MATERIAL PARAMETER DETERMINATION FROM TIME-DOMAIN SIGNALS TRANSMITTED AND REFLECTED BY A LAYERED STRUCTURE

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INTRODUCTION

The modeling of the time-domain signals transmitted and/or reflected by a layered structure is very useful for the simulation of wave propagation in the structure containing deteriorated layers, defects and delaminations and for the characterization of material properties in those layers. In this paper, we first present the relations between the signals transmitted and reflected by a layered plate in terms of transmission and reflection coefficients in the frequency domain. The time domain signals transmitted and reflected by the plate are then expressed by use of the inverse Fourier transform. The simulated signals transmitted and reflected by an Aluminum plate and a Titanium plate and a diffusion bonded Titanium plate are compared with measured signals. The inverse problem for the determination of the unknown parameters of the layered plates in the time-domain is also discussed.

RECONSTRUCTION OF TIME-DOMAIN SIGNALS

For the nondestructive evaluation of a layered plate, the plate is immersed in water and a transducer is placed at each side of the plate, see Fig. 1. In the frequency domain, the ratio of the voltage signals transmitted through the plate, V_{12}, and the corresponding water path, V_{12}^{w}, has been related to the ratio of transmission coefficients of the plate, T_{12}, and the corresponding water layer, T_{12}^{w}, see Ref. [1] as

$$R^{t}(x, \omega) = \frac{V_{12}}{V_{12}^{w}} = \frac{T_{12}}{T_{12}^{w}} = T_{12}e^{ik_0h}, \tag{1}$$

where is $x = x(x_1, x_2, x_3, \ldots, x_{n-1}, x_n)$ is a vector in the parameter space of the layered plate, ω is the frequency, h is the total thickness of the layered plate and k_0 is the wave number in the water.

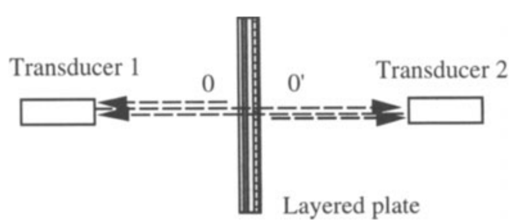

Figure 1. Configuration of NDE of a layered plate.

The time domain signals transmitted through the layered plate can then be obtained by rewriting Eq. (1) and by using the inverse of Fourier transform

$$v_{12}(x, t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} V_{12}^{w} T_{12} e^{ik_0 h} e^{i\omega t} d\omega. \quad (2)$$

Similarly, the ratio for reflection from the specimen and a reference surface has been derived in Ref. [1] as

$$R^{r}(x, \omega) = \frac{V_{11}}{V_{11}^{r}} = \frac{z_r + z_0}{z_r - z_0} R_{11}, \quad (3)$$

where z_0 and z_r are the acoustic impedance of the water and the reference surface, V_{11} and V_{11}^{r} are the signals reflected by the plate and the reference surface, and R_{11} is the reflection coefficient of the plate. The time domain signal reflected by the layered plate can then be obtained by rewriting Eq. (3) and by using the inverse of Fourier transform

$$v_{11}(x, t) = \frac{1}{2\pi}\left(\frac{z_r + z_0}{z_r - z_0}\right)\int_{-\infty}^{+\infty} V_{11}^{r} R_{11} e^{i\omega t} d\omega. \quad (4)$$

where the transmission and reflection coefficients of the plate in the equations above can be obtained from Ref. [2].

EXPERIMENT

The setup for the experiment is shown in Fig. 2. A matched pair of Panametrics broadband piezoelectric transducers with center frequency 10 MHz and diameter 12.7 mm was used. For the determination of the unknown parameters of the layered plate, the signals transmitted or reflected from the plate need to be collected. The alignment of the two transducers is, therefore, important in order that the propagation direction of waves is normal to the plate. In this experiment, a specially designed fixture was used to keep the two transducers perfectly aligned and to keep their distance fixed. The transducers can be kept perpendicular to the specimen by adjusting a rotational and tilt stage. The distance between the transducers was kept at 310 mm and the specimen was placed at 270 mm from the transmitting transducer so that far field reception of transmitted and reflected waves can be assumed. An Aluminum plate, named plate A, a Titanium plate, named plate B, and a diffusion bonded Titanium plate (a 3-layered plate by considering two titanium base plates and an interdiffusion bonding layer in between the base plates), named plate C, were used for this study. The parameters of the plates A and B listed in Table 1 are the measured values. The parameters for plate C listed in Table 2 are the determined values obtained from Ref. [3].

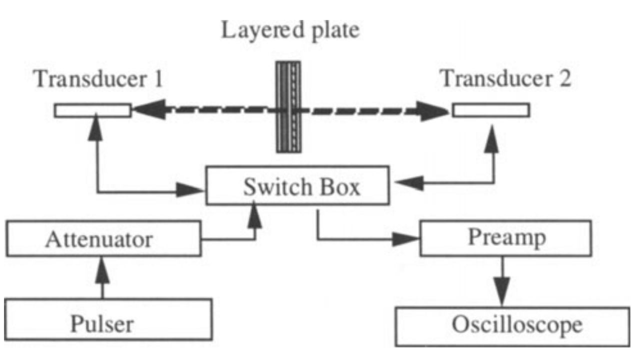

Figure 2. A schematic of the experiment setup.

Table 1. Parameters for plate A and B.

Parameter	Plate A	Plate B
Thickness (mm)	0.469	1.92
Velocity (km/sec)	6.335	6.18
Density (g/cm^3)	2.712	4.54

Table 2. Parameters for plate C.

Parameter-Plate C	Layer 1	Layer 2	Layer 3
Thickness (mm)	0.9587	0.0026	0.9587
Velocity (km/sec)	6.18	2.116	6.18
Density (g/cm^3)	4.54	2.33	4.54

To acquire the data, a short duration pulse signal, generated by a Panametrics Ultrasonic Analyzer Model 5600 and attenuated 10 dB by an attenuator, was applied via a switch box to the transmitting transducer. The signal reflected or transmitted by the specimen was received by the receiving transducer and amplified 34 dB by a Panametrics preamplifier. The signal was then obtained by a Tektronix TDS 540 oscilloscope where it was digitized into 5000 points with a sampling interval of 4 ns. The digitized signal was then acquired by a personal computer through a GPIB interface. The signal through the corresponding water path was obtained in the same manner after the sample in-between the transducers had been removed. The reference signal for reflection was obtained by measuring the first arrival reflected by the front surface of an Aluminum block.

The time domain signals transmitted and reflected by the specimens listed in Table 1 and 2 have been simulated by using Eqs. (2) and (4), respectively. The simulated signals are compared with measured ones. Figure 3 shows the comparison of the signals transmitted and reflected by plate A. The comparison of the signals transmitted and reflected by plate C is shown in Fig. 4. Good agreement has been achieved for all cases.

The sensitivity of the signals to variation of the parameters of the plates has been studied by calculating the signals with the thickness and the phase velocity varied up to 5% around their true values. Figure 5 shows the reflected signal for variation of the thickness and the phase velocity of plate A. Figure 6 shows the transmitted signal for variation of the thickness and the phase velocity of plate B. The results show that both transmitted and reflected signals are sensitive to variation of the thickness and the phase velocity of the plates. However, the sensitivity of the transmitted signals is higher than that of the reflected ones. The sensitivity of the signals to variation of the mass density and the attenuation coefficient was also calculated. The sensitivity is low for these two parameters.

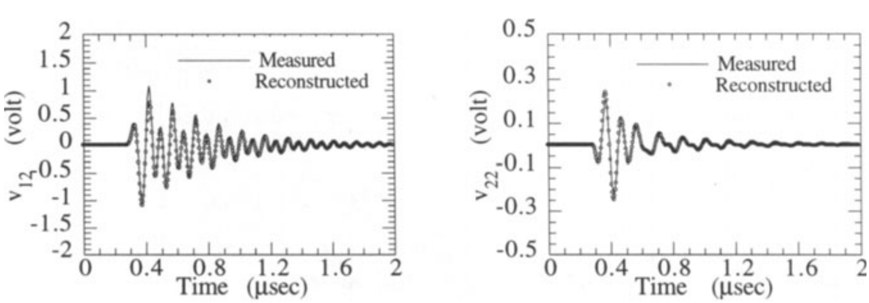

Figure 3. Comparison of the simulated and measured signals transmitted and reflected by plate A.

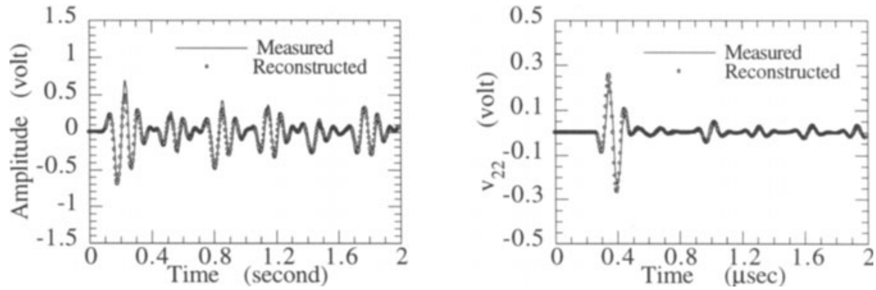

Figure 4. Comparison of the simulated and measured signals transmitted and reflected by plate B.

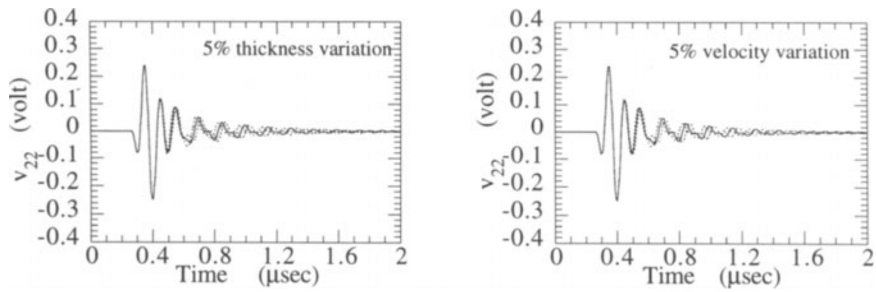

Figure 5. Sensitivity of reflected signal for variation of the thickness and the phase velocity of plate A.

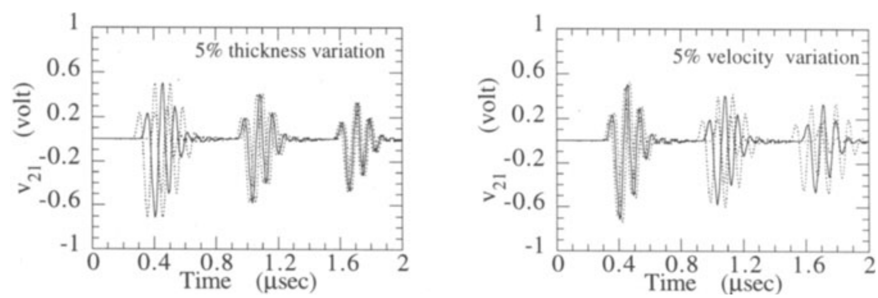

Figure 6. Sensitivity of transmitted signal for variation of the thickness and the phase velocity of plate B.

PARAMETER DETERMINATION

An expression for the error between the simulated and measured time domain signals may be written as

$$E(x)=\frac{1}{n}\sum_{i=1}^{n}\left(v_e(t_i)-v_c(x,t_i)\right)^2, \qquad (5)$$

where v_e is the measured signal, v_c is the simulated signal and n is the number of points of the digitized signals. The Downhill Simplex method for multi-dimensional minimization in Ref. [4] was used for the search of the minimum in an error surface. The parameters determined for plate A and B are listed in Table 3. The same results as listed in Table 2 were obtained for plate C. To confirm the convergence of the minimum, the error surfaces

Table 3. Determined parameters and their relative error.

Parameter	Plate A	Plate B
Thickness (mm)	0.467 (0.617%)	1.928 (0.42%)
Velocity (km/sec)	6.301 (0.54%)	6.15 (0.65%)

have been recalculated for the plates A and C, where the parameters in the simulated signal were taken to vary up to 20 % around their determined values.

The error surface for the signal transmitted by plate A is shown in Fig. 7. The true minimum in the error surface can be located easily. Unlike the case in Ref. [2], no minima valley exists in the error surface for this case due to the constraint of time of flight contributed by the corresponding water path signal. The error surface for the signal reflected by the plate A was also calculated, see Fig. 8. A valley presents in the error surface in the insensitive direction as observed in Ref. [2]. Obviously, no constraint has been contributed by the reference signal. The error along the insensitive direction has been searched and shown in Fig. 9. The error still converges at the true minimum.

The error surface for the signal transmitted from plate C is shown in Fig. 10, where the thickness and the phase velocity of the second layer, the interdiffusion bonding layer, are taken as variables. The error surface for the signal reflected is shown in Fig. 11. The constraint of the water path dose not have much effect on this transmitted case due to thin thickness of the interdiffusion bonding layer evaluated here. For the reflected case, again, a minima valley presents in the error surface in the insensitive direction. The error along the insensitive direction was searched for the reflected case. The convergence of the true minimum has been confirmed, see Fig. 12.

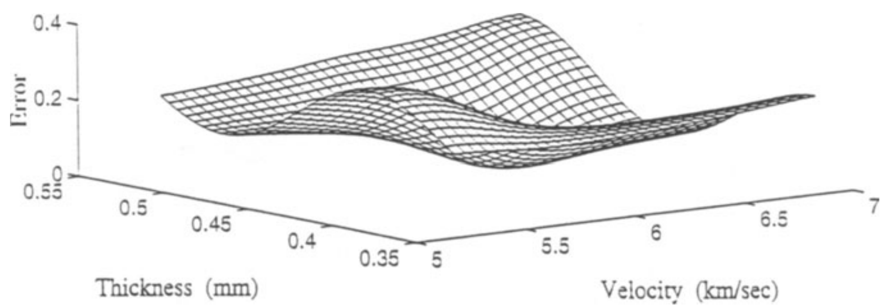

Figure 7. Error surface for the signal transmitted through plate A.

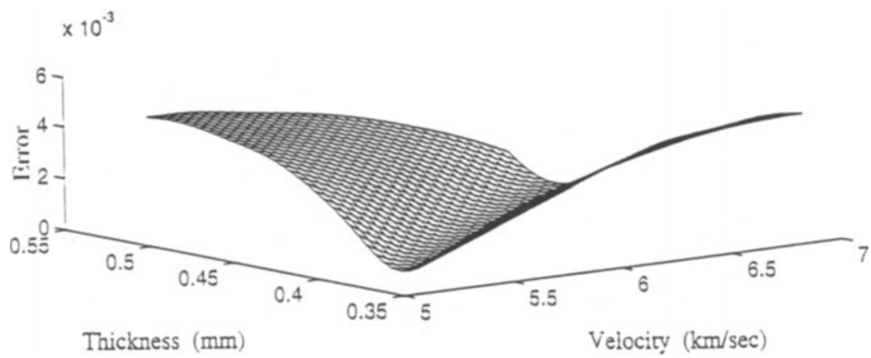

Figure 8. Error surface for the signal reflected by plate A.

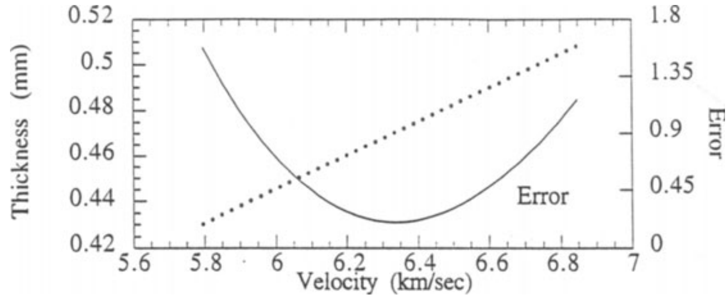

Figure 9. Error searched along the insensitive direction in the error surface for plate A.

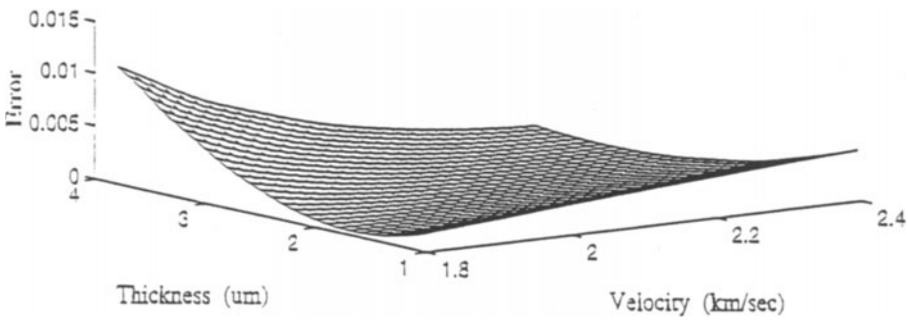

Figure 10. Error surface for the signal transmitted through plate C.

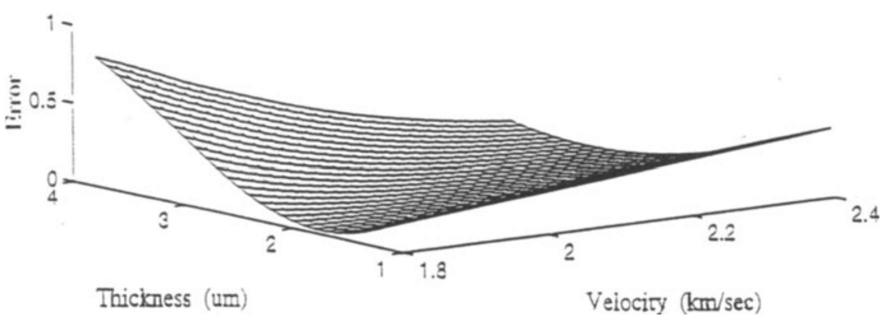

Figure 11. Error surface for the signal reflected by plate C.

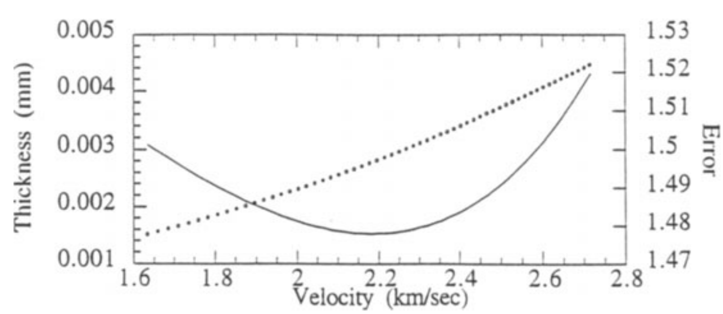

Figure 12. Error searched along the insensitive direction in the error surface for plate C.

In summary, the study of the distribution of minima in the error surface shows that the determination of the unknown parameters for a layered plate can be accomplished by using either transmitted or reflected time-domain signals. Due to the constraint of the water path signal, the determination of the true minimum in the error surface using the transmitted signal may, however, be easier than that using the reflected signal.

CONCLUSION

Analytical models for the simulation of the time-domain signals transmitted and reflected by a layered structure have been presented. The models can be used for the simulation of the waves transmitted and reflected by the structure containing deteriorated layers, defects and delaminations. They can also be used for the characterization of the layered structure in the time-domain. The simulated signals transmitted and reflected by an Aluminum plate, a Titanium plate and a diffusion bonded Titanium plate have been compared with measured signals. Good agreement has been achieved. The inverse problem for the determination of the unknown parameters of the layered plates has also been conducted by determining the least square difference between simulated and measured signals. Satisfactory results have been obtained.

ACKNOWLEDGMENTS

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