7-1980

Materials Characterization by Time Delay Spectrometry Ultrasound

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ABSTRACT

A technique known as Time Delay Spectrometry (TDS), which has been used at JPL for ultrasonic tissue characterization, has promise for similar application in materials characterization as well. This technique differs from the approaches based on pulse-echo techniques which are used by other workers.

Time Delay Spectrometry operates in the frequency domain directly. The transducer is excited by a rapidly swept frequency source and a tracking receiver is used to select signals arriving during a narrow time interval. In the reflection mode this time interval represents the range of the reflecting surface. In the transmission mode this time interval is adjusted to the desired acoustic delay, causing rejection of signals which follow extraneous paths. This swept frequency implementation makes coherent processing of the full analytic signal possible, which in turn allows more representative signatures to be obtained. In the reflection mode, for example, a better indication is obtained of the true strength of an interface or scatterer because the response can be made less dependent on the interference effects that so greatly alter the amplitude peaks of the conventional echo. This technique also permits an enhanced dynamic range to be obtained by applying frequency compensation directly to the transmitted signal. An added bonus is the ability to use data logging systems at rates commensurate with microprocessor operation in place of more expensive high speed transient recorders with limited memory capacity.

Attenuation spectra taken on tissue specimens and on a few material samples will be presented. These data will demonstrate the ability of Time Delay Spectrometry to either minimize reverberation artifacts or to make use of the information contained in the artifact.

INTRODUCTION

Time Delay Spectrometry* (TDS) is an anechoic ultrasonic measurement technique which operates in a domain that is intermediate between the time domain and the frequency domain. This technique has been used in many other fields and is a potential method for directly measuring a "materials signature".

Time Delay Spectrometry was originally developed for loudspeaker testing, where it allows an ordinary room to be used and yet achieves results superior to those obtained by other electronic techniques, even when they are aided by the use of an expensive anechoic chamber. (1,2) This technique was later applied to ultrasonic tissue characterization where it has been used to measure the ultrasonic attenuation coefficients, reflectivity, and velocity of biological specimens as a function of frequency. (2,3,4,5,6) Most recently it has been applied for imaging undersea sediments by ultrasonic reflection, with a resolution and discrimination superior to that of pulse-echo techniques. (7)

PRINCIPLES OF TDS

TDS consists of a swept source frequency and a tracking filter. The received signals arrive at the receiver with a time delay that depends on the pathlength and the propagation velocity. Since the transmitter frequency is swept, the time delay is equivalent to a frequency offset. Thus, by selecting an appropriate offset frequency and bandwidth for the tracking filter, an equivalent time interval is selected. For the case of a linear sweep, the discrimination of arrival times is related to the filter bandwidth by:

\[ \Delta T = \frac{B}{dF/dT} \]

(1)

Where \( \Delta T \) = Time Discrimination
\( B \) = Receiver Bandwidth
\( dF/dT \) = Sweep Rate, Hz/Sec.

This chirp technique is not pulse compression since the frequency information is preserved instead of being "collapsed" to provide improved time resolution.

The principles of operation of TDS are in one earlier paper (3) and equation (1) derived in another (1). The interchanges of the time and the frequency domains by TDS and the effect of applying a Fourier Transform to the TDS output or mixing the received signal with a coherent reference has been treated rigorously (4). The significance of processing the full analytic signal, as opposed to only one of the quadrature components, has been discussed. (2)

TDS is well suited for advanced signal processing. The large (around 200,000) time-bandwidth product permits significant signal to noise enhancement.

*Time Delay Spectrometry is an invention of Richard C. Heyser, U.S. Patent No. 3,466,652, assigned to the California Institute of Technology.
Fig. 1a. TDS instrumentation.

\[ \Delta T = \frac{B}{\left(\frac{dT}{d\omega}\right)} \]

Fig. 1b. TDS signals
A delayed reference is available for coherent detection of both quadrature components. This permits pulse compression for high time domain resolution, true measure of the received energy vs time which is not modulated at the ultrasonic frequency, and phase-of-arrival information for very precise velocity measurements.

A selected portion of the spectrum can be used to produce a raster scan of attenuation, velocity, or reflectivity.

**TDS TRANSMISSION MODE RESULTS**

An example of TDS capability is shown by the test object in Fig. 2, which produces multiple reflection and therefore has a continuous wave (c.w.) transmission spectrum that consists of maxima and minima as determined by the interference of these multiple reflections. The transmission spectrum of the object was measured using the TDS system shown in Fig. 1 with two extreme settings of the filter bandwidth. One of these settings produced results similar to the cw case whereas the other discriminates signals of differing arrival times. In both cases the system was swept from 0 to 10 MHz at the rate of 500 MHz/sec. The TDS transmission response with a bandwidth of 3,000 Hz which results in acceptance of signals arriving within a 7 μs time window is shown in Fig. 3. Since the aluminum-water interface is strongly reflecting and many such interfaces are present, appreciable energy is transmitted only at those frequencies where constructive interference of several such reflections occur. The TDS transmission response with the bandwidth reduced to 340 Hz, which reduced the width of the time acceptance window to 0.7 μs, is shown in Fig. 4. This enables successive arrivals of the ultrasonic energy to be distinguished, as can be seen along the 2 MHz cut in the spectra. The spectra with different time delays are displayed along the delay axis. Since only the energy which arrives within a time interval 0.7 μs wide is considered in producing the swept spectra, the interference of energy from successive reflections is eliminated. The slight remaining irregularly in the spectra (+1 dB) is probably due to complicated surface interactions. This improvement in the time resolution has resulted in a "smearing" of the frequency resolution, which is about 2 MHz in Fig. 4, in contrast to 0.2 MHz in Fig. 3.

TDS has been used extensively for biological tissue characterization at ultrasonic frequencies at the Jet Propulsion Laboratory as part of the biomedical program. A few examples of the results obtained are shown in Fig. 5 and Fig. 6. In both of these figures the attenuation was measured by a substitution technique: the spectrum of the ultrasonic energy through the water path between the transducers in the water tank was recorded with various calibrated electronic attenuators in the system. Typically, these calibration spectra are taken for 0, 5, 10, 40 dB attenuation. The specimen is inserted and the spectra again recorded. From this composite spectrum the attenuation can be interpolated to around 1 dB.

Figure 5 demonstrates the frequency range that can be covered by TDS. These data are the composite of several measurements, each over a frequency sweep of less than 10 MHz.

Figure 6 demonstrates measurements obtained on one specimen, human breast, which is of great biomedical interest. Good agreement was obtained with other published data (8). Research on a larger population of specimens must be conducted before this can be considered useful for medical diagnosis.

**REFLECTION MODE TDS**

Reflection signatures have also been obtained with TDS using both double and single transducer techniques.

Two transducer reflection measurements can readily be made with the system shown in Fig. 1 by placing the transducers on the same side of the sample. The range is selected by a change of the offset of the oscillator sweep and the width of the range window is selected by the filter bandwidth or by the sweep rate.

Single transducer measurements can be made using a heterodyne technique (9) as shown in Fig. 7. This consists of mixing the transmitted and received signals. If the frequency is swept linearly in time, the difference frequency is proportional to
Fig. 3. Spectral response of reverberant test object with nearly c.w. response (time acceptance window 6 µs.)

Fig. 4. Received energy vs frequency and arrival time for a reverberant object.
Fig. 5. Attenuation vs frequency for excised hog specimens (formalin fixed, 14 mm thick) over the frequency range 1.5 to 17.5 MHz.

Fig. 6. Ultrasonic attenuation vs frequency in breast tissue.
Fig. 7. Block diagram of system for single transducer reflection measurements.

Fig. 8. Reflection spectra from regions of flattened human aorta and from plane reflector with calibrated electronic attenuation.
the range of the reflector. Thus the desired range is selected by varying the receiver frequency and the width of the range gate by the receiver bandwidth.

Among the advantages of TDS for reflection mode measurements are that surface and interior reflections are readily separated and it produces a direct spectral display. TDS appears to have great promise for characterizing materials, internal flaws and distributed properties of materials could be characterized by TDS reflection spectra. Characterization of distributed material properties by ultrasonic backscatter has been treated elsewhere in the literature.

One application of TDS in the reflection mode is demonstrated in Fig. 8. The reference spectra are the reflected energy from a plane reflector with the receiver gain reduced by the indicated number of dB. These were obtained with a 10 MHz, 0.5-inch diameter transducer with a 3-inch focus. The reflectivity spectrum of a calcified region in an excised human aorta is shown to be around 5 dB below that of a plane reflector, whereas the reflectivity of a normal section of the same aorta is shown to be around 30 dB lower. Irregularity in the spectra is due to interference of reflections from the two walls (adventitial and intimal surfaces), which exists in all specimens studied. Calcium deposits cause further interference effects.

SUMMARY

Time Delay Spectrometry (TDS) consists of a swept frequency transmitted signal and a tracking receiver which is adjusted to receive only signals with the desired propagation time delay. TDS can be operated in either the transmission mode or in the reflection mode. It can produce time or frequency domain information that is equivalent to that of pulse-echo systems. In addition, it is especially suited to processing the full analytic signal, which provides a better measure of the arriving energy than does processing the real portion of the waveform alone as is usually carried out in pulse-echo systems. Other advantages are that it allows signal-to-noise enhancement through coherent processing, optimization of time or frequency resolution is straightforward and naturally apodized, and conversion between time and frequency domains is readily implemented by analog as well as by digital techniques.

Time Delay Spectrometry has several unique features. TDS can operate intermittently between the pure time domain and the pure frequency domain, providing optimal characteristics for otherwise difficult applications, such as loudspeaker evaluation in an actual room. Continuous adjustment is possible, giving time domain response at one extreme and frequency domain response at the other. The time domain sampling is apodized by the smooth receiver passband, rather than being abruptly chopped off by a gate. After the time and frequency domains are interchanged by TDS, the time window is selected by a tracking filter. The apodization is produced by the roll-off characteristics of this filter. A slower data rate aids digital sampling since the data rate is determined by the sweep rate, rather than by the speed of sound and frequency alone. If the velocity dispersion is known, compensation can be effected by dynamically programming the sweep offsets. Pre-whitening the transmitted signal to improve the dynamic range at the receiver is practical.

ACKNOWLEDGEMENTS

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS7-100, sponsored by the National Aeronautics and Space Administration.

The authors wish to thank David H. Blankenhorn, M.D., Chief of Cardiology at the University of Southern California-Los Angeles County Hospital, for the preparation and use of the aorta specimen.

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