DETERMINATION OF ACOUSTIC PROPERTIES OF PMMA USING ULTRASONIC THROUGH-TRANSMISSION TECHNIQUE

XÁC ĐỊNH TÍNH CHẤT ÂM CỦA PMMA SỬ DỤNG KỸ THUẬT TRUYỀN SIÊU ÂM

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Abstract - In this paper, a non-destructive experimental method based on ultrasonic through-transmission technique has been developed to measure phase velocity and attenuation of both compressional and shear waves. Two pairs of transducers are used for the measurements, one with center frequency of 5 MHz, and the other pair with center frequency of 10 MHz. The method is tested on the homogeneous material Polymethylmethacrylate (PMMA). The measurement results show a good agreement with published values in literature, hence, verifying the accuracy of the measurement method. In addition, the influences of temperature on acoustic parameters of the PMMA are experimentally studied and discussed. A small variation of approximately 3% is obtained for the phase velocity, whereas the temperature influence on the attenuation is considerably large, increasing 35% with an increase in temperature from 20℃ to 37℃. These acoustic properties and their temperature effects are essential and should be considered for designing ultrasound transducers.

Key words - Ultrasound; attenuation; phase velocity; temperature effects; ultrasonic through-transmission technique.

Tóm tắt - Trong bài báo này, phương pháp thực nghiệm không phá vỡ kết cấu dựa vào kỹ thuật truyền siêu âm được phát triển để đo vận tốc và độ suy giảm của sóng ngang và sóng dọc trong vật liệu. Hai cặp biến năng được sử dụng để đo đạc, một cặp với tần số trung tâm 5 MHz, cặp còn lại với tần số trung tâm 10 MHz. Phương pháp được kiểm tra trên vật liệu đồng chất Polymethylmethacrylate (PMMA). Những kết quả đo đạc trên PMMA cho thấy sự phù hợp với các kết quả đã công bố trên tạp chí, vì vậy, kiểm chứng được tính chính xác của hệ thống. Thêm vào đó, ảnh hưởng của nhiệt độ lên thông số âm thanh cũng được thảo luận. Một lượng biến đổi nhỏ, khoảng 3% cho vận tốc pha, trong khi ảnh hưởng của nhiệt độ lên sự suy giảm âm lớn hơn nhiều, tăng 35% khi nhiệt độ thay đổi từ 20℃ đến 37℃. Những đặc tính âm thanh và ảnh hưởng của nhiệt độ lên thông số âm thanh là cần thiết và nên được xem xét khi chế tạo những biến năng siêu âm.

Từ khóa - Siêu âm; sự suy giảm; vận tốc pha; ảnh hưởng của nhiệt độ; phương pháp truyền siêu âm.

1. Introduction

Acoustic properties of materials such as phase velocity and attenuation are important material properties in many ultrasonic applications, i.e. non-destructive evaluation and ultrasound tissue characterization [1]. Design of ultrasound transducers, for example clinical applications, requires reliable characterization of these properties. Therefore, characterization of the acoustic properties of materials especially transducer materials is necessary to give experimental data for the design and modeling of transducers. In addition, for complex materials such as composites, the dispersions of velocity (phase velocity versus frequency) and attenuation may deform the acoustic pulse, resulting in inappropriate interpretation of the acoustic pulse signal. Therefore, it is extremely important to understand the characteristics and structure of these materials. For some applications, the knowledge of the dependence of materials on frequency are also required in wide range of frequencies and temperatures. Consequently, the effects of temperature and frequency variation on the acoustic parameters should be considered when characterizing materials. Among various techniques reported in literature, ultrasonic through-transmission has been considered as the most widely used method for characterizing acoustic material properties. Using this technique with mode conversion allows measuring acoustic properties of compressional waves and shear waves in solids, including porous and composite materials [2].

In this paper, the through-transmission technique has been applied to characterize samples of a homogenous material, PMMA. Because of being widely used and characterized in literature, PMMA can serve as a test material for the measurement methods and calculations. The transmission coefficients of acoustic waves as function of the incident angle is also calculated and plotted to illustrate the energy transmission into the PMMA. In addition, temperature effects on phase velocity and attenuation of the ultrasonic waves in the PMMA are also studied. Based on the -6 dB bandwidth of the power spectrum of the received signal without sample inserted, the useful frequency ranges are chosen from 2.5 MHz to 6 MHz for the 5 MHz transducer pair and from 5.5 MHz to 10.5 MHz for the 10 MHz transducer pair. Temperature dependence is investigated by first heating the water in the tank containing the sample, and then letting it passively cool down during the measurements, letting the operating temperature vary from 37℃ to 20℃. The aim of this study is to obtain reliable data for the variations of acoustic material properties of PMMA on the temperature and frequency, which can be used in transducer designs.

2. Experimental implementation

2.1. Theory

Figure 1 shows the basic principle of the through-transmission technique for characterizing acoustic properties of materials. Through-transmission technique employs two transducers which are coaxial aligned and immersed in a water tank. One transducer is used as a transmitter, and the other is used as a receiver. A sample with parallel sides is inserted between two transducers. Acoustic pulses are recorded with and without a sample inserted into the acoustic transmission path. The amplitude and phase spectra of the received pulses are calculated by Fast Fourier Transform (FFT). By comparing the spectra of the signals received with and without sample inserted, the phase velocity and attenuation of the ultrasonic waves as function of frequency are calculated. At the normal incidence angle ($\theta_i=0$), the compressional wave properties are measured. Without sample inserted, the received pulse is acquired. By using FFT algorithm, the magnitude (A_w) and the phase of spectra (ϕ_w) of the acquired signal are calculated. After that, the sample is inserted between the two transducers and the second received signal is measured. Its magnitude (A_s) and phase of spectra (ϕ_s) are also computed. The phase velocity (c_l) and the attenuation coefficient (α_l) are calculated from [2,3]:

$$c_l = \frac{c_w}{1+\dfrac{(\phi_s-\phi_w+2\pi f\tau)c_w}{2\pi fd}}, \qquad (1)$$
$$\alpha_l = \alpha_w + \ln\left(\frac{T_{TP}A_w}{A_s}\right)/d,$$

where c_w is the speed of sound in water, d is the sample thickness, τ is the trigger delay of the two time-windows used to acquire the signal, T_{TP} is the total transmission coefficient for the compressional wave, and α_w is the attenuation of water. Typically, α_w is much smaller than α_l, thus can be neglected.

With an incident angle greater than the critical angle of the compressional wave, only the shear wave can propagate through the sample. In this case, the phase velocity (c_s) and the attenuation coefficient (α_s) of the shear wave can be calculated by [2, 3]:

$$c_s = \frac{c_w}{\sqrt{\sin^2\theta_i + \left[\dfrac{(\phi_s-\phi_w+2\pi f\tau)c_w}{2\pi fd}+\cos\theta_i\right]^2}}, \qquad (2)$$
$$\alpha_s = \alpha_w\cos(\theta_l-\theta_i)+\ln\left(\frac{T_{TS}A_w}{A_s}\right)\frac{\cos\theta_l}{d},$$

where θ_i is the angle of incidence, θ_l is the refractive angle of the shear wave calculated from Snell's law, and T_{TS} is the total transmission coefficient of the shear wave.

The mathematical equations for determining the total transmission coefficients of the compressional wave (T_{TP}) and shear wave (T_{TS}) are given in [2].

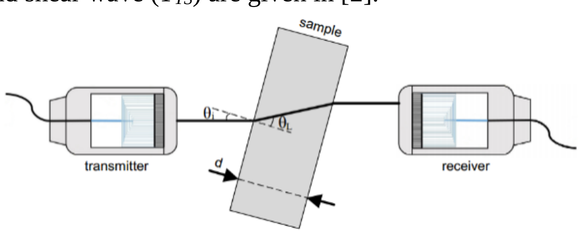


Figure 1. *Principle of the through-transmission technique*

2.2. Experimental setup

Figure 2 shows the experimental setup of the ultrasonic through-transmission technique for characterizing the phase velocity and attenuation of materials. Two pairs of transducers are used, one with center frequency 5 MHz (Olympus C309-SU) and the other with center frequency 10 MHz (Olympus V327-SU). Each pair of transducers is coaxial aligned and immersed in a cylindrical water tank. The sample is placed halfway between the two transducers, and could be rotated to vary the incident angle of the acoustic wave relative to the sample. The transmitting transducer is excited by a pulser-receiver (Panametrics 5800, Olympus Inc., Waltham, MA), set to transmit short electrical pulses. The received pulses are recorded and sampled by a digital oscilloscope (LeCroy 9310AM, Teledyne LeCroy, Chestnut Ridge, NY) at a sampling rate of 100 MS/s. The pulses received by the oscilloscope are transferred to a computer using the GPIB interface, using software written in LabVIEW (National Instruments Inc., Austin, TX) and stored to disk. Processing is done offline using self-developed codes in MATLAB software (The MathWorks, Natick, MA).

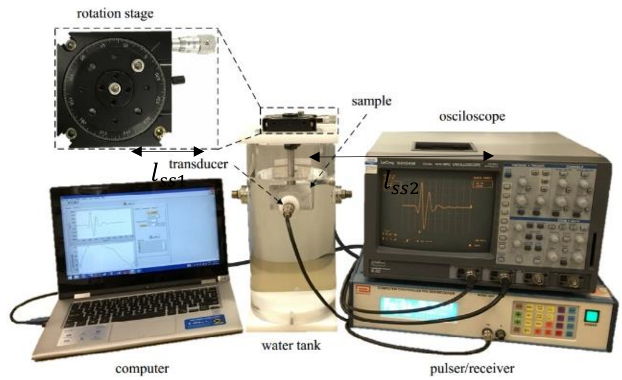


Figure 2. *Experiment setup for measuring acoustic properties of materials*

3. Results and discussions

The density of the PMMA samples is measured at 20±0.5°C, which is 1.18±0.06 g/cm^3. The sample density is assumed to be independent of temperature when determining the attenuation coefficients.

The phase velocity and attenuation of compressional and shear waves in the PMMA samples, measured with the 5MHz and 10 MHz transducer pairs are shown in Figure 3 and 4, respectively. In both cases, the phase velocity of both compressional and shear waves has only a small negative dispersion within the investigated frequency range. For the 5MHz transducer pair, the changes in the phase velocities of compressional and shear waves are 0.2% and 0.4%, respectively (Figure 3). Their average dispersion values are approximately 2 m/s/MHz for both compressional and shear wave velocity. The phase velocity found for the compressional wave at 5 MHz is 2741±2 m/s, which is close to the reported value in [4], i.e. 2757 m/s. In contrast, the attenuation coefficients are found to increase approximately linearly with frequency, which is characteristic of many viscoelastic materials [5]. Alternatively, the attenuation increases 0.8 dB/cm/MHz for the compressional wave and 2 dB/cm/MHz for the shear wave. The attenuation of shear wave is much larger than that of the compressional wave. The attenuation of the compressional wave at 5 MHz is 5.16±0.06 dB/cm (Figure 3a), which is in good agreement with published values in literature, i.e. 60.8 Np/m (~5.28 dB/cm) [6] and 61 Np/m (~5.29 dB/cm) [7].

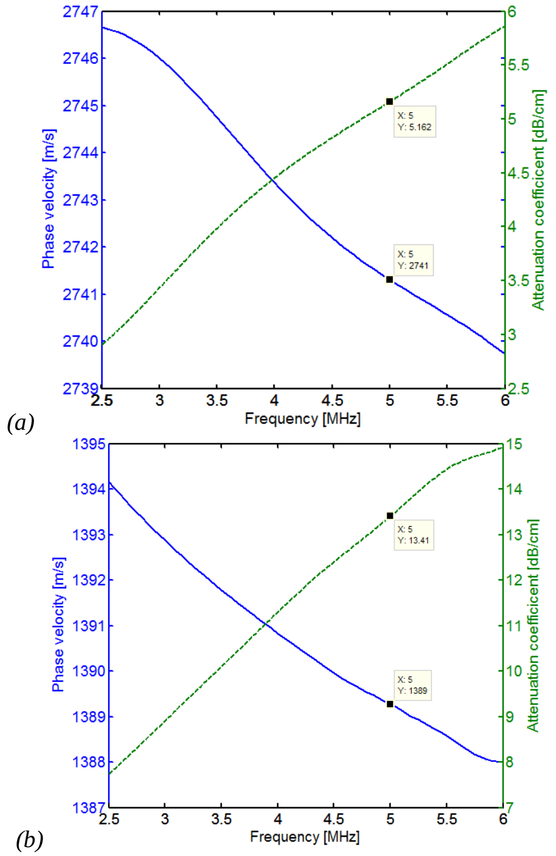


Figure 3. *Phase velocity and attenuation of the (a) compressional and (b) shear waves in PMMA samples measured at 20±0.5°C with the 5 MHz transducer pair*

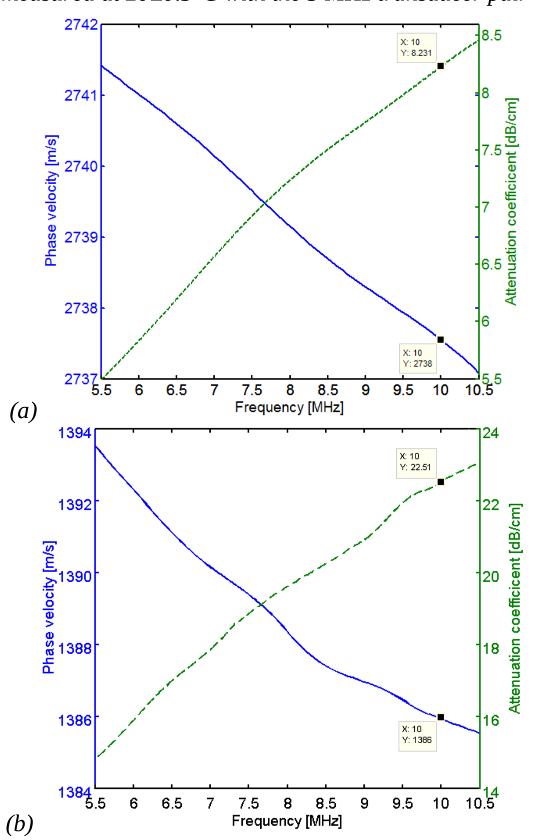


Figure 4. *Phase velocity and attenuation of the (a) compressional and (b) shear waves in PMMA samples measured at 20±0.5°C with the 10 MHz transducer pair*

For the 10 MHz transducer pair, the trend is similar (Figure 4). Their dispersion values are 0.8m/s/MHz and 1.7 m/s/MHz for the compressional and shear waves, respectively. In addition, the phase velocity of the compressional wave is about twice that of shear wave. The difference in the phase velocities measured at 5 MHz and 10 MHz is less than 0.3%. However, the attenuation significantly increases for both compressional and shear waves, compared with those measured with the 5 MHz transducer pair. According to the power-law relation, the higher the frequency, the higher attenuation obtained [8]. Nevertheless, the increase in attenuation of the compressional and shear waves is slightly lower, i.e. 0.6 dB/cm/MHz and 1.8 dB/cm/MHz, respectively.

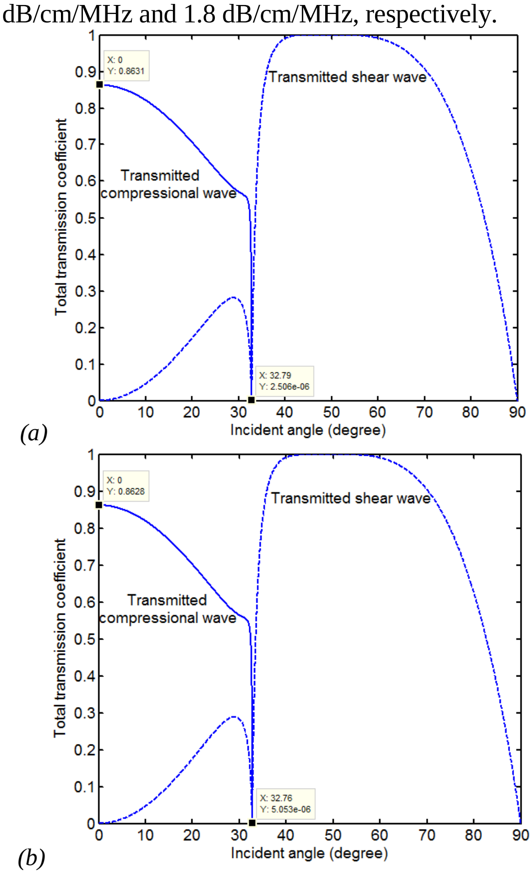
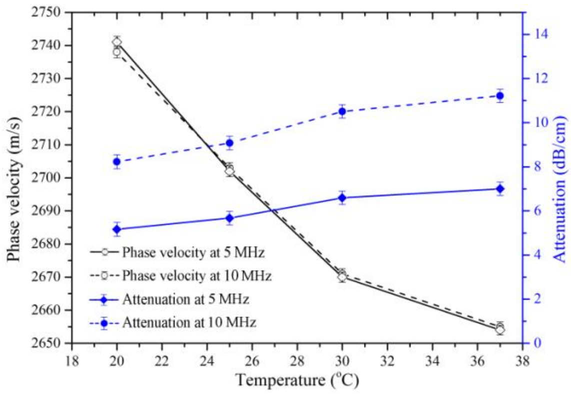
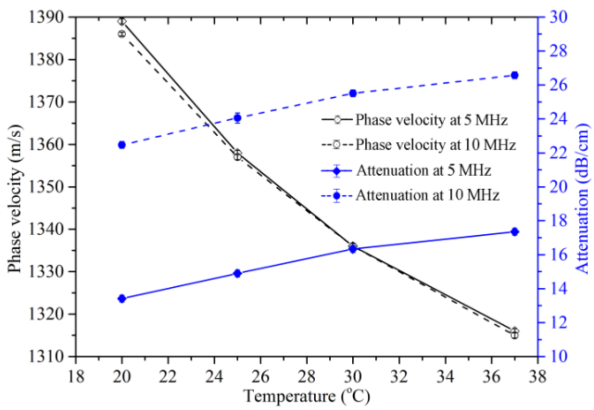


Figure 5. *Total transmission coeffiecients of compressional and shear waves in the PMMA sample measured with (a) the 5 MHz transducer pair and (b) the 10 MHz transducer pair at 20±0.5°C*

Figure 5 shows the total transmission coefficients of the compressional and shear waves as a function of the incident angle, calculated by using equations in [2]. The first critical angle for the water-PMMA interface, is approximately 32.8° when using both transducer types. At the normal incident angle, only compressional wave is excited in the PMMA, the compressional transmission coefficient is approximately 0.86 for both cases, and the shear transmission coefficient is zero. When increasing the incident angle prior to the normal incident angle, both compressional and shear waves are excited in PMMA. At the first critical angle, the compressional wave propagates along the surface so no energy is propagated into the PMMA. The shear wave amplitude goes to zero at this angle and there is total reflection. As the incident angle increases to the second critical angle, shear waves are no longer generated in the material. Because the velocity of shear wave in PMMA is slower than the speed of sound in water, thus no second critical angle or shear wave critical angle phenomena occurs. Similar diagrams are shown in [9]. The transmission coefficients when using 10 MHz transducer pair are similar to that of 5 MHz transducer pair.



(a)



(b)

Figure 6. *Phase velocity and attenuation of (a) compressional and (b) shear waves in PMMA samples versus temperature*

Figure 6 shows the effects of temperature on the phase velocity and attenuation of compressional wave in the PMMA samples. A 3% decrease in phase velocity and a 35% increase in attenuation of the compressional wave is observed when the temperature increases from 20℃ to 37℃, at both 5 MHz (5 MHz transducer pair) and 10 MHz (10 MHz transducer pair). The difference in the phase velocity between 5 MHz and 10 MHz is less than 0.3%. These values are identical for both the compressional and shear waves. Furthermore, the attenuation is found to increase almost linearly with frequency and temperature over the studied temperature range. According to the power-law relation, the attenuation also significantly increases when using the 10 MHz transducer pair. The attenuation of the shear wave is about 2.5 times higher than that of the compressional wave. At 5 MHz, the attenuation of compressional and shear waves increases from 5.16 dB/cm to 7.00 dB/cm and 13.61 dB/cm to 17.55 dB/cm, respectively when increasing the temperature from 20℃ to 37℃. The measured values are found to agree well with published values for 20℃ and 37℃ [4, 7, 10].

4. Conclusion

An experimental setup for characterizing the phase velocity and attenuation of compressional and shear waves using the through-transmission technique is implemented. The acoustic properties of PMMA have been investigated over the frequency range from 2.5 MHz to 10.5 MHz using two pairs of transducers. The measurement results show a good agreement with published values, thus verifying the accuracy of the measurements. The verified system is then used to characterize the temperature effects on the phase velocity and the attenuation of PMMA, which has many potential applications. The study shows that the temperature has a small influence on the phase velocity, but much larger influence on the attenuation. The phase velocity of both compressional and shear waves is found to decrease when increasing the temperature from 20°C to 37°C. However, a large increase in the attenuation of approximately 35% is observed over this temperature range. The attenuation of the shear wave is much higher than that of the compressional wave. From this study, it has been showed that the variations in acoustic parameters with frequency and temperature are significant and should be taken into account when designing ultrasound transducers, especially for clinical applications.

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