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Differentiate low impedance media in closed steel tank using ultrasonic wave tunneling

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Abstract

Ultrasonic wave tunneling through seriously mismatched media, such as steel and water, is possible only when the frequency matches the resonance of the steel plate. But it is nearly impossible to realize CW wave tunneling if the low acoustic impedance medium is air. The issue might be resolved using tone-burst signals. Using finite element simulations, we have determined the optimum number of cycles which can excite the resonance propagation and increased the -6dB bandwidth of energy transmission from 0.001% to 5.9% for air medium. We show that the tunneling waves give us enough information to distinguish low acoustic impedance medium inside a steel tank.

Keywords: wave tunneling; bandwidth; ultrasonic NDE; optimization.

1. Introduction

Ultrasound has been widely employed in the detection and diagnosis of defects or details of structures, such as medical imaging [1-4], nondestructive testing [5-7], food safety inspection [8-10], etc. However, in some applications, the ultrasound transducer cannot directly in touch with the object, such as monitoring the oil level in the pipeline [11], detecting the level of different media in a closed tank, etc. In these cases, especially when the impedance difference between the medium and the tank is very large, the acoustic energy transmission will be very small [12]. According to the T-matrix theory, if the system was excited at resonance frequency or the corresponding harmonic frequencies of the steel palate, the whole energy can go through the mismatched impedance layers [13-14]. Hence, this resonance tunneling (RT) method should be explored.

In this work, we will discuss how to detect the level of different liquid media in a closed steel tank by the RT. The T-matrix theory is based on continuous wave, however, in practical measurements, tone burst is preferable because the tunneling bandwidth is very narrow and it is impossible to make an ultrasonic transducer of exact frequencies. Therefore, it is essential to know the least number of tone burst cycles which can excite the resonance condition. In addition, the relationship between the -6dB bandwidth of energy transmission coefficient and the impedance medium has been comprehensively investigated.

2. Setup and Methods

2.1. Setup and Materials

In the closed tank showed in Fig. 1, assuming there are three possible media in the tank, water, air and foam of soup water, respectively. The tank is made of steel plate and the designed thickness is 2.89 mm. A pair of pitch-catch transducers are used to send and receive the ultrasound signals. All the material parameters are listed in Table I.

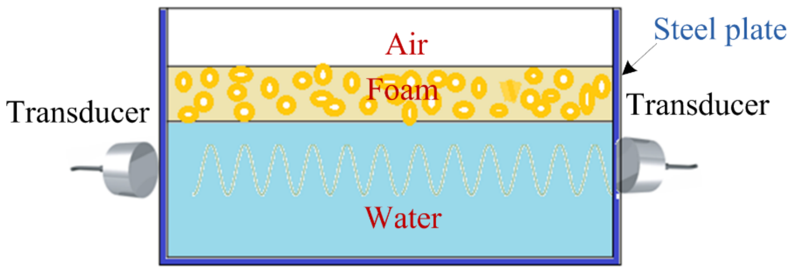

Fig. 1. Schematic diagram of the measurement system, the media in the steel tank are water, air and foam.

Table I. Material properties at room temperature

Materials	Density(kg/m^3)	velocity(m/s)	Impedance(MRayl)
Steel	7850	5780	46.6
Water	~1000	1500	1.5
Air	1.239	340	4.2×10^{-4}
Foam	20	1000	2×10^{-2}

The impedance of the steel, water and air are 46.6 MRayl, 1.5 MRayl and 4.2×10^{-4} MRayl, respectively. The acoustic energy transmission coefficient (AETC) is given by [12],

$$T=\frac{4Z_1Z_2}{(Z_1+Z_2)^2} \tag{1}$$

where Z_1 and Z_2 are impedances of the incident material and transmitting material, respectively, and $Z=\rho v$, where ρ and v are the density and velocity of the medium, respectively. Hence, the energy transmission coefficient from the steel to water is 12%, and to air is only 0.38%. Taking consideration of other factors, such as scattering and absorption, the catch transducer can hardly receive any signal for the air case. In order to solve this problem, the RT is used to excite the resonance propagation in the steel plate.

2.2. Determination of the AETC

First, we used the finite dimension T-matrix model to perform the calculations. Our experimental setup can be simplified as a steel-water-steel system. Assuming a longitudinal acoustic wave enters into the steel layer, then to the water layer and transmit through the other steel layer. The wave function in each layer is in the following form:

$$u(x,t) = \left[A_+^j e^{ik^j x} + A_-^j e^{-ik^j x} \right] e^{-iwt}, \tag{2}$$

where the wave number k=ω/v, ω and v are the angular frequency and velocity of the corresponding layer, respectively. Also, assuming there is no reflection after the wave transmitting through the second steel layer into the air.

The transfer matrix for layer i is T_i, and it has the following form,

$$T_i = \begin{bmatrix} \cos(k^j d^j) & (1/Z_i)/\sin(k^j d^j) \\ -Z_i/\sin(k^j d^j) & \cos(k^j d^j) \end{bmatrix}, \tag{3}$$

And the total transmission T is the product of transfer matrices as follows,

$$T = T_n T_{n-1} \ldots T_1, \tag{4}$$

For the steel-water-steel system, the total transfer matrix is given by

$$T = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \cos(k^s d^s) & (1/Z_s)/\sin(k^s d^s) \\ -Z_s/\sin(k^s d^s) & \cos(k^s d^s) \end{bmatrix} \begin{bmatrix} \cos(k^w d^w) & (1/Z_w)/\sin(k^w d^w) \\ -Z_w/\sin(k^w d^w) & \cos(k^w d^w) \end{bmatrix}$$
$$\begin{bmatrix} \cos(k^s d^s) & (1/Z_s)/\sin(k^s d^s) \\ -Z_s/\sin(k^s d^s) & \cos(k^s d^s) \end{bmatrix}$$
(5)

where k^s and k^w are the wave numbers and d^s and d^w are layer thickness of steel and water, respectively, the superscript *w* represents water, *s* represents steel.

Both displacement continuity and stress continuity are satisfied at the layer interface, the acoustic energy transmission coefficient of the above system is as follows,

$$t=\left(\frac{A_{N+1}}{A_0}\right)^2=\left(1-\frac{-w\mathrm{i}Z_sT_{11}-w^2Z_s^2T_{12}-T_{21}+w\mathrm{i}Z_sT_{22}}{w\mathrm{i}Z_sT_{11}-w^2Z_s^2T_{12}+w\mathrm{i}Z_sT_{22}}\right)^2, \tag{6}$$

where A_0 and A_{N+1} are the amplitude of incident and transmission waves, respectively.

3. Results and Discussion

3.1. The relationship between AETC and excited frequency

The calculation results in Fig. 2a) show that, when the steel plate is excited at its resonance frequency or harmonic frequencies， the energy can transmit 100%. Our simulation results verified the T-matrix calculations. Fig. 2b) shows the steel plate resonates at its resonance frequency 1.0 MHz, second harmonic 2.0 MHz and third harmonic 3.0 MHz, which corresponding to the (½) λ (λ is wavelength is steel), λ, and (3/2) λ vibrations, respectively. At other frequencies, the vibration displacements are irregular.

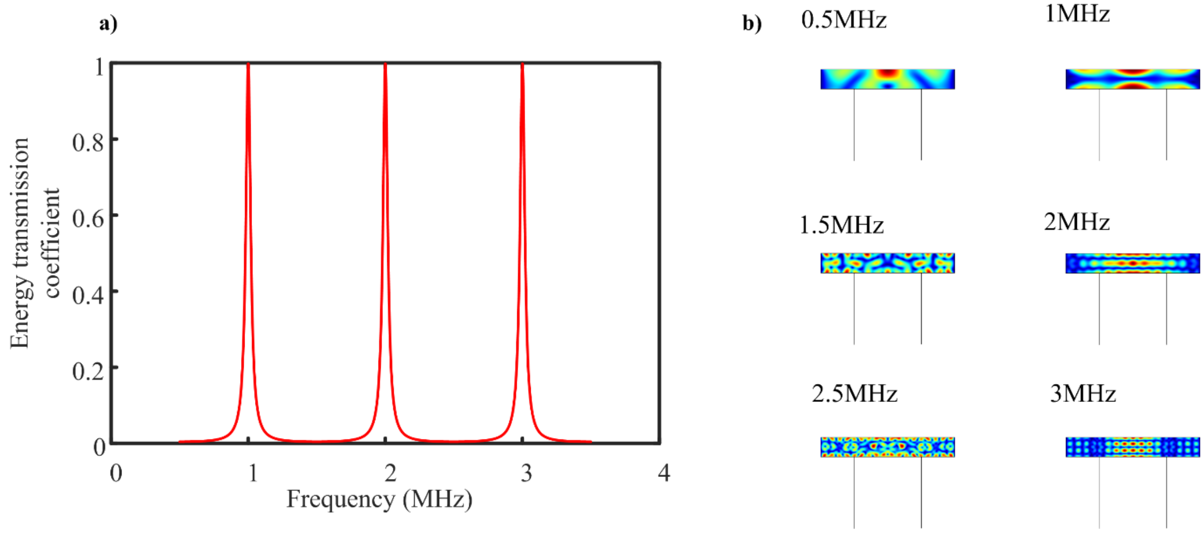

Fig. 2. a) The energy transmission coefficient from steel plate to water excited by a range of frequencies, b) The vibration displacement distribution of steel plate at several representative frequencies with a finite size transducer in the center.

3.2. The relationship between AETC and excited cycle number

However, in practical measurements, it is very difficult to make a transducer with exact 1.0 MHz and the transmission will be drastically reduced if the transducer frequency is slightly off the resonance due to the extremely narrow bandwidth of the transmission coefficient. Hence, we need to study the optimum number of cycles of tone burst signal which can excite the resonance. The steel plate was excited by tone burst of different number of cycles with the center frequency 1.0 MHz in a cycle number ranging from 1 to 20. The energy transmission coefficients were calculated for each case, and the vibration displacement of steel plate was simulated using finite element software. As showed in Fig. 3, the energy transmission coefficient monotonically increases with the number of cycles, and reaches 45% when the burst signal is about 20 cycles. In addition, the steel vibration displacement pattern gradually approaches 1/2 λ resonance as the number of cycle increases.

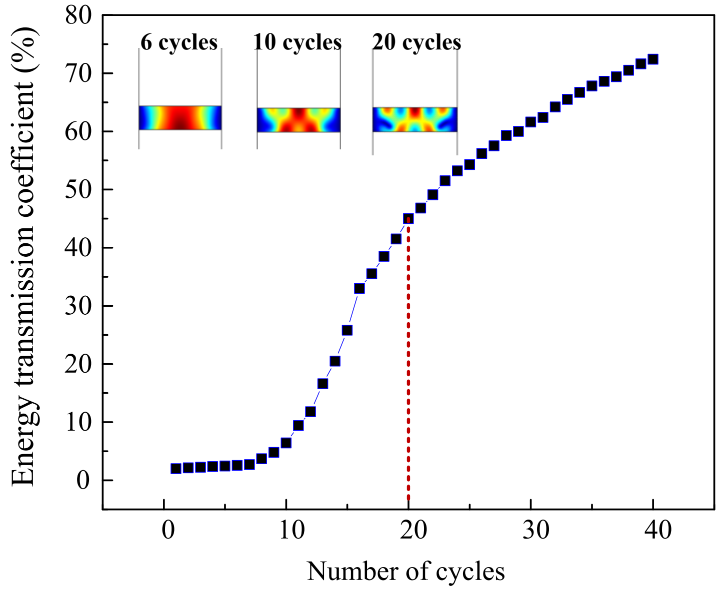

Fig. 3. Relationship between energy transmission coefficient and the number of tone burst cycles. The inset figure is the vibration displacement distribution of steel plate excited at different number of tone burst cycles.

3.3. The relationship between AETC and media impedance

Based on the design of our measurement system, the relationship between -6 dB bandwidth of transmission coefficient and the acoustic impedance of the medium was investigated. Fig. 4 shows the bandwidth of the transmission peaks with media water, foam and air, they were 4.2%, 0.05% and 0.001%, respectively. When the impedance difference between the steel plate and medium is very large, the bandwidth almost linearly decreases with the decrease of medium acoustic impedance. Since the bandwidth of air case is much narrower than that of the water case, the energy could not transmit the steel plate if a tiny deviation from the resonance frequency occurred, which is a too high a demand for the ultrasonic transducer. In this case, the tone burst signal has an advantage compared to the CW since its relatively broader bandwidth could make some portion of the signal to match the resonance. Sinusoidal wave with a center frequency of 1MHz was used its bandwidth was obtained with different number of cycles using the Fourier transform. The results in the inset figure of Fig. 4b) shows that when the number of cycles increases, the bandwidth decreases and the center frequency approaches 1MHz. When the number of cycle number was 20, the bandwidth and center frequency were 5.9% and 1.025MHz, respectively. Besides, the commercial broad bandwidth (BW) transducers could achieve the -6dB bandwidth more than 80% [15-16], it is therefore easy to satisfy and adjust the frequency to excite the resonance of the steel plate. In other words, to excite the steel plate resonance, the transducer frequency band must cover this resonance frequency.

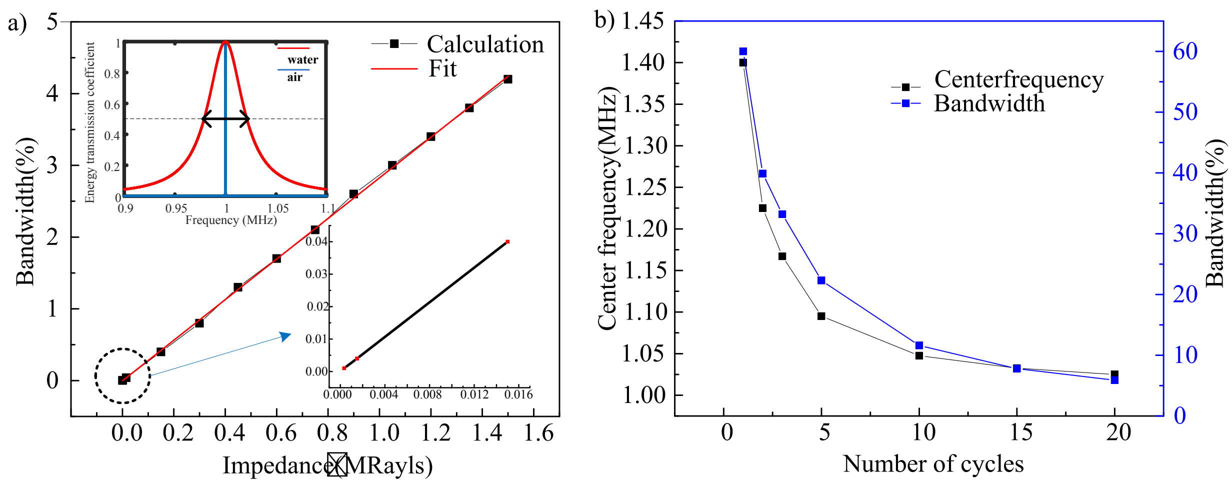

Fig. 4. The relationship between a) -6dB bandwidth of energy transmission coefficient and impedance of medium, b) -6dB bandwidth of different period of 1MHz sine wave signal.

3.4. Simulation of AETC through three different media tank

Based on the above analysis, we know that the energy can transmit 100% irrespective of the medium inside the steel tank for a CW wave. However, the premise is to neglect the attenuation of the medium and the steel plate. In reality, the ultrasonic wave suffers attenuation, for a plane wave the acoustic attenuation can be expresses as

$$P = P_0 e^{-2\alpha x}, \tag{7}$$

where P_0 is the incident power, and x is the propagation distance, α is the attenuation coefficient given by,

$$\alpha = \frac{\eta\omega^2}{2v^3\rho}, \tag{8}$$

where η is the dynamic viscosity, ω, ρ and v are the angular frequency, phase velocity and density of the medium[12]. The dynamic viscosity of air and water are 1.8×10^{-5}Pa·s and 1×10^{-3}Pa·s, respectively.

We simulated the steel tank filled with different media. For example, the pitch transducer was excited by 20 cycles tone burst with 1.0 MHz center frequency, the excitation voltage is 1.0 V and the catch transducer was used to receive the transmission signal on the other side of the tank as illustrated in Fig. 1. In order to reduce computation time, the medium thickness was set as 20mm, which was much smaller than practical systems.

As showed in the Fig. 5a), these three kind of media can definitely be distinguished due to different wave propagation velocities in the three media. The received signals showed phase difference, with the water case signal being the front whereas air case signal at a much delayed time. However, according to Eqs. (5) and (6), $P_{water} = P_0 e^{-2\times9.3\times10^{-4}x}$, if the x is very small, the difference between P_{water} and P_{air} is also very small. As the distance increases, the voltage amplitudes of the received signals, which reflect the medium attenuation, will show obvious difference.

When the excitation signal cycle decreases to 10 cycles, the receive voltage is about half of the value of 20 cycle cases, as showed Fig. 5b). Besides, due to the ringdown effect after specified number of cycles, higher voltage can be achieved compared with analytic value.

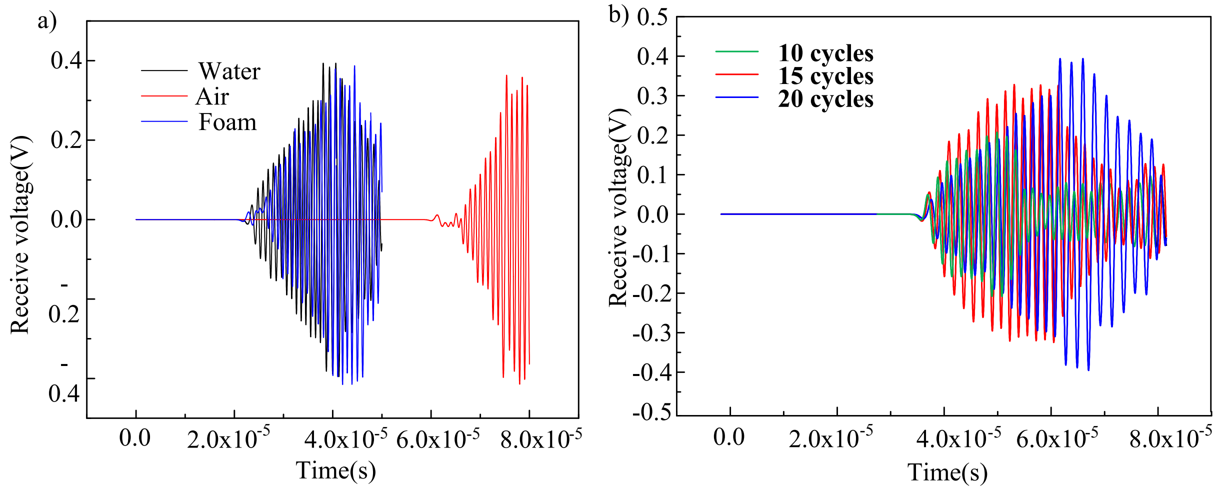

Fig. 5. The receive voltage a) after the 20 cycles excitation signal transmit through three different media, b) with different cycles in the water tank.

4. Conclusion

An ultrasound tunneling method was analyzed and used to detect the level of different media in a closed steel tank. The outer steel plate was excited at its resonance frequency based on the T-matrix theory. However, the -6dB bandwidth of energy transmission coefficient was very narrow when the impedance of medium was very small, which brings difficulty to excite the steel plate. In order to solve this issue, the tone burst with center frequency 1.0 MHz was used to excite the steel plate, and the optimum number of tone burst signal to excite the resonance was 20 based on the finite element simulation using the Comsol software, for which the corresponding bandwidth of the above signal is 3.1%, broad enough to cover the transducer frequency uncertainty in matching the resonance frequency of steel plate for air medium. Due to different attenuation and propagation velocity in the media, three different media were accurately distinguished by this method. Our method can be extended to other practical applications, such as oil level detection, fluid and gas media detection, etc. which cannot be directly measured. We only need to know the property and thickness of the outer material which will determine the excite frequency, and know the possibly medium inside, based on the wave propagation time and received signal amplitude, it is easy to detect the medium inside. In a word, this method offered an application guidance.

Acknowledgments

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1. An ultrasound tunneling method was proposed to detect very low acoustic impedance media in a closed steel tank.
2. CW tunneling is possible only at the resonance frequency and its harmonics of the steel wall.
3. 20 cycle tone-burst signal is sufficient to generate tunneling effect with a reasonable transmission bandwidth.