TIME AND FREQUENCY DOMAIN MEASUREMENTS OF MATERIALS WITH
HIGH ULTRASONIC ATTENUATION USING TIME DELAY SPECTROSCOPY

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INTRODUCTION

Time delay spectrometry (TDS) uses a swept frequency source and a tracking receiver in the place of a conventional pulse-echo system for ultrasonic measurements. This technique can directly provide a frequency domain display of amplitude and even phase. Since the signal is of longer duration than that of a pulse-echo system, a large amount of averaging is intrinsic with this method, making it ideally suited for the study of highly attenuating materials.

PRINCIPLES

The operation of TDS in the frequency domain has been treated elsewhere [1,2] and exemplary data shown on measuring attenuation [1] particularly of highly attenuating materials. With suitable processing, TDS can provide better time domain information than pulse-echo methods, with a great signal-to-noise improvement from compressing the long-duration signal.

The system in Figure 1 demonstrates both the time and the frequency domain operation of TDS in the single transducer [3] reflection mode. The transducer is energized by a source whose frequency is linearly swept in time. If the sound velocity does not vary appreciably over the frequency range swept, the reflected signals exhibit a linear frequency-vs-time trajectory that is offset from the corresponding trajectory of the transmitter by a frequency that is proportional to the time delay of propagation. If the linearly swept frequency is subtracted from the received signal (as by heterodyne and selecting the difference frequency), the result is a narrow band signal with frequency components that remain practically steady throughout the sweep. Each component represents the reflection of ultrasonic energy from interfaces at a particular range. These specific range components can be selected by further filtering.

The best performance of any heterodyne scheme is obtained when the amplitudes of the signals are appropriate. The hybrid coupler provides the proper levels by attenuating (but not eliminating) the signal from
the source and combining it with the received signal. An envelope
detector is one means for extracting the difference frequency signal
from this signal detector the desired band of ranges, represented by a
corresponding band of frequencies, is selected by a band-pass filter.

The difference-frequency signal, or TDS "I-F" signal, contains all
of the time and frequency domain information available at the transducer
from this band of ranges. This information can now be extracted with
similar signal processing methods and equipment, the normal roles of the
time and frequency domains being interchanged.

The magnitude of the frequency response is obtained by rectifying
this signal, the ultrasonic frequency being represented by the time from
the start of the sweep. The phase response can be obtained by phase
detection using a reference that is coherent with the sweep repetition
[4,5]. This differs from the conventional sweeping spectrum analyzer in
that signals with a specific range of time delays can be isolated. If
the bandwidth of the filter is relatively broad, the interference of the
returns from a set of interfaces can be displayed. A narrow filter
bandwidth allows individual interfaces to be isolated and
characterized. The versatility of TDS in this respect has been
demonstrated [2].

If signals from several interfaces were initially accepted by a
relatively wide filter bandwidth, they could be separated by yet another
filter. (Note that a narrower filter has a longer impulse responses,
which means that neighboring frequency responses will be averaged during
the sweep display: the fundamental time-frequency uncertainty
relationship still applies, as it must!)

The Fast Fourier Transform (FFT) analyzer shown in Fig. 1 performs
the ultimate of bandpass filtering, compressing all of the information
on the frequency dependence and producing a display of the received
energy (which is an estimate of the interface reflectivity) vs range.
This is equivalent to the conventional A-mode, with the signal-to-noise
ratio enhanced by a processing gain equal to the ratio of the duration
of the sweep to the duration of an impulse covering the same frequency
range.

The system used in this study is swept from 0 to 20MHz in 20ms.
The ratio of the duration of the sweep to the duration of a pulse (50ns)
of about 20MHz bandwidth is 400,000. Thus the TDS system provides the
same signal-to-noise as averaging 400,000 pulse-echo signals of the same
excitation amplitude, but does it in only 20ms! Since the bandwidth of
the heterodyne signal is small (typically 1kHz to 100kHz, depending on
the sweep rate and the range window to be covered), conventional FFT
analyzers designed for audio frequency and underwater sound appli-
cations, which have high resolution digitizers, can be used. As will be
explained later, by choosing the appropriate FFT output, the "R-F"
waveform, its Hilbert transform, the magnitude of this complex pair
(which is the analytic signal magnitude), the phase of the signal, or
even the conventional rectified A-mode signal can be obtained.

PROCEDURE

The merits of TDS for frequency domain characterization of
materials have been demonstrated elsewhere [1,2]. The capabilities of
TDS in time domain operation will be demonstrated using the multiple
arrival times from the reflection of ultrasound within a simple test
object, namely a 6mm thick glass plate. Experiments were conducted
using a TDS system slightly modified from that of Fig. 1, which,
Fig. 1. Reflection mode TDS system. a) Equipment diagram. b) Sweep trajectories. The displays are actual data.

Fig. 2. TDS frequency domain displays.
nevertheless demonstrates the same principles. The system differs in that two transducers were used in order to measure the transmitted signal. This type of operation is detailed elsewhere [2,5].

Figure 2. shows the TDS "I-F" signal. Fig. 2a is the log magnitude of this signal, which is a time record representing the spectral response of the specimen and transducers over the swept frequency range of 0 to 20 MHz. The expected half-wavelength resonances of the sample, spaced 476 kHz apart, are clearly evident. The 3-18 MHz portion of this signal is also shown in DISPLAY 1 of Fig. 1. Fig. 2b is the same signal before the log magnitude operation. This is the signal that is processed by the FFT analyzer. This signal contains all of the phase information needed to reconstruct the time domain signal: different times of arrival are represented by different modulation components and their interference produces the familiar cusps or fringes in the spectral display of Fig. 2A. The Fourier transform of the signal of Fig. 2B, which separates out the signal components representing different times of arrival, produces the familiar "A-mode" display. The FFT of the waveform of Fig. 2B is shown in DISPLAY 2 of Fig. 1. Here the decay of the signal at successive arrival times is clearly evident.

Most of the special features of commercial FFT analyzers can be used to good advantage in processing this signal. Interpretation will differ only in that the roles of time and frequency in the display labeling will have been reversed. Multiple decay processes can be analyzed using a logarithmic display (which converts an exponential decay to a straight line).

The first peak of the signal of DISPLAY 2 of Fig. 1, interpolated by appending zeroes ("zero-padding") to the signal of Fig. 2b, is shown in Fig. 3. Fig. 3a is the magnitude of the FFT, which is the magnitude of the time domain response. Figures 4b and 4c are the real and imaginary parts of the FFT. This pair represents the conventional R-F A-mode signal (which is an estimate of the impulse response of the transducers and the sample) and its Hilbert transform (or some orthogonal pair of linear combinations thereof, depending on the phase shifts in the system). The magnitude of a linear combination of these two signals would be equivalent to the "rectified" r-f of a conventional A-mode. (Changing the linear combination is equivalent to changing the phase shifts of the A-mode system.)

TDS allows recovery of time domain information since the phase of the signal is retained. (This is in contrast to the simple sweeping spectrum analyzer and most chirp type pulse compression systems which process only the power spectrum and can, at best, provide only the autocorrelation function of the target signature.)

If a single sweep direction is processed (that is, not both an up and a down chirp), the Fourier transform is being performed on a single-sided spectra, and the two parts of the complex result are the impulse response and its Hilbert transform, the doublet response [4]. Together these constitute the analytic signal [4,6] the magnitude of which provides superior time resolution [6]. This magnitude, demonstrated in DISPLAY 2 of Fig. 1, is obtained by simply using the magnitude output operation of commercial FFT analyzers.

Fig. 4 demonstrates the relationship between the analytic signal obtained from processing pulse-echo signals [5,6] and the results of Fourier transform processing a TDS signal [7], both of which are treated
Fig. 3. Time domain signals from Fourier transform of TDS "I-F" signal.

Fig. 4. Analytic signal processing with pulse-echo and TDS.
Heyser's notation [4,7] is used except for: h, H, u, and U. Time domain forms are denoted by lower case letters and the corresponding frequency domain forms by upper case. w(t) denotes the excitation signal (either impulse or chirp). s(t) is the impulse response of the system (transducers and sample) under test. h(t) = 1/t is the Hilbert transform kernel, whose Fourier transform is \( H(f) = i \text{sgn}(f) \). U(f) is the unit step: unity for positive and zero f, and is zero for negative f. Double lines denote complex data or quadrature channels.

The conventional pulse-echo system uses an impulse excitation for \( w(t) \) and provides an approximation to the impulse response directly. (The approximation is due to the convolution of the desired system response with the often poor approximation to an impulse provided by the pulser, in addition to non-linear considerations of the transducer at high excitation levels.)

The doublet response can be obtained by direct convolution with \( 1/t \), or by a Fourier transform, multiplication by \( i \text{sgn}(f) \), and an inverse Fourier transform. Both the doublet and the impulse response are provided in the complex arrays of the Fourier transform if, instead of multiplying by \( i \text{sgn}(f) \), the negative frequency components are simply set to zero. The inverse Fourier transform of this single-sided spectrum produces the analytic signal [4,5,6,8,9].

This single-sided spectrum is already provided by a TDS system if a sweep in only one direction (i.e., an up-chirp or a down-chirp) is processed. The signal at the receiving transducer is the single-sided spectrum modulated by the excitation signal (which is a constant amplitude, quadratic phase function). At the TDS I-F this modulation has been removed by multiplication with the complex conjugate of the sweep. (Generally the signal at this point is still modulated by some constant intermediate-frequency carrier which simplifies electronic processing but has no adverse impact on the mathematics.) The same single-sided spectrum that was used in the pulse-echo Hilbert transform processing is available here. (The frequency components are presented over the approximately 20ms of the sweep, so in a practical sense, the time and frequency domains are interchanged.)

Causality is never violated since the Hilbert transform is obtained by Fourier transforming the signal after the complete record is obtained. Since the sweep only requires 20ms, and an FFT can be carried out in comparable time, the results can be displayed in near-real time (i.e. less than 100ms). An excellent discussion of the relation between the Hilbert Transform and causality is available in the review literature [9,9].

CONCLUSIONS

The ability of TDS to provide high quality time domain as well as frequency domain information with a large processing gain has been demonstrated. In the time domain the analytic signal is readily obtained.

The capabilities of this technique and its profound theoretical significance has been demonstrated for audio signals (especially for loudspeaker testing [4], by R. C. Heyser, who invented the technique [10]. Commercial TDS systems are available in the frequency ranges to 30KHz (Crown Electronics, 1718 W. Mishawaka Road, Elkhart, Indiana, 46517), and to 200 KHz (Bruel and Kjaer, Marlborough, Massachusetts,
(The mention of manufacturers is for information only, and does not imply endorsement by the author or his institution.)

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REFERENCES


