Mohd S. A. M. Yusoff,
Jyoti K. Sinha,
P. Mandal

School of Mechanical, Aerospace and Civil Engineering.
The University of Manchester, Oxford Road, Manchester,
M13 9PL, UK.

***(mohdshahrulazmi.mohamadyusoff@postgrad.*
manchester.ac.uk)

INPUT PULSE FREQUENCY SENSITIVITY FOR ACOUSTIC PULSE REFLECTOMETRY IN PIPELINE NDT

RINGKASAN: Paip digunakan bagi pelbagai aplikasi industri sebagai contoh, saliran air dan gas ke rumah, pengangkutan bahan kimia, bekalan minyak dan gas dan pelbagai kegunaan lain. Pengesanan kerosakan pada peringkat awal adalah penting di dalam memastikan tiada kehilangan nyawa mahupun wang. Pengujian tanpa kemusnahan (NDT) merupakan teknik penting didalam aplikasi tersebut. Pelbagai kajian telah dijalankan berkaitan teknik NDT oleh penyelidik dari seluruh pelusuk dunia, terutamanya menggunakan aplikasi gelombang bunyi berfrekuensi ultra dan akoustik. Di dalam penyelidikan ini, kami telah menjalankan analisa matematik bagi mengenalpasti frekuensi yang menepati applikasi NDT berkaitan beserta pengesahan eksperimen. Dengan penemuan ini, aplikasi NDT akan dibantu dengan input baru sebelum setiap pemeriksaan dijalankan.

ABSTRACT: Piping are used for several applications, e.g., water and gas distribution to homes, chemicals, oil and gas supplies for different industrial applications, steam supply to steam turbines, etc. Early detection of defects (holes and/or blockage) due to scale deposit in such pipe is important so that it can be rectified in time. Non-destructive methods are inevitable within the multi-million industry to prevent losses, in both human and money. Much research has been done using the guided waves inspection techniques, more often by means of studying the ultra-sonic wave propagation characteristic within the solid isotropic structures with the needs to empty pipelines for such study. In this paper, an impulse wave is introduced at open end of a pipe and then the travel of the longitudinal wave within the pipe is studied. Multiple widths of half sine input pulse were analysed in a mathematical model and compared with experimental data. The paper presents the potential travelling distance and peak values using both analytical modelling and experimental results.

Keywords: Non-destructive methods, pipeline, pulse reflectometry, soundwave propagation

INTRODUCTION

This work presents a pipeline blockage detection techniques using acoustic pulse input wave. A safe and well maintained pipeline system is normally safe with low risk of failure that would jeopardise its operational capacity. Blockage such as black powder deposit in oil and gas pipelines can be both dangerous and costly if not detected early. The rapid growth of pipeline around the world requires fast, effective and easy interpretation of detection, particularly with non-destructive mechanism (EGIG,2011).

Current advancement in sensing technology enables long range detection in pipeline such as the Long Range Ultrasonic Testing (LRUT). Although it is a fast detection method, the interpretation of soundwave propagation data is very complicated due to the dispersive nature of ultrasonic signals within the investigated domain. It is a method specially designed for Corrosion Under Insulation (CUI) with so many advantages over other techniques. However, detection of blockage is not currently effective with LRUT method of detection. Pigging (PIG) is another popular non-destructive method that uses the sensor advancement technology (Sharp, 1997). Even though it does travel along longitudinal distance of the pipe, the mobilisation can be expensive and highly risky to pigging components and the pipe itself.

Early researcher's worked on the acoustic understanding within the pipeline through acoustic pulse reflectometry, while recent researchers are using the acoustic pulse for detection of blockage and leakages within longer pipeline without detail discussion on the input pulse of choice (Lee *et al.*, 2013 and Duan *et al.*, 2015). As an added knowledge to the existing practice, our research offers greater understanding of the input pulse parameters. These can be the solutions to long range detection. However, greater depth of understanding is needed on the choices of input pulse for such detection.

This work proposed an analytical solution to the input pulse parameters with experimental investigation of the analytical results. The suitable pulse frequency and amplitude for long range detection will be determined for various pipes diameters. The potential detection capability will be analysed through the understanding of its peak decay characteristics.

THEORY

As acoustic pulse travel along the longitudinal length of the pipe, the sound energy will encounter losses due to viscosity, heat conduction, internal molecular processes and wall friction at boundary layer. Adding to these losses is the impedance due to cross sectional area changes of the pipe. Assuming a straight pipe with uniform internal cross sectional area and zero losses due to internal molecular processes, the decay to peak values along the longitudinal length of the pipe is:

$$Pc(\chi) = P_i \exp(-\alpha\,\chi) \tag{1}$$

where P_i and α are the initial input pressure and the attenuation coefficient values for the fluid soundwave travel. By including the thermal heat conduction and the viscosity losses, the attenuation coefficient can be determined by equation (2) (Rienstra and Hirschberg, 2015):

$$\alpha = \frac{\omega}{c\gamma}\left[\sqrt{\frac{\mu}{2\rho\omega}} + (\gamma - 1)\sqrt{\frac{\kappa}{2\rho\omega\, Cp}}\right] \tag{2}$$

where ω is the angular frequency, c being the speed of sound of the medium acoustic wave, γ is the pipe radius, μ is the shear viscosity, ρ is the density, γ is the ratio of specific heat, κ is the thermal conductivity and Cp is the heat capacity. For the purpose of investigation of the experimental model using single sensing location, it is assumed that the reflected sound wave from closed end of a pipeline will not contribute any losses to the energy of the travelling wave as the cross sectional area is uniform (Papadopoulou *et al.*, 2016 and Morgan and Crosse, 1978). By determining the coefficient of attenuation, the peak decay rate of any pulse frequency can be obtained along the travelling time with the knowledge of the speed of sound, c.

MATERIALS AND METHOD

A detailed study is conducted to determine the attenuation coefficient by experiment. This experiment concentrated on the acquisition responses from all the various frequencies of input pulse.

Mechanical Set-Up

The mechanical set-up consists of a speaker (Visaton), a microphone (B&K), a 12 meter length of PVC pipe with 2 inch internal diameter and 6 mm thickness, and a surface treated pipe end cap. The surface treatment was done in ensuring that the sound pulse does not encounter any losses due to any reflections.

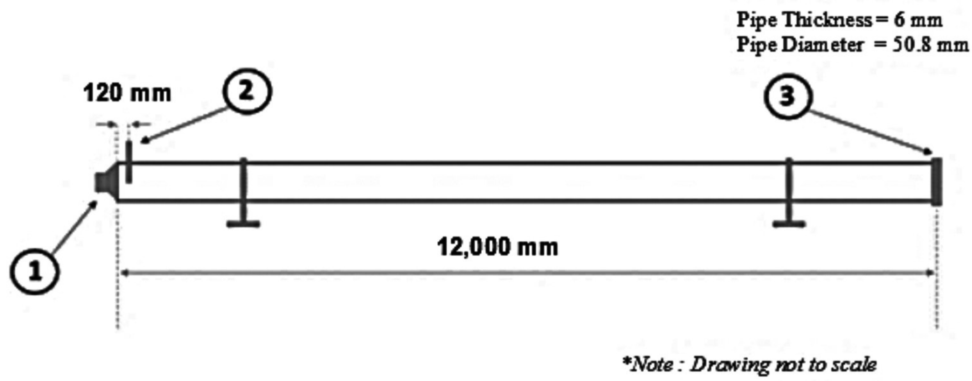

Figure 1. *Showing the schematic of mechanical set-up of test pipe: 1-Visaton speaker, 2- B&K microphone and 3 - Pipe end Cap*

Input Pulse

Propagation of waves occurred when the equilibrium is disturbed as it is subjected to loading condition, i.e. the forces or the displacement of speaker's diaphragm. A sound pulse in the form of half sine wave was introduced in the experiment. The pulse was produced using LabVIEW for various frequency of interest and represented as the period T or the width of the half sine impulse used in the experiment.

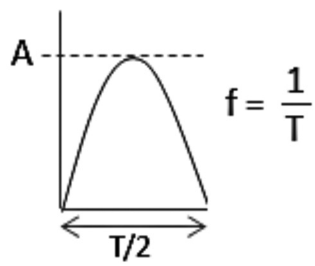

Figure 2. *A typical half-sin input pulse with T/2 pulse width*

Data Acquisition

A B&K microphone located next to the speaker, centroid to both speaker's diaphragm and the pipe cross sectional area, records the sound wave pressure coming from incident and reflective wave within the pipe. Sound pressure recorded on the microphone translated to digital output by a digital output converter (NI USB 6229 DAQ) and recorded in data logger. To validate the initial input, the output signal from the DAQ was also recorded before it was transmitted to the loudspeaker. All data recorded were processed using MATLAB in time domain. The validity of identified signals can be made through travel time calculation within the fluid media, which in this case the speed of sound is 340 m/s (Wang *et al.*, 2016). Plots of acoustic pressure in time domain for all types of defects provide the responses of the acoustic signals to the pipe end's reflection and attenuation decay due to the attenuation that can be observed from the reduction of peak values at all reflection responses.

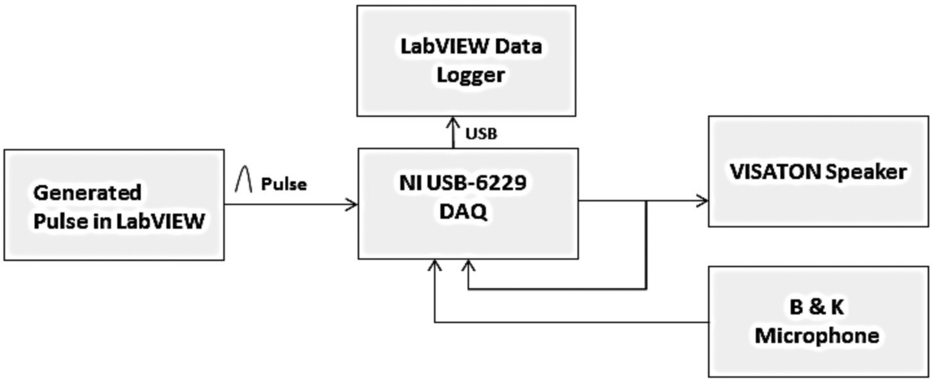

Figure 3. *The schematic of the data acquisition system*

RESULTS & DISCUSSION

In this section we will discussed the findings from both analytical and experimental methodologies. The input pulse parameters are given in Table 1.

Table 1. Input pulse parameters for both analytical and experimental models

	Test No.						
	1	2	3	4	5	6	7
Analytical							
Input Frequency	1 kHz	2 kHz	3 kHz	4 kHz	5kHz	6 kHz	7 kHz
Initial Pressure	0.2 Pa	0.2 Pa	0.2 Pa	0.2 Pa	0.2 Pa	0.2 Pa	0.2 Pa
Experimental							
Input Frequency	1 kHz	2 kHz	3 kHz	4 kHz	5kHz	6 kHz	7 kHz
Voltage	0.9 mV	0.9 mV	0.9 mV	0.9 mV	0.9 mV	0.9 mV	0.9 mV

Theoretical Peak Decay

Based on the input frequency, from the speed of sound of the medium that the acoustic wave travelling in, pipe radius, shear viscosity, density, ratio of specific heat, thermal conductivity and the heat capacity, we obtained the theoretical attenuation coefficient (α) at all frequency of interest. The plotted decay for pulse with zero impedance losses for input frequencies ranging from 1 kHz to 7 kHz is shown in Figure 4. Initial input pressure used for the theoretical model was 0.2 Pa.

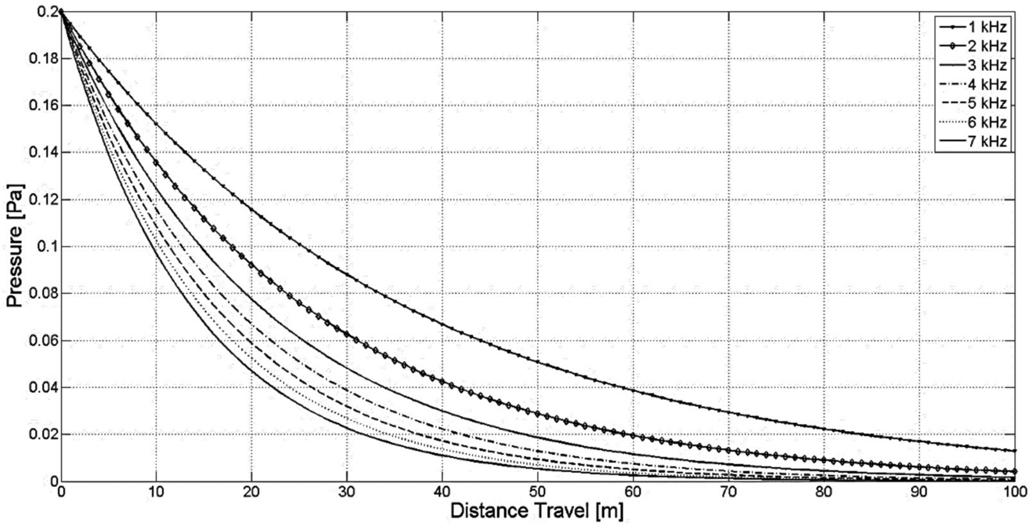

Figure 4. *Plots of decays from the analytical model solution along the longitudinal length of the pipe*

Time Domain Reflectometry by Experiment

The input pulse signals discussed in the experimental procedures were recorded and the plots of input pulse in time domain are shown in Figures 5 to 9, with logging period of 0.7 s. The experiment shows that with single input pulse (Figure 5), incident wave and reflections coming from the end of pipe were observed repeatedly until the peak values were reduced to non-visible amplitudes. At 1 kHz the visible reflections were observed up to the 7th reflections i.e. after travelling for 168 m. Validation of travelling time was done on the first reflection that was based on the 2 x total length (24 m) of the investigated pipe, and was confirmed to the speed of sound discussed in the experimental procedures.

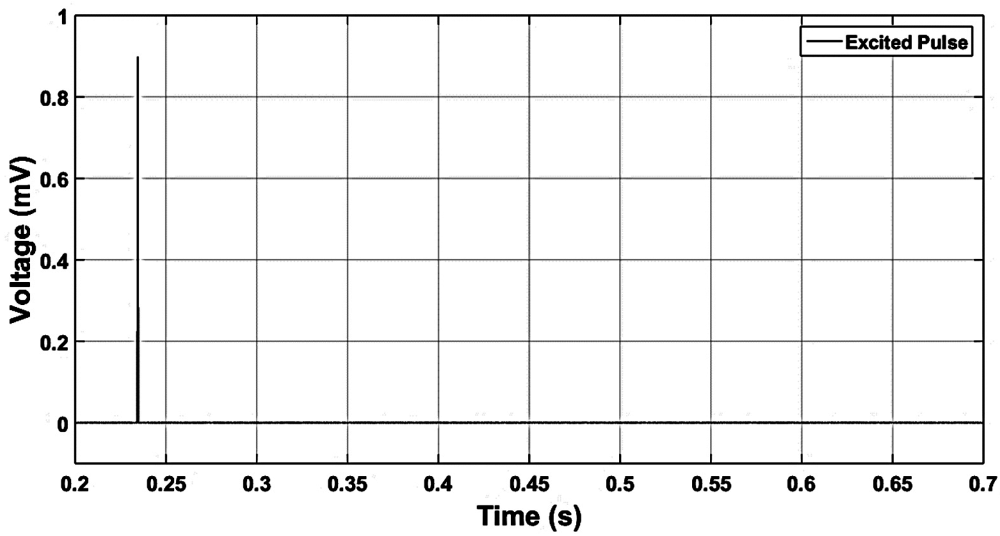

Figure 5. *Plot of the input pulse in time domain used in the experiment*

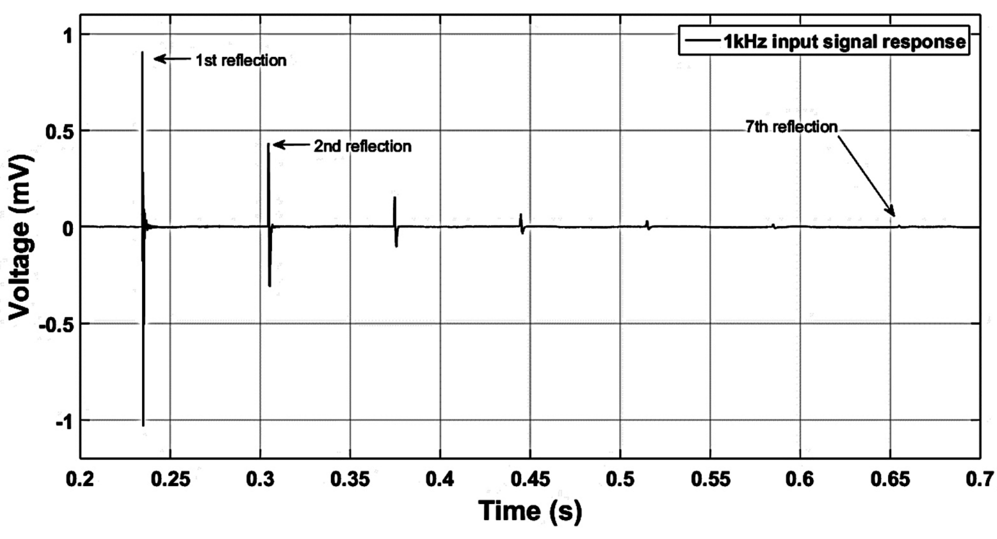

Figure 6. *Plot of the response in time domain used for 1 kHz input pulse in the experiment*

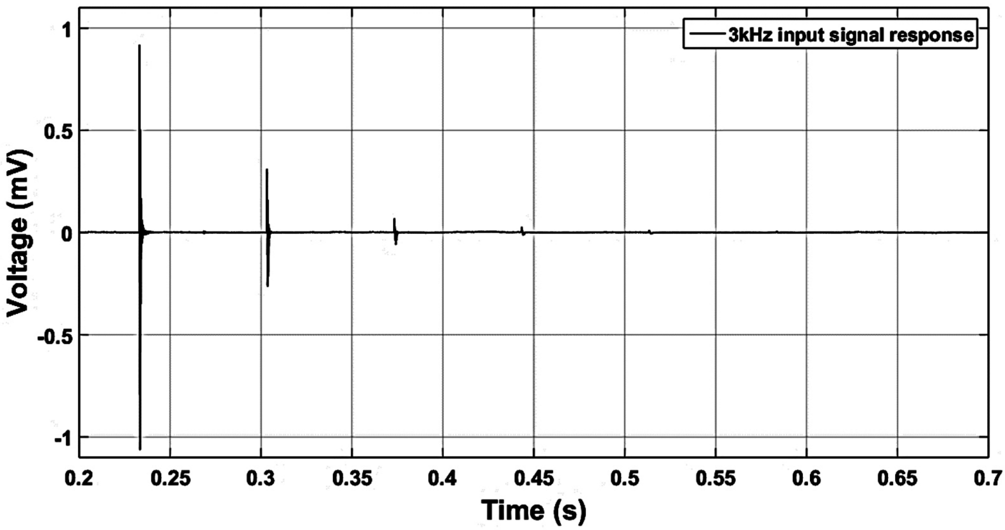

Figure 7. *Plot of the response in time domain used for 3 kHz input pulse in the experiment*

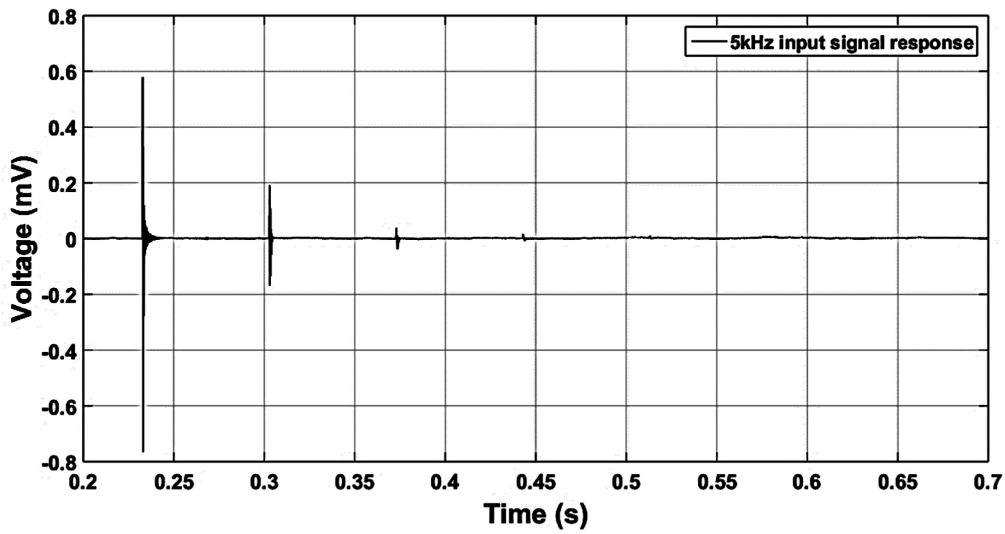

Figure 8. *Plot of the response in time domain used for 5 kHz input pulse in the experiment*

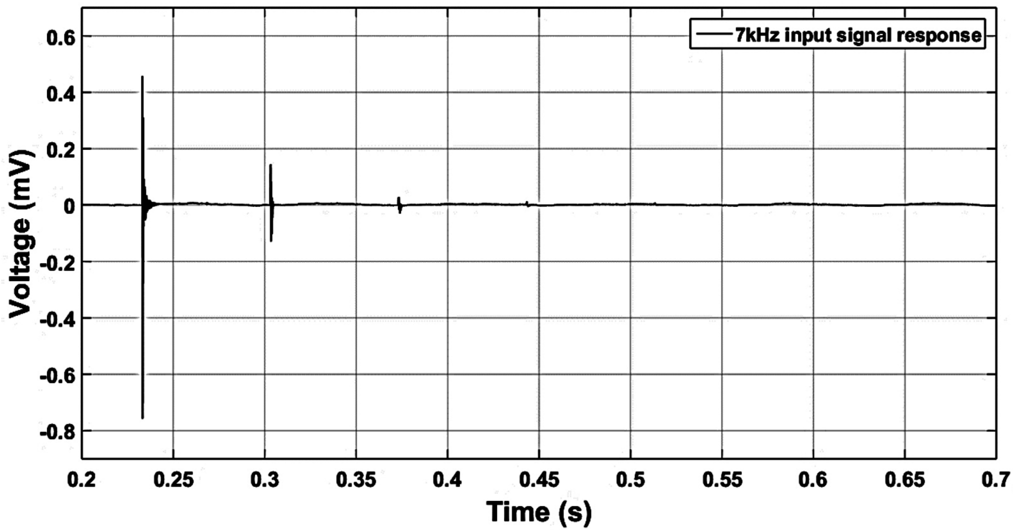

Figure 9. *Plot of response in time domain used for 7 kHz input pulse in the experiment*

Attenuation by Experiment

To determine the experimental attenuation value, an exponential curve fitting was performed on the responses obtained in time domain reflectometry by experiment. The curve fitting parameters for the peak decay attenuations from each echo for multiple frequencies were investigated. Plots in Figure 10 show the comparison of attenuation based on analytical model and experimental results. Although the trends observed with both exercises are consistent, the attenuation coefficients obtained from experimental results are higher than the analytical model. Initial investigation concluded that the losses were primarily due to the location of microphone which created impedance in the pipe.

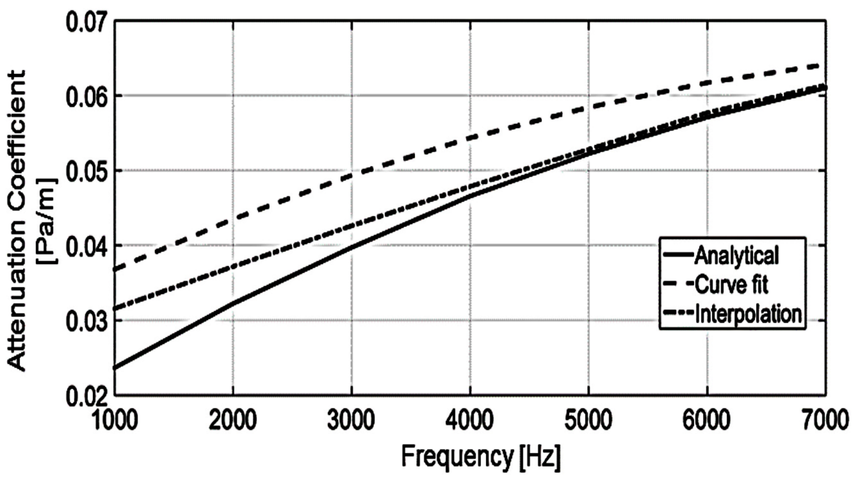

Figure 10. *: Analytical vs experimental attenuation coefficient obtained in this work*

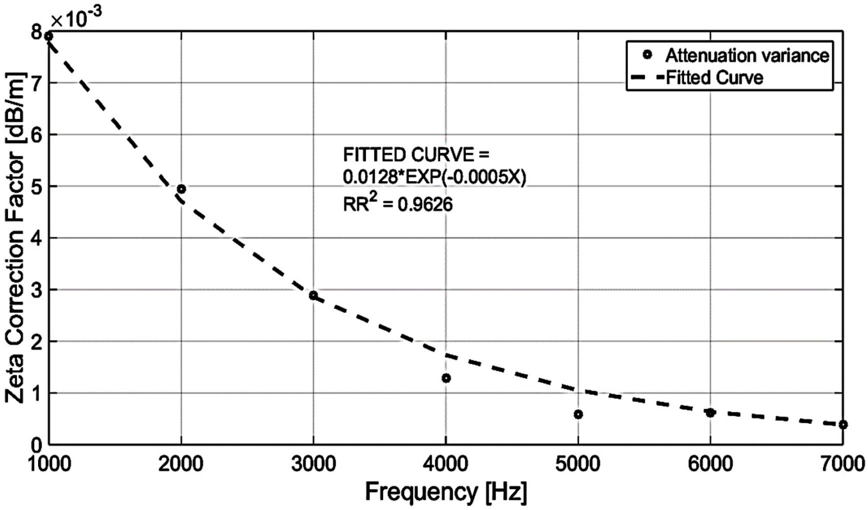

Figure 11. *Attenuation coefficient correction for inspected pipe*

Based on the attenuation exhibited in Figure 10, further curve fitting was performed based on the necessary correction to the initial governing equation (2). The founded correction is presented in the next sub section.

Correction of attenuation equation

The attenuation coefficient from the experiment is higher than the analytical model prediction. By accommodating a new correction factor during inspection, it will compensate the error of peak decay due to the attenuation. Considering as the correction factor for equation (2) obtained from curve fitting in Section 4.3, the new attenuation coefficient equation is defined as:

$$\alpha = \frac{\omega}{c\gamma}\left[\sqrt{\frac{\mu}{2\rho\omega}} + (\gamma - 1)\sqrt{\frac{\kappa}{2\rho\omega\, Cp}} + J \right] \tag{3}$$

where

$$J = 0.0128\, e \frac{2\pi}{\omega} \tag{4}$$

Response Signal Strength

It is important for researchers to know the strength of response signal from an input pulse along the length of inspection. In observing the reflections, the peak values amplitude percentage against the initial pulse amplitude were taken as the parameters of analysis plotted against travelling distance of both experimental and analytical sound waves. :

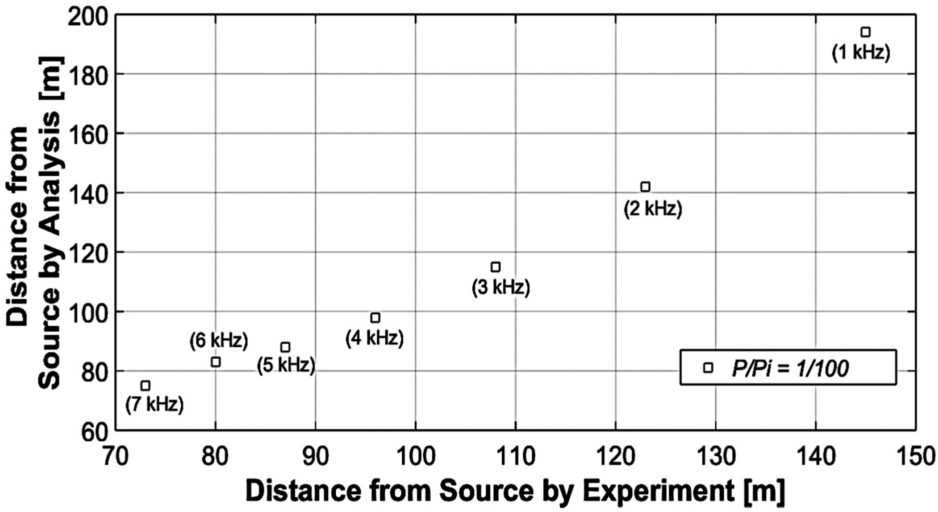

Figure 12. *Attenuation coefficients correction for the inspected pipe*

CONCLUSION

Both analysis and experiments shows that the absorption coefficient intensifies with increase in the pulse width frequencies. Therefore at higher frequency, the attenuation effect on the traveling wave will be higher. Hence the wave traveling distance is likely to be shorter with lower pulse width (higher frequency) of input acoustic wave (Figure 12). It can be concluded from this work that the lower frequency input acoustic pulse wave is more suitable for long pipe faulty detection. The initial observations from the experiments in a pipe also support the analysis but shows higher losses due to attenuation. There is a need to work on the correction of the existing equation for the attenuation coefficient based on the experimental results of different models. Hence the correction to the absorption coefficient is currently underway.

REFERENCES

Duan, W., Kirby, R., Prisutova, J., and Horoshenkov, K. V. (2015). On the use of power reflection ratio and phase change to determine the geometry of a blockage in a pipe. *Journal of Applied Acoustic., 87: pp 190–197*

EGIG (2011). 8th Report of the European Gas Pipeline Incident Data Group. Tech. Rep. EGIG 11.R.0402. European Gas Pipeline Incident Data Group.

Lee, L. H., Rajkumar, R., Lo, L. H., Wan, C. H., and Isa, D. (2013). Oil and gas pipeline failure prediction system using long range ultrasonic transducers and Euclidean-Support Vector Machines classification approach, Expert Syst. Appl., *40(6): pp 1925–1934*.

Morgan, E. S. and Crosse, P. A. E. (1978). The acoustic ranger, a new instrument for tube and pipe inspection. *NDT Int., 11 (4): pp 179–183*.

Papadopoulou, K. A., Shamout M. N., Lennox, B., Mackay, D., Taylor, A. R., Turner J. T., and Wang, X. (2016). An evaluation of acoustic reflectometry for leakage and blockage detection. *Institution of Mechanical Engineers, 222: pp 959–966*.

Rienstra, S. W. and Hirschberg, A. (2015). An Introduction to Acoustics: Eindhoven University of Technology.

Sharp D. M. C. D.B. (1997). Leak detection in pipes using acoustic pulse reflectometry, *Acta Acustica United with Acustica, 83: pp 560–566*

Wang, X., Lewis, K. M., Papadopoulou, K. A., Lennox, B. and Turner, J. T. (2016). Detection of hydrate and other blockages in gas pipelines using acoustic reflectometry. *Institution of Mechanical Engineers Part C 0:1–1: pp 1–11*