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Sound velocity measurement using transfer function method

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Abstract

The transfer function of a piezoelectric transducer, buffer rod and sample assembly is used to measure the sound velocity of solid materials. From the recorded transfer function, pulse echo patterns at frequencies of the passband of the input signal are reproduced after convoluting with monochromatic RF input signals. The time delay is obtained by performing pulse echo overlap and phase comparison measurements on reproduced signals. Results for a single crystal of MgO along the [100] direction from this study are in good agreement with previous measurements but have the advantage of offline data analysis and fast data acquisition.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The ultrasonic technique is an important tool for the study of elastic and rheological properties of materials. It is widely used in physics, medical science, bioscience, Earth science, and non-destructive testing/evaluation. For many years different methods have been developed for the measurement of time propagation, such as pulse echo overlap (PEO), phase comparison, and pulse superposition [1, 2]. In these methods, a RF tone burst pulse is transmitted and received by a piezoelectric transducer attached to the sample or a buffer rod, and the propagation time is obtained by measuring the delay between two consecutive echoes. Typical precision of these measurements is 10^{-6}.

Recently, the development of fast A/D acquisition cards has made it possible to use methods based on digital signal processing, such as the cross-correlation function (CCF) [3], Hilbert transform (HT) [3], and continuous wavelet transform (CWT) [4] in contrast to classical pulse overlapping or phase comparison methods. In this paper, we measured sound velocities of a single crystal of MgO using transfer function method. The transfer function reflects the

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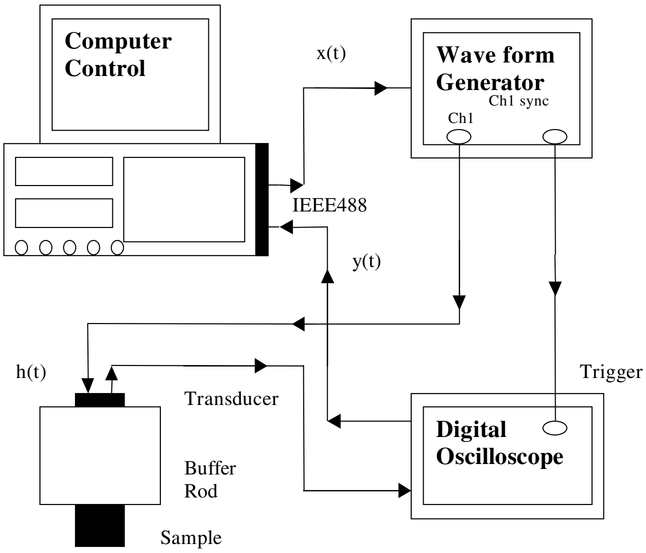

Figure 1. Flow chart of the ultrasonic velocity measurement set-up. A low frequency pulse generator is used to trigger the waveform generator.

response of the system as a function of frequency (e.g., piezoelectric transducers) [4]. In this paper, we use the recorded transfer function to reproduce real-time signals and then PEO and pulse comparison measurements can be simulated offline. Experimental results obtained from this method are compared with those collected in real time using the phase comparison method.

2. Experimental procedure

The experimental set-up uses a waveform generator and a digital oscilloscope connected to a personal computer through IEEE488 (figure 1). A lithium niobate transducer (10° Y-cut, dual-mode excitation at 50 MHz for P wave and 30 MHz for S wave) is mounted on a tungsten carbide buffer rod and the sample is attached to the buffer rod using glycerin and phthalic anhydride (molar ratio 1:1) mixture. A sinc function ($\sin x/x$) is sent to the buffer rod and sample. The input sinc signal $x(t)$ has a centre frequency around the transducer resonance frequency and the bandwidth is set by specifying a frequency passband to cover the frequency range of the transducer response.

The received signal $y(t)$ is a result of the convolution of the input signal and the system response along the wave propagation path, i.e.,

$$y(t) = x(t)^{*}h(t)$$

where $x(t)$ is the input signal, $y(t)$ is the received signal and $h(t)$ is the system response. FFT of the above equation yields

$$Y(f) = X(f)H(f).$$

Since the Fourier transform of the sinc function $X(f)$ is unity, $H(f) = Y(f)$, i.e., in the frequency domain, the received signal is identical to the transfer function of the assembled piezoelectric transducer, buffer rod and sample. Consequently, the response of this assembly to an input pulse with frequencies inside the passband of the sinc signal can be reproduced by convoluting the transfer function with the FFT of the input pulse. The transfer function

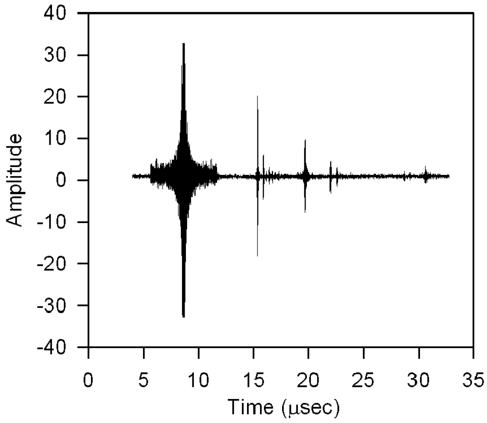

Figure 2. Received signals for a MgO single crystal, [100], on a tungsten carbide buffer rod.

records the system response to all frequencies of the passband at the same time in contrast to sweeping through frequencies in PEO and phase comparison methods which is especially important when travel time is used to study rheological properties of materials. Recording the transfer function takes a few seconds which is about one to two orders of magnitude less than what is needed for sweeping through the same frequency range in PEO and phase comparison methods.

3. Simulation of PEO and phase comparison

We have measured P- and S-wave time delays on a single crystal of MgO along the [100] direction (2.463 mm long). The centre frequency of the input signal was set at 50 MHz with a bandwidth of 50 MHz to cover the transducer response for P and S waves (25–75 MHz). The duration of the received signals is 50 μs (100 000 data points) shown in figure 2. To simulate PEO for phase velocity measurement, a 50 MHz sine wave tone burst is used to convolute with transfer function and an echo pattern corresponding to a monochromatic 50 MHz input signal is reproduced to ensure that such an input signal is reproduced (figure 3). The inset in figure 3 shows an expanded view of the buffer rod echo and the first sample echo from which PEO measurement can be obtained.

We also demonstrated phase comparison measurements using a small polycrystalline sample of diopside ($CaMgSi_2O_6$) (2 mm diameter and 0.87 mm thick). Following the same procedure as described above, the echo pattern for a 50 MHz (5 cycles in duration) sine wave input signal is reproduced. The time delay is measured by shifting the second copy of the echo pattern relative to the original one till the buffer rod echo and sample echo overlap (figure 4, top panel). The bottom panel of figure 4 shows the interference of the original signal and the delayed one. A time window is selected to record the amplitudes of buffer rod, sample, and the interference of the two. While sweeping through the frequency range of the passband, the amplitude of the interference between the buffer rod and sample as a function of frequency is recorded. These data are equivalent to those recorded using the phase comparison method [2, 6]. In this method, the frequencies where in-phase and out-of-phase interference occur can be used to derive time delay [2, 6]. Briefly, time delay is related to the interference extrema as $t = p/f$, where f is the frequency of the interference extrema and p is an integer or half-integer depending on the impedance of the buffer rod and sample. Figure 5

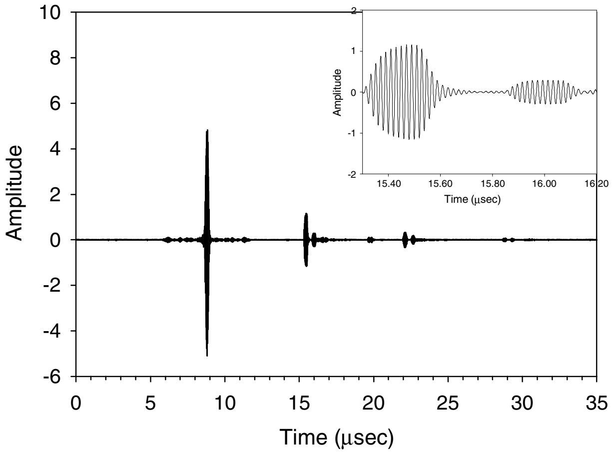

Figure 3. Echo series simulated by convoluting a 50 MHz tone burst with the transfer function for MgO [100] single crystal. The inset shows the details of the buffer rod and the centre frequency of the input signal was set at 50 MHz.

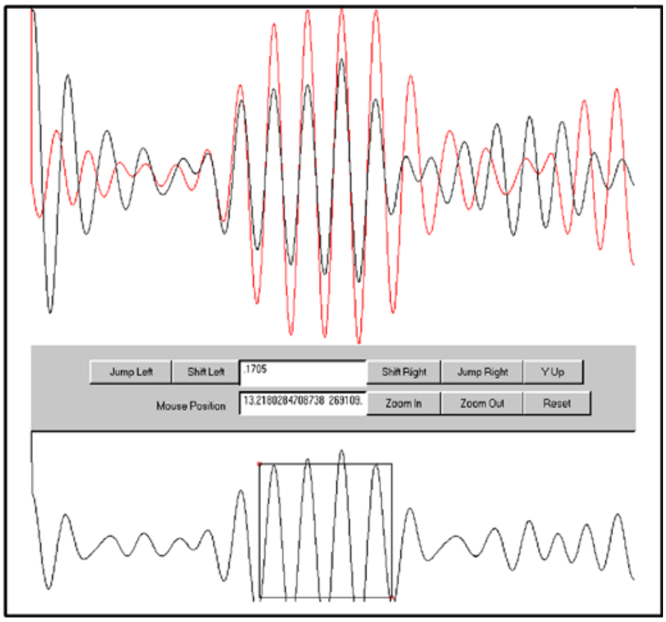

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Figure 4. Simulation of the PEO method (top) and the interference spectrum for the overlapped buffer rod and sample echoes (bottom). The amplitudes of the buffer rod, sample and the interference of the two in the selected window are recorded at all frequencies to simulate phase comparison measurement.

is a comparison of the interference pattern from the transfer function with data collected in real time using the acoustic interferometer from ANU Tech for the specimen set-up [6]. The separation of extrema in the interference pattern obtained using the transfer function is more coherent than the real-time signal, resulting in more consistent results for time delays at different frequencies.

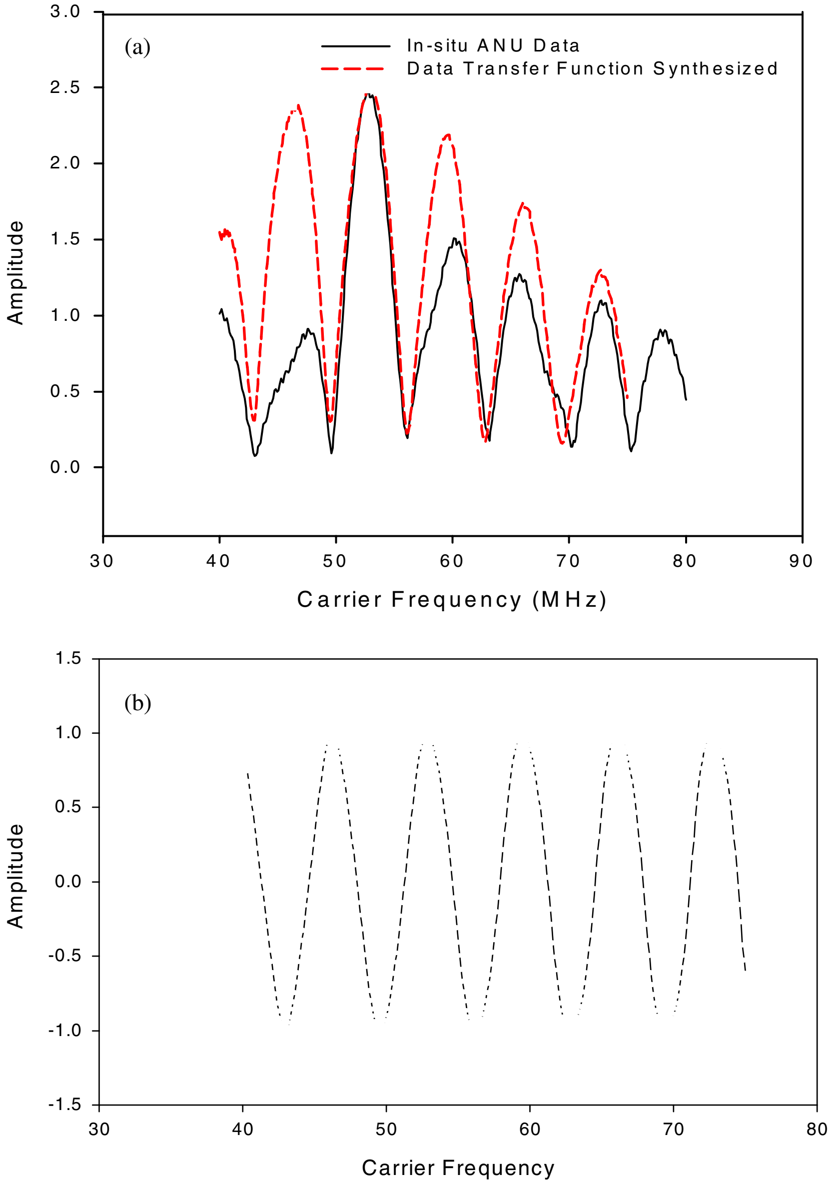

Figure 5. (a) Comparison of the interference pattern from the transfer function and the real-time signal. (b) Results of the interference pattern from the transfer function in (a).

Table 1. Comparison of velocities measured using transfer function and phase comparison methods for MgO [100] single crystal at 40 MHz.

Methods	P wave (km s^{-1})	S wave (km s^{-1})
Transfer function	9.18(5)	6.65(3)
Phase comparison	9.13(5)	6.65(3)

Precise determination of the extrema can be obtained by removing the envelope of the transducer response from the interference pattern using the amplitudes of the buffer rod, sample and their interference [7]. Figure 5(b) shows the results after the transducer response removal for the interference pattern in figure 5(a). Fitting to the spectrum in figure 5(b) with a sine function yields precise determination of the in-phase (amplitude 1) and out-of-phase (amplitude -1) interference. Using the transfer function, such simulations can be conducted multiple times for optimized time measurements through adjusting the data collection window and step size for sweeping frequency.

4. Conclusions

We have successfully implemented a transfer function method for sound wave velocity measurement. Real-time signals can be reproduced offline by convoluting with a RF pulse using the transfer function recorded during the experiment. Time delay can be measured using PEO and phase comparison methods in the frequency range of the input signal. Time delays from real-time measurements and those from the transfer function method are in excellent agreement for a single crystal of MgO. Compared with real-time measurements, this method reduces the data collection time from minutes to seconds. This will enable us to study time-dependent processes, such as phase transformation and deformation, by measuring time delay as a function of time. Since real-time signals are reproduced offline, time delay measurements can be optimized by adjusting the input signal duration, frequency and the overlap of the buffer rod and sample echoes. Moreover, this method records the response of the system in a continuous frequencies band at the same time, in contrast to sweeping frequencies as in the phase comparison method, which is especially important for studying time-dependent processes.

Acknowledgments

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