

PULSE ECHO TECHNIQUE TO DETERMINE BONDLINE REFLECTION COEFFICIENTS

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INTRODUCTION

Using reflection coefficients to obtain bond strengths and other bondline characteristics has been proposed by previous researchers(1,2). For configurations where the bondline of interest is well separated from the specimen surface and adjacent boundaries, measuring the reflection coefficient using broadband, pulse-echo, ultrasound can be done by processing the bondline echo taken directly from the A-scan. For configurations where the bondline is close to a parallel surface however, reverberations in the layer between the bondline and surface will cause successive bondline echoes to overlap in the A-scan, so that individual echoes can not be processed to determine the reflection coefficient directly. This paper presents a technique for processing the A-scan to obtain the desired reflection coefficient for the case when the bondline is near a surface.

PROBLEM STATEMENT

The specific configuration considered was a thin, homogeneous elastic layer bonded to a homogeneous elastic half-space, as shown in Fig. 1. It was assumed that immersed pulse-echo ultrasound would be used to measure the reflection coefficient of the bondline between the layer and half-space. The thickness of the layer is assumed to be less than the resolution distance of the transducer (normally about three wavelengths of the nominal center frequency).

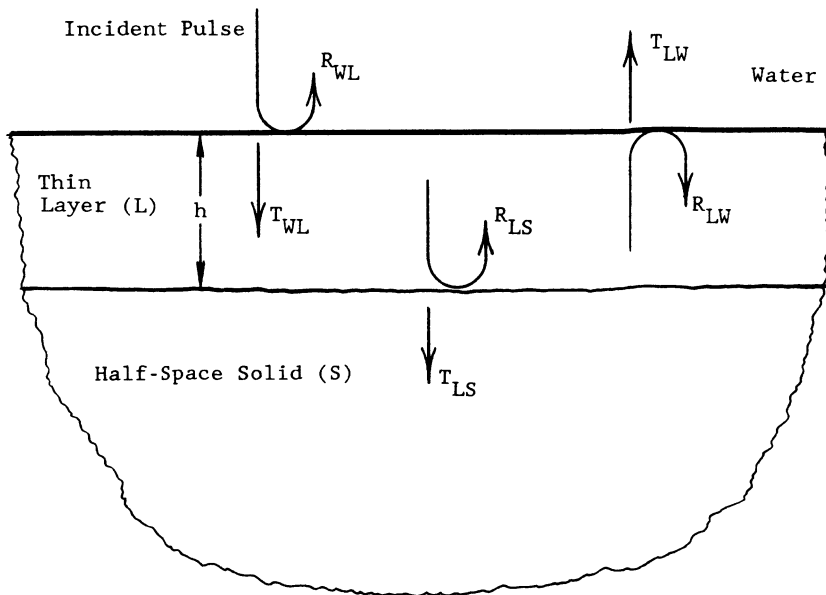


Figure 1. Thin Layer Bonded to an Elastic Half-Space

For the configuration described, there are three sets of reflection/transmission coefficients involved. One for waves passing from the water into the layer (WL subscripts), one for waves passing from the layer into the solid half-space (LS subscripts), and one for waves passing from the layer back into the water (LW subscripts). The double subscript notation uses the convention that the first letter represents the medium from which the wave is incident and the second letter represents the medium into which the wave transmits.

WAVEFORM MODELS AND DECONVOLUTIONS

The received signals were modeled using linear input/output concepts. In these systems the output is equal to the input convolved with the system response function. Letting $X(\omega)$ represent the Fourier Transform of the signal received by the pulse-echo system from a perfect reflector, the signal from the half-space alone can be modeled by

$$Y(\omega) = X(\omega) R_{WS}(\omega) + N_1(\omega) \quad (1)$$

Here $N_1(\omega)$ is additive noise, and the time origin is being taken as the arrival of the reflected pulse. Similarly, the signal from the bonded configuration of Fig. 1 becomes

$$\begin{aligned}
 Y_L(\omega) = & X(\omega) R_{WL}(\omega) + X(\omega) T_{WL}(\omega) R_{LS}(\omega) T_{LW}(\omega) e^{-i\omega\tau} \\
 & + X(\omega) T_{WL}(\omega) R_{LS}(\omega) R_{LW}(\omega) R_{LS}(\omega) T_{LW}(\omega) e^{-i\omega 2\tau_L} \\
 & + X(\omega) T_{WL}(\omega) R_{LS}(\omega) R_{LW}(\omega) R_{LS}(\omega) R_{LW}(\omega) R_{LS}(\omega) T_{LW}(\omega) e^{-i\omega 3\tau_L} \\
 & + \dots + N_2(\omega)
 \end{aligned} \quad (2)$$

Each successive term in this expression represents one successive pulse in the received A-scan. The time of flight of a single pulse through the layer and back is equal to τ_L

$$\tau_L = 2h/c_L \quad , \quad (3)$$

where c_L is the propagation velocity of the longitudinal wave in the layer and h is the thickness of the layer. In Eqs.(1) and (2) the effects of attenuation in the material have been omitted, but they can easily be included.

The expression for $Y_L(\omega)$ can be simplified (to shorten the notation, frequency dependence will be implied but not explicitly indicated in the expressions). Rearranging first leads to

$$Y_L = X R_{WL} \left\{ 1 + \frac{T_{WL} T_{LW}}{R_{WL}} R_{LS} e^{-i\omega\tau_L} \left[1 + R_{LW} R_{LS} e^{-i\omega\tau_L} + R_{LW}^2 R_{LS}^2 e^{-i\omega 2\tau_L} + \dots \right] \right\} = N_2 \quad (4)$$

Letting $z = R_{LW} R_{LS} e^{-i\omega\tau_L}$, and using

$$\sum_{n=0}^{\infty} z^n = \frac{1}{1-z}, \quad |z| < 1.0 \quad (5)$$

to simplify the series in square brackets gives

$$Y_L = X R_{WL} \left\{ 1 + \frac{T_{WL} T_{LW}}{R_{WL}} \frac{R_{LS} e^{-i\omega\tau_L}}{1 - R_{LW} R_{LS} e^{-i\omega\tau_L}} \right\} + N_2 \quad (6)$$

Effects of the measuring system and the added noise can be eliminated by a least-square optimum, linear deconvolution(3,4)

$$A_M = \frac{\Delta E[Y^* Y_L]}{E[Y^* Y]} \frac{E[X^* X] R_{WS}^* R_{WL} \left\{ 1 + \frac{T_{WL} T_{LW}}{R_{WL}} \frac{R_{LS} e^{-i\omega\tau_L}}{1 - R_{LW} R_{LS} e^{-i\omega\tau_L}} \right\}}{E[X^* X] |R_{WS}|^2 + |N_1|^2} \quad (7)$$

Assuming the energy of the additive noise in the half-space signal is small compared to the total energy then gives

$$A_M = \frac{R_{WL}}{R_{WS}} \left\{ 1 + \frac{T_{WL} T_{LW}}{R_{WL}} \frac{R_{LS} e^{-i\omega\tau_L}}{1 - R_{LW} R_{LS} e^{-i\omega\tau_L}} \right\} \quad (8)$$

This expression can be solved directly for R_{LS} , the bondline reflection coefficient

$$R_{LS} = \frac{\left(A_M \frac{R_{WS}}{R_{WL}} - 1 \right) \frac{R_{WL}}{T_{WL} T_{LW}}}{1 + \left(A_M \frac{R_{WS}}{R_{WL}} - 1 \right) \frac{R_{WL} R_{LW}}{T_{WL} T_{LW}}} e^{-i\omega\tau_L} \quad (9)$$

This approach offers the advantages of a broadband method, eliminates effects of the measuring system and additive noise, requires no questionable windowing of A-scans, and no phase unwrapping, such as would be required using cepstral processing.

SYNTHETIC EXPERIMENTS

Before applying the method to actual measurements we tested it using synthetically generated data. Time domain waveforms were synthesized using Eqs. (1) and (2) as models. The input was

$$X(\omega) = A_0 \quad |\omega| < \omega_0 \quad , \quad (10)$$

where ω_0 is a constant. The reflection and transmission coefficients, except for R_{LS} , were calculated by substituting the properties of graphite epoxy into the usual plane interface expressions. Actual values used were: $R_{WL}(\omega) = R_{WS}(\omega) = 0.5336$, $T_{WL}(\omega) = 0.4664$, $R_{LW}(\omega) = -0.5336$, and $T_{LW}(\omega) = 1.5336$. R_{LS} was taken as

$$R_{LS}(\omega) = \frac{iB\omega}{1 - iB\omega} \quad , \quad (11)$$

where B is a constant. This expression represents the reflection coefficient for two half spaces joined by a layer of uniformly spaced springs(5,6). Figures 2 and 3 show R_{LS} as a function of nondimensional frequency. White noise was also added to the waveforms. Figures 4 and 5 show examples of the synthesized waveforms for the half-space and bonded configuration respectively.

Using FFT's, the linear deconvolution represented in Eq. (6) was applied to the synthetic waveforms. The linearly deconvolved spectrum [Eq. (7)] is shown in Figs. 6 and 7. The periodic nulls appearing in Fig. 6 have a spacing of $1/\tau_1$, as expected(7). The sharp decay of the spectrum beyond the nondimensional frequency of 80 is due to the finite bandwidth (ω_0) of the input sinc function. Results above this frequency should be regarded as noise.

Using the plane wave reflection coefficients presented earlier, Eq. (8) was applied to the linearly deconvolved spectrum to recover R_{LS} . The recovered reflection coefficient is shown in Figs. 8 and 9. Over the valid bandwidth, this recovered result compares very well with Fig. 2, and hence the procedure worked well for the synthetic data.

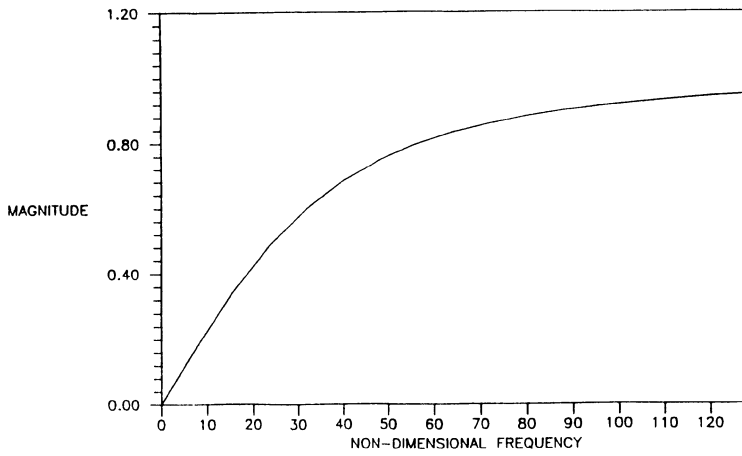


Figure 2. Reflection Coeff. R_{LS} Used to Synthesize Waveforms

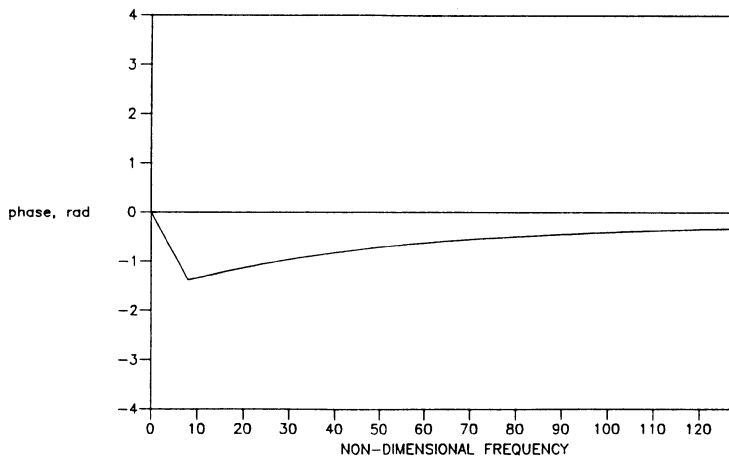


Figure 3. Phase of R_{LS}

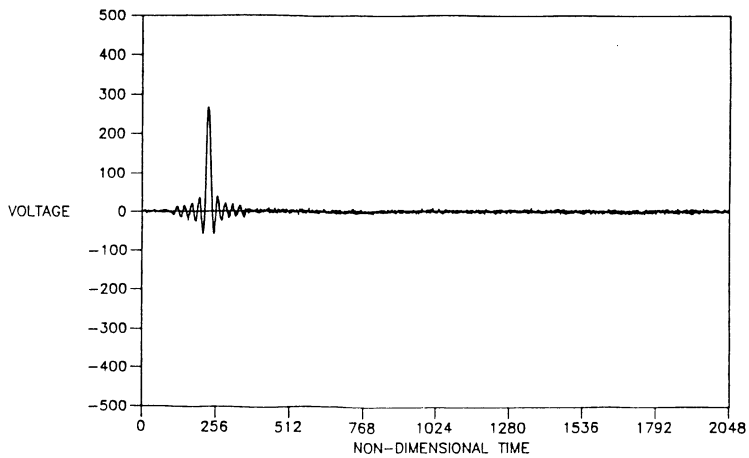


Figure 4. Surface Reflection and Additive Noise

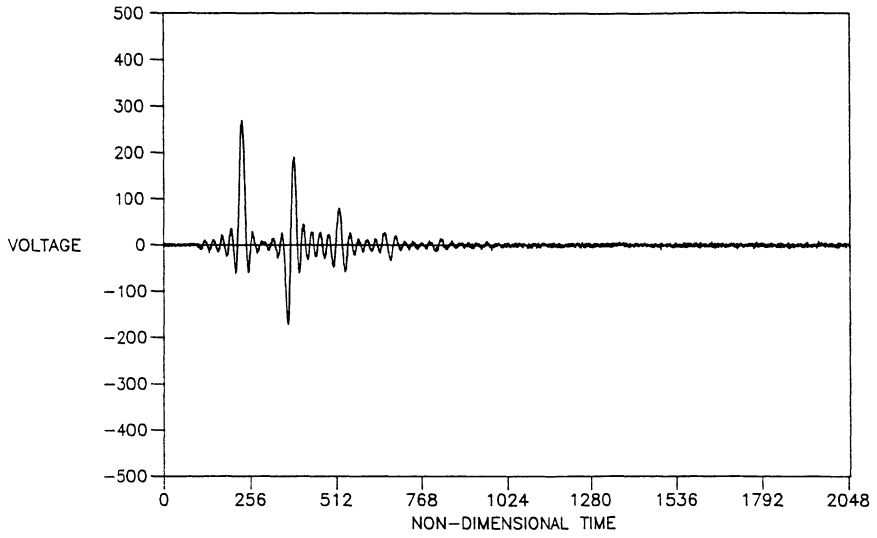


Figure 5. Surface Reflection and Reverberations Inside Layer

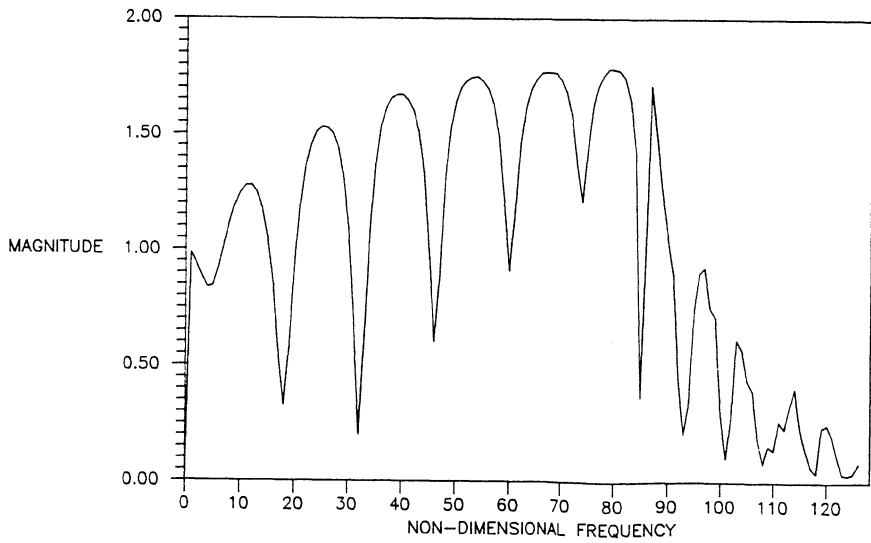


Figure 6. Linearly Deconvolved Spectrum, A_M

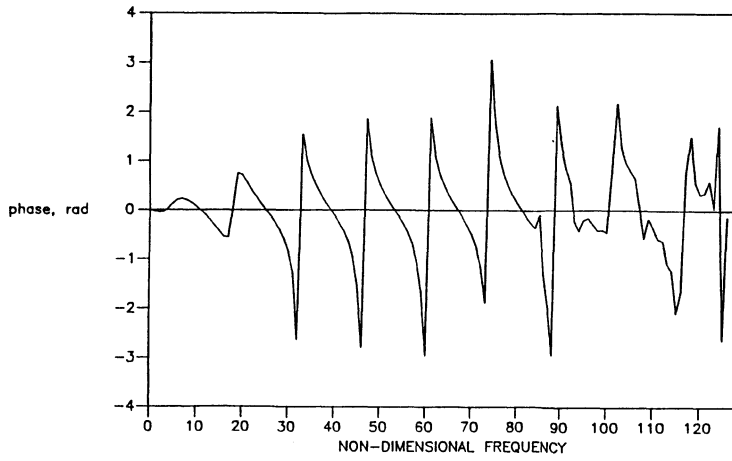


Figure 7. Phase of A_M

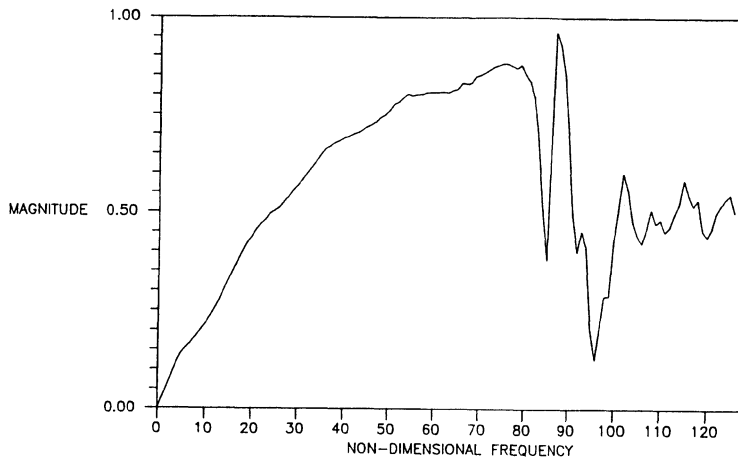


Figure 8. Recovered Reflection Coefficient, R_{LS}

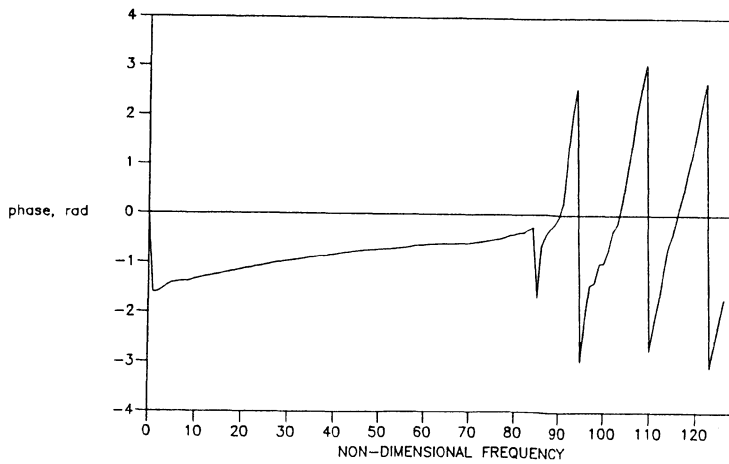


Figure 9. Phase of Recovered R_{LS}

EXPERIMENTAL RESULTS

To further test the procedure, it is being applied to some real pulse-echo measurements. The specimen being used is a thin lucite plate clamped to a thick lucite block with a very thin sheet of Latex rubber separating them. Measurements have been taken on the thick block alone and on the bonded specimen, just as for the synthetic experiments. As before, the linear deconvolution represented in Eq. (6) has been applied to these waveforms. Over the bandwidth of the transducers, characteristic nulls and other features of the linearly deconvolved spectrum are very similar to those of the synthetic experiments. Additional work is being done to recover the bondline reflection coefficient using Eq.(8).

CONCLUSION

A procedure for recovering the reflection coefficient of a bondline between a thin elastic layer and an elastic half-space using broadband, pulse-echo ultrasound has been presented. The method employs a linear deconvolution to eliminate effects of the measuring system and additive noise, but requires no questionable windowing of the A-scans or unwrapping of the phase. Only straightforward algebraic operations applied to the linearly deconvolved spectrum are used.

The procedure worked very well when applied to synthetically generated data. In these experiments the recovered reflection coefficient agreed closely with the true one. Most of the procedure also seemed to work well when applied to measured data. The results using measured data agree with the results from synthetic data up through the linearly deconvolved spectra. Work is continuing to apply the algebraic operations and recover the bondline reflection coefficient.

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