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SIMULATIVE STUDIES ON ULTRASOUND INTERACTIONS FOR STEEL PIPE TRANSMISSION

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Graphical abstract

Abstract

This paper presents the simulative studies on the use of ultrasonic sensors for steel pipe investigation. Using the acoustic impedance, calculations are done to estimate the propagated ultrasound signal based on its reflection and transmission percentage. The ultrasound wave propagation simulations are then further studied using a modeling software to simulate and visualize the wave interactions between different boundaries. Experiments done with real hardware have shown correlation with the numerical and simulation studies.

Keywords: Simulation, ultrasound, transmission, steel, boundaries

Abstrak

Kertas kerja ini membentangkan kajian simulasi berkenaan penggunaan sensor ultrasonik untuk pemeriksaan paip keluli. Berdasarkan *acoustic impedance*, pengiraan dilakukan untuk menganggarkan pergerakan isyarat ultrasonik berdasarkan kadar peratusan refleksi dan transmisi. Simulasi perambatan gelombang ultrasonik kemudiannya dikaji menggunakan perisian pemodelan untuk penghasilan simulasi dan menggambarkan interaksi gelombang antara sempadan yang berbeza. Eksperimen dilakukan dengan instrumentasi elektronik telah menunjukkan korelasi antara pengiraan dan simulasi.

Kata kunci: Simulasi, ultrasonik, transmisi, keluli, sempadan

1.0 INTRODUCTION

Previous researches on tomography system especially for Ultrasonic Tomography system has concentrated more on the industrial applications using non-metallic investigated vessel. This type of vessel or pipeline is most commonly used to convey liquid from one location to another such as in many water distribution systems. Other than liquids, different types of material such as gases are also transferred using pipelines. Pneumatic tubes using compressed air can also transport solid capsules. As for gases and liquids, any chemically stable substance can be sent through a pipeline.

Therefore sewage, slurry and water pipelines exist; but arguably the most valuable are those transporting crude petroleum and refined petroleum product including fuels: oil (oleoduct), natural gas (gas grid), and biofuels [1]. The importance of oil and gas pipelines proves to be an also crucial asset for the economic development of almost any country, the corresponding government regulations or internal policies requires that the safety of the assets, including the population and environment where these pipelines run is ensured [2].

There is essential need for the industry to have an online flow monitoring system especially where steel pipes are used for process transfer such as in the oil and gas industries. The importance of flow measurement is obviously critical to many industrial processes. Without the knowledge of the flow parameters, it would be difficult to control the balance of materials, for improving process quality and even for the operation of continuous processes.

2.0 ULTRASOUND IN STEEL

Successful Ultrasonic Tomography application for investigating industrial processes is based on the use of 40 kHz and up to 333 kHz ultrasonic sensors [3, 4, 5]. Most of the widely ultrasonic sensors in the market also have a "Matching Layer" used to construct a suitable impedance matching layer with air, which makes it works great in air. Preliminary studies however have shown that air-coupled ultrasonic sensors suffer reduced performance for steel pipe imaging.

A useful descriptor of the interactions of ultrasound with a material is its acoustic impedance.

$$Z = \rho c \tag{1}$$

Where
Z = the acoustic impedance (kg/m²s)
ρ = the density of the medium (kg/m³)
c = the sound velocity in the medium (m/s)

Ultrasonic coefficients at interface are used and calculated to estimate the transmission and reflection of ultrasound waves and boundaries.

Reflection coefficient,

$$R = \frac{P_r}{P_e} = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1}\right] \tag{2}$$

Transmission coefficient,

$$D = \frac{P_d}{P_e} = \left[\frac{2Z_2}{Z_2 + Z_1}\right] \tag{3}$$

P_e = the incident wave sound pressure,
P_r =the reflected wave sound pressure,
P_d = the transmitted wave sound pressure

The results from the numerical studies of ultrasound interaction at different boundaries (green line) using above equations is as shown in Figure 1 and Figure 2.

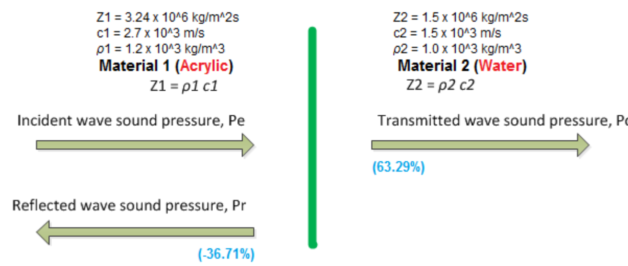

Figure 1 Ultrasonic wave propagation from pipe-section into liquid media (Acrylic–Water)
(*Negative sign indicates phase reversal relative to incident wave)

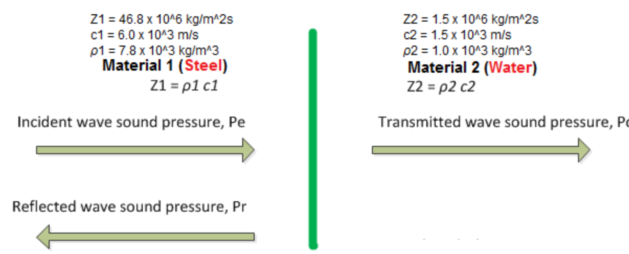

Figure 2 Ultrasonic wave propagation from pipe-section into liquid media (Steel–Water)

3.0 ULTRASOUND INTERACTION AT BOUNDARIES

As the objectives of this research is focused for ultrasound penetration into steel column for imaging the internal activities, the numerical studies is expanded further to investigate more into the complexities and challenging issues.

Figure 3 Transmission stages along different boundaries

Further investigation has found that at Stage 5 and Stage 6 (shown in Figure 3) has shown big difference of the magnitude of final transmitted ultrasound signal that will reach the receivers for different matching layers.

Table 1 Ultrasound interaction at boundaries for steel pipe (matching layer: air)

Sensor's Matching Layer: AIR					
Ultrasound transmission using STEEL pipe					
	Medium 1	Medium 2	Transmission (%)	Reflection (%)	V
Stage 5	Steel	Grease	10.0925	-89.9075	0.7155
Stage 6	Grease	Air (sensor)	0.0358000000	-99.9642000000	0.0002563400

As can be seen in Table 1, only a mere 0.0358% of the ultrasound energy will be transmitted where a staggering 99.964% will be reflected. This also means that for a 15V of transmitted pulse, it is expected if there's no gas obstruction between the sensors, the voltage reading at the receiver will be 0.256 mV (assuming no loss or attenuation) which is very small for standard data acquisition system. Conclusively if an air-coupled transceiver is to be used, significant signal amplification will be required.

Table 2 Ultrasound interaction at boundaries for steel pipe (matching layer: steel)

Sensor's Matching Layer: STEEL					
Ultrasound transmission using STEEL pipe					
	Medium 1	Medium 2	Transmission (%)	Reflection (%)	V
Stage 5	Steel	Grease	10.0925	-89.9075	0.0361
Stage 6	Grease	Steel (sensor)	189.908	89.908	0.0686

Ultrasonic transceiver with a steel matching layer promises better signal amplitude (as in Table 2). The numerical studies for steel-matched sensor estimates that the receiver will receive voltage reading higher than air-matched sensor, which is at 0.0686V (assuming no loss or attenuation).

The preceding result may appear strange since the transmission is at 189.9%, as though conservation of energy were being violated. However such case has been reported (Figure 4(b)) [6] and further investigation is warranted for better explanation but conclusively, steel-coupled transceiver will provide better transmitted energy.

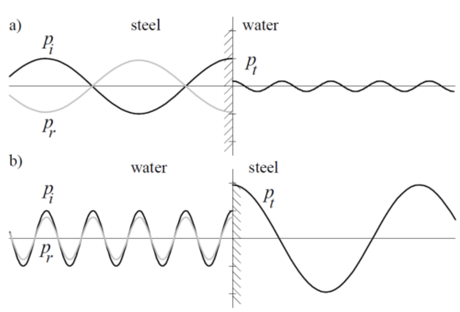

Figure 4 Sound pressure values in the case of reflection from (a) a steel-water and (b) a water-steel interface at normal incidence [6]

This conclusion is further supported by using COMSOL for simulative studies as shown in Figure 5 and 6, where the top figure shows the simulation of ultrasound propagation in the different boundaries of Steel/Grease/Air while bottom figure shows the simulation result for Steel/Grease/Steel boundaries.

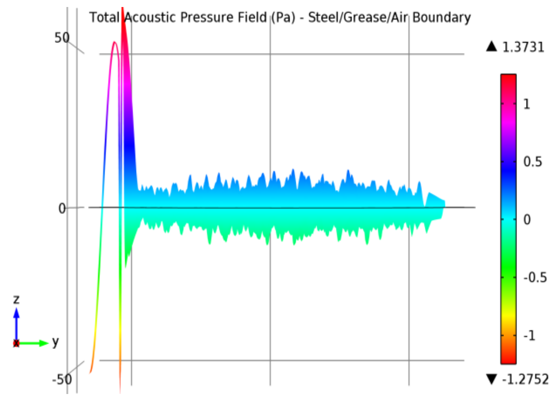

Figure 5 Simulative studies for ultrasound interaction at Steel/Grease/Air Boundary

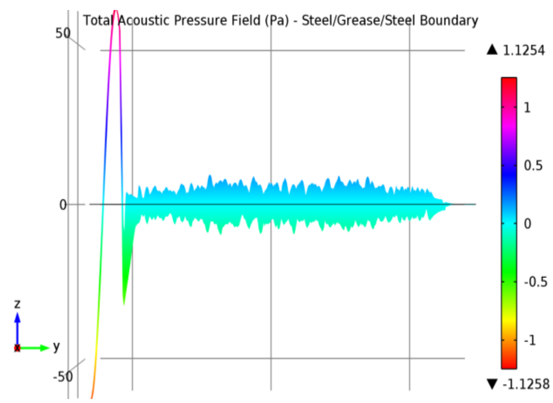

Figure 6 Simulative studies for ultrasound interaction at Steel/Grease/Grease Boundary

Above studies shows the conclusive difference at air-coupled sensor boundaries where the wave propagation abruptly decreased its amplitude while for the steel-coupled sensor boundaries, shown smaller propagation amplitude yet more significant if compared with air-coupled (Figure 7).

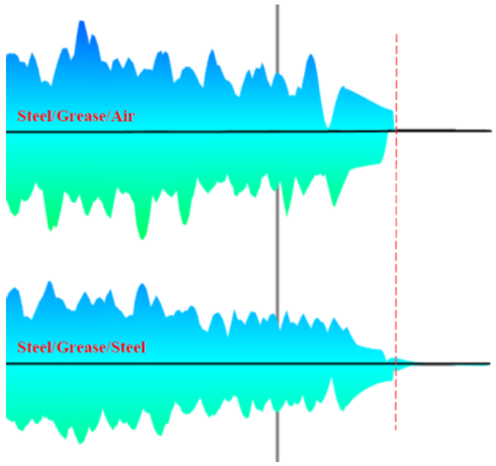

Figure 7 Zoom-in image of COMSOL simulation studies

4.0 CONCLUSION

The initial experiment for ultrasound penetration on steel pipe has also been conducted using a 333 kHz air-coupled transceiver. The result shows fairly promising correlation with the numerical studies (shown in Figure 8 and Figure 9).

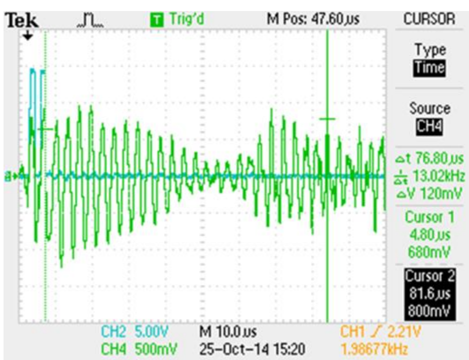

Figure 8 No gas obstruction

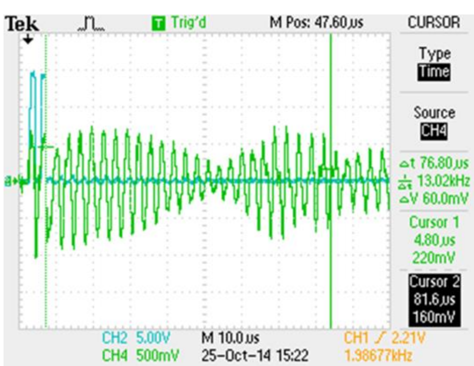

Figure 9 Gas obstruction

A two-stage cascaded amplifier circuit with a total gain of 10,000 is used to significantly amplify the output value at receiver where a reading of 800 mV is recorded. It is expected that there will be much difference in real-world voltage readings with the numerical studies since there will be ultrasound attenuation in propagation. However, the experiment proves that significant amplification will be needed for use of air-coupled ultrasonic transceiver.

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