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A method to characterise transients from pressure signals recorded in real water distribution networks

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ABSTRACT

The dynamics of water distribution systems (WDS) manifest within a range of time scales, seasonally and diurnally and down to minutes and seconds. Due to advances in instrumentation an increasing body of evidence is starting to suggest that transients occur widely throughout the complex, branched and looped layout of WDS. This paper aims to contribute to the current knowledge on the occurrence and characterisation of pressure transients in WDS. A method to characterise pressure transient waves in order to quantify the pressure changes experienced by a pipe is presented. This method provides a unique, site specific 'transient fingerprint'. The method is ultimately intended to be used to investigate the role of transient events on structural and water quality failures in WDS. Examples will be presented to demonstrate the applicability of the method to different transient time series data measured in operational WDS.

1 INTRODUCTION AND BACKGROUND

The collection of pressure data from WDS in the UK is usually undertaken at a 15 minute resolution, to satisfy regulations and provide good characterisation of daily patterns. This practice reinforces the belief that WDS are pseudo-steady state systems in which changes in pressures occur over periods of minutes and hours. Fast changing transient conditions will not be detected by such conventional monitoring. As a result the magnitudes and rates of occurrence of pressure transient waves in WDS are currently largely unknown. However, due to advances in instrumentation, an increasing body of evidence is starting to suggest that pressure transients exist widely throughout WDS, even in complex, branched and looped systems [1]. Only a limited number of transient field studies have been published. Some of them have presented the detailed investigation of pressure transient waves in operational systems for specially selected activities such as leak detection [2], burst detection [3] or pipe condition assessment [4]. None of these studies conducted a rigorous analysis of how often pressure transient events of different magnitudes occur in operational systems. In addition there have been no reported field studies assessing the role of transients in operational WDS and possible links to damage and failures within those systems.

Historically high magnitude pressure transients were anticipated and managed in the vicinity of pumping stations. Extreme pressure transients have been understood to cause failures of simple, single transmission pipelines [5], [6], with the source of such transients often associated with pump switching [7], [8]. With the extreme events that occur in a single pipelines it is often very easy to see the causal links between the transient event and catastrophic failure. In the wider distribution system the same causal relationships are harder to determine; this may be due to a time delay between the transient event, the impact and its recording (i.e. discolouration events due to the time for discoloured water reaching a consumer), or that an impact is not caused by a single catastrophic transient event. Studies into mechanical behaviour of materials have revealed that damage mechanisms can occur when metals are subject to periodic or variable loading [9]–[11], therefore, the cyclic nature of transients should be taken into account to fully understand and quantify the role of transients in mechanical behaviour or pipes [12]. These studies enabled researchers to link cumulative dynamic impacts due to pressure transients with the structural integrity of a pipe, but remain un-validated by field data. If it is not possible to determine a direct causal link between transients and their impacts it may still be possible to infer the link through statistical models. Previous attempts to model the causes of pipe failures with system characteristics (i.e. pipe material, diameter, age, average pressure etc.) have had some success [13], [14] but often they have not been able to fully explain the rates of pipe failures. None of these previous studies have included the transient activity experienced by a pipe. To be able to input the system transient response into this type of model it is necessary to convert the large quantities of time series data captured from the WDS into some series of summary statistics that characterise the number and magnitude of transient pressure fluctuations experienced by a pipe.

To allow inference of system impacts any method developed to characterise the system pressure response must be able to accurately represent the magnitude of the oscillations in pressure and also the rate at which these changes occur. Given that it is currently unknown whether it is solely large transient events that cause impacts to networks the method of characterisation should be able to represent the full range of oscillations in pressure as small magnitude (low intensity) but high in number of occurrences may cause a fatigue effect on a pipe. There is no commonly established method to characterise and count different magnitudes of transient events in recorded time series pressure signals. The ability to characterise transient (magnitude, time duration and number of occurrences for different ranges of pressure transient events) allows further investigation of correlation with system response e.g. through statistical methods. Pressure transients are a series of discontinuous events in the network, hence some of the signal processing techniques, such as Fourier transform methods do not produce useful representations of the pressures experienced by the pipe in the frequency domain. These techniques cannot give the actual magnitudes or time duration of a series of transient pressure events which compose a single pressure transient wave. A fundamental disadvantage of these methods is the assumption that the signal is infinite and continuous.

Due to the fact that pressure transient waves are discontinuous events some other techniques, which deal with discontinuity in signals are more appropriate. Wavelet analysis has been successfully applied in transient analysis for peak detection [15], leak detection [16], burst detection [17] and also in other fields for singularity detection in electrocardiogram signals [18]. Wavelet analysis has proven it use as a tool for the detection of signal discontinuities and for denoising a signal in a number of contexts [19]–[21]. However it is still unknown if this method can capture all magnitudes and time duration of pressure transient events. In particular if a high magnitude pressure transient events is comprised of small magnitude ones, and if this method is effective for large datasets.

Peak-trough detection techniques have been successfully developed and applied to characterise features in complex time series data in other fields [15], [22]. These techniques have enabled researchers to count significant events in time series data and are generally fast and easy to implement on large datasets. Such peak-trough detection algorithms have not been applied to pressure transient time series data. However, direct unconditional application of these techniques will not provide the full characterisation of all magnitudes and rate of occurrences of transient events observed in operational WDS. This is because high magnitude pressure transient waves frequently comprises of smaller waves resulting from reflections at junctions, etc. To fully characterize the range of pressures changes that a pipe experiences a more sophisticated algorithm/method needs to be developed to count the full range of event magnitudes.

The aim of this paper is to describe a method to characterise transient pressure waves in the form of a series of discrete pressure transient events. The characterisation should be such that it produces a reasonable representation of the pressure changes, in terms of magnitude and duration, that a pipe experiences. This method should be effective, efficient and applicable to large amounts of pressure data.

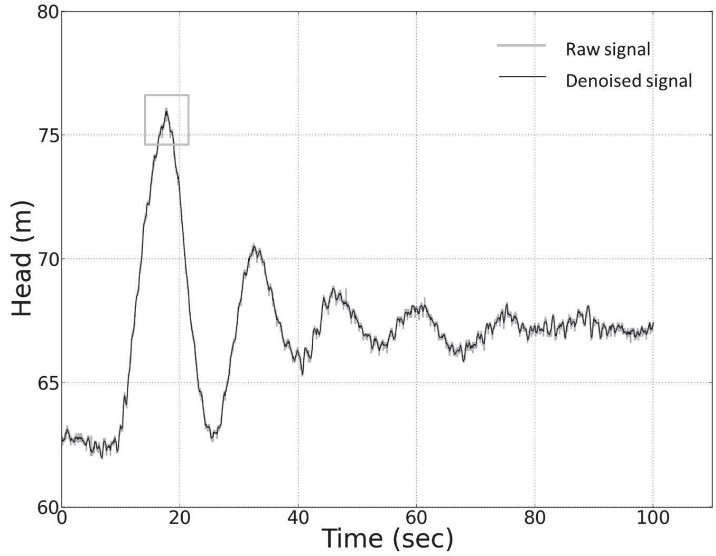
2 METHODOLOGY

In this section the development of a new method for quantification and characterisation of pressure transient events will be described. The method should be able to show magnitudes and time durations of pressure transient events and show how these are unique between different sampling locations and characterise these differences. Firstly a standard peak-trough identification/detection method is presented to identify all peak-trough pairs in a signal. This is followed by a process to select the peak-trough pairs that constitute a representation of the variety of magnitudes and durations of the pressure transient events. The method described is then applied to pressure signals which were recorded in two different water networks. Finally the resulting site specific 'transient fingerprints' are presented, showing a graphical representation of pressure transient events characterisation.

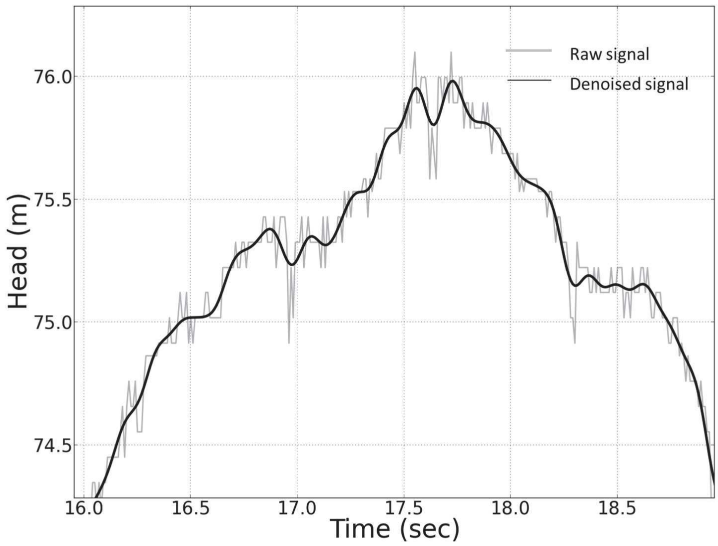
2.1 Instrumentation

The collection of the data reported herein was enabled through custom built high speed pressure data loggers. Pressure data was continuously recorded at 100Hz. The logger was GPS time stamped, which allowed time synchronisation with other loggers, if required, to double check the results through cross verification from more than one area.

Instrument precision was assessed by steady state pressure tests. The measured noise was characterised as being ± one standard deviation of 0.06 pressure head (m), therefore the events of magnitude less than 0.1 head (m) were excluded from the analysis (see section 2.2). Analogue to digital resolution was 0.005 pressure head (m) therefore it did not have an effect on the analysis. A low pass filter was employed to remove spurious instrumentation noise, with care taken to avoid impacting the small scale pressure fluctuations. A typical raw and denoised signal is presented in Figure 1.



(a)



(b)

Figure 1. (a) Example of a denoised pressure transient wave and (b) magnification of its part

2.2 Signal event identification

Peak-trough identification was undertaken using the peak finding algorithm (MAT-LAB script: http://billauer.co.il/peakdet.html). This method identifies all peak-trough pairs with differences in magnitudes of pressure greater than a threshold which is called 'delta h'. To collect all the possible peak-trough pairs the value of 'delta h' is steadily increased and all results recorded.

A short description of the algorithm is presented in a series of steps, and conceptually shown in Figure 2, with selected peaks and troughs marked from A-F:

1. A minimum 'delta h' = 0.1 pressure head (m) is chosen (minimum absolute magnitude required for the event). Below this value the signal variation was considered as to small to be a pressure transient of possible interest (below the precision of the measuring instrument).

2. The peak finder process is then run. The process finds all sequential peak and trough pairs with differences in magnitude greater or equal to 0.1 pressure head (m) which are then saved in the List 1. During this step maximum ‘delta h’ is also identified as a maximum detected value from peak to through for the database.
3. Increase ‘delta h’ in steps of 0.1 pressure head (m).
4. Rerun the peak-finder process. In this step another set of peaks is detected. The outcome is saved in the List 2.
5. Compare the List 1 and the List 2 to remove duplicates because some of the peak-trough pairs in the List 2 are repeats of the pairs already detected in the List 1.

Repeat the steps 3), 4) and 5) until ‘delta h’ reaches the maximum magnitude detected in Step 2 and save the final list (Full Outcome list).

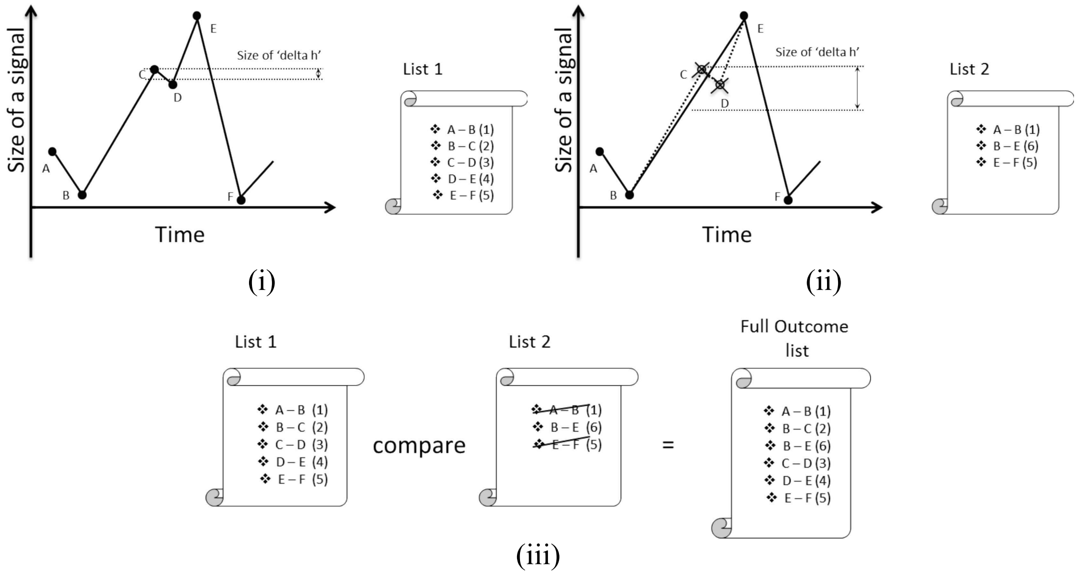


Figure 2. Representation of the application of the algorithm for the peak-through pairs where the value of a size of a signal between two points is (i) less than the size of ‘delta h’ and (ii) greater than the size of ‘delta h’. (i) When the size of ‘delta h’ is smaller than the difference in size between points C and D it allows both points to be selected and saved in a List 1. Five events were saved in the List 1. (ii) When the difference in size between points C and D is less than the size of ‘delta h’ points C and D are not selected and not saved in a outcome list. Three events were saved in the List 2. (iii) The full outcome list is compiled at the end of the algorithm and comprises unique pairs of points: max – min and min – max saved during the selection process

Figure 3 shows the output of the peak-trough pair finder algorithm for a short section of high speed pressure data. In the trace it can be seen that the algorithm has found a large number of peak-trough pairs. During the preliminary peak-finder process all the peak-trough pairs are detected, this ensures that all the potential magnitudes and time durations of events are captured. However, this process also includes spurious peak-trough pairs which are not good representations of the pressures that the pipe actually experiences.

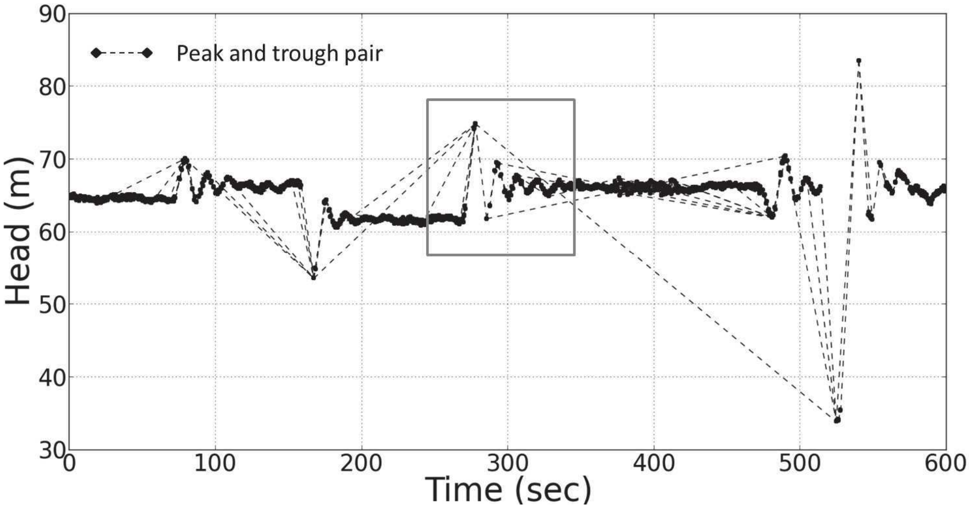
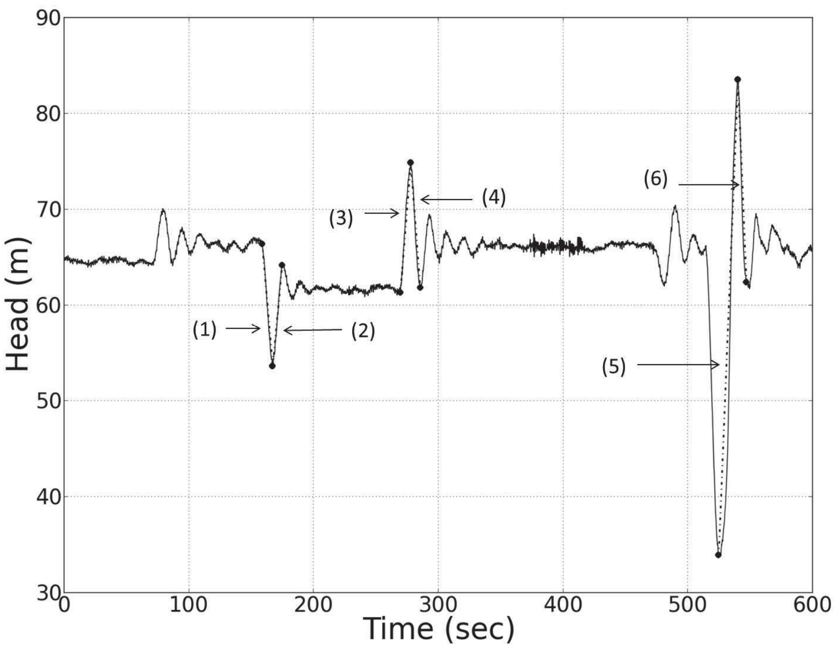


Figure 3. Demonstration of the collection of all the peak-trough pairs on a sample of high speed data

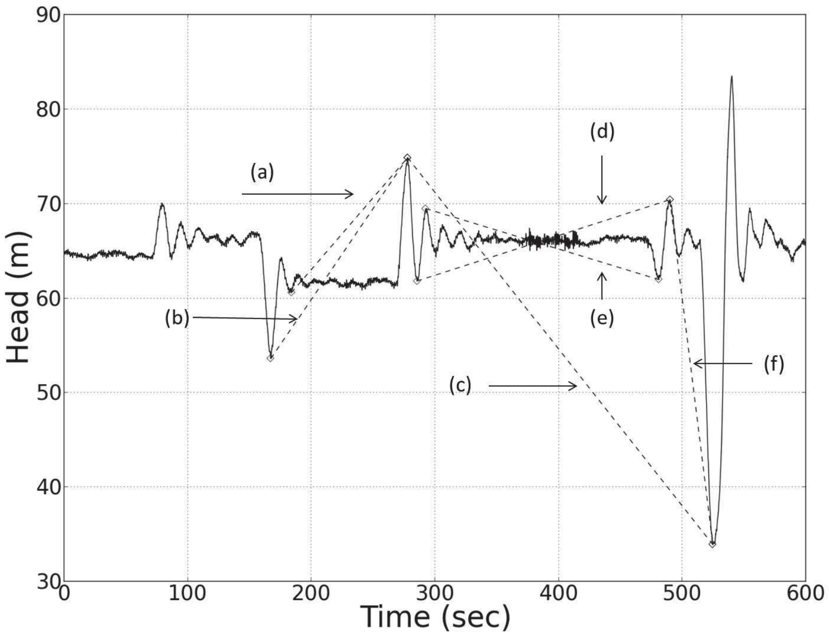
2.3 Transient events selection

After the generation of all possible peak-trough pairs is completed a process of rationalisation is undertaken to remove any spurious events. A goodness-of-fit technique is used to compare the peak-trough pairs to the original signal, and any which fall below a chosen threshold of fit are discarded.

Figure 4 highlights a number of the peak-trough pairs detected by the algorithm in section 2.2. Figure 4 (a) shows some examples of the pairs that are a good representation of the actual pressure response and therefore should be kept. Figure 4 (b) shows examples of the pairs which obviously are not a good representation of what the pipe actually experiences and should be removed from the characterisation. The next section will highlight the method used to assess the goodness of fit of the original signal to the peak-trough pairs.



(a)



(b)

Figure 4. Examples of (a) correctly identified peak-trough pairs (b) incorrectly identified peak-trough pairs which are not reasonable representation of what the pipe experiences

2.3.1 Correlation measures

To evaluate which pairs are realistic representations of pressure transient events experienced by the pipe and which are not, the original signal was compared to the detected events. During the algorithm development process a number of goodness of fit coefficients were tested to assess this fit. These ranged from R^2, Mean Absolute Error (MAE) and coefficients based on the Root Mean Squared Error (RMSE). To ensure that the process removed spurious events, regardless of overall magnitude or duration, it is required that the chosen correlation measure should remove spurious events (see Figure 4 (b)) regardless of their magnitudes and time durations.

The family of (RMSE) measures was found to give the best results. RMSE itself was unsuitable for use, as it did not cope well with transients of different sizes. However, it showed a sufficient sensitivity to the shape of pressure transient events. NRMSE, which is RMSE normalized by the range of observed values, has a high sensitivity to the shape of transient events and is capable of dealing with events of different sizes. This measure appeared as potentially suitable for pressure transient event selection; however a threshold is required to select between reasonable and poor representations of the data. Selection of this threshold was a manual process compromising between removing spurious events and not removing events which were good description of pressure transients. For the data sets presented here it was found that an NRMSE threshold of 0.23 should be applied as the selection criterion to discard peak-trough pairs which should not be considered as part of the pressure transient event. Figure 5 shows a scatter plot for each unique peak-trough pair characterised by $\Delta h/\Delta t$ against NRMSE. The threshold is marked, as well as the events from Figure 4 (a) and (b).

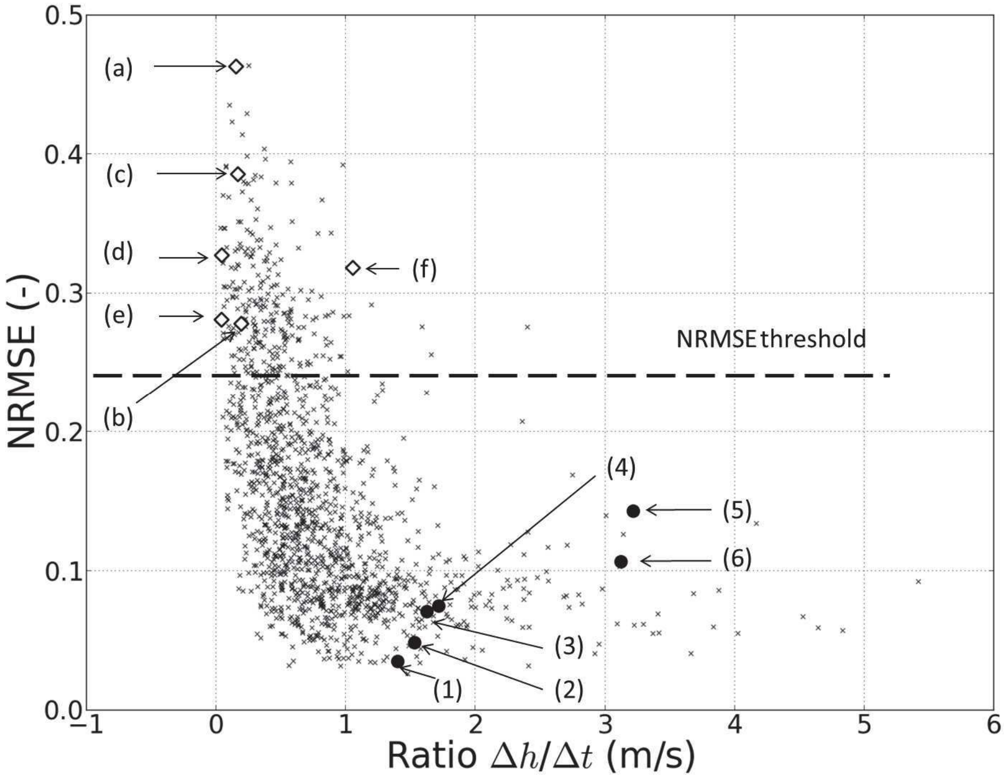


Figure 5. Peaks and troughs NRMSE vs Ratio Δh/Δt

Figure 6 shows the previously investigated dataset (Figure 3 and Figure 4) to which the NRMSE threshold was applied. From this figure it can be seen that all previously identified problematic events were removed leaving peak-trough pairs which can be seen to be a reasonable representation of the original pressure signal and what the pipe actually experiences.

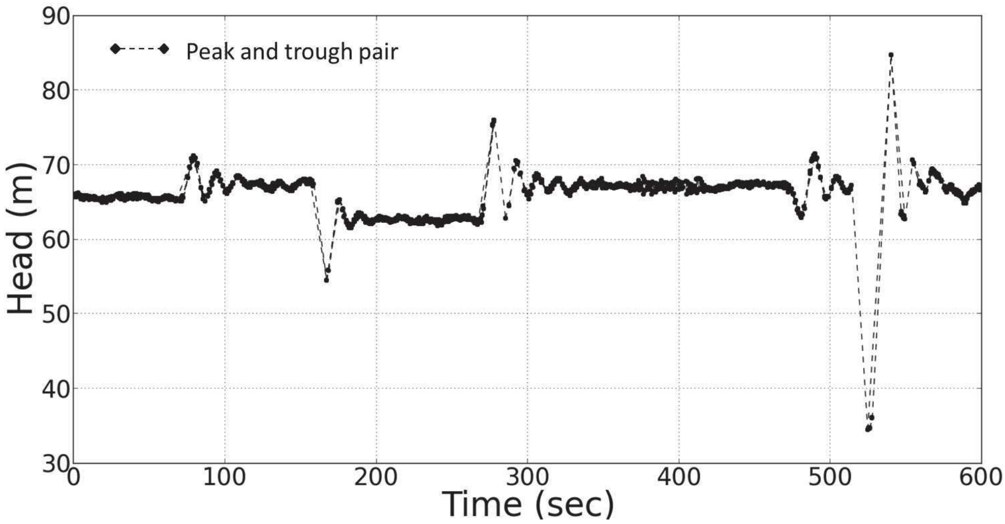


Figure 6. Transient events with the NRMSE values <=0.23

The peak-trough pairs shown in Figure 6 are listed as a series of peak-through events of different magnitudes and durations and provide a characterisation of the pressure regime experienced by a pipe. From this list it is possible to determine summary statistics about the magnitude and durations of the individual transient events in the system. For instance in the example above there were 965 events of magnitude less than 1 m, 8 upsurges with magnitude greater than 10 m and 6 downsurges with magnitude greater than -10 m. It is informative to visually represent the events as system specific 'transient fingerprint'.

The transient fingerprint is the final output of the pressure transient characterisation method, it provides information about the pressure transient experienced at a given point of a network in the form of a 2D histogram. Figure 7 shows the transient fingerprint for the data shown as time series in Figure 6. More 'energetic' transient events, those with a greater magnitude and shorter duration, will appear in the bottom left and bottom rights of the plot, depending if they are downsurges or upsurges respectively. Towards the centre of the plot are events of low magnitude and the top of the plot shows events of long duration. In addition to the grid lines of constant magnitude or duration, radial lines of constant Δh/Δt have been added to the plot to help identification of transient events.

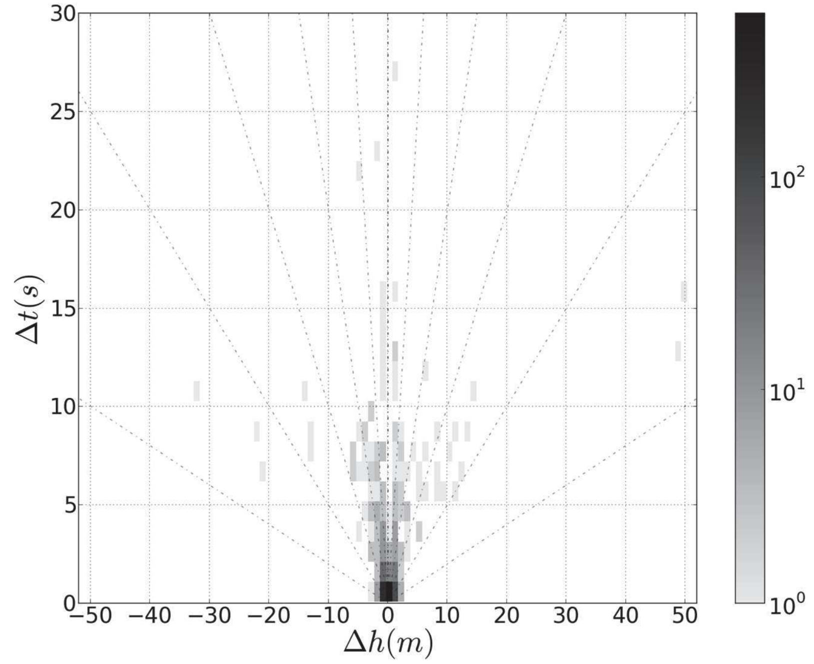


Figure 7. A site unique 'transient fingerprint' for 10 minutes of pressure data, from Figure 6

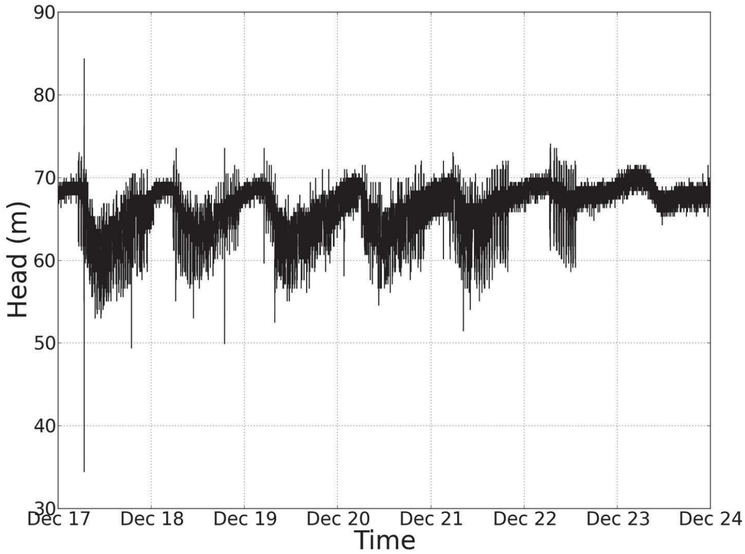
3 RESULTS

In this section results are presented from applying the method to characterise and count different magnitudes of pressure transient events in the recorded time series pressure signal from two diverse pressure signals. Week long data sets were analysed to present both week and weekend activity. The two areas are industrial and pump dominated respectively with corresponding differences in pressure transient behaviour.

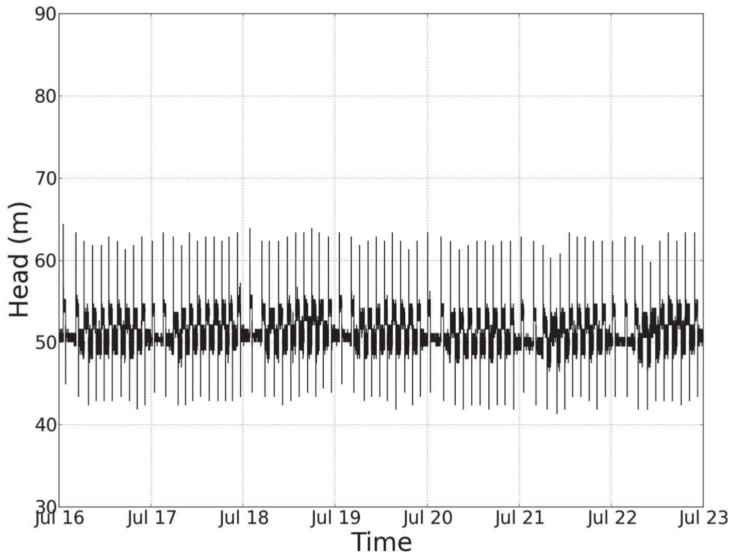
In the first of the two systems the dynamics of the response appear to be dominated by pressure transients generated by the industrial users drawing water from the system. Figure 8 (a) shows the time series data from this site. This system is composed predominantly of metal pipes (83.8%) with 11.5% plastic pipes and a small amount of asbestos cement (4.7%). The configuration of the network was branched, with a large main distribution pipe, along with infrequent network extensions to various industrial customers. The logger was connected to a 6” diameter, asbestos cement pipe, about 80 m from one of the industrial users.

The second system has a 6” cast iron pipe with several branches downstream of a booster pump, connected to this is a 4” asbestos cement pipe to which the pressure logger was attached at approximately 0.9 km from the pump. The pressure trace is dominated by transient events generated as the pump switches on and off, Figure 8 (b). Downstream of the pressure logger the network was highly branched and led to a series of domestic users. The network approximately comprises of 17.4 km of pipe of which about 65% is metal pipes, 27% asbestos cement. Plastic pipes constituted only around 8%.

Figure 8 shows the recorded pressure traces from the two sites and Figure 9 the associated ‘transient fingerprint’ output of the characterisation method which allows visualisation of the number of occurrences of different magnitudes and time durations of pressure transient events.

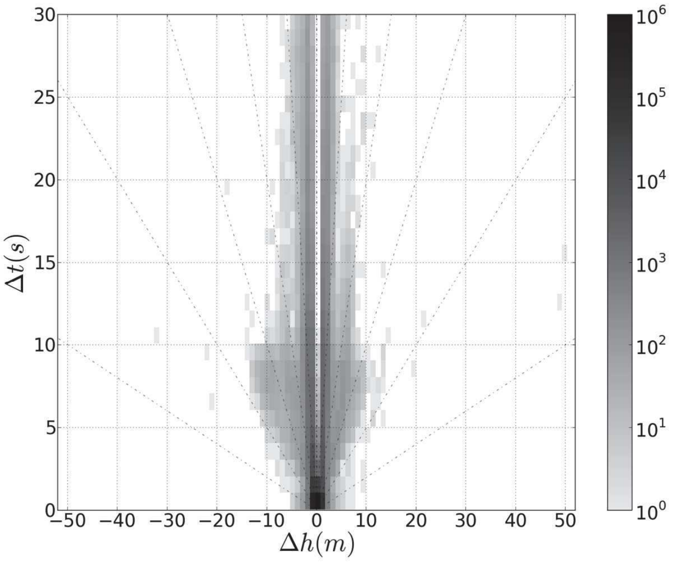


(a)

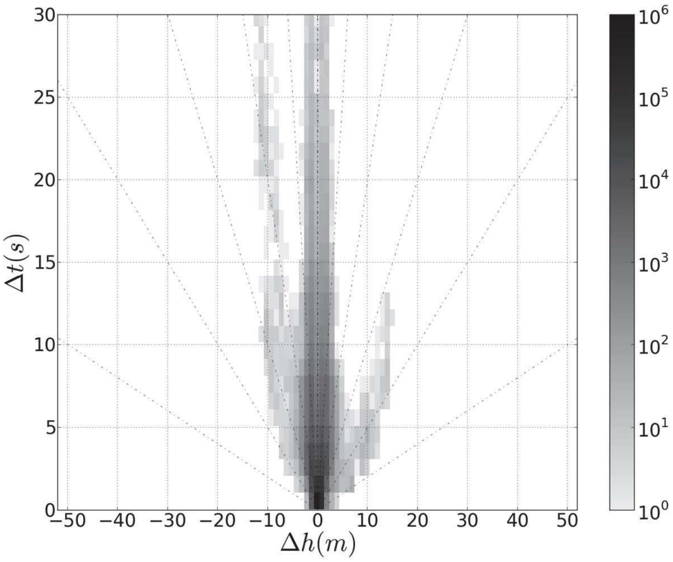


(b)

Figure 8. One week of data (down sampled to 1Hz for plotting purposes)



(a)



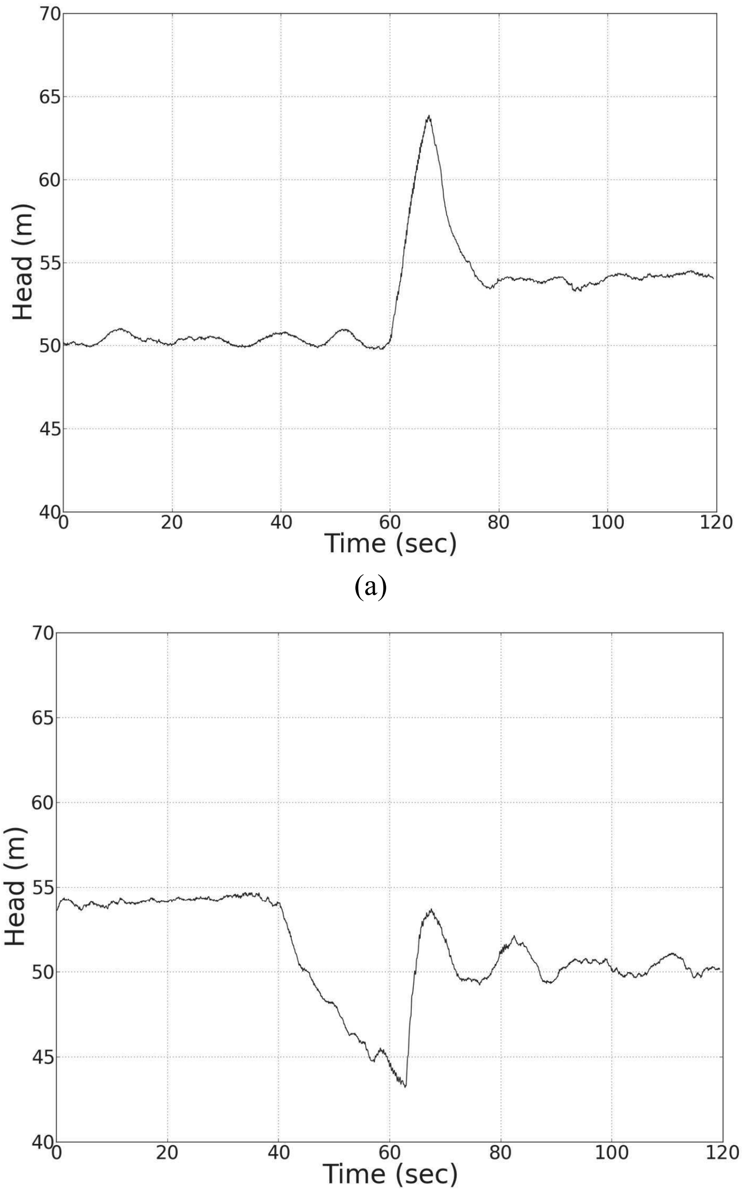
(b)

Figure 9. Sites unique 'transient fingerprint' (a) industrial site (b) pump site

4 DISCUSSION

Figure 8 (a) shows data from the first of the two locations. In this pressure trace we can see an obvious diurnal cycle through the 5 days of the working week. During this time it can also be seen that the instrument measured a series of repeated transients with magnitudes of approximately ±10 to 15 m generally occurring during lower pressure day time hours. In addition a large magnitude (~50 m) transient was recorded at the start of the week. The final two weekend days of the time series show less activity. This pattern suggests transient behaviour driven by industrial users. Figure 8 (b) shows the time series pressure response from the second system. Here it can be seen that there is a very regular pattern of 10-15 m upsurge and downsurge transients being experienced, with periods of slightly higher or lower pressure between; this is consistent with transients due to start/stop of the pump supplying the system.

Figure 9 (a) and (b) present the 'transient fingerprints' from the industrial and pumped system respectively. The differences in the pressure traces are clearly visible in the 'transient fingerprints'. Figure 9 (a) is generally symmetrical (around $\Delta h = 0$), with a large cluster of events at low magnitude regardless of duration. There is a slightly larger number of downsurge events with a magnitude of 5 – 15 m that occurs for a duration of 5 – 10 seconds than the equivalent magnitudes of upsurges. There are a few events captured with very high magnitudes ($\Delta h = + 50, - 32$ m) that do not form part of the main mass of the plot, these are associated with the large scale transient event that occurred at the start of the recording period (Figure 8 (a)). The corresponding plot for the pumped system is very different in shape. Similar to the industrial site, a large number of events of low magnitude are seen corresponding to the low level fluctuations seen in Figure 8 (b), however there is also an obvious asymmetry to the plot with Δh of downsurge events appearing to have a much greater duration than the corresponding Δh of upsurge events.



(a)

(b)

Figure 10. Examples of the upsurge (a) and downsurge (b) observed in the pump site (both show duration of two minutes)

Figure 10 presents 120 sec of data of a (a) typical upsurge and (b) down surge observed in the pump site. The upsurge (a) is due to the pump switching on and takes about 8.8 sec with a magnitude of 14.1 m. This sharp pressure rise is then followed by the sharp downsurge of magnitude -10.5 m and duration 11.18 sec. The differences in magnitudes are a result of the increase in static pressure due to the pump being switched on. Conversely the down surge due to the pump stop (b) of magnitude about -11.5 m takes about 28.73 sec and it is followed by sharp upsurge of magnitude 10.5 m with duration 4.7 sec. For these events the magnitude of the initial upsurges and downsurges are approximately the same (10 – 15 m) however the durations of the downsurge is longer than the upsurge which accounts for the asymmetry seen in Figure 9 (b). The ability of the 'transient fingerprint' to distinguish the differences in the pressure traces gives us confidence that it is a good method for characterising the pressure response of the system, the forces and cyclic loading patterns the pipe experiences, hence the potential to associate this loading with material fatigue effects [9]–[12].

One known limitation of the system is that due to the peak-finder algorithm events may appear to be counted twice. Recalling the wave example from Figure 2 it can be noticed that during the signal event identification process the pairs A-B, B-C, C-D, D-E and B-E are identified. Some may argue that events B-C and D-E have already been counted, as a part of B-E. The method proposed here counts all events and acknowledges them as equally valid parts of the signal. Counting the events 'twice' has the potential to explore what is useful and what is not, or this double counting can be efficiently eliminated in the event selection process and its importance in association with impact explored.

As developed and implemented the method is comprehensive, capturing very large numbers of very small events (see section 2.3.1, reporting 965 events of magnitude greater than 0.1 m and less than 1 m) through to infrequent extreme events. While the association between transient events and structural or other impacts remain uncertain this is useful and all possibilities can be explored. As understanding of the impact of different transient effects improves the method can be readily refined to filter out events that prove to be unimportant.

For this study a threshold of the NRMSE of 0.23 was chosen based on a visual assessment of the events being selected and those being rejected. This removed the events that were visually not a good representation of the pressure regime experienced by the pipe. In the future a sensitivity analysis should be carried out to assess the impact of the choice of threshold on the final characterisation.

The validity of the method of characterisation has been demonstrated by application to two different real-world pressure traces. The 'transient fingerprints' are able to characterise system pressure transient responses due to typical excitation observed in this system, i.e. pump operating (switching on and off), industrial activity due to water being drawn at the fast rate from the network, valve operating, etc. 'Transient fingerprint' are a way to capture pressure transient main characteristic such as their magnitudes, time duration and number of occurrences at a point in the system. Now that we are able to characterise the pressure response of the system in a rigorous manner it will be possible to implement the characterisations into future research to determine whether transients are a contributing factor for pipe failures, and/or water quality failures.

5 CONCLUSION

A pressure transient characterisation method has been presented which allows the quantification of transients in terms of all the discrete $\Delta h/\Delta t$ events that comprise complete time signals and hence provide a measure of what a given pipe experiences. The method yields a unique ‘transient fingerprint’ for each signal recorded from the water network. Examples of site specific ‘transient fingerprints’ are presented showing the complexity variety and wide spread nature of pressure transients within WDS.

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