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Application of the through transmission ultrasonic technique for estimation of the phase velocity dispersion in plastic materials

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Abstract

In many industrial applications through transmission ultrasonic measurements are widely used because they enable to perform characterization and long term monitoring of material properties. The waveform of the signal transmitted through the plastic object usually is distorted due to different factors, such as frequency dependent attenuation, phase velocity dispersion, diffraction, geometry of boundaries and etc. In order to increase the accuracy of ultrasonic measurements it is necessary to take into account these factors.

A few techniques have been applied in order to estimate the phase velocity dispersion in a planar PVDF plastic sample: estimation using the narrowband filtering and estimation from the phase spectra. Both of them gave similar results with a reasonable for practical applications accuracy.

Keywords: attenuation, phase velocity dispersion, through transmission, waveform prediction, narrowband filtering.

Introduction

Ultrasonic pulse echo or through transmission measurements are used for a quality control of products in various areas of industry. This technique is sufficiently fast to enable monitoring deviations of thickness or ultrasound velocity under industrial conditions. The estimation of appropriate thickness or ultrasound velocity values is based on measurement of the time of flight of an ultrasonic signal in the test sample. In this case propagation time and distortion of the received signal waveform includes information about measurement object and its internal structure. The delay time estimation is one of the most essential procedures in ultrasonic through transmission measurements. In the case when transmitting and receiving transducers are placed in water tank, two signals are being exploited: the signal transmitted only through water and the signal transmitted through the immersed test sample which has been placed between transducers. The time interval between these two signals is the physical quantity necessary to measure [1-9].

There are many methods used for estimation of this time interval, but the most reliable and accurate are methods based on calculation of a cross-correlation function between these two signals. The signal transmitted only through the water usually is used as a reference signal in the cross-correlation analysis. Such an approach may be imagined as a search in the time domain of another signal, which is very similar to the reference signal. The instant of the best correlation in the time domain corresponds to the instance of the arrival time of the second signal. The main problem, which is met in implementation of this approach, is that the accuracy of this technique depends on a degree of similarity of these two signals. However, the highly attenuating plastic materials, like polyvinylidene fluoride (PVDF), posses a high frequency dependent attenuation and phase velocity dispersion of ultrasonic waves [1-9].

The waveform of the signal transmitted through the plastic object usually is distorted due to different factors, such as the frequency dependent attenuation, phase velocity dispersion, diffraction, geometry of boundaries and etc. Selecting optimal parameters of ultrasonic transducers and measurement distance enable to reduce the influence of some of them, however the distortions caused by attenuation and phase velocity dispersion of ultrasonic waves always exist. In order to increase the accuracy of ultrasonic measurements it is necessary to take into account these factors [1-9].

The objective of the presented research is to estimate the phase velocity dispersion of the bulk waves in a highly attenuating planar PVDF plastic sample.

2. Experimental set-up

In the case when a broadband ultrasonic signal passes through a medium of the plastic sample, the pulse waveform changes as a result of the frequency dependent attenuation and the phase velocity dispersion. In most cases the output signal is a convolution of the input signal and the complex transfer function of the object being tested. The class of the plastics have been observed to have an attenuation function that increases with a frequency. As a result, higher frequency components of the pulse are attenuated more than lower frequency components, therefore the shape of the pulse becomes distorted. The effect of the phase velocity dispersion causes the propagating pulse waveform to change because wave components with different frequencies travel at different speeds [4-7].

For investigation of the ultrasonic waves propagation through highly attenuating plastics, the through transmission ultrasonic technique was used [4, 5]. In Fig. 1 the simplified drawing of the experimental set-up for through transmission measurements of material properties is shown. Two ultrasonic transducers are placed in a water tank and aligned properly. The transmitting ultrasonic transducer was driven by a generator and the receiving ultrasonic transducer was connected to the digital oscilloscope HP54645A. The measurement data have been transferred to a computer via IEE 488 interface for the further processing.

For a specially prepared planar PVDF plastic specimen with a thickness of x=4.35 mm, two measurements were performed: one only through a water path and another one through the specimen inserted between two transducers having 1 MHz central frequency and 15 mm diameters (Fig. 1). The distance between transducers was d=52 mm. The plastic specimen was carefully aligned parallely to the surface of the transducers by maximizing the amplitude of the transmitted pulse. This method directly measures changes in a phase velocity. Two pulses were recorded, without the specimen and with the specimen inserted between the transducers. Ten measurements were carried out and averaged.

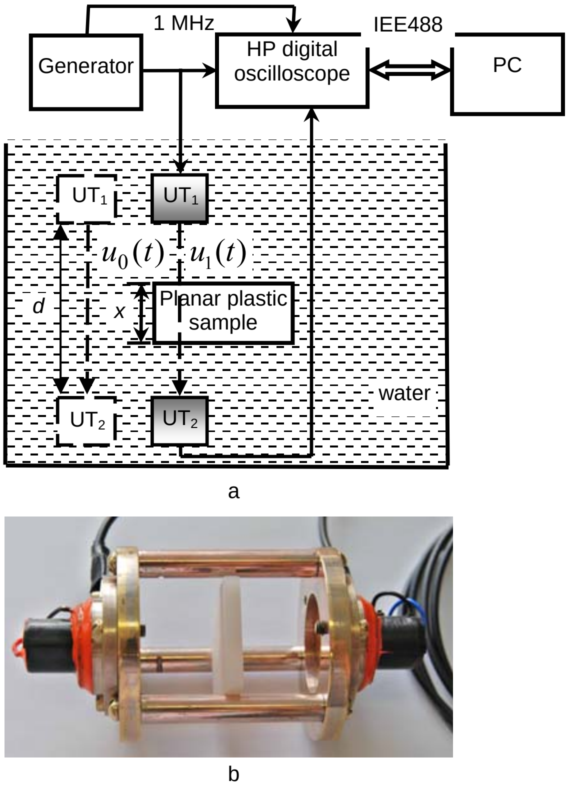

Fig.1. **Experimental set-up: a - principle of the through transmission investigation, measurement without sample and measurement in the case when the test sample is placed between ultrasonic transducers (UT$_1$ and UT$_2$), b – photo of the ultrasonic transducers and the test sample which were used for investigation**

Transmission losses due to mismatch of the acoustic impedances in water-specimen-water interfaces are given by:

$$\frac{1}{T_0}=\frac{A_0}{A_1}=\frac{(z_s+z_w)^2}{4\cdot z_s\cdot z_w}, \tag{1}$$

where A_0 is the amplitude of the signal transmitted only through water (without plastic sample), A_1 is the amplitude of the signal transmitted through the plastic sample which was placed between transducers, Z_s is the acoustic impedance of the plastic sample, Z_w is the acoustic impedance of the water, T_0 is the transmission coefficient (T_0=0.81). The assumption was made that the transmission coefficient is frequency independent. During analysis, influence of the ultrasonic wave attenuation in water was neglected.

The received ultrasonic signals and the calculated appropriate amplitude spectra are presented in Fig. 2.

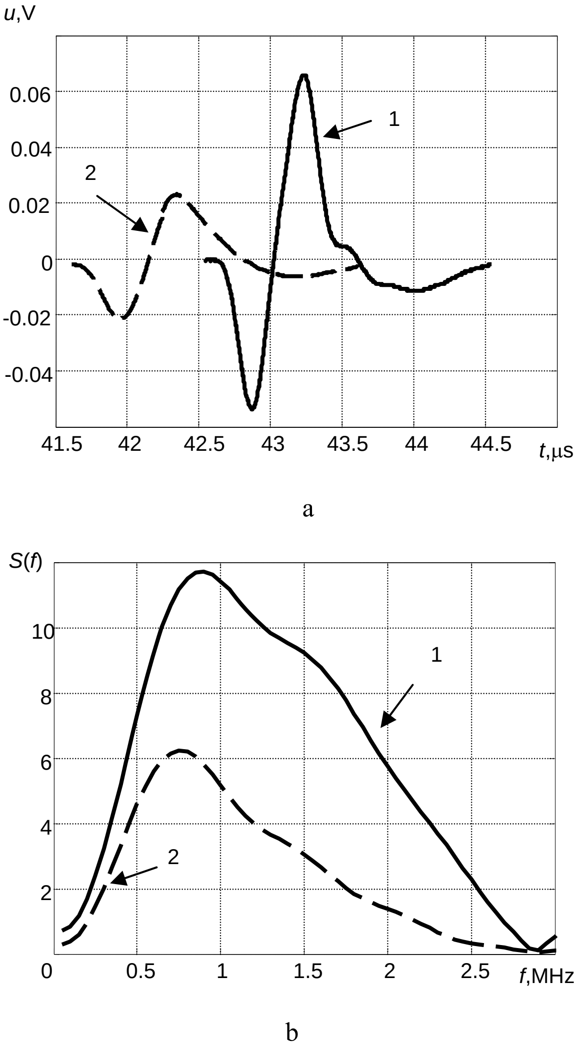

Fig. 2. **Received ultrasonic signals: a – received waveforms in the time domain, b – spectra of the received signals, 1 - reference signal $u_0(t)$ transmitted only through the water medium, 2 - signal $u_1(t)$ transmitted through the water-PVDF plastic sample-water medium.**

In the case of the signals, received in the through transmission set-up, the correction of the diffraction was performed by [8, 9]:

$$D_L=1-e^{-j(2\pi/s)}[J_0(2\pi/s)+jJ_1(2\pi/s)], \tag{2}$$

where s is a the Fresnel parameter for diffraction determination. Values of the Fresnel parameters in the case of the through transmission experimental set-up are given by [8, 9]:

$$s_w=\frac{d\cdot c_w}{f\cdot a^2},\ s_s=\frac{(d-x)\cdot c_w}{f\cdot a^2}+\frac{x\cdot v_p(f)}{f\cdot a^2}. \tag{3}$$

where d is the distance between the transducers, a is the transducer radius, x is the thickness of the sample, c_w is the ultrasound velocity in water (c_w=1468 m/s at t=15.5°C ±0.1 °C), $v_p(f)$ is the experimentally determined (using Eq. 4) phase velocity dispersion from the spectra of the measured signals. The results of the diffraction correction for both transmitted pulses are presented in Fig.3.

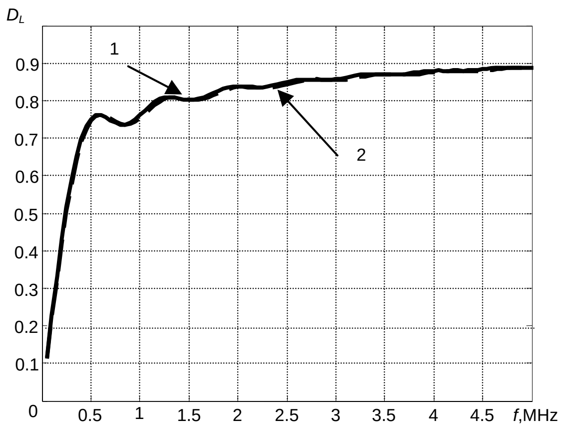

Fig. 3. **Diffraction corrections for the transmitted signals: 1 - signal transmitted through the water, 2 - signal transmitted through the immersed plastic sample.**

Estimation of phase velocity dispersion

There are a few techniques for estimation of phase velocity dispersion from the measured signals. The first technique is based on the difference between phase spectra [4, 6]:

$$v_p(f) = \frac{x}{\frac{x}{c_w} - \Delta t_w + \frac{\phi_0(f) - \phi_1(f)}{2 \cdot \pi \cdot f}}, \tag{4}$$

where x is the wall thickness of the specimen, Φ_0 is the phase spectra of the ultrasonic signal transmitted only through water, Φ_1 is the phase spectra of the ultrasonic signal transmitted through water and the plastic specimen inserted between the two transducers, Δt_w is time difference between sampling windows of the transmitted signals $u_0(t)$ and $u_1(t)$. The both signals in the sampling windows were circularly shifted to the left to avoid $2\pi n$ phase ambiguity due to the initial delay. The estimated phase velocity dispersion is presented in Fig. 4. The measured phase velocity at the frequency f=1.45 MHz was v_p= 2131 m/s ±4 m/s.

Another technique for phase velocity estimation is based on the spectrum decomposition technique. In the spectrum decomposition technique using a bank of the Gaussian filters the broadband back-surface pulse was decomposed into narrowband components. The phase velocity was estimated by comparing the time of flight of the appropriate filtered pulses with and without the specimen inserted between the transmitting and the receiving transducers. When the bandwidth of each component is narrow enough, the relative time delay of the filtered pulse at the specific value of the phase velocity can be evaluated [7].

The parameter of the filter narrowband is given by:

$$B < \sqrt{\frac{2 f_0 \delta}{\beta x}}. \tag{5}$$

The assumed value of the threshold is δ=5%, $\beta = \frac{\alpha_0}{f_0^{\,n}}$, B<0.29 MHz, the parameter B selected to be B=0.05 MHz, x is a thickness of the test sample. The frequency range of the informative signal spectra is given by: f_H=3 MHz, f_L=0.1MHz; $k \geq 1 + \frac{f_H - f_L}{B}$, k>=59.

The amplitude spectra of the i-th narrowband filter is given by [7]:

$$S_i(f) = \frac{1}{\sqrt{\pi}} e^{-\left(\frac{f - f_L - (i-1)\cdot B}{B}\right)^2}, i = 1..k. \tag{6}$$

Based on this frequency range, 59 band pass filters were used to decompose spectra of the informative and the reference signals into its narrowband components (Fig.2 b). The time difference between narrowband components of these two signals, after the inverse Fourier transform, corresponds to the phase velocity value at the particular frequency.

The cross-correlation function $y_{cc,m}(t)$ between the i-th filtered signal $u_{0,i}(t)$ transmitted through water and the i-th filtered signal $u_{1,i}(t)$ transmitted through the immersed sample is given by [7]:

$$y_{cc,m}(t) = \frac{1}{T}\int_0^T u_{0,i}(t) \cdot u_{1,i}(t-\tau)dt, \; i = 1..k, \tag{7}$$

$$u_{0,i}(t) = \mathrm{IFT}\left[\mathrm{FT}(u_0(t)) \cdot S_i(f)\right],$$

$$u_{1,i}(t) = \mathrm{IFT}\left[\mathrm{FT}(u_1(t)) \cdot S_i(f)\right],$$

where τ is the time delay between signals $u_{0,i}(t)$ and $u_{1,i}(t)$, T is the duration of the analysed signals, m=k-1.

Determination of the cross-correlation function $\hat{t}_{cc,m}$ maximum, which corresponds to the time delay between the filtered signals $u_{0,i}(t)$ and $u_{1,i}(t)$ is performed by [7]:

$$\hat{t}_{cc,m} = \arg\left\{\max\left[y_{cc,m}(t)\right]\right\} + \Delta t_w, \tag{8}$$

where Δt_w is the time delay between the sampling windows of the signals $u_0(t)$ and $u_1(t)$.

The phase velocity at the m-th central frequency of the i-th narrowband filter is given by [7]:

$$v_{ph,m} = \frac{x}{\hat{t}_{cc,m}}. \tag{9}$$

The estimated phase velocity dispersion is presented in Fig.4. The measured phase velocity value at the frequency f=1.45 MHz was v_p= 2130 m/s ±4 m/s.

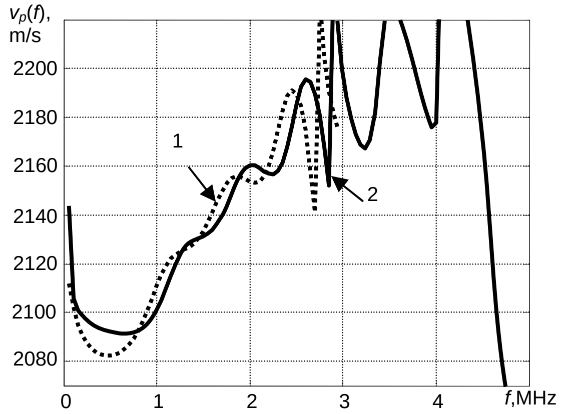

Fig. 4. **Phase velocity dispersion in PVDF planar plastic material: 1 - calculated using the narrowband filtering technique, 2 - calculated from phase spectra difference between the measured signals.**

The accuracy and reliability of the proposed techniques was tested by comparing the predicted waveforms with the experimentally measured. Prediction of the appropriate waveforms has been performed using the technique presented in our previous study [8, 9]. The frequency dependent attenuation after correction of the diffraction effects and phase velocity dispersion have been taken into account during the waveform prediction.

The waveforms of the experimentally measured and predicted signals are presented in Fig. 5.

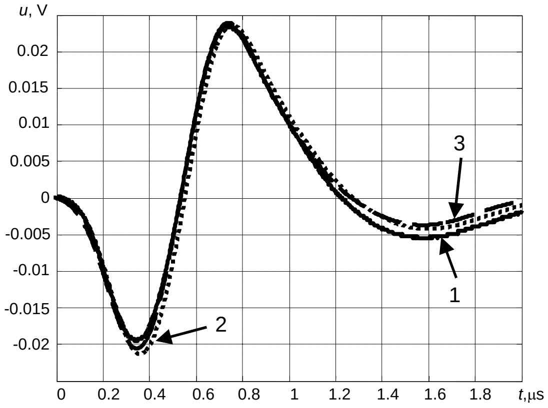

Fig. 5. **Ultrasonic pulse transmitted through planar PVDF sample: 1- experimentally measured, 2- predicted: phase velocity dispersion calculated using the narrowband filtering technique, 3 – predicted: phase velocity dispersion calculated from the phase spectra difference of the measured signals**

The predicted waveforms are quite similar to the waveform of the measured signal. The calculated correlation coefficient between the measured and predicted waveforms taking into account phase velocity dispersion calculated by narrowband filtering technique is 0.995. The calculated correlation coefficient between the measured and predicted waveforms taking into account phase velocity dispersion calculated from the difference of phase spectra is 0.997.

Conclusions

In order to increases the accuracy of ultrasonic measurements in the case of investigation of the highly attenuating plastic materials it is necessary to take into account distortions of the transmitted signals due to attenuation and phase velocity dispersion. In our previous study [8, 9] we have proposed that the inverse solution of the material properties identification is based on the waveform reconstruction. The most close shape of the predicted waveform to the experimentally measured corresponds to the optimum set of the approximation parameters of the transfer function of the appropriate group materials, like PVDF plastics. Such transfer function includes information about attenuation and phase velocity dispersion. A few techniques have been applied in order to estimate the phase velocity dispersion in the planar PVDF plastic sample: estimation using the narrowband filtering and estimation from the phase spectra.

Application of the narrowband filtering gives results with a good agreement to the results obtained using the technique of the phase velocity dispersion estimation from phase spectra. The obtained difference is close to 1 m/s and is negligible.

The calculated correlation coefficient between the measured and predicted waveforms taking into account phase velocity dispersion calculated by the narrowband filtering technique is 0.995. The calculated correlation coefficient between the measured and predicted waveforms taking into account the phase velocity dispersion calculated from the difference of phase spectra is 0.997. The presented results illustrate that the proposed approach of the phase velocity dispersion estimation enables to predict waveforms of ultrasonic signals in highly attenuating materials like plastics (PVDF) with a reasonable for practical applications accuracy.

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Tiesioginio perėjimo ultragarsinis metodas fazinio greičio dispersijai nustatyti plastikiniuose objektuose

Reziumė

Gamyboje tiesioginio perėjimo ultragarsinis metodas taikomas siekiant nustatyti ir stebėti tiriamosios medžiagos savybes. Ultragarsinio signalo, perėjusio ultragarso bangas stipriai slopinantį plastikinį objektą, forma iškraipoma veikiant šiems veiksniams: nuo dažnio priklausančios absorbcijos, fazinio greičio dispersijos, difrakcijos, tiriamojo bandinio geometrinių formų. Siekiant padidinti ultragarsinių matavimų tikslumą šiuos veiksnius būtina įvertinti.

Fazinio greičio dispersijai plokščiame PVDF plastiko bandinyje nustatyti buvo pasiūlyti keli būdai: siaurajuosčio filtravimo ir fazių spektrų skirtumo. Abu būdai leido gauti panašius ir gana tikslius taikyti praktikoje rezultatus.

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