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The Study on the Ultrasonic Transducer Back Layer

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Abstract: With the mixture of tungsten particles and epoxy resin, the change law of the ultrasonic attenuation compared with the volume fraction of tungsten particles in the transducer back layer, as well as the change law of the ultrasonic speed and impedance with the particle volume fraction and particle size were analyzed. The theoretical support for improving the narrow pulse and high-resolution ultrasonic probe was proposed in this article.
Keywords: ultrasonic transducer back layer, acoustic attenuation, wave velocity, acoustic impedance

1. INTRODUCTION

In ultrasonic non-destructive testing, the back layer of ultrasonic transducer is a critical factor to generate a narrow pulse signal, which is very important to improve the distinguishability. In industrial design, some composite materials such as tungsten particles and epoxy resin, metal-polymer is usually used to make the transducer back layer of ultrasonic transducer. The acoustic attenuation in the transducer back layer is affected with two factors. The first one is that scattering attenuation produced by solid particles which could transform ultrasonic energy into thermal energy while the ultrasonic wave propagates in the transducer back layer. The second one is the viscosity effect in the transducer back layer which led to the particles rub against each other. And it could also transform ultrasonic energy into thermal energy. It is feasible to adjust the acoustic impedance and attenuation coefficient by controlling the size and quantity of the solid particles in the transducer back layer.

2. THEORETICAL DERIVATION

The ultrasonic attenuation in the transducer back layer is as flowing:

$$P(x) = P_0 e^{-\alpha x} \tag{1}$$

Where α is ultrasonic attenuation coefficient when the plane wave propagation in the transducer back layer. P_0 is initial sound pressure. x is sound transmitting distance.

Assuming that corresponding parameters are as follows: The density of matrix materials in transducer back layer is ρ_1 and Lame constant is λ_1 and μ_1; The particle diameter of filling material is r_0 and the density is ρ_2 and Lame constant is λ_2 and μ_2; As a whole, the density of composite materials in transducer back layer is ρ and Lame constant is λ and μ.

When plane p-wave propagation in transducer back layer, the propagation characteristics are connected with the physical properties and proportionality of all materials in transducer back layer. According to the scattering theory of Waterman-Truell model, acoustic propagation constant is defined as:

$$\beta = \frac{\omega}{v_l} + i\alpha \tag{2}$$

Where v_l is ultrasonic velocity in transducer back layer and α is ultrasonic attenuation coefficient, and ω refers to the angular frequency. To estimate β, a multiphase version is employed as follows:

$$\left(\frac{\beta}{k_1}\right)^2 = 1 + \frac{4\pi n_0}{k_1^2} f(0) + \frac{4\pi n_0^2}{k_2^4}\left[f^2(0) - f^2(\pi)\right] \tag{3}$$

In formula 3, n_0 is number of solid particles per unit volume in transducer back layer, k_1 is longitudinal wave numbers in matrix materials. k_2 is longitudinal wave numbers in filling material, $f(0)$ and $f(\pi)$ are the forward and backward scattering amplitudes in transducer back layer defined as:

$$\begin{aligned} f(0) &= \frac{1}{ik_1}\sum_{m=0}^{\infty}(2m+1)A_m \\ f(\pi) &= \frac{1}{ik_1}\sum_{m=0}^{\infty}(-1)^m(2m+1)A_m \end{aligned} \tag{4}$$

In formula 4, A_m is scattering coefficient of composite materials in transducer back layer. On the basis of Ying and Truell's single scattering theory, a system of linear equations is derived:

$$\begin{aligned} &A_m \cdot (k_1 r_0) \cdot h_{m+1}(k_1 r_0) + B_m \cdot m \cdot (\kappa_1 r_0) \cdot h_{m+1}(\kappa_1 r_0) - C_m \cdot (k_2 r_0) \cdot j_{m+1}(k_2 r_0) \\ &- D_m \cdot m \cdot (\kappa_2 r_0) \cdot j_{m+1}(\kappa_2 r_0) = (-i)^{m-1} \cdot (2m+1) \cdot \frac{1}{k_1} \cdot (k_1 r_0) \cdot j_{m+1}(k_1 r_0) \end{aligned} \tag{5}$$

$$A_m \cdot h_m\left(k_1 r_0\right) + B_m \cdot \left[\left(m+1\right) \cdot h_m(\kappa_1 r_0) - (\kappa_1 r_0) \cdot h_m(\kappa_1 r_0)\right] - C_m \cdot j_m(k_2 r_0) + D_m \cdot \left[\left(m+1\right) \cdot j_m(\kappa_2 r_0) - (\kappa_2 r_0) \cdot j_m(\kappa_2 r_0)\right] = (-i)^{m-1} \cdot (2m+1) \cdot \frac{1}{k_1} \cdot j_m(k_1 r_0) \quad (6)$$

$$\begin{aligned} & A_m \cdot \left[\left(\kappa_1 r_0\right)^2 \cdot h_m(k_1 r_0) - 2 \cdot (m+2) \cdot \left(k_1 r_0\right) h_{m+1}(k_1 r_0)\right] + B_m \cdot m \cdot \\ & \left[\left(\kappa_1 r_0\right)^2 \cdot h_m(\kappa_1 r_0) - 2 \cdot (m+2) \cdot \left(\kappa_1 r_0\right) h_{m+1}(\kappa_1 r_0)\right] - C_m \cdot p \cdot \\ & \left[\left(\kappa_2 r_0\right)^2 \cdot j_m(k_2 r_0) - 2 \cdot (m+2) \cdot \left(k_2 r_0\right) j_{m+1}(k_2 r_0)\right] - D_m \cdot p \cdot \\ & \left[\left(\kappa_2 r_0\right)^2 \cdot j_m(\kappa_2 r_0) - 2 \cdot (m+2) \cdot \left(\kappa_2 r_0\right) j_{m+1}(\kappa_2 r_0)\right] \\ & = (-i)^{m-1} \cdot (2m+1) \cdot \frac{1}{k_1} \cdot \\ & \left[\left(\kappa_1 r_0\right)^2 \cdot j_m(k_1 r_0) - 2 \cdot (m+2) \cdot \left(k_1 r_0\right) j_{m+1}(k_1 r_0)\right] \end{aligned} \quad (7)$$

$$\begin{aligned} & A_m \cdot \left[\left(m-1\right) \cdot h_m(k_1 r_0) - \left(k_1 r_0\right) h_{m+1}(k_1 r_0)\right] - B_m \cdot m \cdot \\ & \left[\left(m^2 - 1 - \frac{(\kappa_1 r_0)^2}{2}\right) \cdot h_m(\kappa_1 r_0) + (\kappa_1 r_0) \cdot h_{m+1}(\kappa_1 r_0)\right] - C_m \cdot p \cdot \\ & \left[\left(m-1\right) \cdot j_m(k_2 r_0) - \left(k_2 r_0\right) j_{m+1}(k_2 r_0)\right] - D_m \cdot p \cdot \\ & \left[\left(m^2 - 1 - \frac{(\kappa_2 r_0)^2}{2}\right) \cdot j_m(\kappa_2 r_0) + (\kappa_2 r_0) \cdot j_{m+1}(\kappa_2 r_0)\right] \\ & = (-i)^{m-1} \cdot (2m+1) \cdot \frac{1}{k_1} \cdot \left[\left(m-1\right) \cdot j_m(k_1 r_0) - \left(k_1 r_0\right) j_{m+1}(k_1 r_0)\right] \end{aligned} \quad (8)$$

In these formulas, j_m is m-order spherical Bessel Function and h_m is m-order Hankel Function. Besides that:

$$p = \mu_2 / \mu_1 \quad (9)$$

$$k_1 = \omega\left(\lambda_1 + 2\mu_1 \big/ \rho_1\right)^{-\frac{1}{2}} \quad (10)$$

$$\kappa_1 = \omega\left(\mu_1 / \rho_1\right)^{-\frac{1}{2}} \quad (11)$$

By solving all above linear equations, scattering coefficient in composite materials transducer back layer (A_{m}) would be figured out easily.

3. EXPERIMENTAL MEASUREMENT

Take a ultrasonic probe with tungsten powder and epoxy resin composite as example and set $r_0 = 100\mu m$ and other parameters in Table 1 .The change rule of A_{m} with the change of $k_1 r_0$ is shown in Fig. 1.

Table1 mechanics property parameters of tungsten powder and epoxy resin

material	$E(10^9\ \mathrm{N/m^2})$	$\lambda(10^9\ \mathrm{N/m^2})$	$\mu(10^9\ \mathrm{N/m^2})$	$\rho\ (\mathrm{Kg/m^3})$
tungsten powder	360	180	140	18.7
epoxy resin	2.5	1.45	0.96	1.17

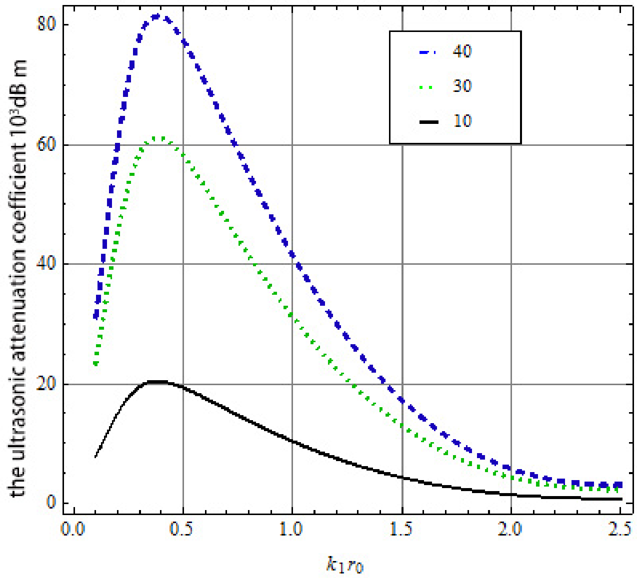

Fig.1 The change rule of A_{m} with the change of $k_1 r_0$

As you can see from Fig. 1, ultrasonic attenuation in composite materials transducer back layer is noticeably increasing with the increase of volume concentration of tungsten powder. But A_{m} is up to its maximum when $k_1 r_0 \approx 0.4$. Therefore, if the center frequency of the piezoelectricity crystal is known, it can be realized the maximum attenuation in composite materials transducer back layer by the control of tungsten powder particle size.

More over, in order to make impedance matching well, the theoretical calculation about acoustic impedance of composite materials transducer back layer is required to identify the relationships between volume concentration of particle and its impedance. Referencing to sayer's autocorrelation theory, the first step is often to determine the equivalent density and equivalent elastic constants of composite materials transducer back layer, and the second step is to work out ultrasonic velocity and acoustic impedance (formula 12-14).

$$\rho = \rho_1 \cdot (1-\delta) + \rho_2 \cdot \delta \tag{12}$$

$$(1-\delta)\left[1-\frac{3\cdot\left(\frac{k_l}{k_t}\right)^2}{3\cdot p_1\cdot\left(\frac{k_{l1}}{k_{t1}}\right)^2-4\cdot(p_1-1)}\right]+\delta\left[1-\frac{3\cdot\left(\frac{k_l}{k_t}\right)^2}{3\cdot p_2\cdot\left(\frac{k_{l2}}{k_{t2}}\right)^2-4\cdot(p_2-1)}\right]=0 \tag{13}$$

$$(1-\delta)\left[\frac{p_1-1}{(p_1-1)+\frac{1}{2}\left(3p_1+\frac{9}{2}\right)\left(\frac{k_l}{k_t}\right)^2}\right]+\delta\left[\frac{p_2-1}{(p_2-1)+\frac{1}{2}\left(3p_2+\frac{9}{2}\right)\left(\frac{k_t}{k_l}\right)^2}\right]=0 \tag{14}$$

Among formula 12-14, k_{l1} is longitudinal wave numbers in matrix materials. k_{l2} is longitudinal wave numbers in filling material. k_{t1} is transverse wave numbers in matrix materials. k_{t2} is transverse wave numbers in filling material. k_1 is equivalent longitudinal wave numbers in composite materials transducer back layer. k_2 is equivalent transverse wave numbers in composite materials transducer back layer. δ is volume concentration of tungsten powder. $p_1 = \mu_1/\mu$, $p_2 = \mu_2/\mu$.

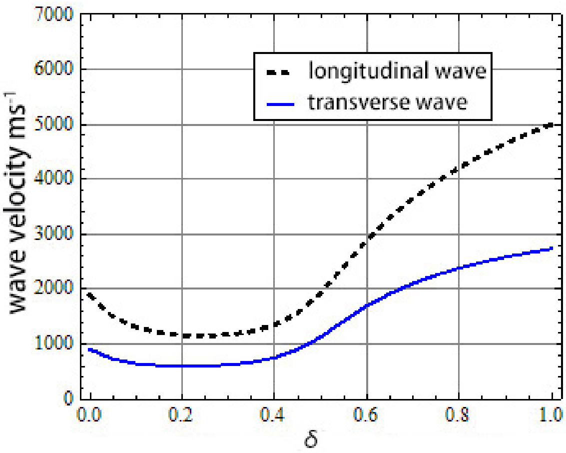

Fig.2 The curves of the longitudinal wave velocity and transverse wave velocity changing with δ

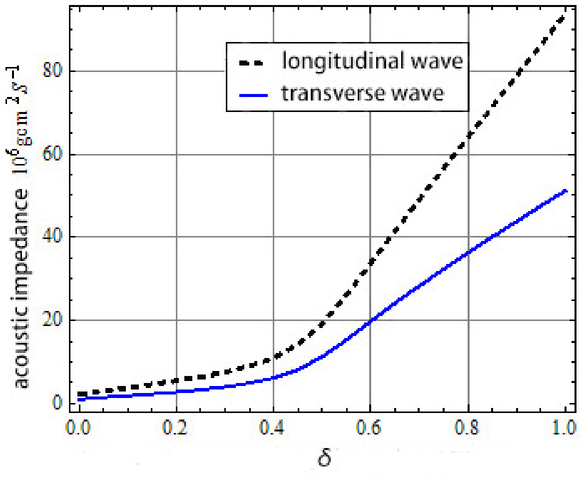

Fig.3 The curves of the longitudinal acoustic impedance and transverse wave acoustic impedance changing with δ

4. CONCLUSION

As can be seen from Fig. 2: When δ is lower, the wave velocity is gradual decrement with the δ increasing, with which the particle scattering factor of filling material. But when δ is over 50%, the wave velocity increased sharply with δ increasing, which gradually closed to the standard value in pure tungsten.

As can be seen from Fig. 3: When δ is less than 40%, the change of acoustic impedance is not really obvious. Yet the acoustic impedance changed drastically while δ varied in the 40%-60% range.

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