Polymer Testing 70 (2018) 426–433

Contents lists available at ScienceDirect

Polymer Testing

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

Test Method

Integrated measurement of ultrasonic parameters for polymeric materials via full spectrum analysis

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ARTICLE INFO

Keywords:
Polymeric material
Ultrasound velocity
Attenuation coefficient
Spectrum analysis
Flexible material

ABSTRACT

Ultrasound velocity and attenuation coefficient are important parameters for characterizing polymeric materials. How to accurately and conveniently measure ultrasonic parameters is always a significant topic. This paper presents a novel method for integrally measuring ultrasonic parameters via full spectrum analysis (UFSA). Reflected signals from the upper and lower surfaces of the polymeric materials are connected by a frequency dependent transfer function. The logarithm of the transfer function can be linearly fitted, and the ultrasonic parameters, including the ultrasound velocity and attenuation coefficient, can be calculated from the vertical intercept and slope of the fitting line. Experiments with various polymeric materials of different stiffnesses and dimensions, as well as several influence factors, were carried out to verify the proposed UFSA method. Compared to the conventional method, the proposed method does not need to measure the thickness of the polymeric material and makes full use of data in measured waves. Experimental results showed that the proposed method has high accuracy in measuring ultrasonic parameters and characterizing flexible materials. The proposed method would have broad applications in polymer testing.

1. Introduction

Polymeric materials offer significant properties, such as low weight, high durability and easy processing [1,2]. They have wide applications in daily life, industry and cutting-edge research [3–6]. Recently, many researches have been conducted to characterize polymeric materials by their acoustic properties. Zhao et al. found that the inverse ultrasound velocity has a linear relationship with the degree of crystallinity [7]. He et al. characterized the orientation of HDPE/PP blends by the ultrasound velocity of shear waves [8]. Carson et al. employed the attenuation of ultrasonic waves to calculate the grain size of microstructure [9]. Zhang et al. reported that ultrasound velocity was able to characterize ductile damage in polyethylene plate [10]. Michaeli investigated injection molding process via ultrasonic parameters [11]. Therefore, the measurement of ultrasonic parameters, including ultrasound velocity and attenuation coefficient, has garnered significant attention. While the current calculation methods of ultrasonic parameters are mainly based on the amplitude of the acoustic wave and the time difference between wave crests [7,10,12–14], they scarcely make full use of data in the acoustic wave, and the calculation results are easily affected by fluctuations in experiments. Thus, an ultrasonic measurement method that has high-accuracy, simple to use and can make full use of all available data would have broad application in non-destructive characterization of polymeric materials.

The ultrasonic spectrum is obtained by Fourier transformation of a time domain waveform. It makes the most of data in an acoustic wave and is closely related to the ultrasonic parameters. The ultrasonic spectrum is widely used in defect detection [15], thickness measurement of co-injection molding products [16] and thin film [17], roughness and micro-structure characterization [18,19], and performance evaluation [20–23]. However, to our best knowledge, the ultrasonic spectrum has not been used to integrally measure the ultrasonic parameters, including ultrasonic velocity and attenuation coefficient, for polymeric materials.

In this study, a novel integrated measurement method for measuring the ultrasonic parameters of polymeric materials via full spectrum analysis (UFSA) is proposed. Only the density of the polymeric material is known. Reflected signals from the upper and lower surfaces of the polymeric material are connected by a frequency dependent transfer function, which is related to the ultrasonic parameters of the polymeric

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https://doi.org/10.1016/j.polymertesting.2018.08.003
Received 24 June 2018; Accepted 1 August 2018
Available online 02 August 2018

material. The logarithm of the transfer function can be well approximated by a linear function. The ultrasound velocity and attenuation coefficient of the polymeric material can be calculated by the vertical intercept and slope of the fitting line, respectively. Then, the thickness can be calculated by the ultrasound velocity and propagation time. Experiments with various polymeric materials of different stiffnesses and dimensions, as well as several influencing factors were carried out to verify the proposed UFSA method. Experimental results demonstrated that the UFSA method can be used to measure and characterize stiff polymers (i.e., polymethyl methacrylate) and flexible materials (i.e., polydimethylsiloxane). Conventional methods for measuring ultrasound velocity and attenuation coefficient need to treat thickness as a prior parameter. However, due to geometrical limitations and potential shrinkage, the thickness of the polymeric material is difficult to measure accurately, especially for flexible materials, which may cause errors in the ultrasonic parameters measurement [7]. Since flexible materials are widely used in biomedical engineering, the UFSA method can be exploited for many potential applications, such as material characterization for flexible microrobots and microfluidic chips. The proposed method offers high-accuracy, portability and simplicity-of-use. In summary, it has extensive application prospects for the on-line measurement of polymeric materials.

2. Experimental methods

2.1. Ultrasonic measurement device

The ultrasonic device for measuring polymeric materials is shown in Fig. 1. A polymeric part was placed on an aluminum block. The ultrasonic signal was generated by a signal generator (CTS-8077PR, Shantou Goworld Co., China). A longitudinal wave pulsing/receiving ultrasonic transducer with 2.5 MHz central frequency (Guangzhou Doppler Electronic Technologies Co., Ltd, China) was selected in pulse-echo mode. A digital oscilloscope (DS0X2002A, Agilent Technologies Inc, USA) was employed to acquire the ultrasonic data. The study used an ultrasonic water immersion method. The longitudinal ultrasonic waves were generated by the transducer, and they propagated into the polymeric material. One portion of the ultrasonic signals were reflected from the surface of the polymeric material, and they were received by the digital oscilloscope.

2.2. Measurement theory

The schematic representation of the ultrasonic detection is shown in Fig. 2.

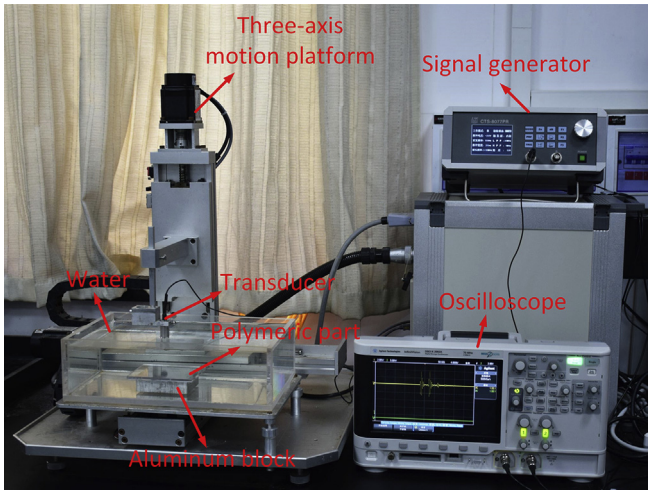

Fig. 1. Photograph of the ultrasonic measurement device.

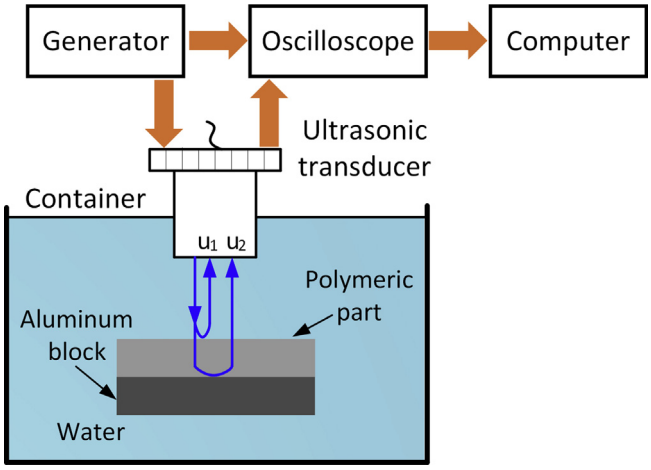

Fig. 2. Ultrasonic measurement model diagram.

As shown in Fig. 2, when an ultrasonic longitudinal wave propagates in the polymeric material, the ultrasonic signals will reflect from the top polymer/water interface ($u_1(t)$) and bottom polymer/aluminum interface ($u_2(t)$). The reflected signals are connected by a transfer function, as shown in Eq. (1).

$$H(f) = \frac{U_2(f)}{U_1(f)} \tag{1}$$

In Eq. (1), $H(f)$ is the transfer function of the polymeric material. $U_1(f) = |FT\ (u_1(t))|$ is the amplitude spectrum of the ultrasonic signal $u_1(t)$. FT represents the Fourier transformation. Considering the phenomena of reflection, transmission and attenuation that occur during the ultrasonic propagation, the transfer function can be calculated by Eqs. (2) and (3) [16,24].

$$H(f) = Ke^{-2md\alpha\left(\frac{f}{f_c}\right)^n - j(\phi_1(f) - \phi_2(f))} \tag{2}$$

$$K = \frac{R_1 T_0 T_0'}{R_0} = \left|\frac{4Z_0 Z_1 (Z_2 - Z_1)}{(Z_2 + Z_1)(Z_1^2 - Z_0^2)}\right| \tag{3}$$

In Eq. (2), d is the thickness of the polymeric material, α is the attenuation coefficient and n is the power of the attenuation slope. The unit of attenuation coefficient in Neper per centimeter (Np/cm) can be converted to decibel per centimeter (dB/cm) by dividing with m ($m = 0.115$). f_c is the central frequency of the transducer, j represents the imaginary unit, and $\Phi_1(f)$ denotes the phase spectra of $u_1(t)$. In Eq. (3), K is a proportionality coefficient determined by the reflection coefficient and the transmission coefficient. R_0 and R_1 represent the reflection coefficients from the top polymer/water interface and the bottom polymer/aluminum interface, respectively. T_0 and T'_0 are the transmission coefficients through the top polymer/water interface in direct propagation direction and opposite direction, respectively. $Z_1 = \rho_1 \times c_1$ represents the acoustic impedance of the polymeric material, where ρ_1 and c_1 are the density and ultrasound velocity of the polymeric material. Z_0 and Z_2 are the acoustic impedances of the water and aluminum block, respectively, where $Z_0 = 1.473 \times 10^6$ Pa s/m and $Z_2 = 1.776 \times 10^7$ Pa s/m. Thus, the coefficient K is a function of the density (ρ_1) and ultrasound velocity (c_1) of the polymeric material. The modulus and logarithm of $H(f)$ were calculated as shown in Eq. (4).

$$\ln(|H(f)|) = ln(K) - 2md\alpha\left(\frac{f}{f_c}\right)^n \tag{4}$$

The relationship between $ln\ (|H(f)|)$ and f is a polynomial function. For many bio-tissues and polymers, $n \approx 1$ [24–29]. The curve that $ln\ (|H(f)|)$ varies with f can be obtained by the reflected signals and Eq. (1). Through data fitting, the following equation can be obtained: