Ultrasonics 82 (2018) 130–133

Contents lists available at ScienceDirect

Ultrasonics

journal homepage: www.elsevier.com/locate/ultras

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

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ARTICLE INFO

Article history:
Received 26 April 2017
Received in revised form 20 June 2017
Accepted 30 July 2017
Available online 2 August 2017

Keywords:
Wave tunneling
Bandwidth
Ultrasonic NDE
Optimization

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 continuous wave tunneling if the low acoustic impedance media is air because the transducer frequency cannot be made so accurate. The issue might be resolved using tone-burst signals. Using finite element simulations, we found that for air media when the cycle number is 20, the −6 dB bandwidth of energy transmission increased from 0.001% to 5.9% compared with that of continuous waves. We show that the tunneling waves can give us enough information to distinguish low acoustic impedance media inside a steel tank.

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], and food safety inspection [8–10]. However, in some applications, the ultrasound transducer cannot directly in touch with the object, such as monitoring the oil level in the pipeline [11] and detecting the level of different media in a closed tank. In these cases, especially when the impedance difference between the media 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 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 resonance tunneling method. The T-matrix theory is based on continuous wave (CW) which is a wave of fixed amplitude and frequency. However, in practical measurements, tone burst is preferable because the tunneling bandwidth is very narrow for CW waves 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 this work, we have simulated the tone-In addition, the relationship between the −6 dB bandwidth of energy transmission coefficient and the impedance media 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 1.

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],

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

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 media, 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 scatter-

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http://dx.doi.org/10.1016/j.ultras.2017.07.018
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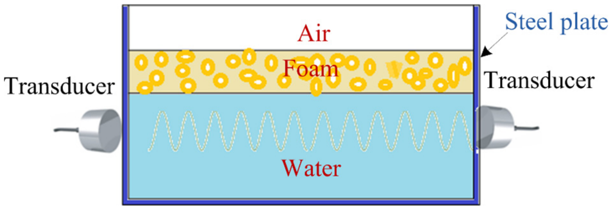

Fig. 1. Schematic diagram of the measurement system, the media in the steel tank are water, air and foam.

Table 1
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}

ing and absorption, the catch transducer can hardly receive any signal for the air case. In order to solve this problem, the resonance tunneling method 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:

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

where the wave number $k = \omega/v$, 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

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

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,

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

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

The finite element simulations were performed using Comsol Multiphysics® finite element package (COMSOL, Inc.).

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 (1/2) λ (λ is wavelength is steel), λ, and (3/2) λ vibrations, respectively. At other frequencies, the vibration displacements are irregular.

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 cycle number 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 40. 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.

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 media 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 media is very large, the bandwidth almost linearly decreases with the decrease of media acoustic impedance. Since the bandwidth of the air case for the CW wave is much narrower than that of the water case, the energy could not transmit through the steel plate if a tiny deviation from the resonance frequency occurred, which is an unpractical demand for the ultrasonic transducer. In this case, the tone burst signal has an advantage compared to the CW since its relatively broader bandwidth will give enough tolerance of the transducer frequency resonance frequency. Sinusoidal wave with a center frequency of 1 MHz was used its bandwidth was obtained with different number of cycles using the Fourier transform. The results in Fig. 4b show that when the number of cycles increases, the bandwidth decreases and the center frequency approach 1 MHz. When the number of cycle number was 20, the bandwidth and center frequency were 5.9% and 1.025 MHz, respectively. Besides, the commercial broad bandwidth (BW) transducers could achieve the −6 dB bandwidth more than 80% [15,16], it is therefore easy to satisfy and adjust the frequency to excite the resonance of