

SIMULATION STUDIES OF WAVES TRANSMISSION IN A STEEL-VESSEL ULTRASONIC TOMOGRAPHY SYSTEM

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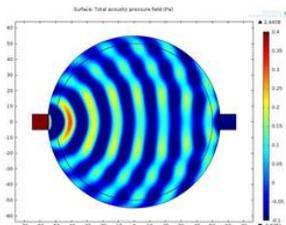
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Graphical abstract



Abstract

This paper addresses a specific form of inspection, that of ultrasonic wave propagation in the ultrasonic tomographic imaging system. From the sensing configuration standpoint, ultrasound wave simulation is an important imaging process. From the simulation results, ultrasonic sensors with suitable centre frequency can be mounted spherically on a sealed vessel, facilitating the local pitch-catch measurements of the fan-beam sensor configuration to reconstruct the ultrasound image as a fluid flow diagnostic tool. Two basic quantities are measured in ultrasonic flow systems: time-of-flight or the amount of time for the sound to travel through the sample, and the amplitude of the received signal. We used the acoustics pressure model in COMSOL version 4.2a to predict the propagation of acoustic waves through three-phase structures and bubbly flow. Our overall goal is to enable structurally specific inspection tasks to be optimized, taking into account both the physical aspects of the ultrasound propagation and the dynamic capabilities and restrictions of the vessel platform.

Keywords: Ultrasonic Transducer, Tomography, Acoustic Pressure, Imaging, Wavelength

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1.0 INTRODUCTION

The ultrasonic wave is strongly reflected when it interfaces between one substance and another, and one of the major constraints on the application of a multi-phase flow ultrasonic tomography (UT) system is the limitation of attenuation media [1]. In a liquid–solid boundary, especially a metal pipe, the reflection rate is about 90%, in which the solid interface is almost a perfect mirror for an acoustic wave [2], creating difficulty in collimating the sound wave into the investigated medium. Due to the above reflection rate constraint, the ultrasonic technique has been widely applied in metal pipe cracking or corrosion detection;

it is not yet practically applied in the cross-sectional flow imaging tomographic system. Research into the ultrasonic tomographic system commonly uses non-metallic pipes, such as ($Z_a = 3.35 \times 10^6 \text{ kg}/(\text{m}^2\text{s})$), and acrylic ($Z_a = 3.22 \times 10^6 \text{ (kg}/\text{m}^2\text{s)}$), in which the acoustic impedance Z_a is much lower than in a metallic pipe ($Z_a = 45.45 \times 10^6 \text{ kg}/(\text{m}^2\text{s})$), to investigate the performance of ultrasonic imaging in the multi-phase flow [3]. This study aims to create a simulation model that can be used to predict how the attachment and frequency of ultrasonic transducers affect the sound wave propagation behavior in a metal vessel. From the sensing configuration standpoint, this simulation is an important imaging process. For example, with the

results of simulation, ultrasonic sensors with preferred center frequency can be mounted circularly on a sealed vessel, facilitating local pitch-catch measurements of fan-beam sensor configurations, to reconstruct the ultrasound image as a fluid flow diagnostic tool.

In this paper, we first present in Section 2 the fundamentals of ultrasound in a tomographic imaging system. Then, we discuss in detail our simulation setup and methods. In Section 3, we discuss and provide the analysis of simulation results. Finally, we conclude our work in Section 4.

2.0 FUNDAMENTALS OF UT SYSTEM

In the ultrasonic flow measurement system, the fixture jig with the ultrasonic transducers is clamped at the outer layer of the flow regime, and flow measurements are taken outside the pipeline. Figure 1 shows the typical ultrasonic fan-beam sensor configuration [4] applied by recent UT researchers. It is always important to know the potential achievements of the ultrasonic flow imaging modality in order to correctly understand the challenges in designing the ultrasonic front-end circuitry design. First, the goal of the ultrasonic flow imaging system is to provide an accurate representation of the inside of the investigated pipeline. Second, through signal display processing, is the determination of movement inside the pipe, for example, fluid flow mixtures.

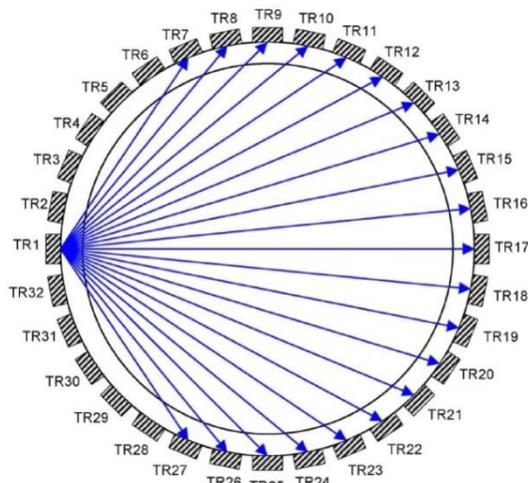


Figure 1 Ultrasonic Sensor Fan-Beam Configuration

Ultrasound waves can propagate or vibrate to some extent in any elastic material. When sound travels through a medium, its signal amplitude or wave pressure diminishes with distance. When sound waves travel in idealized materials, the sound pressure is only reduced by the spreading of the waves. However, in natural materials, natural properties and loading

conditions can be related to attenuation caused by scattering and sound absorption [5]. In short, wave pressure is reduced by the spreading, scattering and absorption of the wave. Basically, there are four principle modes of sound propagation, based on the way the particles oscillate and propagate in a stable manner. Sound can propagate as longitudinal waves, shear waves, surface waves and plate waves. Longitudinal waves are also called pressure or density waves; sound oscillations occur in the same direction as wave propagation, through the atomic vibration structure. Longitudinal waves can happen in solids and liquids, as well as in air. In shear waves, the particles oscillate at a certain angle or transverse to the direction of propagation. Shear waves propagate with the longitudinal waves' energy, and can only travel well in solid material. Surface waves and plate waves happen on surfaces and at interfaces and are various types of elliptical or complex vibrations generated due to sound propagated at the boundaries of different materials. In solids, surface or Rayleigh waves are generated in a combination of both longitudinal and transverse motions to create elliptic orbit motion. Plate waves, commonly referred to Lamb waves, are complex vibrational waves that propagate in parallel throughout the thickness of the material, and can only be generated in materials a few wavelengths thick. In steel-based material, Lamb waves can travel several meters, and are influenced by the center frequency of the ultrasound. When investigating multi-phase flow in a sealed steel-based vessel, which is a hard boundary interface, the ultrasound propagation involves all four wave modes, making the oscillation pattern a challenge to estimate and measure. Another challenge is the large acoustic impedance mismatch between the transducer elements and the body of the investigated medium. The acoustic impedance can be minimized by applying coupling gel, which has high acoustic impedance. The coupling gel, usually referred to simply as couplant, forms a good contact with the investigated body. It is practically impossible to efficiently transmit ultrasound from the transducer to the object to be measured without the aid of a suitable couplant [6]. Couplants frequently used are oil, gel, glycerine, and propylene glycol [7]. In practice, a small amount of couplant is applied between the transmitting face of the transducer and the test surface.

2.1 Finite Element Modelling (FEM) Setup

We used the Acoustics Module (COMSOL version 4.2a) to predict the propagation of acoustic waves through three-phase structures. In this section, we present the construction of FEM: a simple full water medium is first simulated (Case 1), followed by adding in a sealed steel vessel (Case 2). Next, the investigation was furthered with study of a bubble inside the vessel (Case 3). We undertook sound wave propagation imaging pressure acoustic studies in both frequency domain analysis and time domain analysis. The computational domain is a sphere (radius $R_{\text{fluid}} = 50$

mm) filled with fluid. Three cases are studied: simple full water medium, water encapsulated by a steel vessel, and a gas bubble in the steel vessel. The steel-based vessel has an inner radius the same as fluid (water) area and outer radius (R_{steel}) is 55 mm. In case three, a spherical air bubble of a different size (R_{bubble}) and with properties different from those of the surrounding fluid located in the centre of the domain. In the classical case of pressure acoustics, the flow is assumed to lose less, the viscous effects are ignored, and the pressure of the acoustic field is governed by the wave Equation (1) below [8].

$$Q = \frac{1}{\rho_0 c^2} \frac{\delta^2 p}{\delta t^2} + \nabla \left(-\frac{1}{\rho_0} (\nabla p - q) \right) \quad (1)$$

where t is time (s), ρ_0 is the density of the fluid (kg/m^3), and both q and Q are possible acoustic dipole and monopole source terms (N/m^3 and $1/\text{S}^2$ respectively). Acoustic problems often involve simple harmonic waves, such as sinusoidal waves, expanded into harmonic components through their Fourier series. Considering that the pressure varies with time, the acoustic pressure in a time-harmonic wave can be expressed using complex variables [8] as in the Equation (2) below.

$$p(x, t) = p(x) e^{i\omega t} \quad (2)$$

where $\omega = 2\pi f$ (rad/s) is the angular frequency and f (Hz) is the frequency of the ultrasound. With Equation (2), the time dependent wave equation in Equation (1) can be simplified to the well-known Helmholtz Equation (3) as below.

$$Q = \nabla \left(-\frac{1}{\rho_0} (\nabla p - q) \right) - \frac{\omega^2}{\rho_0 c^2} p \quad (3)$$

For the plane wave, termed the homogenous case, the two sources q and Q are zero and the equation above can be simplified as Equation (4) and is used to describe the propagation of harmonic sound waves in the fluid surrounding the spherical scatterer.

$$\nabla \left(\frac{1}{\rho_0} (\nabla p) \right) + \frac{\omega^2 p}{\rho_0 c^2} = 0 \quad (4)$$

where ρ_0 is the fluid density and c is the sound speed in the fluid (water: $\rho_0 = 1,000 \text{ kg/m}^3$, $c = 1,500$

m/s). In our simulation, a radiation boundary condition is applied on the surface of the outer spheres (R_{steel} and R_{bubble}). With this choice of boundary condition, a spherical outgoing wave is allowed to leave the modeling domain with reflection and an incident plane wave is specified (amplitude $p_0 = 1,000 \text{ Pa}$, propagation along x -axis). Ultrasonic transducers are simulated to be placed at surface of steel's outer spheres. The simulated ultrasonic sensors are with flat epoxy front end, with diameter 9.8mm. COMSOL simulation was run based on the mechanical mesh. It is critical to have a dense enough mesh; in order to get an accurate solution, the mesh should be fine enough to both resolve the geometric features and the sound wavelength. Sound waves are characterized by a wavelength (λ) in space, while the λ value depends on the frequency, f , and speed of sound, c , in the medium according to the equation (5) below.

$$\lambda = \frac{c}{f} \quad (5)$$

As a rule of thumb, the mesh size should be less or equal to λ/N , where N is between 5 and 10. The higher the N value, the heavier the computation and the higher the memory load needed in the computer. Computer run-time is prohibitively expensive, especially when the N value is higher than 10. In our harmonic load simulation, the parametric sweep feature is used to compute the Helmholtz equation into a frequency range study.

3.0 RESULTS AND DISCUSSION

Ultrasonic waves travel in a stable manner based on the way the particles oscillate. Under non-disturbance circumstances, the wavelength is the constant distance between the waves. Table 1 tabulates data for the λ value based on Equation (5). Solutions to acoustic inverse problems are wave-like. We can observe the influence of frequency on the wavelength from Table 2, the higher the frequency value, the smaller the wavelength. Table 2 shows the ultrasonic sound propagation wave for Case 1 and Case 2 stated in simulation setup. In Tables 2, we primarily looked at the waves in the forms of two-dimensional plots of ultrasound attenuation versus wave position. Case 1 simulation is the single-phase ultrasonic analysis; water is the only investigated medium. In the acoustic pressure model, ultrasound was simulated to propagate in a condition with no hard boundary. In an ideal case, there should be no distortion or disturbance along the propagating waves. Since there is no hard boundary in Case 1, the shear waves did not effectively travel on the liquid surface. Referring to the 100 KHz waveform in Case 1, when sound travelled in the single-phase medium, the waves propagated out from the transducer face with a circular wave front and only longitudinal waves were observed in the

simulation results as if a single sinusoidal wave was propagating through the water.

Table 1 Wavelength Based on Wave Frequency

Properties	100 kHz	500 kHz	1 MHz	2 MHz	3 MHz	4 MHz	5 MHz
Wavelength, mm	15.000	3.000	0.150	0.750	0.500	0.375	0.300

Table 2 Ultrasonic Propagation Wave Simulation Result

Freq.	Case 1: Single Phase	Case 2: Multi-Phase
	Full Water	Steel-Water-Steel
100 KHz		
500 KHz		
1 MHz		
2 MHz		
3 MHz		
4 MHz		
5 MHz		

Table 3 Bubbly Flow Simulation Result

Bubble Size, λ (mm)	Case 1: Single Phase	Case 2: Multi-Phase
	Water Column	Steel-Water-Steel Column
No bubble (0)		
4λ (1.5)		
2λ (0.75)		
λ (0.38)		
0.5λ (0.19)		
0.25λ (0.09)		
0.20λ (0.08)		

However, when the frequency increased, particles oscillated in the smaller wavelength, and scattering happened more often. Scattering is the reflection of the sound in a direction other than its original direction of propagation. Wave attenuation occurred not only by the spreading of the wave but also by the scattering and absorption of the wave. From the waveforms in Case 1 of Table 2, attenuation rose from 100 KHz to 5 MHz, from a clear sinusoidal sound wave to a more collimated wave propagation; even at frequencies of more than 3 MHz, no sound reflections were viewed in a stable manner. The results from Case 1 form the basis of analysis in the Case 2 and Cases 3 disturbance studies.

In Case 2, when the sound travelled through more than one medium (steel-water-steel), interference of sound was observed. The spherical metal-based pipeline created the hard boundary surface for the wave propagation. At the boundary interface, all the four wave modes (longitudinal, shear, Rayleigh and Lamb) existed. The refraction and reflection of the sound waves made the wave propagation pattern even more complex. When waves interact, they superimpose on each other, and the amplitude of the sound pressure at the interaction is the sum of the amplitudes of the two individual waves. When they are in phase, at which time the peaks of the waves are exactly aligned with the peaks of other waves, they combine and double the pressure acoustic. In contrast, when they are completely out of phase, at which time the peak of one wave is exactly aligned with the valley of another, the waves cancel each other out. When the two waves are not completely in phase or out of phase, the resulting wave is the sum of the wave amplitudes. As the investigated area is a symmetrical area, refraction and reflection happened in homogeneous energy and a uniform and intense wave field developed in a fan-beam shape in all the investigated frequencies of Case 2. From the waveform analysis, we can apply ultrasonic sensors in the sealed vessels flow tomographic imaging system. The uniformity of ultrasound wave propagation in a fan-beam shape can benefit the system measurements since the majority of sensor arrangements for the imaging system have a fan-beam configuration.

Next, in Case 3, we simulated the scenario of a bubbly flow in an industrial vessel using the above 2 MHz pressure acoustic model. A spherical air bubble with a different size (R_{bubble}) was located at position (-20, 0) in the investigated domain. In the Case 3 simulation, our aim was to provide an analysis of the size of the detectable gas hold-up. Based on the wave propagation pattern corresponding to the acoustic pressure at the receiver end, the gas hold-up size that is able to be detected by the system is equal to or bigger than the size of half an ultrasound wavelength. When the size of the gas hold-up is smaller than half a wavelength, the results of the bubbly flow simulation show no significant difference compared to the “no bubble” simulation result. We

observed that reflection of waves happened at the water–air boundaries, with most of the wave being reflected back to the ultrasonic point of source. Compared to all the three simulation cases, it can be summarized that even when the sound waves propagate in a lose-less medium, attenuation often occurs by interaction with the surroundings at the boundaries of the system.

4.0 CONCLUSION

We were able to simulate acoustic attenuation from a simple single-phase flow to a three-phase flow. Ultrasound propagation pattern and resonance behaviours were well predicted. Results in fan-beam shape wave propagation provide us with the confidence to implement ultrasonic sensors, in practice, in industrial flow imaging systems. In addition, the results obtained for the encapsulated bubble were compared with those obtained using the ideal non-disturbance acoustic model, and showed that the detectable bubble size has to be equal to or more than half of the ultrasound wavelength. These first attempts of simulation works to use ultrasonic transducers operating in sealed vessels are satisfactory. Future works will focus on adding analytical solutions with hardware performance analysis.

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