Field tests for leakage, air pocket, and discrete blockage detection using inverse transient analysis in water distribution pipes[1]

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1 ABSTRACT

It has been suggested that the application of fluid transients could potentially lead to improved leak detection and calibration of pipe roughness in pipe networks using a technique referred to as Inverse Transient Analysis (ITA). During the intervening time, a large amount of numerical and laboratory research has not addressed the complexities involved in the application of ITA to the field. This paper presents preliminary results for an implementation of ITA in a field environment. Leaks, air pockets and discrete blockages with defined characteristics are introduced into two single branch pipelines in a "controlled manner" and their effects on an induced transient are measured. Where possible, ITA is used to detect the introduced phenomena. Findings are made regarding the sensitivity of each type of pipeline phenomena to detection and, where possible, ITA is also used to locate and size leaks and air pockets.

2 INTRODUCTION

Numerical and laboratory research into the use of ITA for leak detection and calibration of pipe roughness has been previously undertaken by, amongst others, Brunone (1999) and Vitkovsky et. al. (2000). Transients were first used in the field for system calibration by Tang et. al. (1999).and in a quasi-field setting by Covas et. al. (2003). The last mentioned authors concluded that ITA was a promising technique for leak detection and diagnosis of existing water supply systems. However, they emphasised that the accuracy of the transient solver was very important.

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Stoianov et al. (2003) attempted field verification of the use of controlled hydraulic transients for leak detection in water transmission mains. A number of practical difficulties and limitations were identified and the authors concluded that the use of transients and ITA for the purpose of leak detection would be "unlikely to have any practical value for the water industry". However, this conclusion may be premature. Previous research has suffered from a lack of understanding of the response of field pipelines and networks to transients and the effects caused by physical uncertainty in the condition of pipelines, variable flows and pressures and the possible presence of air pockets

Field testing has been carried out by the University of Adelaide in conjunction with United Water International on a water distribution system (WDS) in the township of Willunga, Adelaide, South Australia. In contrast to the work conducted by Stoianov et. al. (2003) the testing focussed on two single branch water distribution pipelines. The results revealed that the transient response of the pipelines can vary markedly depending on the size of an introduced leak, air pocket or discrete blockage.

The successful application of ITA depends upon the ability of the numerical transient model to accurately predict the effects of variations in the location and size of leaks, air pockets or discrete blockages, and other transient behaviour that might be observed in a pipeline. This paper tests the ability of the explicit Method of Characteristics (MOC) transient model to replicate field measured responses. Where the MOC has proved satisfactory, ITA has then been performed.

3 INVERSE TRANSIENT ANALYSIS

ITA was first proposed by Liggett and Chen (1994) and involves taking an initial set of parameters from a numerical transient model, varying them, and then determining a set of predicted responses. Parameter variations are guided by the inverse analysis such that predictions improve, when compared to a set of measured responses, with each trial. An objective function is used to determine whether the match between the predicted and measured responses has improved. The objective function is calculated using a "least squares" approach by summing the squares of the differences between the measured and predicted responses using

$$E = \sum_{i=1}^{M} \left(H_i^m - H_i \right)^2$$

where E = objective function, H_i = predicted head, H_i^m = measured head, and M = number of measured data. The analysis conducted for this paper has used the Shuffled Complex Evolution (SCE) global search algorithm to guide the inverse analysis.

4 FIELD APPROACH

4.1 Decomposition of field networks into branch pipelines

The "near universal" presence of isolation valves at each end of individual sections of pipeline in the Adelaide, South Australia WDS allows decomposition of the system into branch pipelines by closing an isolation valve at one end while leaving the other end open. Any transient induced in the pipeline near the closed valve remains unaffected by the "outside" network until it has traveled along the pipeline and reached the open end. Information contained within the transient response for this first period includes only information relating to this branch section of pipeline (including any possible leak, block or air pocket).

4.2 Introduction to field test pipelines

The pipelines are called the Kookaburra Court (KCRT) and St Johns Terrace (STJT) pipelines after the streets where they are located within the township of Willunga (refer to Figures 1 and 2 respectively). There was no need to operate isolation valves to form branch sections of pipeline because the two test pipelines formed existing dead end branches.

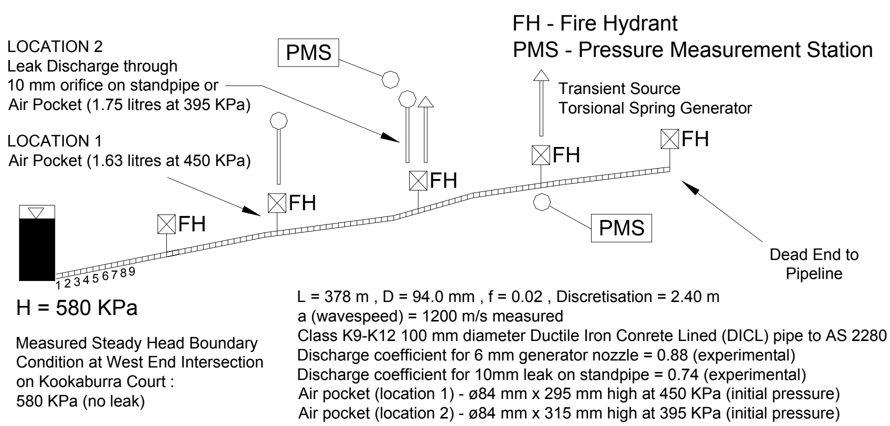


Figure 1 - Elevation view and physical details of Kookaburra Court branch pipeline

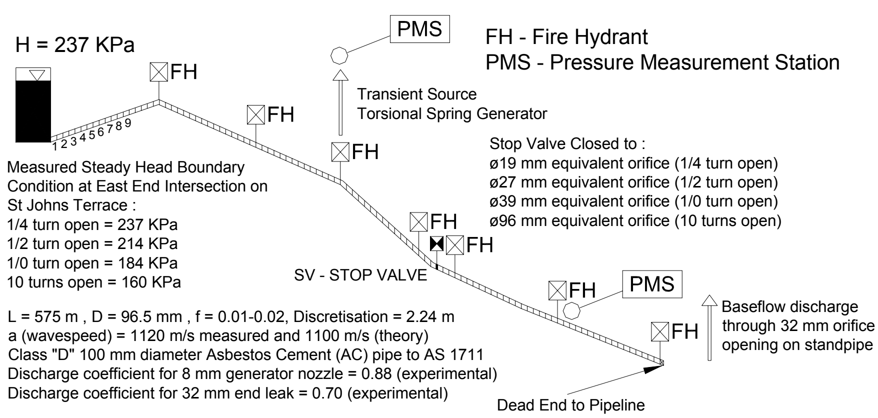


Figure 2 - Elevation view and physical details of St Johns Terrace branch pipeline

4.3 Method of generating (inducing) transients

By focusing on the first period of the transient response of branch sections of pipeline, the reflection information, rather than periodic damping information, contained in the response is crucial. Furthermore, it is necessary to generate a "fast transient" in order to obtain clear reflections from features within the branch section of pipeline. Controlled transients were induced in the pipelines by either closing or opening a small ball valve (15 mm) located directly behind an orifice on the end of a 1.8 m high "standpipe" mounted on existing fire plugs as shown in Figure 3 (a).

The closure or opening could be performed manually (approximately 250 ms) or more quickly (4 ms) using a torsional spring arrangement to power the maneuver as shown in Figure 3 (b). Voltage potentiometers were used to gauge the time over which closures or openings occurred. In order to avoid large transients, discharge orifices of 6 mm and 8 mm were used for the tests on the KCRT and STJT pipelines respectively.

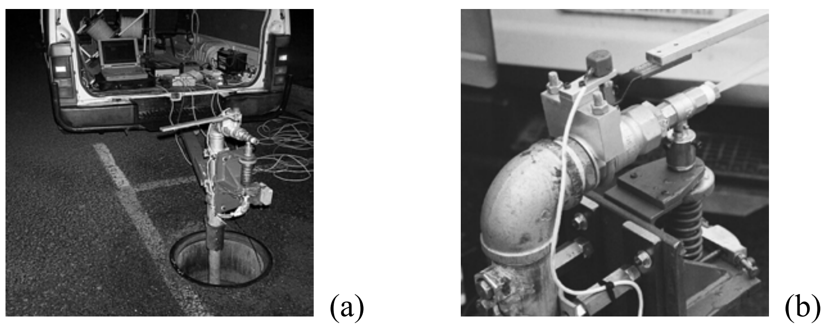


Figure 3 (a) and (b) - Photographs of torsional spring transient generator

The 1.8 m high "standpipe", in combination with the fast 4 ms closure or opening, produced a short lived and localized oscillating pressure response within the "standpipe" before establishing a more stable rise or fall in pressure in the main pipeline. Figure 4 (a) shows two typical pressure responses, following a 4 ms closure of a 6 mm orifice at Kookaburra Court, for a period of 0.5 seconds measured at 500 and 2000 Hz. Figure 4 (b) shows the same responses over a period of 0.02 seconds together with the recorded potentiometer response for the 500 Hz test. Both recording rates appear to be adequate over the longer time scale.

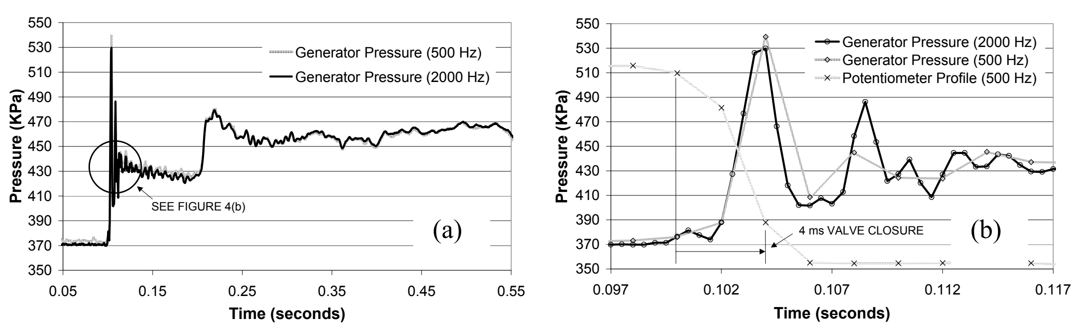


Figure 4 (a) and (b) - Comparison of transient generator response over 0.50 second (a) and 0.02 second (with potentiometer trace at 500 Hz) (b)

5 SIMULATION ERROR

5.1 Physical and temporal complexities affecting model accuracy

WDS pipelines have many physical complexities including consumer connections (often uPVC plastic pipes which can exhibit visco-elastic behaviour), rubber joints at regular spacing, general junction and fire plug fittings, and turburculation and other deposits causing constrictions (ie. extended blockage). Furthermore, temporal variations exist in the form of variable demands and/or variable quantities of distributed or concentrated air. During the testing the pipelines were regularly flushed, including fire plugs, to remove any concentrated pockets of air. Notices were issued to consumers warning that water quality might deteriorate during the testing period and this had the effect of minimising usage, and hence demand, along the pipelines.

5.2 Defining "simulation error"

The responses of both the KCRT and STJT pipelines to induced "fast transients", in their existing condition, contained both complex reflections and unexpected trends in the pressure profiles. There is a limit to the level of information that can be realistically pre-determined about the pipelines and the differences that remain between the measured and predicted responses can be attributed to further physical or temporal uncertainties leading to "simulation error".

Figures 5 (a) and (b) show the transient response of the KCRT and STJT pipelines to the opening of a 6 mm orifice and the closure of a 8 mm orifice, both in 4 ms, respectively. Figure 5 (a) shows that, for the KCRT pipeline there are differences between the measured and predicted responses, in terms of the size, shape and timing of reflections along the low pressure plateau, in the order of 5-10 KPa. Figure 5 (b) shows that, for the STJT pipeline, there is an error in the general trend of the high pressure plateau up to a maximum of plus or minus 20 KPa in addition to there being differences in the size, shape and timing of reflections.

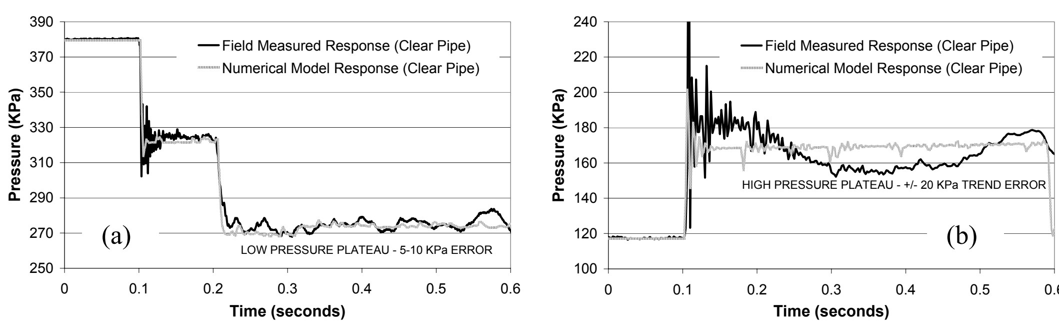
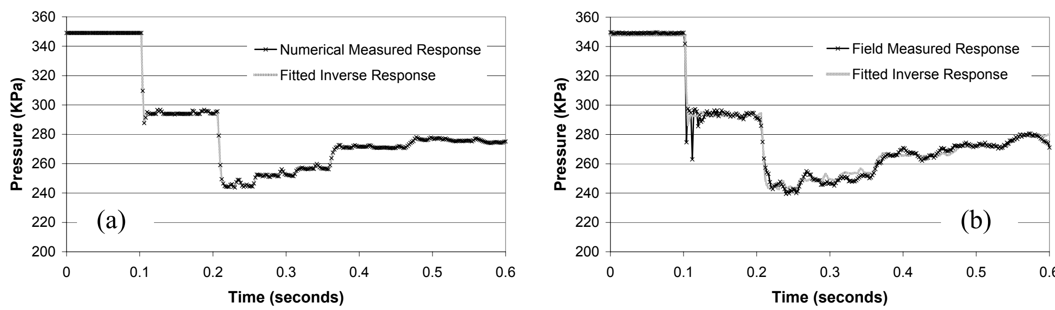


Figure 5 (a) and (b) - Numerical model error for the Kookaburra Court (a) and St Johns Terrace (b) pipelines respectively

6 LEAKS AND AIR POCKETS - KOOKABURRA COURT PIPELINE

6.1 Inverse transient analysis for leak detection

Numerous tests were conducted on the KCRT pipeline with leaks introduced via “standpipes” connected to fire plugs. The purpose of the tests was to determine if leaks could be successfully detected using ITA. ITA was used to detect and size a 10 mm leak located at a fire plug as shown in Figure 1. The leak had 15 potential locations along the pipeline, corresponding to known locations of fittings or connections, and a size range between 0 mm to 15 mm. The analysis predicted an 8.5 mm leak at the correct location. ITA was also performed using numerical “measured” data for illustrative purposes. Figure 6 (a) shows the numerical “measured” and inverse fitted responses at one location (as shown in Figure 1). Figure 6 (b) shows the field measured and inverse fitted responses at the same location.



Figures 6 (a) and (b) - Numerical "measured" (a) and field measured (b) versus inverse transient responses, determined at one location in the pipe, to a 10 mm leak at location 2

6.2 Inverse transient analysis for air pocket detection

Air is one factor that can contribute to “simulation error”. Numerous tests were conducted on the KCRT pipeline with air pockets introduced via “standpipes” connected to fire plugs. ITA was used to detect and size an air pocket of 1.6 litres in volume located at a fire plug as shown in Figure 1. The air pocket had 15 potential locations along the pipeline, corresponding to known locations of fittings or connections, and a size range between 0 to 5 litres. The analysis predicted a 1.4 litre air pocket at the correct location. Figures 7 (a) and (b) show the measured and inverse fitted responses at two locations (as shown in Figure 1).

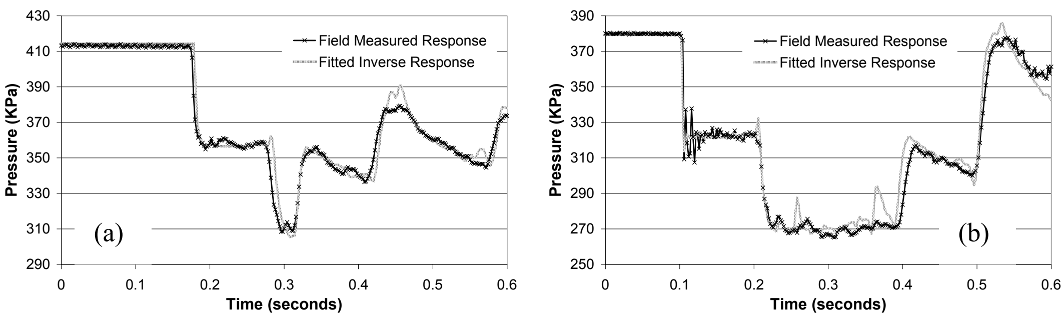


Figure 7 (a) and (b) - Field measured and inverse transient responses, determined at two locations in the pipe, to a 1.6 litre air pocket at location 1

6.3 The relative sensitivity of leaks and air pockets to ITA analysis

Figure 8 (a) compares the objective functions, calculated at each potential leak location, for ITA performed using both numerically simulated and field measured responses. The ITA has performed almost as well in locating and sizing the 10 mm leak based on numerically simulated and field measured responses. The relative sensitivity of the 10 mm leak and 1.6 litre air pocket can be assessed numerically by examining the objective function versus leak or air pocket location plots shown in Figure 8 (b). The objective functions in both plots are calculated on the basis of field measured responses.

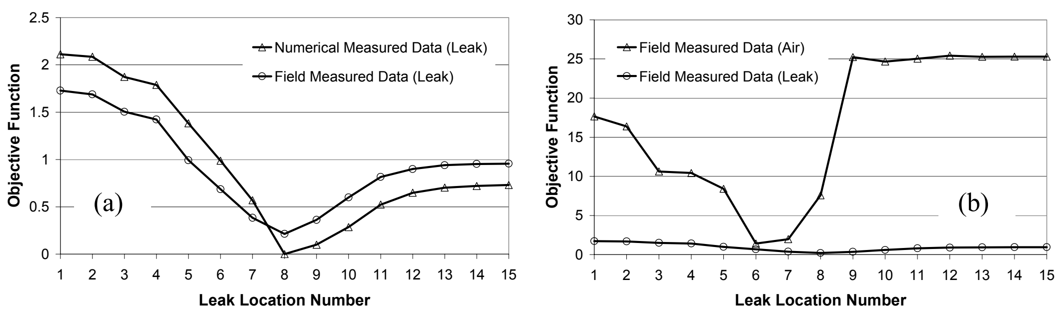


Figure 8 (a) and (b) - Objective function plots corresponding to (a) numerical and field 10 mm leaks at location 2 and (b) a field 1.6 litre air pocket at location 1

ITA is more sensitive to the location and size of the air pocket than the leak. This observation can be reinforced by a direct comparison of the transient response to a 10mm leak or 1.6 litre air pocket at the same location (e.g. location 2). Figure 9 (a) and (b) illustrate this comparison and it is clear that the transient response is more sensitive to the presence of the air pocket than the leak.

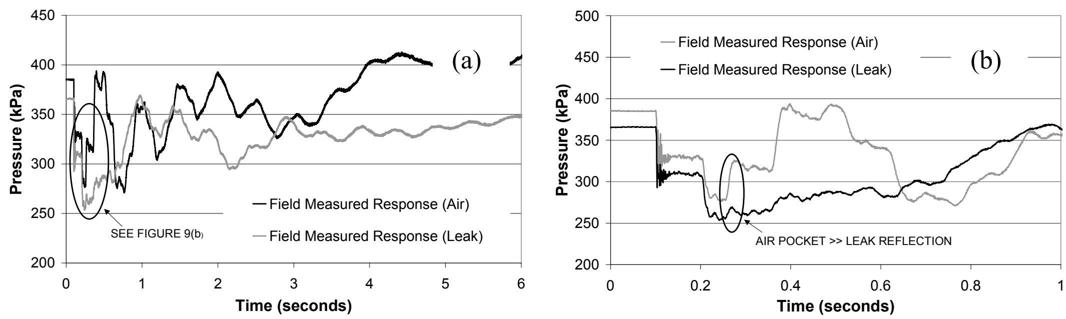


Figure 9 (a) and (b) - Air pocket and leak transient responses from the Kookaburra Court pipeline over 6.0 seconds (a) and 1.0 seconds (b)

7 DISCRETE BLOCKAGE – ST JOHNS PIPELINE

7.1 Blockage detection using ITA

While the presence of a blockage in a branch section of pipeline can be broadly determined using steady state flow and pressure tests, operators are then usually forced to use invasive cameras to confirm the location and form of the suspected blockage. ITA can be used, under certain conditions, to both locate and size discrete blockages. Steady state information relating to flows and pressures provide a set of initial conditions that must be matched in the inverse analysis. However, the transient response of a pipeline containing a discrete blockage will include an additional reflection. The timing of this reflection can be used to locate the discrete blockage while the magnitude will be proportional to the head loss across the blockage (and hence, indirectly, the degree of the blockage).

7.2 Using a gate valve to simulate a discrete blockage

The STJT pipeline includes an existing gate valve (as shown in Figure 2), which could be adjusted to different apertures and used to simulate a discrete blockage in the pipeline. “Baseflows” were established, by opening a 32 mm valve at the dead end of the pipeline, in order to increase the head loss across the gate valve and the size of any reflection. The pressures along the pipeline were checked, for each of the gate valve apertures, to confirm they would not become negative during a transient. A similar gate valve to that in the field was calibrated in the laboratory to determine steady loss coefficients for a range of apertures and flows.

8 ANALYSIS OF RESPONSES FROM DISCRETE BLOCKAGE

8.1 Numerical analysis and comparisons with the field results

As mentioned previously, the application of ITA to discrete blockage detection in the STJT pipeline is complicated by "simulation error" and further investigation of the pipeline and improvement of the numerical transient model is currently being undertaken. However, the initial steady state flow and pressure conditions could be matched using the calibrated steady loss coefficients and other initial flow and pressure data. Furthermore, reflections of different magnitudes, corresponding to different gate valve apertures, could be discerned.

Figures 10 (a) and (b) and 11 (a) and (b) show the results of transient modeling (not ITA), for gate valve apertures of ten (i.e. fully open) and one quarter turns open. The valve aperture at one quarter turn open corresponds to an equivalent orifice diameter of 19 mm (i.e. an 80% reduction from the open diameter of 96 mm. The predicted responses are compared with the measured responses at two locations (as shown in Figure 2). The pressure transducers were located on the reflection and transmission sides of the blockage.

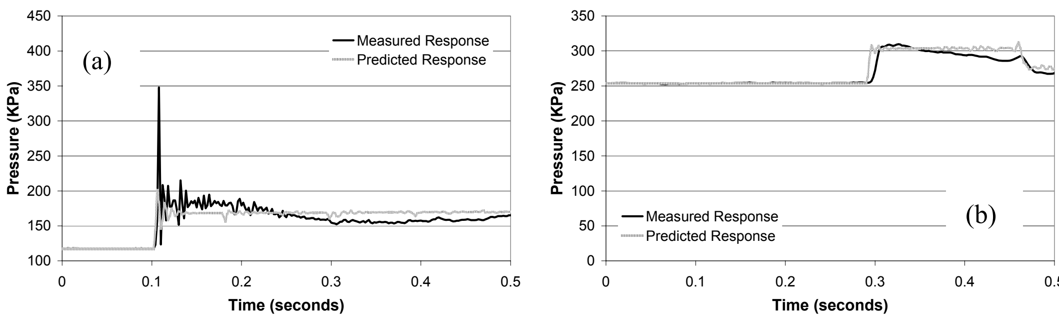


Figure 10 (a) and (b) - Transient responses for the gate valve fully open at the reflection transient generation (a) and transmission (b) measurement locations

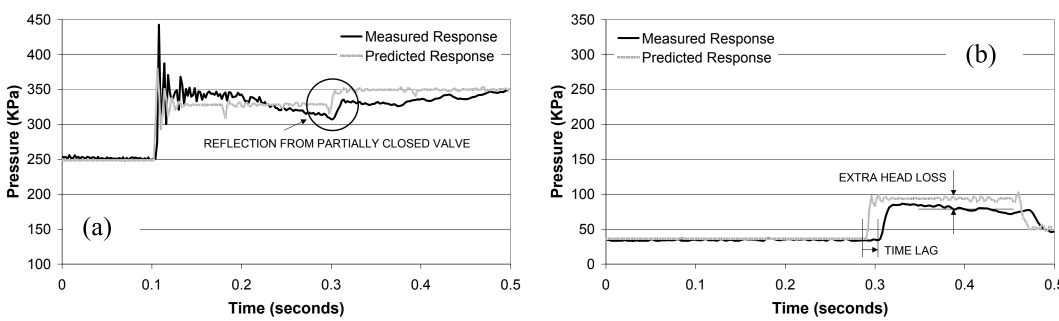


Figure 11 (a) and (b) - Transient responses for the gate valve one quarter turn open at the reflection transient generation (a) and transmission (b) measurement locations

The steady state in-line orifice loss equation was used to approximate the head loss behaviour of the gate valve and implemented in the MOC in the form

$$Q_{orifice} = C_d A_{orifice} \sqrt{2g\Delta H}$$

The field results indicate that discrete blockages with equivalent orifice diameters of up to at least 40 mm can be located and sized for the STJT pipeline. Furthermore, as the valve aperture is reduced, a proportional time lag and additional head loss in the transmission response, neither predicted using the steady state in-line orifice loss equation, become increasingly apparent (refer to figure 11 (b)). This observation may be attributable to unsteady minor losses that cannot be predicted using steady state loss approximation under transient conditions (Prenner (2002)).

9 CONCLUSIONS

The field results demonstrate that a leak, air pocket and discrete blockage can affect the transient response of a WDS pipeline. Furthermore, the sensitivity of the responses to an air pocket, and to a lesser degree a leak, enabled ITA to be successfully applied. That said, the general applicability of ITA can be limited by "simulation error". While discrete blockages can be located and sized by analysing transient responses, ITA could not, at this stage, be successfully performed. Further work is currently being undertaken to understand both the theoretical and practical complexities that inhibit accurate modelling of "real" transients. Finally, further measurements of the transient responses of field pipelines must be obtained in order provide a database upon which to work.

10 REFERENCES

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