TIME-DOMAIN FIRST BORN APPROXIMATION TO ELASTODYNAMIC BACKSCATTER FROM COMPOSITE MATERIALS

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INTRODUCTION

The high specific strengths attainable from composite materials can be negated by pores between the plies in the material. Classical acoustic attenuation measurements can indicate the presence of porosity if all other material properties remain constant. Even though attenuation measurements accurately predict the amount of porosity, its spatial distribution cannot be inferred from these data. To make accurate predictions of structural performance, current micromechanical models of composite materials require accurate estimates of the volume fraction of porosity and its spatial distribution. This work is an attempt to model the acoustic interactions that occur between plane compressional waves and the fiber arrays and pores in order to develop an ultrasonic technique to estimate the spatial distribution and volume fraction of porosity.

THEORETICAL BACKGROUND

If the incident elastodynamic wave is a plane dilatation pulse, with displacement field

$$\underline{u}(\underline{x},t) = \underline{e}g(t - \frac{\underline{\underline{e}}\underline{x} + b}{a})$$

then, in the first Born approximation, the backscattered dilation waves in the far field have a time variation proportional to

$$\int_0^t \ddot{g}(t-\tau)A(\tau)d\tau \qquad (1)$$

where A(t) denotes the cross-sectional area of the scatterer intercepted by planes perpendicular to the line-of-sight direction $\underline{e}$, as a function of the dilation wave's time-of-flight. We have found it convenient to generate approximations for scattering by actual transducer outputs by fitting the observations of the outputs with polynomial splines to obtain the function g(t). A comprehensive description of the theoretical development and the numerical computation schemes are presented in Ref. 1, to which the interested reader is referred.

EXPERIMENTAL RESULTS AND DISCUSSION

Appropriate specimens were fabricated to test the analytical prediction of the model mentioned above. Boron fibers, 100 μm in diameter, either singly or in periodically spaced rafts were cast in polyester cylinders with a hemispherical cap to facilitate contact acoustic measurements. In some cases, glass spheres were inserted into the curing resin to simulate pores. A single 5 MHz narrow band transducer was used both to send and receive the acoustic waves. The output of this transducer is shown in Fig. 1a. The ordinates of all graphs in this paper are in arbitrary amplitude units while the abscissa are in units of microseconds. Figure 1b shows the backscattered wave from a single 100 μm diameter fiber predicted by Eq. (1) for this transducer. From these data one would expect that an ultrasonic wave backscattered from an array or raft of fibers would consist of a chain of responses such as the one in Fig. 1b. This would be the case if the fibers were widely separated.

However, for the technologically important case of structural composite materials, the fibers are arranged in an approximate hexagonal array with a center-to-center spacing of approximately 1.2 D, where D is the fiber diameter. For such an array, Eq. (1) predicts pronounced returns from the beginning and end of a fiber raft with relatively low amplitude backscattering from the interior of the array. These somewhat surprising predictions are confirmed by experiments. Figure 2a shows the predicted backscatter return from an array of 10 fibers with a center-to-center spacing of one fiber diameter. The experimental verification of this prediction is shown in Fig. 2b, but for a 6 fiber raft with a center-to-center spacing of 1.5 D. The similarity of the analytical and experimental results is striking.

The next investigation was for a 50 fiber raft as shown in Fig. 3a, again for a fiber spacing of 1.0 D. The destructive interference from the internal fibers is readily apparent. The experimental verification of this prediction is shown in Fig. 3b. The only differences between the prediction and measurement are the larger fiber spacing in the cast rafts (1.5 D) and the reduced returns from end of the raft furthest from the transducer caused by

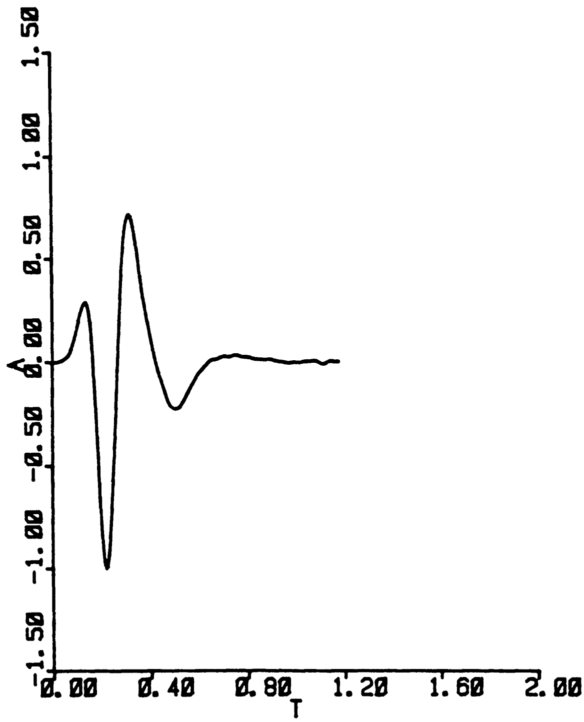

Fig. 1a. Observed transducer output pulse.

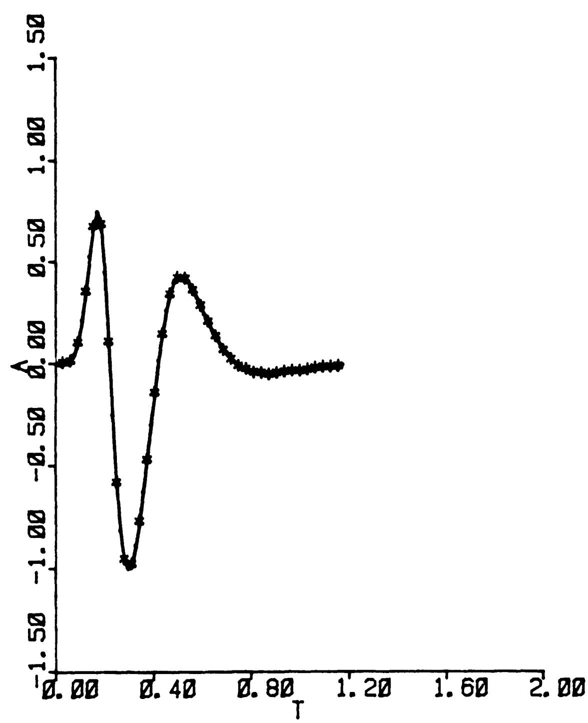

Fig. 1b. Predicted return from single cylinder.

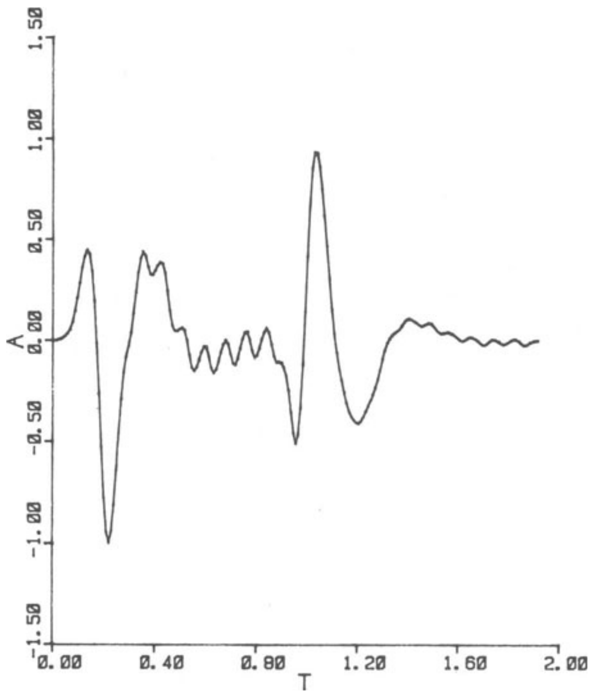

Fig. 2a. Predicted return from linear array ("raft") of 10 cylinders.

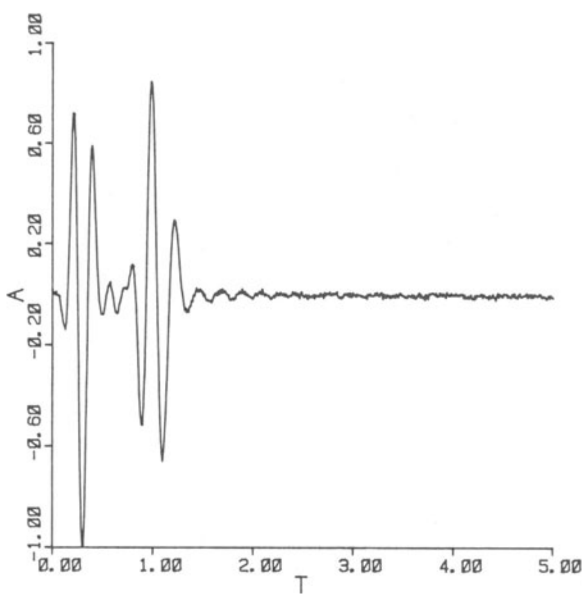

Fig. 2b. Observed return from raft of 6 born fibers.

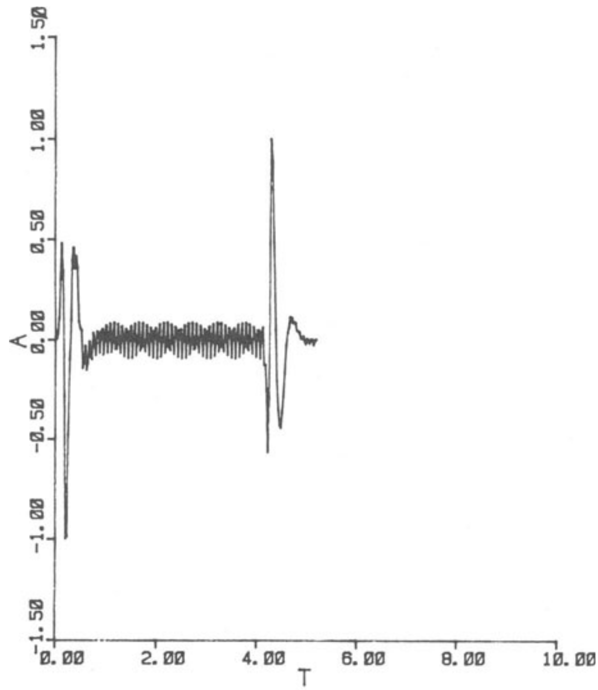

Fig. 3a. Predicted return from linear array of 50 cylinders.

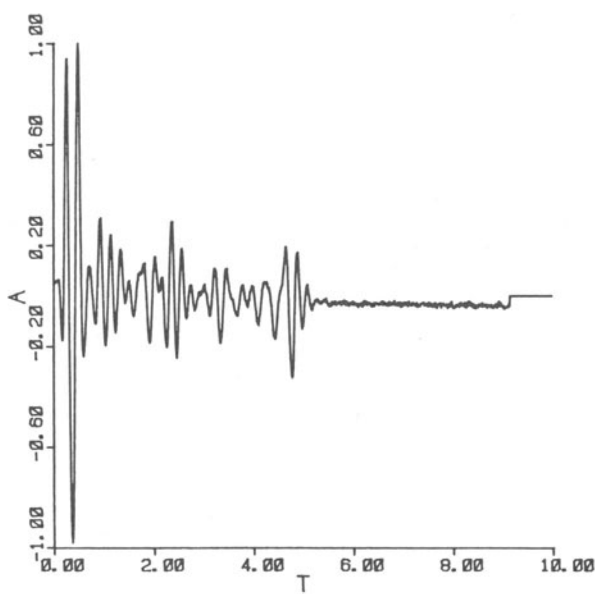

Fig. 3b. Observed return from raft of 50 boron fibers.

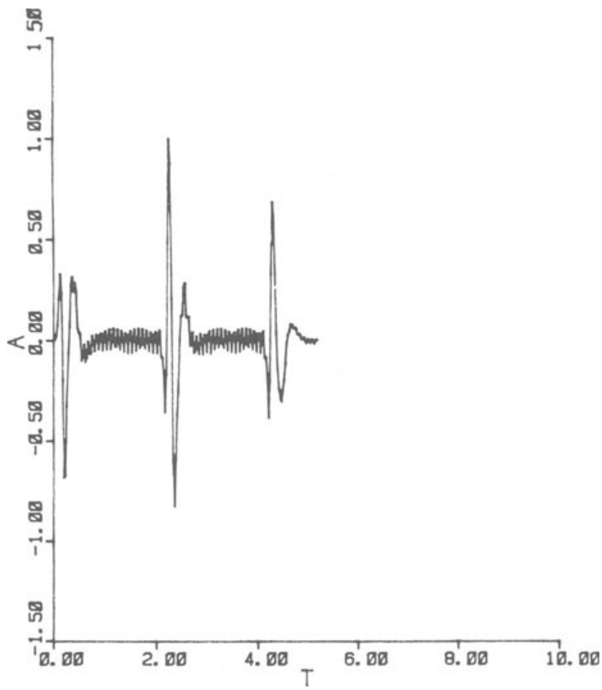

Fig. 4a. Predicted return from raft of 50 cylinders, 25th cylinder missing.

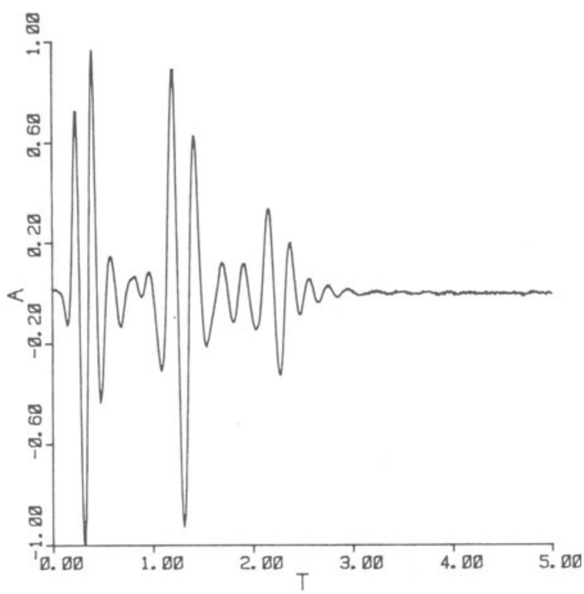

Fig. 4b. Observed return from raft of 17 boron fibers with center cylinder missing.

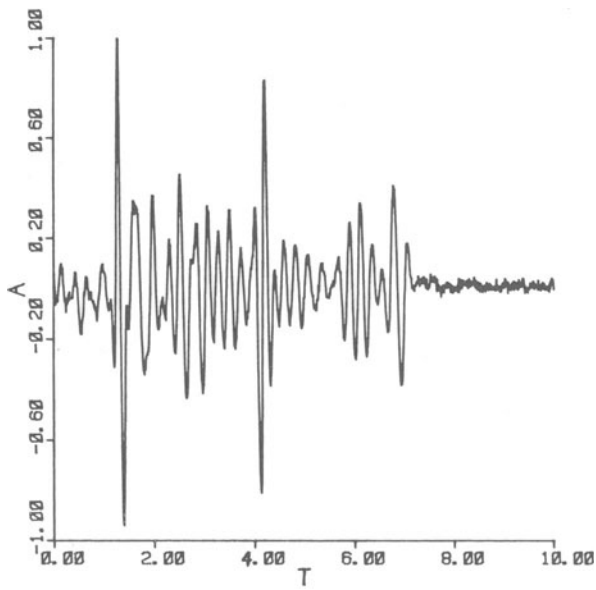

Fig. 5. Observed return from a 100 μm diameter glass sphere above raft of 50 boron fibers.

the very high attenuation of the polyester casting resin. In all, the agreement between prediction and measurement is excellent. This is particularly surprising since scattering from arrays of cylinders is just the sort of situation in which one might expect the first-Born approximation to fail.

A final set of experiments was conducted to investigate the effects of missing fibers and inclusions on the return signal. Figure 4a shows the effects of removing the 25th fiber from a 50 fiber raft. Experimental results were obtained from a 17 fiber raft with a missing center fiber as shown in Fig. 4b. Again, the only substantial differences arise from the attenuation of the casting resin and fiber spacing. Since the effects of a single missing fiber were so dramatic, it was only natural to expect that an inclusion over the fiber raft would produce similar results. Indeed, this is the case as shown by Fig. 5, in which case a 200 μm diameter glass sphere was placed approximately 100 μm above the boron fiber raft. Again, this break in the periodicity produced a substantial return. While this particular configuration was not examined numerically, the experimental results are consistent with previous analytical and experimental results.

SUMMARY AND CONCLUSIONS

Time-domain first-Born predictions for backscattering from closely-packed regular arrays of cylinders show marked destructive interference among returns from cylinders interior to the arrays. This approximation also predicts that gaps in arrays, and inclusions near arrays, could be detected. Experiments confirm these predictions. It thus appears that detection of porosity in fiber-reinforced composites may be easier to detect than simple comparisons of scattering cross-sections of fibers and voids would suggest.

REFERENCE

1. G.T. Warhola, "Time-Domain First-Born Approximation to Elastodynamic Backscatter with Application to Nondestructive Evaluation to Composites," AFWAL-TR-82-4044, October 1982.