measurement/generation point and that boundary. The window of the data that is necessary to find the location of the leak starts from t_{tr} and has a length equal to

$$2\max(X_{M,B1}, X_{G,B2})/a$$

Alternatively, a transient model of the system can be used to simulate the leak at both *L* and *L'*. The simulated traces can then be subtracted from the simulated no-leak trace and the resulting differences compared to the difference between measured traces.

3.2. Size of a leak

The size of the leak can be defined using the lumped orifice discharge parameter C_dA_o. The coefficient C_d is an orifice discharge coefficient and A_o is the cross-sectional area of the orifice. An approximate value of C_dA_o can be estimated using the magnitude of the transient wave reflection from the leak point:

$$C_d A_o = \frac{2gA|\Delta H_L|}{a\sqrt{2gH_0}\left(\sqrt{1+\frac{\Delta H}{H_0}-\frac{|\Delta H_L|}{H_0}}-1\right)} \tag{2}$$

where C_dA_o = lumped orifice discharge parameters
g = gravitational constant
A = pipe cross-sectional area
a = wave speed of the pipe
H_0 = steady-state head
ΔH = magnitude of the generated transient wave
ΔH_L = magnitude of the reflection from the leak

4. PLACEMENT OF MEASUREMENT AND GENERATION POINTS

The analysis presented in the previous sections can be used to derive basic guidelines for the placement of transient generation and measurement points:

1) The generation and measurement points should be placed as close to each other as possible. If the leak occurs in between the measurement and generation points, the location of it becomes more complicated. The generated transient wave is reflected from the leak before it reaches the measurement point. This means that the reflection of a generated wave from the leak is no longer detected in the measured trace. Only the change in difference $H_{no\ leak}$ - H_{leak} that occurs upon arrival of the reflections from the pipeline boundaries can be used to detect and locate the leak.

2) It is beneficial to have both generation and measurement points at the dead-end boundary of the pipeline. There are two main benefits of such a setup: (i) both the generated wave and its reflection from the leak will be magnified two times due to the immediate reflection from the dead-end boundary and (b) there will be only one possible leak location corresponding to the distance $a(t_a\text{-}t_{tr})/2$ at all times. It is likely that most pipelines will not have a permanent dead-end as one of the boundaries. Since the leak diagnosis is performed periodically at selected time instances, the dead-end boundary can be artificially created for the time of the procedure. It could be a check valve of a pump that is not running or a valve that is closed during the time of the leak diagnosis procedure. At all other times the pipeline can be kept in its normal operational state.

3) In case generation and measurement points cannot be located at the dead-end boundary, the leak will have two possible locations only in case when

$$t_a\text{-}t_{tr} < 2\ \min(X_{M,B1}, X_{G,B2})/a$$

This suggests that placing measurement and generation points close to the boundary will increase the probability of only one possible location of a leak. On the other hand, to reduce the effect of friction, it is desired that the measurement point is as close to the leak as possible. To minimise the distance from the measurement station to the leak for all possible leak locations, the measurement point has to be placed not far from the middle point of the pipeline. However, to avoid the simultaneous arrival of reflections from the boundaries to the measurement point, placement at the middle point is not recommended. The setup of transient generation and measurement points has to be designed specifically for a particular pipeline. The guidelines listed above should be considered along with the physical parameters of the pipeline to find the optimal solution.

5. VALIDATION ON A FIELD PIPELINE

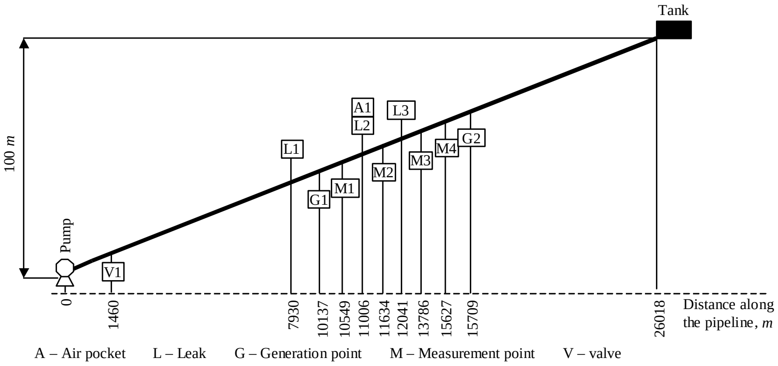

Figure 8. Layout of the test pipeline

The proposed leakage detection and location technique was tested on a large water transmission pipeline. The layout of the pipeline is shown in Figure 8. A 26018 m long mild-steel concrete-lined (MSCL) pipeline has a diameter of 750 mm and an experimentally estimated wave speed of 950 m/s. At the downstream end there are two storage tanks and on the upstream end there is a treatment plant and a pumping station. For all tests presented in this paper, inline valve (V1 in Figure 8) was used as an upstream boundary. The transient was artificially generated by fast closure (around 10 ms) of the side-discharge valve mounted on a scour valve. Two sizes of the side-discharge valve nozzle were used - 40 mm and 50 mm. The pressure was measured at the sampling rate of 2000 Hz and the resolution of the pressure measurement was 0.049 kPa.

The performance of the proposed method was tested for single and a multiple leak cases. Additionally, the capability of detecting and locating an air pocket and blockage was explored.

5.1. Single leak

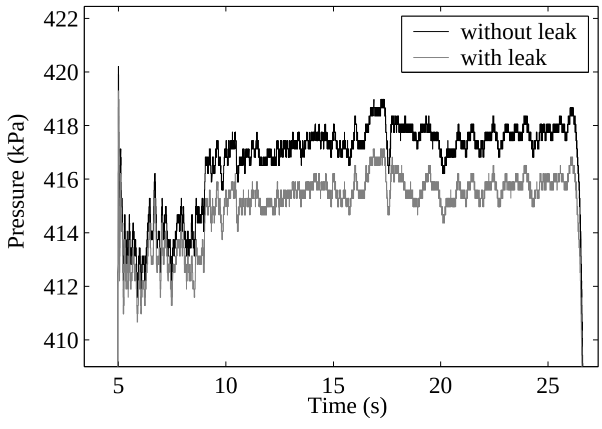

Figure 9. Comparison of pressure traces measured at M3 with and without leakage

The proposed methodology was first tested for a single leak case. Two pressure traces were measured. In the first trace, which was to be used as a reference trace, the transient response of the intact pipeline was recorded. The transient was generated at position G2 (Figure 8) using a closure of the side-discharge valve

with a diameter of 50 mm. In the second trace, the same transient was generated with a leak (approximately 15 L/s) opened at position L3 (Figure 8). The diameter of the leak orifice was around 30 mm (4% of the pipe diameter). The pressure was measured at position M3. Figure 9 shows the comparison of data windows for no leak and leak cases. The data window corresponds to the time interval between the first transient wave arrival to the measurement station and the arrival of its reflections from the boundaries.
The change in difference between the two traces in Figure 9 indicates the presence of a leak. The actual difference between measured pressures can be analysed to get a better resolution as shown in Figure 10.

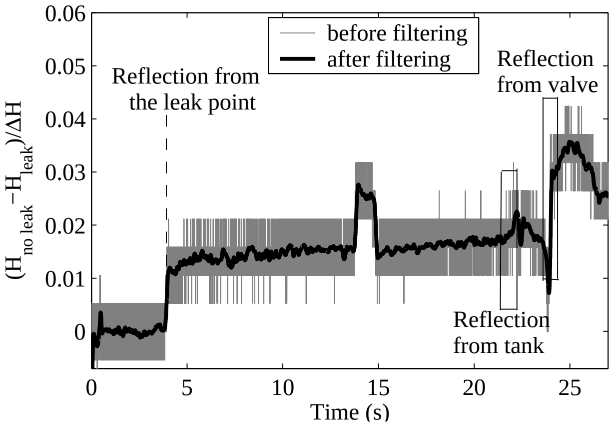

Figure 10. Difference between pressure without leak and with leak. Measurements at M3.

Measured data was pre-processed for better visual presentation. A steady-state pressure baseline was subtracted from the measured traces and data was normalised by the magnitude of the generated transient. However, these procedures are not essential, since leaks are detected from changes of the difference between pressures rather than the absolute value of the difference. A Butterworth low-pass filter with a cutoff frequency of 5 Hz was applied to reduce the measurement noise as shown in Figure 10.

The first positive change in difference between measured pressures at around 3 s indicates the reflection from the leak point. An important feature of the change in the difference between measured traces, which is caused by the reflection from the leak, is that is remains unchanged until the reflection from the boundaries arrive to the measurement point. In other words, if, after the change, the value of $H_{no\ leak}$ - H_{leak} goes back to what is was before the change, the change was not caused by the leak. As an example, the first positive change (around 3 s) in the trace in Figure 10 changes the value of $(H_{no\ leak} - H_{leak})/\Delta H$ from 0 to approximately 0.012 and the difference between measured traces does not change back to zero. This indicates that the change at around 3 s was caused by the reflection from the leak. Meanwhile, the positive change at around 13 s is followed by a negative change of the same size (at around 15 s) which shows that this change is not induced by the reflection of the leak. This change was caused accidentally when the side discharge valve that was used to generate the transient was slightly opened and closed within two seconds. Although the discharge through the valve was very small, its effect is obvious.

As explained in Section 2, there are two possible locations of the leak (see Figure 6). The reflection in Figure 10 can be coming from 12086 m or from 17409 m along the pipeline. To identify the actual location of the leak, the effect of reflections from boundaries on the difference $H_{no\ leak}$ - H_{leak} is analysed. As indicated in Figure 10, no substantial change in $H_{no\ leak}$ - H_{leak} is observed at the time corresponding to the arrival of the reflection from the tank. Thus, the conclusion can be made that the leak is located between the measurement station and the valve, i.e. at 12086 m along the pipeline. To provide additional confirmation, the time that corresponds to the arrival of the reflection from the valve is indicated on the trace in Figure 10.

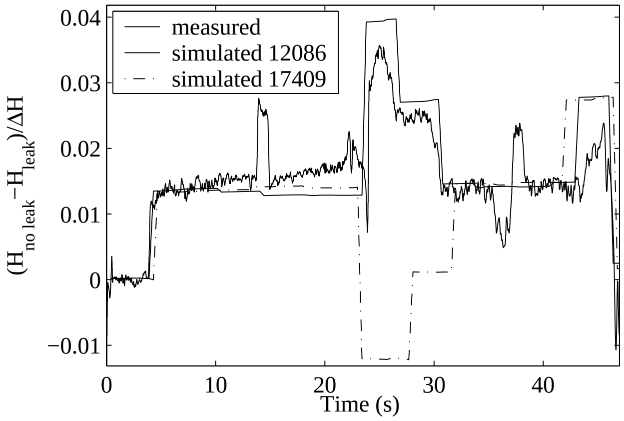

Figure 11. Differences between leak and no leak cases derived for two candidate leak locations using simulation results and compared to the measured (filtered) one

There is an obvious change in difference $H_{no\ leak}$ - H_{leak} at that point, which confirms that the leak is at 12086 m along the pipeline. An alternative approach of identifying which out of the two possible leak locations is the actual one was also tested. The leak was simulated at both possible locations (12086 m and 17409 m) using a hydraulic transient simulation model based on the method of characteristics (MOC) (Wylie and Streeter 1993). Differences between the two cases and the simulated leak-free case were compared to the difference between measured and reference traces. The comparison is shown in Figure 11.

Results of a leak simulated at 12086 m along the pipeline match the difference between measured traces better indicating that the reflection coming from 12086 m represents the leak. The actual location of the leak was at 12041 m and the error of the location estimated by the technique is 45 m.

For the second test, the same transient generation point and the same leak location were used. The pressure was measured at M4. The difference between the measured trace and the reference (leak-free) trace is shown in Figure 12.

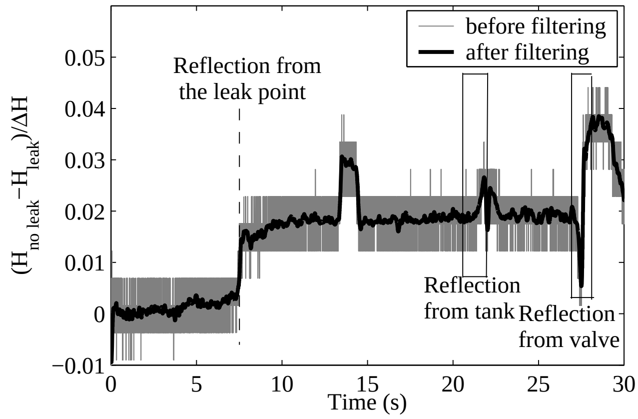

Figure 12. Difference between pressure without leak and with leak. Measurements at M4.

The change in difference between measured pressures indicates that the reflection from the leak point is coming from 12082 m or from 19254 m. The true location of the leak can be identified in the same way as for the previous case. The actual location of the leak is at 12041 m and the error of the estimated location is 41 m.

Using two measurement locations can give a direct estimate of the true leak location. Two possible locations of the leak are estimated for each measurement point. If two measurement points are used, two out of four calculated locations should coincide (or be close) indicating the actual location of the leak. If measurements at M3 and M4 are considered, locations at 12086 and 17409 m were estimated from measurements taken at M3, and locations at 12082 and 19254 m were found from measurements at M4. It is clear that 12086 m (M3) and 12082 m (M4) are indicating the same point. The average of 12084 m can be used to define the real location of the leak.

5.2. Multiple leaks

The technique was also tested for the case of multiple leaks. The transient was generated at G1, the pressure was measured at M1 and two leaks were present at L1 (approximately 8 L/s) and L2 (approximately 15 L/s).

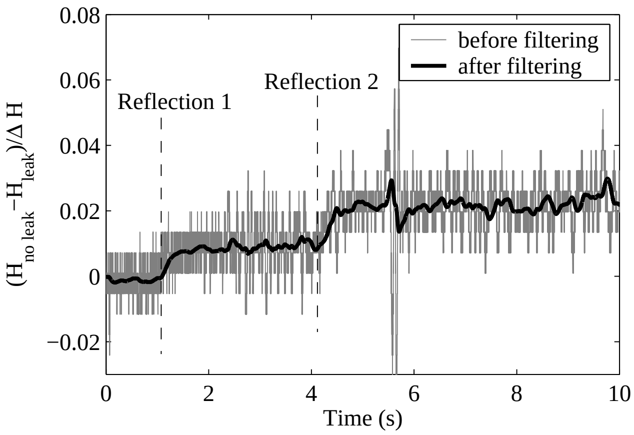

Figure 13. The difference between measured pressure traces for no leak and two-leaks cases

The changes in difference between measured pressures shown in Figure 13 indicate the reflection from leak points. Reflection 1 is coming from 9631 m or from 11077 m. Reflection 2 is coming from 8124 m or from 12483 m. The same principles as for the single leak case were used to identify the actual leak locations. The data window was extended to include the reflections from pipeline boundaries as shown in Figure 14.

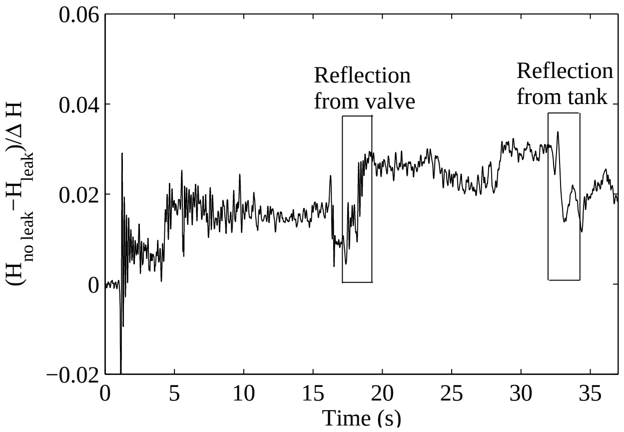

Figure 14. Longer data window including reflections from pipeline boundaries that are used to identify leak locations

Changes in the difference $H_{no\ leak}$ - H_{leak} that can be observed on the trace in Figure 14 indicate that the leaks are located on both sides of the generation/measurement point. Based on the size of the change in the difference between reference and measured traces, the exact locations of the two leaks can be found. Since the change in $H_{no\ leak}$ - H_{leak} caused by the reflection from the tank is smaller than the change caused by the reflection from the valve, the conclusion was made that the smaller leak was located between the measurement point and the tank, i.e. at 11077 m along the pipeline and the larger leak was located at 8124 m along the pipeline. The actual locations of the leaks were at 11006 m and 7930 m, respectively. The errors were 71 m and 194 m. Results from all leak tests are summarised in Table 2.

Test No.	1	2	3	4
Leak location (m)	12041(L3)	12041(L3)	12041(L3)	7930(L1) and 11006(L2)
Measurement at	M3	M4	M3 and M4	M1
Generator	G2	G2	G2	G1
Estimated leak location (m)	12086	12082	12084	8124(L1) 11077(L2)
Leak location error	45	41	43	194(L1) 71(L2)
ΔH (m)	5.62	5.52	5.57	4.55
ΔH_L (m)	0.0924	0.0919	0.0922	0.0615(L1) 0.03(L2)
$\Delta H_L/\Delta H$	0.0164	0.0167	0.0166	0.0135(L1) 0.0066(L2)
C_dA_o (m^2)	$4.52\cdot10^{-4}$	$4.58\cdot10^{-4}$	$4.56\cdot10^{-4}$	$4.52\cdot10^{-4}$ (L1) $2.02\cdot10^{-4}$ (L2)
D_l/D (%)	3.69	3.72	3.71	3.69(L1) 2.47(L2)
Q_L (L/s)	13.4	13.6	13.5	16.6(L1) 6.8(L2)

Table 2. Summary of leak detection and location tests and results

6. EXTENSION OF THE METHODOLOGY FOR OTHER HYDRAULIC FAULTS

The leakage detection technique described in this paper can be applied for detecting other hydraulic faults, such as blockage or entrapped air pocket. As an example, results of the detection and location of (1) air pocket and (2) blockage are presented in this section.

6.1. Air pockets

In the addition to leaks, the approach was also tested for entrapped air. An air chamber was attached to the fireplug at location A1, the transient wave was generated at G1 and the pressure was measured at M1 (Figure 8). The measured trace was compared to the reference air-free trace and the difference between the two traces is shown in Figure 15.

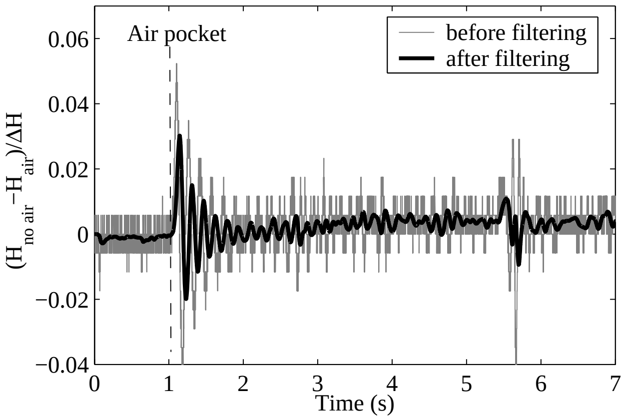

Figure 15. Difference between measured pressure traces for no air and air pocket cases

The difference between an air pocket and air-free traces in Figure 15 contains an oscillation that indicates an air pocket in the pipeline. The reflection is coming from 9655 m or 11053 m along the pipeline. By using the model or having two measurement locations, the actual location of the air pocket can be identified. The true location of the air pocket is 11006 m and the error of the estimate is 47 m.

6.2. Blockage

The last set of tests was performed to test the ability of the proposed technique to detect partial blockage in a pipeline. To simulate blockage, the inline valve V1 (Figure 8) was closed and the bypass of the valve with a diameter of 250 mm was open. The difference between measured pressure traces without blockage (valve open and bypass closed) and with blockage (valve closed and bypass open) are shown in Figure 16.

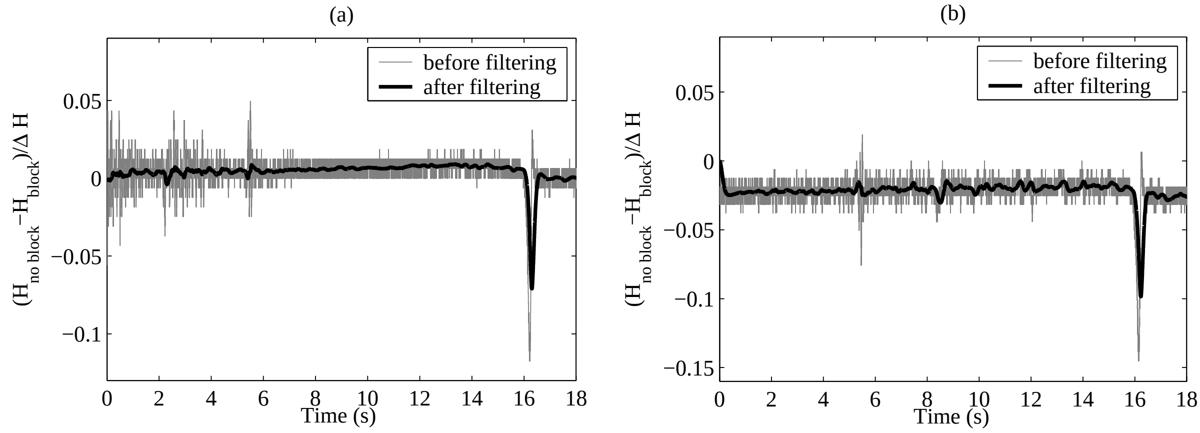

Figure 16. Difference between measured pressure traces without blockage and with blockage. The measurement was taken at (a) M1 and (b) M2.

The pressure was measured at two stations - M1 and M2 (see Figure 8 for positions). As shown in Figure 16, the spike (around 16 s) is present in the pressure difference trace for both measurement stations. According to the traces measured at M1, the spike indicates a reflection that is coming from 1457 m or 19229 m along the pipeline. From the traces measured at M2, the reflection is coming from 1518 or 20253 m along the pipeline. One of the two alternative locations is common for both stations (1458 and 1518) and the blockage location was selected to be at the middle point between the two estimates, i.e. 1487.5 m along the pipeline. The actual blockage was at 1460 m along the pipeline. The technique was able to determine the location of the blockage with an error of 27.5 m.

7. PERFORMANCE LIMITS

Validation results from the laboratory and field pipelines have demonstrated that the proposed technique is capable of detecting and locating leaks of a certain size. However, the limited flexibility of the tests does not always allow for validation of the method for the whole range of failures that may occur. Thus, the performance limits of the techniques have to be estimated. The performance of the failure management techniques can be evaluated using three main parameters: (1) the minimum size of the failure that can be detected and located, (2) the precision of the derived location and (3) the detection and location time, i.e. the time from the actual failure to the time when it is detected and located.

The minimum size of a detectable leak. The minimum size of a leak that can be detected by the technique depends on the following parameters: the resolution of pressure measurements; the level of measurement noise; the size of the transient that is generated; and the intensity of the hydraulic activity in the pipeline. High resolution pressure measurements can be achieved using modern measurement equipment. In the tests that were conducted to validate the approach, a 12 bit A/D card was used together with a variable-gain amplifier. As a result, pressure measurements had a calculated resolution of 0.049 kPa. The observed reflection from the 15 L/s leak was 0.92 kPa, i.e. almost 20 times larger than the resolution. Theoretically, if there was no measurement noise present, a 2.1 L/s (D_l/D = 1.4%) leak should be detected. Furthermore, if a 16 bit A/D card was used, the resolution would increase to 0.0023 kPa and the corresponding minimum leak size would be 0.1 L/s (D_l/D = 0.31%). The actual limit of the detectable leak size for a real installation is expected to be higher and would depend on the measurement noise level.

The size of the transient that is generated has considerable influence on the size of the reflection from the leak and, consequently, affects the minimum size of the leak that will be detected. The larger the magnitude of the generated wave, the smaller the leak that will be detected. However, too large transients can be hazardous to the pipeline. In the presented tests, transients with magnitudes around 50 kPa were generated. On a large pipeline, such transients are not likely to have any damaging effect. If a higher resolution-to-noise ratio can be achieved in pressure measurements, the size of the generated transient can be further reduced.

Hydraulic events in the pipeline have the potential to corrupt the measured pressure trace and lead to false alarm situations. As already mentioned earlier, to avoid this problem, tests have to be conducted during the time when the pipeline system is in its most stagnant state. It is preferable that the variation in demand is minimal and no pumping is performed during the leak diagnosis tests. These conditions are likely to be feasible on most water transmission pipelines as a part of the normal operation. If the pipeline leak diagnosis cannot be made when the pipe is online, a temporary suspension of the operation can be used.

The precision of the location. The average error of the derived leak location for the validation tests was less than 80 m (0.3% of the total length of the pipeline). This error can be further reduced by increasing the precision of the estimated wave speed value for the pipeline. If necessary, the exact location of the leak can be confirmed using noise correlators or other sounding equipment. A pipeline section of 80 m can be inspected using a single correlator setup and, therefore, the inspection procedure should take relatively little time.

The detection and location time. The time required for detecting and locating a leak primarily depends on the frequency of leak tests. A period of leak diagnosis has to be selected by the operator. More frequent checks will allow for faster reaction to the leak. However, in some cases, the operational regime of the pipeline may limit the frequency of leak diagnosis. Some additional time may be required when listening equipment is used to find the precise location of the leak after it has been detected. Generally, the location time is likely to be reduced considerably using the proposed techniques in comparison to the current practice.

8. APPLICATION

The primary application of the proposed techniques is failure monitoring in water transmission pipelines. Large, long mains often present a challenge to the conventional failure detection and location methods. Leak detection and location times can be increased due to the extensive length and remote location of the pipeline. The periodical leak diagnosis system can provide an alternative to the frequent visual inspection, which is time and resource consuming. The consequences of failure in transmission pipelines can be hazardous and expensive, especially when pipelines are located close to other urban infrastructure assets, such as gas mains, communication networks, etc. In such situations, it is essential to react to the pipe failure as quickly as possible; therefore, a continuous monitoring is preferable.

It is practically infeasible to extensively apply the proposed failure monitoring methods in water distribution networks. In order to apply these techniques to a network, installation of a separate monitoring system on every single branch in the network would be required, which is cost prohibitive. However, pipes that are the most critical in the network can be chosen for burst monitoring or leak diagnosis systems. The burst monitoring technique presented in (Misiunas *et al.* 2005) has been tested on a single dead-end branch in a distribution network. Despite the presence of service connections and the uncertainty in demands, burst detection and location was successful. Periodical leak diagnosis can also be applied on a single branch in a network.

8.1. Implementation

Since only one pressure measurement point and a single transient generation point is required for the operation of the proposed leak diagnosis system, its implementation on an actual pipeline should be fairly straightforward. A transient generator and pressure measurement unit are the two main components of the periodical leak diagnosis system. As already noted earlier in the paper, it is beneficial to install the generator and the pressure monitoring point as close to each other as possible. The actual location along the pipe has to be chosen for a particular pipeline. A micro controller can be used to operate the transient generator and collect the required data. The length of the data window that has to be collected depends on the length of the pipeline. Once measured, the transient response trace can be analysed locally (compared to the reference leak-free trace) or sent to a control room. The proposed leak diagnosis system can be integrated with the burst monitoring system presented in (Misiunas *et al.* 2005), forming a complete pipeline failure monitoring system.

8.2. Calibration and tuning

The only parameter that has to be calibrated to derive the precise location of a leak is the wave speed of the pipeline. A theoretically calculated wave speed value usually contains some error, and better precision of the wave speed can be achieved by estimating the value from experimental data. The calibration procedure is simple. By measuring the time it takes for the generated transient wave to travel from the measurement point to the boundary of the pipeline and back to the measurement point, the wave speed can be calculated. Alternatively, two measurement points can be used and the wave speed can be calculated based on the wave travel time between the two points. Other parameters of the pipeline do not have to be known precisely for failure detection and location.

Tuning of the failure monitoring system involves the adjustment of system's parameters for the optimal operation. The optimal operation is associated with a high reliability, where reliability is generally understood as a measure of the certainty that the system will perform as intended. The failure monitoring system can be unreliable in two ways: (1) it may not generate an alarm in the case of a failure, or (2) it may generate an alarm when no failure has occurred (false alarm). Thus, the reliability of the failure monitoring system can be defined using the following expression:

reliability = (alarms-false alarms)/failures

To increase the reliability, the number of successfully detected and located leaks has to be increased. However, at the same time, the rate of false alarms has to be minimised. The main purpose of the tuning process is to enhance the reliability of the failure monitoring system. As every pipeline has individual physical and hydraulic characteristics, it is clear that tuning has to be performed once the failure monitoring system is installed on a particular pipeline.

9. CONCLUSIONS

By installing a periodical leak diagnosis system on a pipeline, the efficiency of the pipeline leak detection and location process can be increased considerably in comparison to the current situation. Losses associated with pipe leaks can be reduced significantly. The proposed leak diagnosis system is tuned to detect and locate leaks that are larger than a certain threshold. The performance of the method was evaluated on the real large water transmission pipeline and positive results were observed. The lower limit of the detectable leak diameter was estimated to be as small as 0.31% of the pipeline diameter. The observed precision of the derived leak location was less than 0.3% of the total pipeline length. As mentioned previously, most leaks are likely to increase in size over time and eventually become large enough to be detected by the proposed method. Additionally, as was shown during field testing, the periodic leak diagnosis approach allows for the detection and location of air pockets and partial blockages in the pipeline.

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