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Problem of calculating time delay between pulse arrivals

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ABSTRACT: *This work compares the performance of four different methods of estimating the time delay between pulse arrivals at the sensors subjected to different levels of attenuation, distortion and noise. The accuracy of the calculated time between the pulse arrivals at the sensors is determined and analysed for each of the methods based on the ideal attenuation (no change in shape), ideal attenuation with added noise to the pulse signal and ideal attenuation but with distortion. Based on the analysis carried out, it is clear the cross correlation method gives the best estimate of the delay in pulse arrival times irrespective of the signal to noise ratio and so is the preferred technique used in the remainder of this research.*

KEYWORDS: *attenuation, pulse, signal, distortion, correlation*

I. INTRODUCTION

When calculating the location of an event, the ability to accurately determinethe time delay $(t_2 - t_1)$ between the arrivals of a pulseat the sensors is very important. During the propagation of the pulse due to an event as shown in Figure 1, the shapes and amplitudes of the pulse signals at the sensors are different due todistortion, frequency dependent attenuation and noise. If sensor 1 is closer to the event, the pulse travelling to it suffers less propagation loss than does that travelling to sensor 2, and therefore has a larger amplitude and higher signal to noise ratio, and is also less distorted. This effect of distortion, frequency dependent attenuation and noise on the pulse shape introduces uncertainty in the measurement of the time of arrivals and hence in the estimation of the time delay between arrivals, thus resulting in uncertainty in the location of the event site.

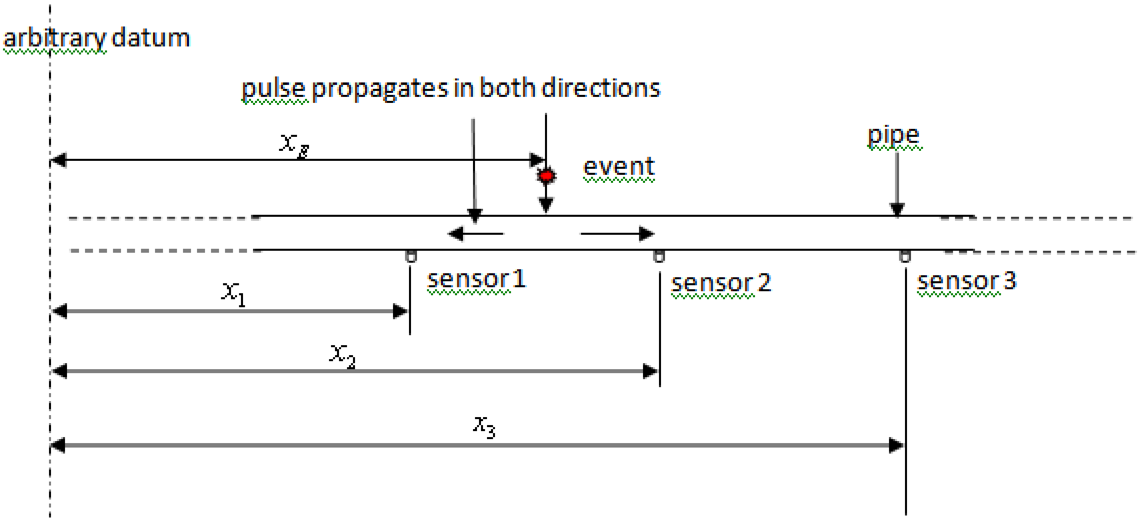


Figure 1 Schematic representation of sensors on a pipeline

Attenuation

As the pulse propagates along the pipeline, its intensity diminishes with distance. The amplitude of the pulse is reduced by the spreading of the pulse. Further weakening of the pulse results from scattering, which is the reflection of the pulse in directions other than the direction of propagation. Attenuation is the decay rate of the pulse as it propagates along the pipeline and is normally exponential. The amplitude change of the decaying pulse can be expressed as;

$$A = A_o e^{-\beta x} \tag{1}$$

In this expression A_0 is the unattenuated amplitude of the propagated pulse at some location. The amplitude A is the reduced amplitude after the pulse has travelled a distance x from that initial location. The quantity β is the attenuation coefficient of the pulse travelling in the x-direction. This value of the attenuation is generally proportional to the square of frequency [1] and it can be obtained experimentally.

1.1 Dispersion

Dispersion is a phenomenon caused by the frequency dependence of velocity of the pulse. As the pulse propagates, the phase relation between the spectral components of the pulse varies with distance and hence the pulse shape becomes progressively distorted, generally widening as the propagation distance increases.

A pulse normally comprises a range of different frequencies. The pulse as a whole propagates at the "group velocity", whereas each frequency component propagates within the pulse at its own "phase velocity". This, coupled with the frequency dependent attenuation, can cause the pulse shape to change considerably with long distances.

II. METHODS OF CALCULATING TIME DELAY BETWEEN PULSE ARRIVALS

The four methods of estimating the time delay in arrivals between the pulse as considered by this research are:

(i) peak detection
(ii) threshold crossing
(iii) cross correlation
(iv) pulse centroid

2.1 Peak Detection

This process involves locating the position of the highest peak of the pulse signals at the sensors. Consider the pulse propagating along the pipeline as illustrated in Figure 1; the generated pulse propagates in both directions of the pipeline arriving first at sensor 1 then later after some time at sensor 2. Figure 2 shows the arrival of an idealised pulse at sensors 1 and 2. The true arrival times are the points where the signals first leave the zero level and the measured arrival times are the points of highest magnitude. If the pulses are the same shape, i.e. there is no distortion during the propagation, then the delay (d1 and d2) between the measured and true time of arrivals of the pulse signals at the sensors are the same and the calculated time delay is correct but the distortion of the pulse will introduce error in the calculation.

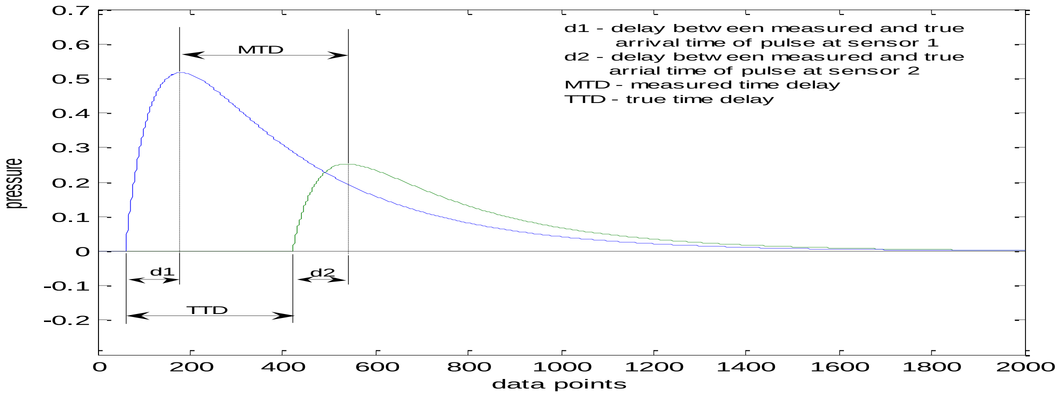


Figure 2 Pulse arrival time measurementsby peak detection

Figure 3 shows the effect of noise on the estimate of the time delay by peak detection. The addition of noise to the otherwise undistorted pulse signals at the sensors results in the blurring of the peaks which makes it uncertain where the highest instantaneous peak value will occur. The horizontal lines within the envelope bounding the noisy signals give the range of possible measured peaks since the highest measured data points must lie on or above these lines. These are shown expanded in Figures 4a and 4b. If the noise level is the same at both sensors as shown, then the amount of uncertainty at sensor 2 is greater because the smaller signal has a lower signal to noise ratio. This uncertainty in the measured arrival times of the pulse signals results in uncertainty in the estimate of the time delay and hence in the estimate of the location of the event site.

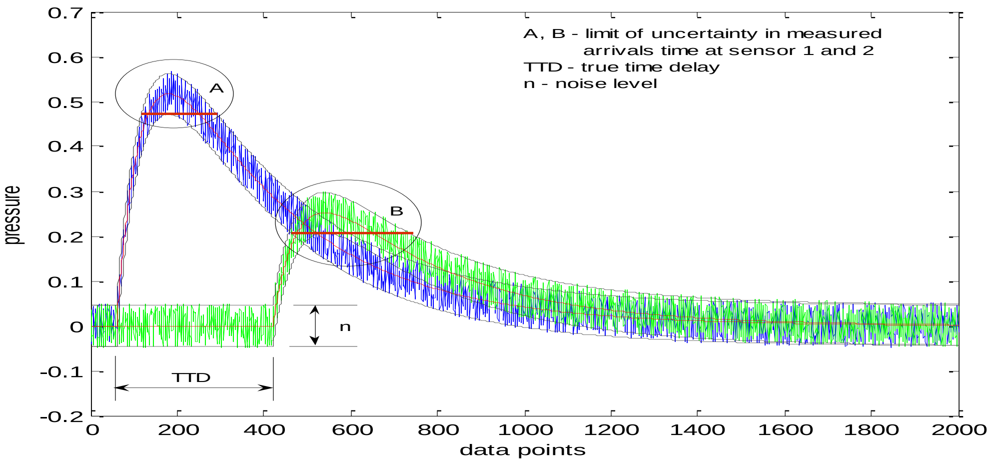
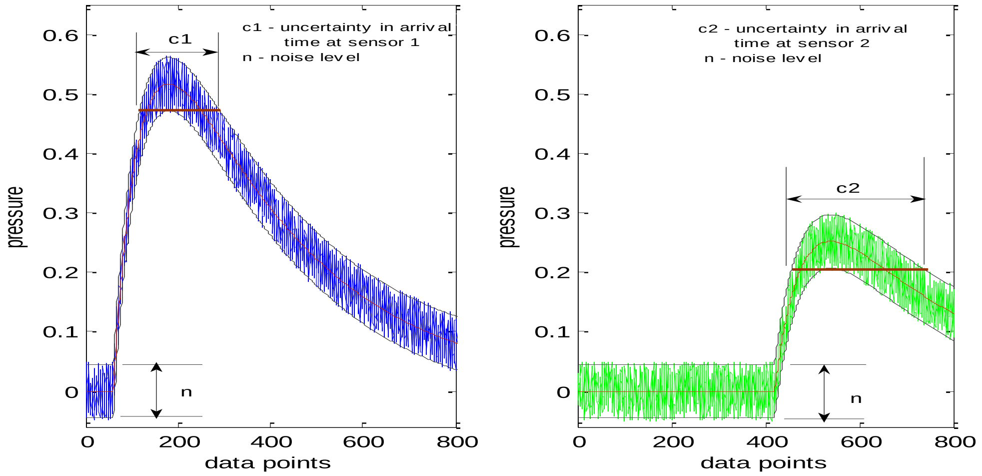


Figure 3 Effect of noise on pulse arrival time by peak detection



(a) sensor 1 (b) sensor 2

Figure 4 Showing detailed section of limit of uncertainty (c1 and c2) in arrivals time by peak detection at the sensors with the same level of noise (n)

Figure 5 shows the effect of distortion on the estimate in time delay in arrivals between the pulse signals by peak detection. The shape of the pulse signal at sensor 2 indicates that the high frequency components of the pulse responsible for the sharp pulse rise have attenuated in the course of pulse propagation, resulting in the peak of the pulse arriving late. With the pulse signal at sensor 2 distorted, the delay (d2) between the measured and true arrival times at this sensor is greater than the delay (d1) at sensor 1. The difference in estimate of the time delay of the measured and true arrivals between the pulse signals is large in this case, but it could be small if the distortion happened to leave the maximum point in the same place. This suggests that the error obtained in the estimate of the time delay in arrivals will depend on the form and amount of distortion encountered by the pulse during propagation.

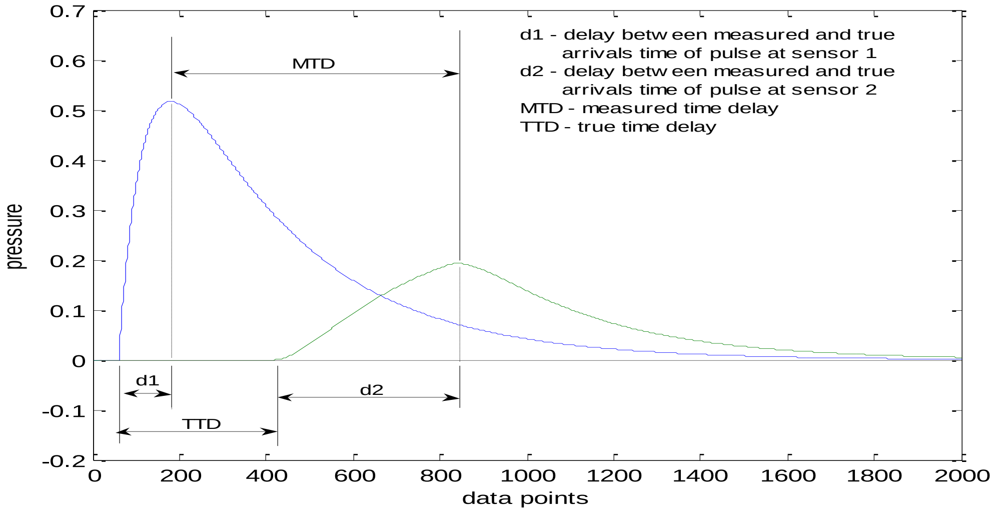


Figure 5 Effect of distortion on pulse arrival time by peak detection

2.2 Threshold Crossing

The threshold crossing method is another simple technique for calculating the time delay in arrivals using estimates of the arrival times [2]. The time of arrival is taken as the time when the pulse first crosses a predetermined threshold level as shown in Figure 6. For this case where the pulse is attenuated but undistorted, the delay (d1 and d2) between the measured and true arrival times of the pulse signals are quite different and the estimate of the time delay is overestimated.

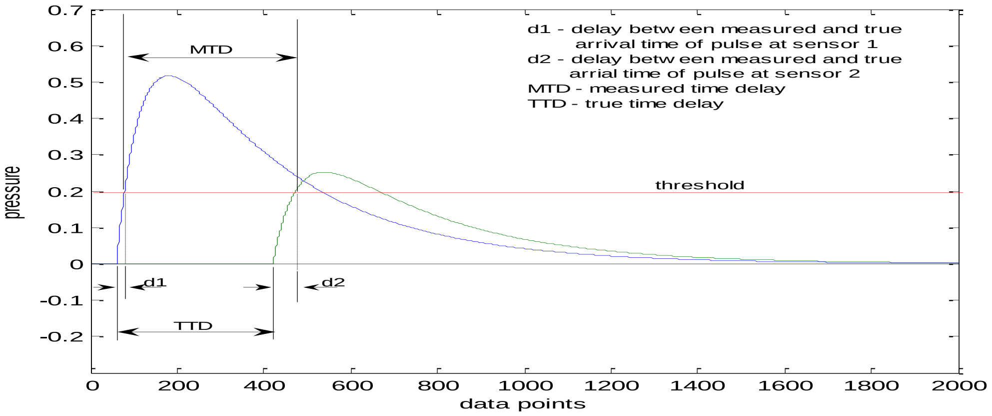


Figure 6 Pulse arrival time measurementsby threshold crossing

A practical limitation in the use of the threshold crossing method is shown in Figure 6 where setting of the threshold level too high (above 0.27, the highest peak of the pulse at sensor 2) would result in non-detection of the pulse at sensor 2, making it impossible for the estimate in the time delay to be determined. This requires some advance knowledge of pulse height and limits the smallest pulse that can be detected in the presence of noise. To ensure large signals, sensors therefore need to be spaced relatively closely along the pipeline thus making this process of damage detection expensive.

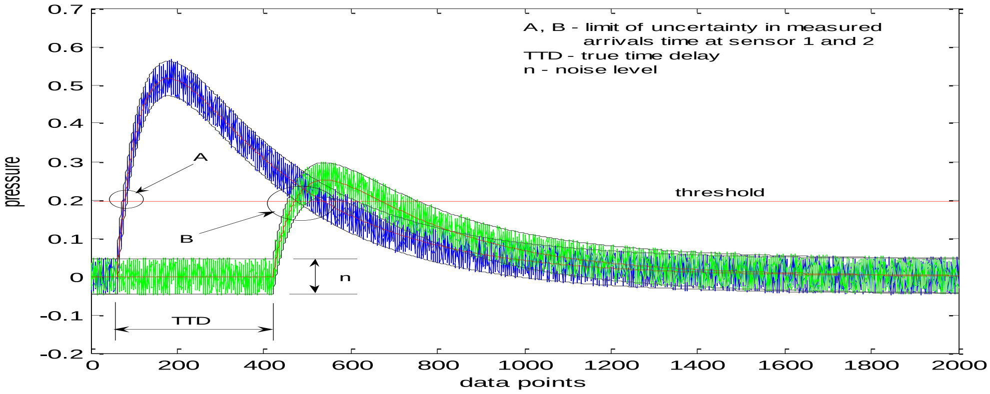


Figure 7 Effect of noise on pulse arrival time by threshold crossing

Figure 7 shows the effect of noise on the estimation of the time delay in arrivals between the pulse signals based on the threshold crossing. The region of the threshold crossings are shown expanded in Figure 8.

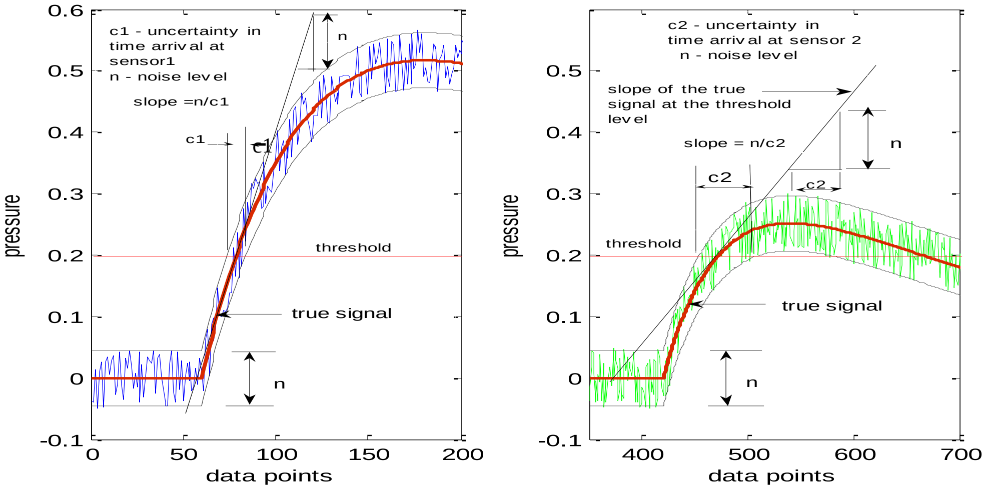
Figures 8a and 8b shows how the uncertainty in the arrivals time measurements of the pulse signals at the sensors are determined. The slope θ of the true pulse signals at the threshold crossing level is taken as the underlying slope of the noisy pulse signals. The noise level n is measured near to the pulse and is assumed to be approximately constant over the short period of the pulse. The uncertainty of the arrival time, obtained from the first threshold crossing of the pulse signal at sensor 2 is thus given by equation 2;

$$c_2 = \frac{n}{\tan \theta_2} \qquad (2)$$

Similarly, the uncertainty in the arrival time at sensor 1 is given by equation 3;

$$c_1 = \frac{n}{\tan \theta_1} \qquad (3)$$

The values of c_1 and c_2 give the uncertainty in arrival times at sensors 1 and 2, respectively.



(a) sensor 1 (b) sensor 2

Figure 8 Showing detailed limit of uncertainty in the measured arrivals time by the threshold crossing.

The calculated uncertainty of the pulse at sensor 1 which has a steep slope is smaller than that of the pulse at sensor 2 having a less steep slope at the threshold crossing. This clearly shows that as the pulse propagates farther away from the event site, the uncertainty in measurements of arrival times of the pulse increases. Thus, the estimate of the time delay between the measured and true arrivals will be significantly large using the threshold crossing when the signal to noise ratio is small.

Setting of the threshold level is also an important task in the use of this method with the presence of noise. Although, setting the threshold level reduces uncertainty in the time of arrival measurement, it presents the inconvenience of a high probability of false alarm. It causes the background noise to cross the threshold, resulting in a great deal of unwanted data being recorded. On the other hand, a high threshold level result in greater uncertainty but reduced probability of false alarms due to noise.

Figure 9 shows the effect of distortion due to frequency dependent attenuation on time delay estimate by the threshold crossing method. In this case, there is a large difference in the delay (d1 and d2) between the true and measured arrival times; hence there will be a large error in the calculated time between arrivals. This also suggests that the magnitude and form of the distortion determines the size of the error in the calculated time delay using this method.

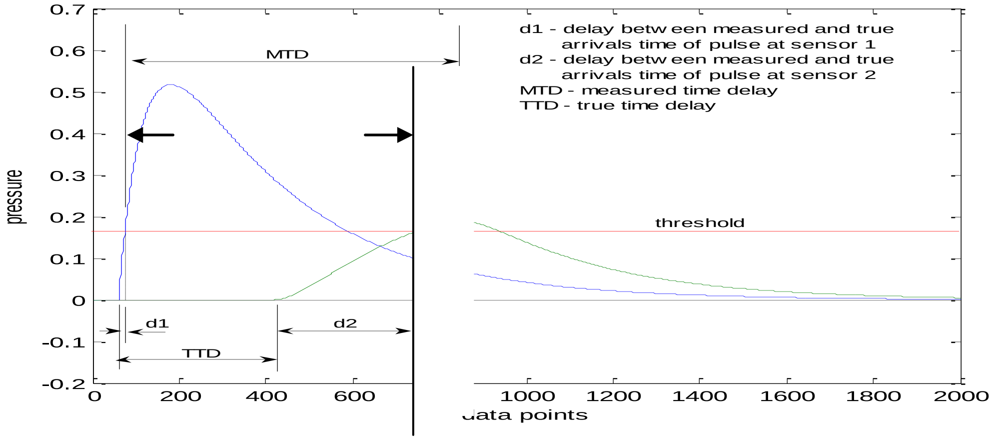


Figure 9 Effect of distortion on pulse arrival time by threshold crossing

2.3 Cross Correlation

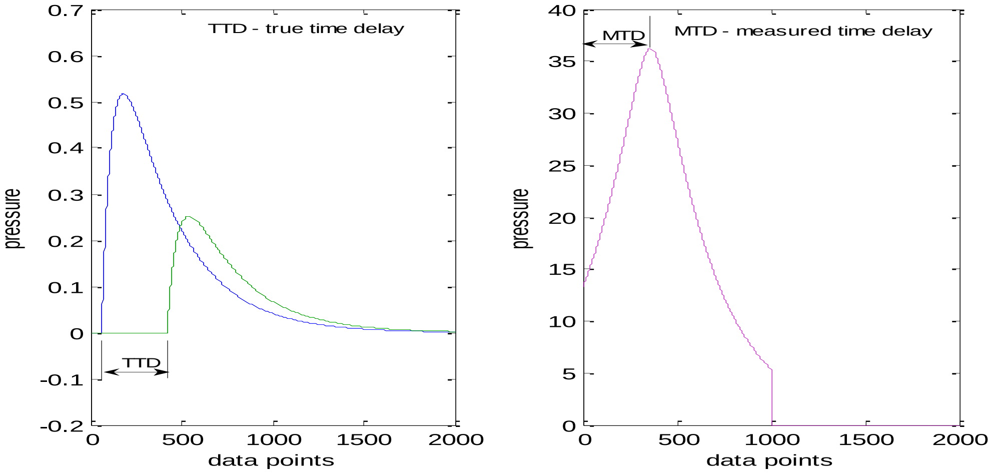
Cross-correlation is a method used to determine the similarities between two signals as a function of a time lag applied to one of the signals [3]. The cross correlation $A_{xx}(t)CC_{x_1x_2}(\tau)$ of two signals, $x_1(t)$ and $x_2(t)$ is given by equation 3;

$$CC_{x_1x_2}(\tau) = \int_{-\infty}^{\infty} x_1(t)x_2(t+\tau)dt \qquad (4)$$

Similarly, for discrete-time signals, this equation is written as in equation 5;

$$CC_{x_1x_2}(m) = \frac{1}{N}\sum_{i=0}^{N-1} x_1(i)x_2(i-m) \qquad (5)$$

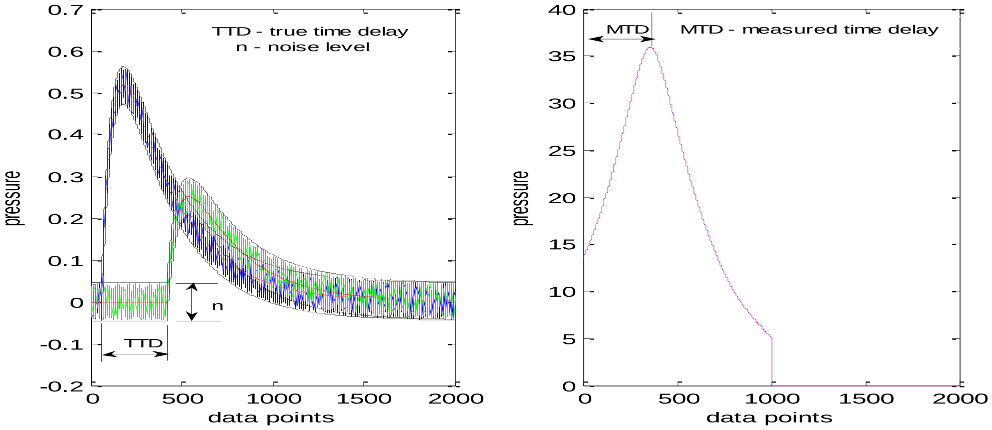
The process of cross correlation of the pulse signals involves movement of the propagating pulse signal at sensor 2 along the time axis by a small time increment and looking at the similarities it has with the pulse signal at sensor 1. By calculating the cross correlation function of the sensor signals a measure of the time delay is obtained from the position of the maximum peak of the cross correlation function as illustrated in Figures 10a and 10b. Figure 10b shows the cross correlation function with a clear peak indicating the location of the maximum best fit between the two pulses in Figure 10a. An advantage of using this method is that it does not require measurements of the time of arrivals of the pulse signals at the sensors in order to calculate the time delay, but rather gives the delay directly.



(a) pulse signals (b) cross correlation function

Figure 10 Pulse time delay estimation by cross correlation

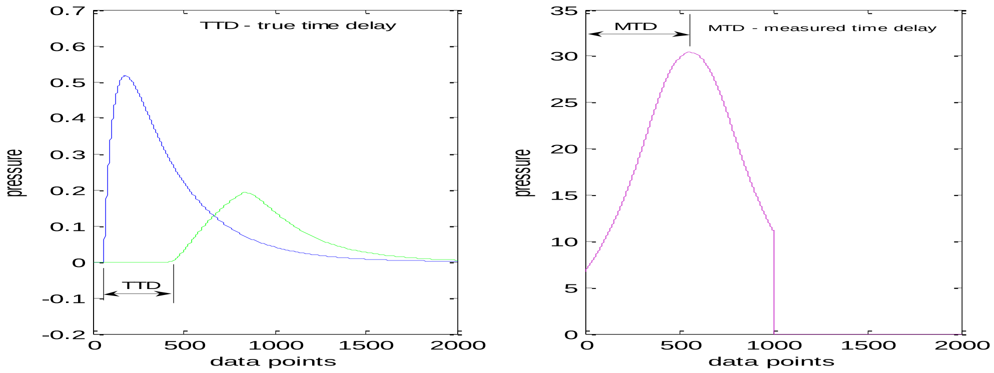
Figure 11 shows the cross correlation of the pulse signals with the addition of noise. It can be seen that even with the addition of noise to the pulse, performing a correlation between the pulse signals still gives a good estimate of the measured time delay in arrivals of the pulse signals. This is attributable to the cross correlation method acting as an integrator (equation 5) which averages the random noise present in the pulse signals.



(a) noisy pulse signals (b) cross correlation function

Figure 11 Effect of noise on pulse time delay estimation by cross correlation

Figure 12 shows the effect of distortion on the time delay measurement by cross correlation. There is some error using this method, though not as much as the uncertainty in the peak detection and threshold crossing methods. The magnitude of the cross correlated peak is lower due to the poorer fit and the size of the error will depend the size and form of the distortion in each application.



(a) distorted and undistorted signals (b) cross correlation function

Figure 12 Effect of distortion on pulse time delay estimation by cross correlation

Figure 12 shows the unfiltered and filter pulse signals at the sensors and Figure 12 shows their cross correlation.

2.4 Pulse Centroid

Another way to measure between pulse arrivals is by the use of a centroid timing technique. The centroid of a pulse is its geometrical centre. For complicated shapes such as experimentally measured pulses the centroid can be found by numerical integration.

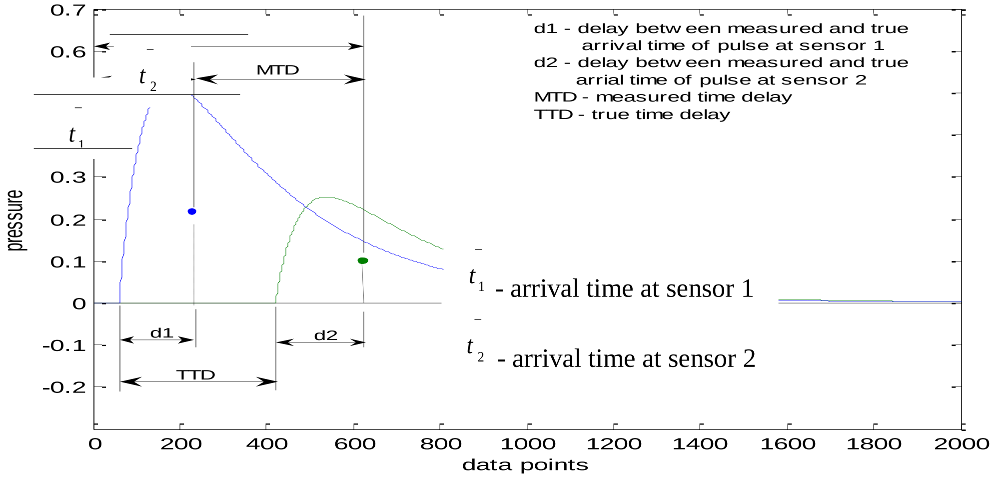


Figure 13 Pulse arrival time by use of centroid

Figure 13 shows how the centroid of the pulse signals is used in estimating the time delay between the pulse signals. The centroid of each pulse signal is determined by equation 6 using numerical integration;

$$\bar{t} = \frac{\int_0^L t_i q(t_i)\,dt}{\int_0^L q(t_i)\,dt} \qquad (6)$$

where L is the length of the pulse, t_i and $\bar{t}$ are both measured from the same datum.

The delay is difference between the calculated values of $\bar{t}$.

Considering Figure 13, the two pulse signals shown only differ in magnitude with no noise or distortion on them. The positions of the centroids from the start of the pulses (d1 and d2) are the same and so there is no error in the calculated delay.

Figure 14 shows the pulses with added noise on which the method of centroids was tried. The noise on the pulse signals makes it impossible to determine the exact limits of integration to be taken and this affects computation of the centroid. Hence, it is not possible to determine the delay by the centroid method.

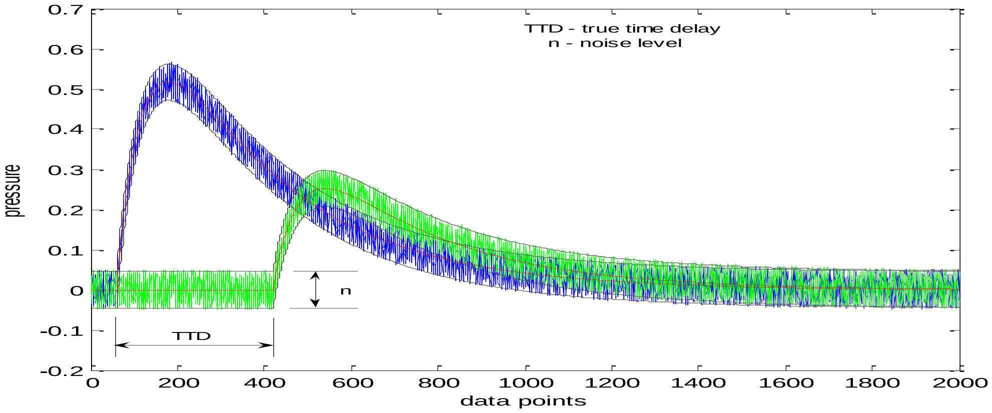


Figure 14 Effect of noise on pulse arrival time by centroid

Figure 15 shows the effect of distortion on the estimate of the time delay in arrivals by the use of centroid. It can be seen that the difference in delay (d1 and d2) between the measured and true arrivals time are different. This indicates that when pulse signals are distorted there will be errors in the estimate of the time delay.

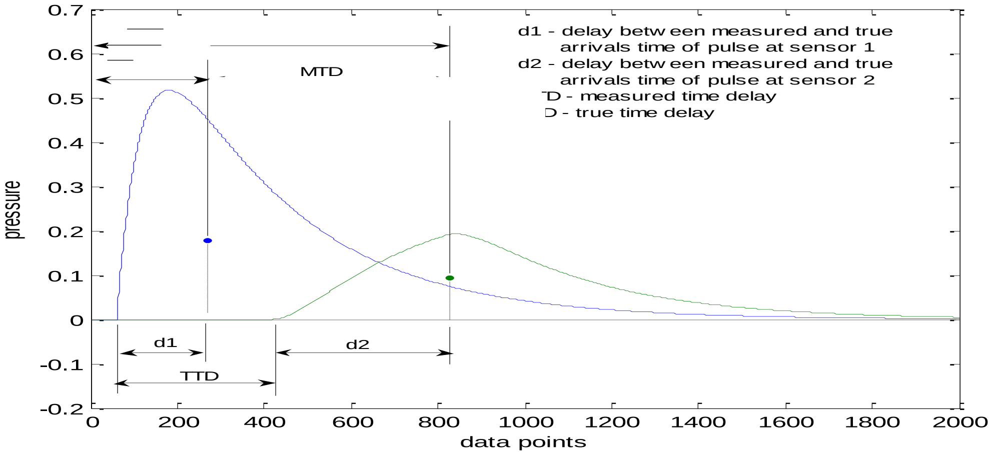


Figure 15 Effect of distortion on pulse arrival time by centroid

III. RESULTS

Test for Effectiveness of the Methods using Experimental Pressure Pulse Signals

To test for the effectiveness of these methods in estimating the time delay between arrivals of the pulse signals, sensor signals from a true pressure pulse obtained in an experimental work were used. These signals, shown in Figure 16, were analysed using a program written in Matlab programming language to measure the time delay using the peak detection, threshold crossing and cross correlation methods. The centroid is not used for the reasons given above.

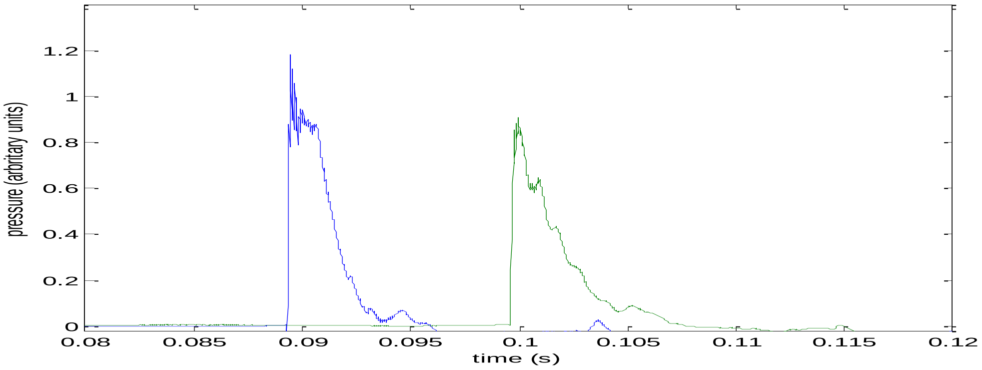


Figure 16 True pressure pulse signal from experiment

Considering Figure 16, the true time delay between the starting points of the two pulses is 0.0104s. The delay calculated using the peak detection method was 0.0105 s; both the cross correlation and threshold crossing methods gave 0.0103s.

The effect of noise was investigated by adding a random number to each data point of the experimental signals. Ten repetitions at various noise levels were carried out for each of the three methods and the spread of values of the calculated delay determined and plotted against noise level in Figure 17. The noise level is measured in the same arbitrary units as the pulse pressure, so that the maximum noise level (0.3 units) is approximately one third of the magnitude of the smaller pulse.

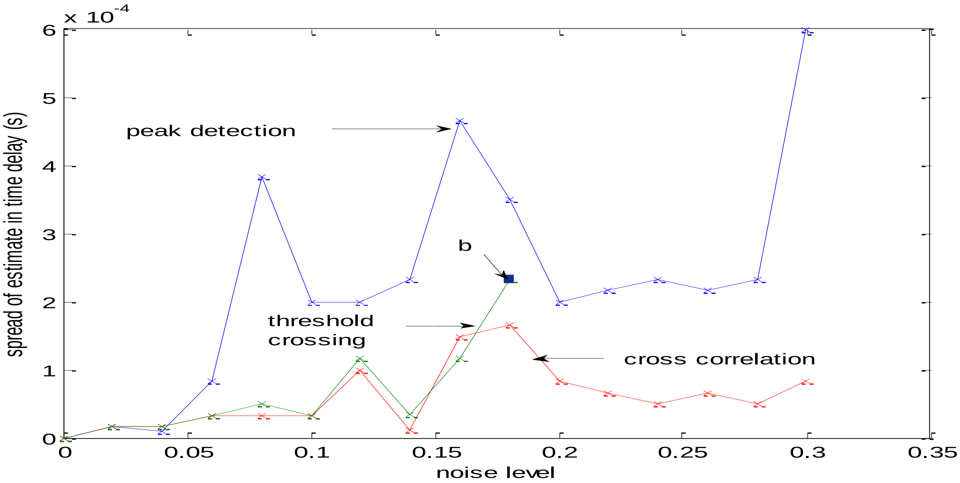


Figure 17 Graph of spread in time delay against increasing noise level

At low noise levels below 0.05 units (5% of the magnitude of the smaller pulse) the three techniques give very similar results with very small spread (<0.02ms). At higher noise levels the peak detection method became progressively less reliable than the threshold crossing and cross correlation methods, though it should be noted that even at the highest noise level investigated the spread of results was only 0.6ms, or <6% of the true value. Up to a noise level of 0.18 the threshold crossing and cross correlation methods gave similar results, with spread of results below 0.16ms (1.5% of the true value). Above a noise level of 0.18 (position “b” in Figure 17) the threshold crossing method could not be used reliably, but the cross correlation method continued to give similarly reliable results up to the maximum noise level investigated.

IV. DISCUSSION OF RESULTS

Four methods have been presented to measure the time delay in arrivals between pulse signals.

The peak detection method uses the measured time between pulse arrivals, defined as the time of the highest peak values. When noise and distortion are not present, this method works well and is accurate. Noise causes blurring of the peaks of the pulse and therefore introduces uncertainty.

The threshold crossing method uses arrival times in the same way, but in this case defined as the time where the signal first crosses a threshold level. This method, though simple, resulted in overestimation of the time delay. The threshold method is effective at high signal to noise ratios but becomes unreliable in higher noise and becomes unusable when the noise level approaches the size of the smaller pulse.

The cross correlation method estimated the time delay directly without the need for measuring the arrival times. The method is effective even in the presence of high noise. The only disadvantage is that it requires much more computation time than the other methods, but this is not significant with today's modern computers.

The use of the pulse centroid estimated the time delay effectively for pulse signals of similarly shapes but results in errors when the pulse signals are distorted and could not be used in the presence of significant noise because of the difficulty of determining the limits of the pulses.

V. CONCLUSION

Based on the foregoing analysis, it is clear the cross correlation method gives the best estimate of the delay in pulse arrival times irrespective of the signal to noise ratio and so is the preferred technique used in the remainder of this research.

REFERENCES

[1] Cao, C.F., Baik, S., Choi, J.B. and Kim, Y.J., "Protection of Underground Gas Pipelines from Third Party Damage by On-Line Monitoring Using Piezoelectric Accelerometers," Proc. of the Institution of Mechanical Engineers, Part E, J. Process Mechanical Engineering, 221, pp. 61 – 67.

[2] Walker, J. F., 1971, "Performance Data for a Double-Threshold Detection Radar", IEEE Transactions on Aerospace and Electronic System, 7(1), pp. 142 - 146.

[3] Sung, P. J., Chan, Y.C., Jin, H.N., Si-Hyung, L., Donghoon, S. and Tae-Yong, C., 2010, "Numerical Study of Leakage Detection and Location in a Simple Gas pipeline branch using an Array of Pressure Sensors,". J. Mechanical Sci. and Tech., 24(24), pp. 983 – 990.

[4] Steven, W. S., 1997, "The Scientific and Engineer's Guide to Digital Signal Processing," California Technical Publishing.