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Finite Element Analysis for Acoustic Wave Transmission in Ultrasonic Tomography Application

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Abstract: A study of acoustic wave transmission through obstacles and boundary surface for ultrasonic tomography applications has been carried out. Ultrasonic tomography for water – crude oil two phase flow sensing relies upon the complex ratio of sound pressure to particle velocity which is the acoustic impedance matching. According to Snell's Law, the ultrasonic transmission properties can be obtained on the basis of incidence angle, acoustic impedance and basic frequency of ultrasound, material and thickness of the pipeline. These parameters correspond to maximum transmission of an ultrasonic wave from one medium to another when the characteristic impedance is matched. To investigate the wave's transmission and diffraction on water – crude oil boundaries, several simulations using finite element method (FEM) have been carried out. The simulated result images successfully visualize the ultrasonic wave transmission and reflection characteristic in the two-phase liquid flow tomography system. Thus, the wave propagation behavior in the boundaries is also presented. The information and results obtained is useful for further development for ultrasonic tomography multiphase flow measurement.

Keywords: Renewable fuel, ethanol, numerical simulation, auto ignition, single-step mechanism

1. Introduction

Ultrasonic tomography is a measurement method using acoustic wave to investigate the activities inside the measurement subject [1, 2]. This method is widely applied in both the medical and process industry such as in oil exploitation and chemical process monitoring [3, 4]. This system is developed with the capability to reconstruct the gas-liquid, liquid-liquid two phase flow over the cross section of a pipe. This method is much complex and costly due to the requirement of utilizing many transducers around the pipeline to detect the echoes scattered around the measurement subject [5].

The aim of this paper is to investigate the acoustic pressure wave propagation behavior in water-crude oil two phase liquid flow in a pipeline. The problem raised is the strong mismatch between the acoustic impedance of the phases [6]. This condition creates a boundary level between two different material and phases which is; (i) Sensor and pipe wall boundary. (ii) Water – crude oil liquid boundary. These complications will result in low efficiency and low accuracy in ultrasonic tomography flow system . Therefore, it has become necessary to get better understanding on the dynamic characteristics of acoustic wave propagation behavior in a pipeline.

2. Ultrasonic Sensor Configuration and Simulation Setup

To investigate the ultrasonic wave transmission and reflection, the simulation ultrasonic sensor configuration 3D model setup is illustrated as in Figure 1.

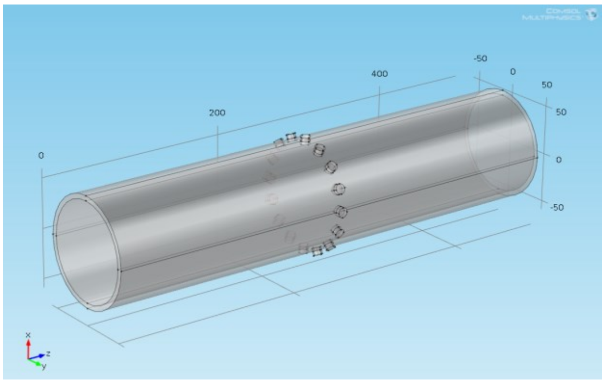
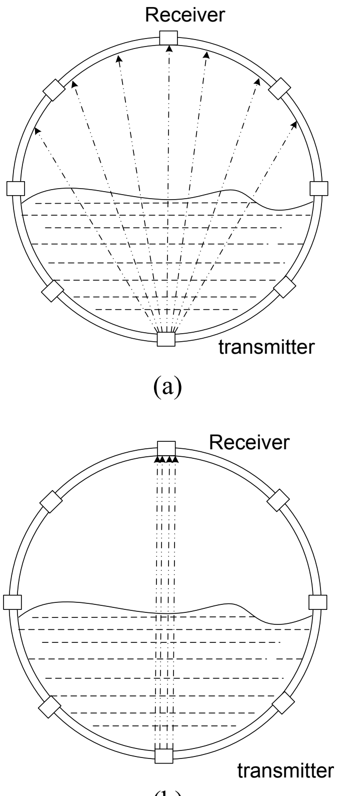


Fig. 1 Ultrasonic sensor configuration on acrylic pipeline

A total of 16 ultrasonic transducers are mounted on an acrylic pipe circumference with a 110 mm of outer diameter as these type of pipes are transparent and convenient to be used for laboratory experiment [7]. These sensors will produce a 335 kHz pulse to measure the two-phase (water-crude oil) flow within the pipe [7].

The ultrasonic sensor system is based upon interactions between the incident ultrasonic waves and the object to be imaged. In most non-destructive testing or medical applications, an object or field of interest is irradiated from a single viewpoint. The transmitted ultrasonic wave has a wide beam angle of 125^0. Some ultrasonic process tomography utilizes a wide beam angle beam as shown in Figure 2 (a) and (b) below.



(a)

(b)

Fig. 2 Wave beam (a) Wide beam projection (b) Narrow beam projection

Whether an ultrasonic beam is narrow or wide angel, it advances as a longitudinal wave front, in common with all sound waves.

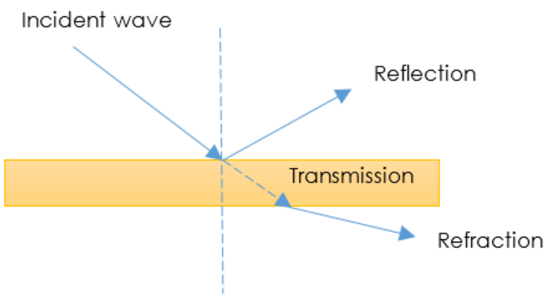


Fig. 3 Ultrasound wave behavior

In multiphase flow applications, ultrasonic tomography relies on the measurement of the ultrasonic wave transmission and reflection in a homogenous or non-homogenous condition [8, 9]. To ensure sufficient wave energy propagates from one end to another, the wavelength is determined in transmission-mode that measures the transmitted signal amplitude according to equation (1).

$$\lambda = \frac{c}{f} \qquad (1)$$

Where c is the speed of sound (m/s) in a medium, f is the ultrasonic frequency (Hz) and λ is the wavelength (m). The higher the frequency will result in shorter wavelength and vice versa. Therefore a 335 kHz ultrasound is sufficient enough to propagate signal from one end to another through a pipe with diameter of 110 mm.

The ultrasonic propagation speed could be measured by using two types of configuration which is the through transmission method and pulse – echo method which will only take effect if the ultrasonic wave able to transmitted through the pipe wall into the liquid medium [10]. This system uses ultrasound to detect the changes of acoustic impedance (Z) which is closely related to density (ρ) of the medium. This can be a useful descriptor to identify the complex ratio of sound pressure to particle velocity which is analogous to electrical impedance. The acoustic equivalent to this relation is given by below equation [11, 12].

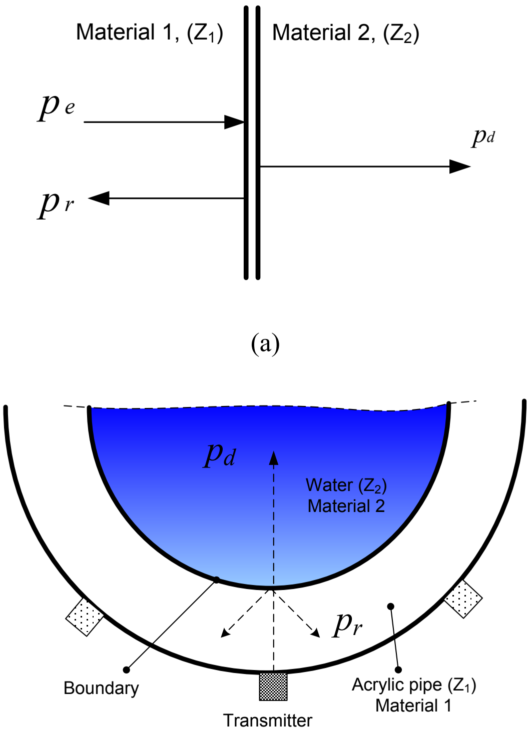
$$Z = \rho\, c \qquad (2)$$

Where Z is the acoustic impedance (kg/m^{2}s), ρ is the density of the medium (kg/m3) and c is the sound velocity in the medium (m/s). When an ultrasonic beam reflects from the boundary, the acoustic reflection coefficient (R) and transmission coefficient (D) from material 1 to material 2 as in figure 2 (a) can be expressed as follows:

$$\text{Reflection coefficient, } R = \frac{p_r}{p_e} = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1}\right] \qquad (2)$$

$$\text{Transmission coefficient, } D = \frac{p_d}{p_e} = \left[\frac{2Z_2}{Z_2 + Z_1}\right] \qquad (3)$$

Where p_e is the incident wave sound pressure, p_r is the reflected wave sound pressure and p_d is the transmitted wave sound pressure [13]. This incident is illustrated as in figure 4 (a) and (b).



(a)

(b)

Fig. 4 Wave propagation; (a) From material 1 to material 2. (b) From pipe section to liquid

3. Ultrasonic Wave at Boundaries

Acoustic impedance is important to determine the acoustic transmission and reflection at the boundary of two different materials. Following are the two conditions to be considered before measurement is carried out:

i) If D > R; Acoustic wave penetration through medium is possible
ii) If R > D; Acoustic wave will face difficulties to penetrate medium

The greater the difference in acoustic impedance at the interface, the greater will be the amount of energy reflected. Conversely, if the impedances are similar, most of the energy is transmitted [14-16].

Two case studies were carried out; i) Ultrasonic wave propagation from experimental pipeline (acrylic pipe) into liquid medium (water) as in figure 4(b). ii) Ultrasonic wave propagation from the water medium into the crude oil medium as in Figure 5. The wave propagation energy transmission from material 1 (pipe) into material 2 (water) can be calculated as follows.

$Z_1 = 3.2 \times 10^6$ kg/m^{2}s (Acrylic)
$Z_2 = 1.5 \times 10^6$ kg/m^{2}s (Water)

$$R_{(Acrylic\,/\,Water)} = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1}\right] = \left[\frac{1.5\times10^6 - 3.2\times10^6}{1.5\times10^6 + 3.2\times10^6}\right]$$

$$= -0.3617 \Rightarrow -36.17\%$$

$$D_{(Acrylic\,/\,Water)} = \left[\frac{2Z_2}{Z_2 + Z_1}\right] = \left[\frac{2\times1.5\times10^6}{1.5\times10^6 + 3.2\times10^6}\right]$$

$$= 0.6383 \Rightarrow 63.83\%$$

From above calculation, more than half of the transmitted ultrasonic wave able to penetrate through the acrylic pipe-section into the liquid medium which is 63.83% the rest 36.17% is reflected and scattered on the pipeline surface. This means, the ultrasound signal intensity is sufficient enough to penetrate through the acrylic pipe wall.

The wave propagation which penetrated through acrylic pipe material into the water medium will have to propagate through the water – crude oil boundary into the second phase material which is crude oil.

To determine the amount of transmitted and reflected ultrasonic wave in the water – crude oil medium, the transmission coefficient and the reflection coefficient are calculated using equation 2 and 3.

$$R_{(Water\,/\,CrudeOil)} = \left[\frac{Z_2 - Z_1}{Z_2 + Z_1}\right] = \left[\frac{3.2\times10^6 - 2.7\times10^6}{3.2\times10^6 + 2.7\times10^6}\right]$$

$$= -0.0847 \Rightarrow -8.47\%$$

$$D_{(Water\,/\,CrudeOil)} = \left[\frac{2Z_2}{Z_2 + Z_1}\right] = \left[\frac{2\times2.7\times10^6}{2.7\times10^6 + 3.2\times10^6}\right]$$

$$= 0.9152 \Rightarrow 91.52\%$$

From above calculation, the ultrasonic wave transmission through the water-crude oil boundary is 91.52% while only 8.47% will be reflected back to the water medium. Meaning, the receiver located on the opposite side will be anticipating incoming signals.

A certain amount of the wave will be able to transmit through the water-crude oil boundary while the rest will be reflected and scattered back in the water medium. This condition is illustrated in below figure 5.

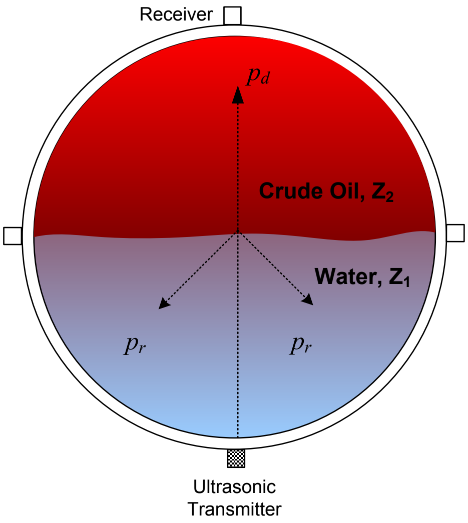


Figure 5 Ultrasonic wave propagation from water to crude oil.

It is mathematically proven that the 335 kHz ultrasonic wave is able to transmit through the pipe surface into the water medium and further transmit through the water-crude oil boundary. Somehow, the transmitted and reflected waves will contact with one another in the pipeline. It is important to take this phenomenon into consideration before designing the tomography system.

When the ultrasonic waves propagate in the cylinder pipe, it reflects off the surface wall. This leads to a distribution of ultrasonic energy in different forms that depend basically on the geometry of the pipeline and the location of sensors placing. The occurrence of these overlapping waves will produce inaccurate results if the measurement system fails to differentiate between transmitted signal and overlapped signal [17]. The direction of this sound propagation is determined by the sound speed gradients in the liquid medium.

Therefore, a theoretical model of acoustic wave scattering from the liquid boundary is required to determine the acoustic pressure distribution in the mixture water/crude oil for ultrasonic tomography applications. This case, a finite element method using COMSOL Multiphysics is implemented to visualize the acoustic wave propagation and the scattering effects.

4. Acoustic wave behavior simulation

The ultrasonic tomography geometry model specification and setup consist of an acrylic pipe with diameter of 110 mm and 10 mm ultrasonic transducers at 335 kHz transmitting frequency. Acrylic pipe is the commonly used material for investigation purposes due to the impedance matching with the internal bulk medium [18].

The finite element analysis (FEM) setup for the UT sensors is developed using pressure acoustics (PA) physics interface module. In PA, the propagation of sound waves in the domain is described by Helmholtz wave equation as follows.

$$\nabla\left[\frac{-1}{\rho_0}(\nabla p - q) - \frac{\omega^2 p}{\rho_0 c^2}\right] = Q \tag{4}$$

where p is the acoustic pressure (Pa), ρ_0 is the density of material (kgm^{-3}), $\omega = 2\pi f$ denotes the angular frequency of incident wave (rad/s), c is the speed of sound (m/s) of the material and Q is the monopole source (1/s^2). Table 2 tabulates the parameters for the material used for the water-crude oil flow measurement [19].

Table 2 Materials parameter for two phase liquid flow measurement

Material	Density [kg/m^3]	Speed of Sound [m/s]
Crude oil	825	1300
Water	1000	1500
Air	1.25	343

By using FEM, the cross-section region of the hardware needs to be discretized as triangular elements with mesh element size 0.002 mm to 0.8 mm. Figure 6 shows the cross-sectional meshed image.

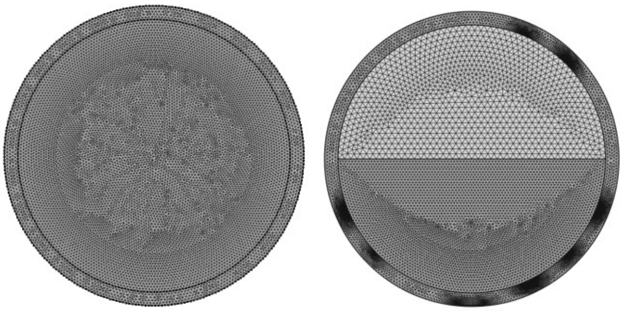

(a) (b)

Figure 6 Cross-sectional meshed image with mesh element size range 0.008mm – 1.5mm (a) homogeneous (b) inhomogeneous

From the meshed element image, the total acoustic pressure field (Pa) for acrylic/water boundary is produced.

The simulated result visualizes the ultrasonic wave propagating from acrylic medium into water medium and its scattering effect due to the reflection on acrylic pipe inner wall.

This result is parallel with the mathematical results earlier where 63.83% of the ultrasonic wave able to penetrate through the acrylic pipe while 36.17% of it will be reflected and scattered along the pipe wall. The residual ultrasonic wave is sufficient enough to propagate to the next boundary; water – crude oil boundary. The simulated ultrasonic wave propagation in homogeneous (full water) and non-homogeneous (water – crude oil) mixture is depicted in Figure 8 below.

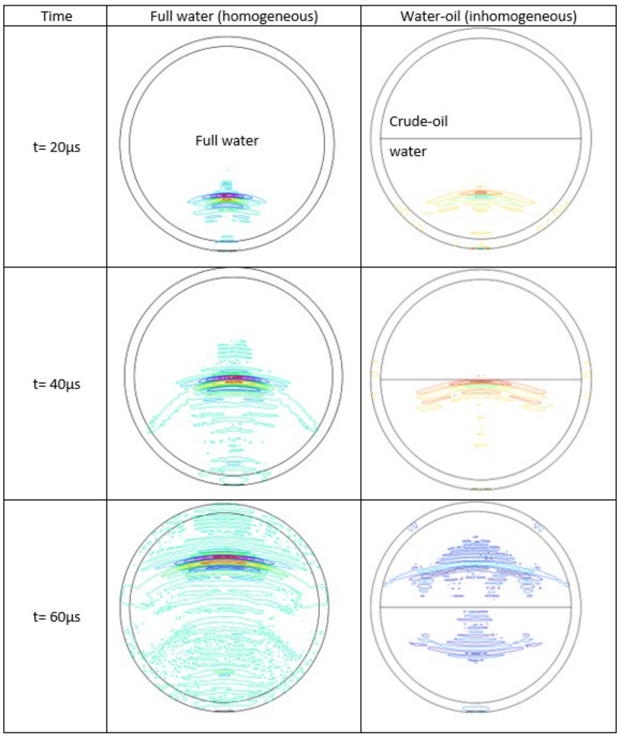


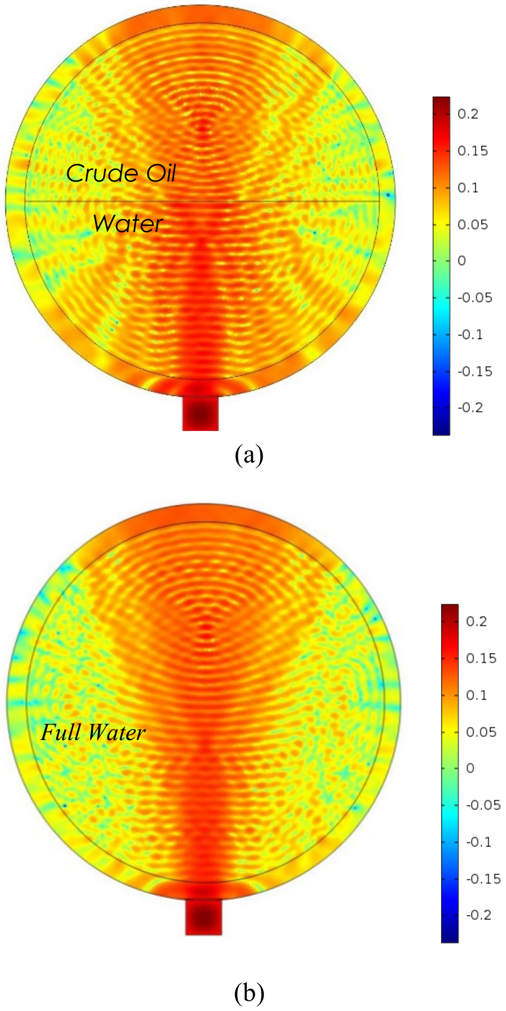
Figure 8 Ultrasonic wave transmission in homogeneous and inhomogeneous condition

The simulated result visualizes the ultrasonic wave behavior propagating from water into crude oil medium. This result is also parallel with the mathematical results where 91.52% of the ultrasonic wave penetrating through the acrylic pipe while 8.47%% of it will be reflected and scattered along the pipe wall.

Due to the high amount of acoustic wave able to penetrate through the water-crude oil boundary, the 8.47% amount of reflection can be seen at t=60 μs. This small amount of losses due to the interaction behavior is complex and depends not simply upon the differences in acoustic impedance, but also on the size and shape of the interface or boundary [8]. To verify and evaluate the reflected and scattered acoustic wave, the sound pressure level was computed and compared as in Figure 9.

The simulated wave propagation is carried out on homogeneous and inhomogeneous condition using time-dependent study in COMSOL. At t= 40us, the wave propagation (homogeneous) arrives at the center of the sensing region. While at t=60us, the waves fully arrive at the opposite end-wall. At this point, the signal strength is the highest. After this time period, reflected waves will mingle and overlap with each other.

The simulation experiment shows that the receiver should capture receiving signal best at t=60us which is the arrival time measured between the starting point to the first peak of the received ultrasound wave on the opposite position [20]. Capturing signals after this time period will result in false signal due to overlapping waves.



(a)

(b)

Figure 9 Sound pressure level (SPL) transmission, reflection and scattering effect; (a) Water / Crude oil mixture (b) Full water

5. CONCLUSION

In the present study, the acoustic wave pressure and sound pressure propagation behavior in mixing flow of water and crude oil in acrylic pipe has been simulated using COMSOL Multiphysics.

Mathematically, it is proven that the greater the difference of impedance in the materials, the higher the wave will be reflected and scattered and vice versa. This can be determined by calculating the reflection and transmission coefficients. To investigate the transmission and reflection behavior, the total acoustic wave pressure distribution, ultrasonic wave propagation, reflection and scattering effect was simulated and presented using FEM generated images.

The result obtained could aid in detection and measurement of two phase liquid flow regime particularly in the ultrasonic tomography applications. Understanding the acoustic impedance matching point will determine the appropriate sensory technique to be used on a particular flow condition. From the simulated experiment, it is shown that ultrasonic tomography can hardly measure the presence of water-crude oil composition due to its very close acoustic impedance. On the other hand, it can detect the presents of liquid-gas composition.

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