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Ultrasonic Verification of Five Wave Fronts in Unidirectional Graphite Epoxy Composite

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Introduction

Many studies of wave propagation in composite materials show that the SV shear wave surface has two cuspidal edges per quadrant [1,2]. This indicates that, at any location within the region defined by the lines from the origin to the tips of the cuspidal edges, it may be possible to observe five different wave fronts when the three different modes (P, SH and SV) of wave propagation are considered.

In this study, experiments are designed to verify the existence of the five different wave fronts in a graphite fiber reinforced epoxy composite by measuring their corresponding phase velocities.

This investigation provides some potentially useful applications for nondestructive evaluation of composite materials. For example, the angular location of the cuspidal tips of the wave surfaces can be used as an auxiliary criterion for the placement of the transducers when experiments are designed. The location(s) where energy is focused can be selected as the receiving region because the signals within this region are expected to be stronger than in other regions due to larger displacement amplitudes.

1. Basic Principles

A schematic of the unidirectional fiber reinforced composite for this investigation is shown in Fig. 1. A cartesian coordinate system is adopted such that 2-3 plane is the isotropic plane. The 1 axis is the zonal axis of the medium, which is parallel to the fiber direction.

The wave surfaces of a graphite epoxy composite material are shown in Fig. 2. For waves propagating between the angles of θ_1 and θ_2 with respect to the 3 axis, five different wave fronts are indicated. If the energy fluxes of the five different wave are propagating at an angle of θ with respect to the 3 axis, at each intersecting point of the energy flux propagation direction and the wave surface, the wave normal direction is collinear with the unit normal from the wave surface [1]. The angle between the energy flux propagation direction and the wave normal direction is called the energy flux deviation angle Δ_e. The wave front at time t = 1 second (defined as the wave surface) represents the locus of energy propagation in the medium after the energy is emitted from a directionally uniform point source at time t = 0 [3]. Thus, if the energy flux propagation velocity (group velocity) is V_g, the corresponding phase velocity V_n of the plane wave is [4]

$$V_n = V_g \cos\Delta_e \tag{1}$$

Fig. 3 illustrates the relation between the group velocity and phase velocity.

Two experimental methods are designed to verify the existence of different wave fronts in filamentary composite materials by measuring their corresponding group and phase velocities of longitudinal and shear waves propagating through the materials.

1.1 Method I

For a given energy flux direction, the group velocity and the energy flux deviation angle can be determined from reference [5] and the direction of the wave normal is (Fig. 4)

$$\theta_n = \theta - \Delta_e \tag{2}$$

where θ_n is defined with respect to the 3 axis. Specimens with parallel faces can be cut from the unidirectional composite plate, such that for each pair of specimen and wave front combination to be considered, the normal to the specimen's surface is in the same direction as the wave normal of the wave front (Fig. 4).

The phase and group velocities are measured using direct through transmission and offset through transmission techniques, respectively. In offset through transmission, the transmitting and receiving transducers are placed on opposite faces of the specimen and offset at an angle defined by the energy flux deviation angle Δ_e [6]. In this transducer arrangement, the energy flux propagation direction of the wave is parallel to the path joining the transmitting and receiving transducers and the wave motion is normal to the specimen's surface (Fig. 5).

1.2 Method II

In practice, structures with their surfaces perpendicular to different modes of wave normals are not always available. Thus, a nondestructive technique for evaluating the existence of different wave fronts other than the experimental method discussed in Method I is desirable.

Fig. 6 shows the energy flux propagating at an angle of θ with respect to the 3 axis, and the wave normal direction is not perpendicular to the structure's surface. The incident wave, with a group velocity of V_g reaches the left-hand boundary (structure's surface) at an angle of θ with respect to the 3 axis. If the thickness of the structure is D and the transmitting and receiving transducers are offset at an angle of θ, the arrival time t of the wave packet is

$$t = \frac{D}{V_g \cos\theta} \tag{3}$$

In this method, the wave normal direction is not perpendicular to the specimen surface and the observed wave may be a combination of multiple different modes with different group velocities propagating in the same direction [7].

2. Experimental Verification Of The Existence Of Five Different Wave Fronts

The wave surfaces of a graphite fiber reinforced epoxy composite are shown in Fig. 7 [5]. The angles θ_1 and θ_2 from the origin to the cuspidal tips of the SV wave surface are 16.88° and 64.77°, respectively, with respect to the 3 axis. The material properties and the elastic constants of the material are tabulated in Table 1 [8].

2.1 Method I

Waves with energy fluxes propagating at an angle of 30° with respect to the 3 axis are selected to verify the existence of the five different wave fronts in the graphite fiber reinforced epoxy composite. This particular angle is chosen so that the maximum distinction of the wave normals is achieved. Fig. 8 shows the relevant section of the wave surfaces with energy flux propagating at 30° with respect to the 3 axis, such that energy fluxes of the longitudinal P and shear SV and SH waves are along this direction. For each mode of wave propagation, the directions of the wave normal are also shown as the directed arrows.

Specimens having parallel faces, shown in Fig. 9, are prepared from a 4.5 cm thick, 5 cm by 25 cm unidirectional graphite fiber reinforced epoxy composite plate. The normals of these faces are in the same direction as the normal to the tangent planes on the wave surfaces at the points defined by the energy flux vector at 30° with respect to the 3 axis. The relationship between the specimen's normal and the 3 axis is also shown in the Fig. 9. In each of the five experimental configurations, the energy flux of the wave is therefore parallel to the path joining the center of the transmitting and receiving transducers (Fig. 10), and the wave normal direction is perpendicular to the specimen's surface.

2.2 Method II

Only SV shear wave propagation is considered in these experiments. Fig. 11 shows the transducer arrangement of this method, where the transmitting and receiving transducers are coupled to opposite faces of a unidirectional specimen with an offset variable angle of θ_i . The input signal is carefully adjusted so that the arrival times of nonoverlapping output wave packets can be measured. Experiments are conducted at three different transducer offset angles : 30°, 45° and 64.77°, with respect to the 3 axis. Fig. 12 shows the SV wave surface with the three offset angles, wave normal directions and their corresponding deviation angles.

3. Experimental Procedures

In experimental method I, the phase velocities are measured by the direct through transmission technique, and the optimum deviation locations where the maximum output voltage amplitudes are received by the receiving transducer are used to measure the group velocities. In experimental method II, the measurements of group velocities are made by the through transmission technique with the transmitting and receiving transducers offset at an angle θ_i. The offset transducer arrangements for the measurements for experimental method I and II are shown in Figs. 10 and 11, respectively. The schematic of the measuring system is shown in Fig. 13. The system consists of a pulse oscillator (Wavetek FC-500) for generating sinusoidal waves, two longitudinal (AET model FC-500) and two shear (Panametrics model V154) wave transducers for transmitting and receiving stress waves, an ultrasonic preamplifier (Panametrics) and an oscilloscope (Nicolet model 4090). Couplants AET SC-6 and Panametrics SWC were used at the interface of the transducers and specimens for the longitudinal and shear wave experiments, respectively.

The transmitting transducer is excited with a 10 volt peak-to-peak tone burst, and the transmitted signal is captured by the receiving transducer coupled on the opposite face of the specimen. The experiments are conducted at an input frequency of 1.5 MHz.

To evaluate the phase and group velocities in experimental method I, the time shift between the corresponding input and output signals is recorded. If the specimen thickness is D and the time shift is t (Fig. 14), the phase and group velocities are defined, respectively, as

$$V_n = \frac{D}{t}$$

$$V_g = \frac{D}{t \cos \Delta_e}. \tag{4}$$

4. Results and Discussion

4.1 Method I

By placing the receiving transducer at different locations on the face of the specimen, the output voltage amplitudes A_x are collected and normalized with respect to the maximum output voltage amplitude A_o received at the location defined by the deviation angle (optimum deviation angle location). The normalized output amplitudes versus the distance from the optimum deviation angle location of the five different wave fronts are shown in Figs. 15, 16, 17, 18 and 19. All these figures show that the output amplitude decreases rapidly as the receiving transducer is moved away from the optimum deviation angle location. This indicates that the maximum output voltage amplitude is received at the location where the line joining the centers of the transmitting and receiving transducers is parallel to the energy flux propagating direction.

The theoretical phase velocities of P, SV and SH waves with their energy fluxes propagating at an angle of 30° with respect to the 3 axis are determined by substituting the group velocities V_g of five different wave fronts and their corresponding energy flux deviation angles Δ_e obtained from reference [5] into eqn (1). The arrival times of the output signals are measured and the experimental group and phase velocities are calculated using eqn. (5), where the specimen thickness D is 8.89 mm. The experimental and theoretical values of group and phase velocities are tabulated in Table 2. The correct placement of the transducers, found by setting the receiving transducer at the location where the maximum output voltage amplitude is received, gives an accurate measurement of the group velocity. As shown in Table 2, the maximum percentage difference between the experimental and theoretical results is 8%. These results show that there exist five different group and phase velocities related to five different wave fronts when the three modes of wave propagation with energy fluxes at an angle of 30° with respect to 3 axis are considered.

4.2 Method II

The output signals received by the receiving transducer with transducer offset angles of 30°, 45° and 64.77°, with respect to the 3 axis are shown in Figs. 20, 21 and 22, respectively. The energy flux directions, wave normal directions, theoretical and experimental values of group velocities and arrival times of different wave packets for the three measurements are tabulated in Table 3. The theoretical arrival times are calculated based on eqn. (3), where the group velocities V_g are obtained from reference [5] and the specimen thickness D is 10.16 mm.

Three wave packets, arriving at different times are observed in Figs. 20 and 21. These wave packets correspond to the three different SV wave fronts of each energy flux propagating at 30° and 45°, with respect to the 3 axis in Fig. 12. At a transducer offset angle of 64.77°, only two distinct wave packets are observed (Fig. 22). The first wave packet corresponds to the wave front at the upper cuspidal tip of the SV wave surface. The experimental values of arrival times of different wave packets correlate well with the theoretical results except the case where the transducer offset angle is 30°. This is due to the overlapping of first, second and third wave packets, cause by the short intervals (0.38 μs) between the arrival times of wave packets.

The output voltage signals received by the receiving transducer are not affected by reflections of stress waves in the transmitting transducer [9] or reflections of stress waves from the specimen's boundaries. Appendix A discusses the potential effects of these two factors on the output voltage signal and verifies that the output signals received by the receiving transducer in experimental method II are not affected by either of these two factors.

The good agreement between the theoretical and experimental arrival times of SV wave packets appear to confirm the existence of three SV wave fronts of different orientations and different phase velocities passing through the same point in the composite medium at different times.

Conclusions

By considering the three modes of wave propagation in an orthotropic graphite fiber reinforced epoxy composite, the phase velocities that were related to the five different wave fronts were determined. The comparison of the experimental and theoretical values of group and phase velocities showed excellent agreement for all three modes of wave propagation. These results verified that there are five phase velocities corresponding to the five different wave fronts when the three different modes of wave propagation at 30° with respect to the 3 axis were considered. It was also verified that the maximum output voltage amplitude was received when the path joining the centers of the transducers was parallel to the energy propagation direction.

By coupling the transmitting and receiving transducers to a unidirectional specimen at different offset angles, the output signals for an SV wave propagating in the specimen were observed and correlated with the arrival times of the different wave fronts. These observations suggested that it is possible to have different plane SV wave fronts of different orientations and different phase velocities passing through the specimen at different times.

The verification of these wave propagation characteristics is potentially important for future studies of the nondestructive evaluation of fiber reinforced composites.

References

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Table 1 Material properties and elastic constants for AS/3501-6 graphite fiber reinforced epoxy composite.

$E_{11} = 130.0$ GPa	$C_{11} = 132.54$ GPa
$E_{22} = 10.5$ GPa	$C_{22} = 12.03$ GPa
$G_{12} = 6.0$ GPa	$C_{33} = 12.03$ GPa
$G_{23} = 3.9$ GPa	$C_{44} = 3.90$ GPa
$\nu_{12} = 0.28$	$C_{55} = 6.00$ GPa
$\nu_{23} = 0.34$	$C_{66} = 6.00$ GPa
$\rho = 1520$ kg/m^3	$C_{12} = 4.54$ GPa
	$C_{13} = 4.54$ GPa
	$C_{23} = 4.19$ GPa

Table 2 Experimental and theoretical phase velocities for graphite fiber reinforced epoxy composite under different modes of wave propagation with energy flux propagating at 30° with respect to 3 axis.

Specimen No.	Wave Mode	Deviation Angle Δ_e (Degree)	Phase Velocity V_n (m/s)			Group Velocity V_g (m/s)		
			A*	B*	C*	A*	B*	C*
1	P	19	2678	2913	8	2888	3100	7
2	SV	13	2424	2590	6	2489	2659	6
3	SV	-18	2239	2336	4	2352	2456	4
4	SV	28	1992	2008	1	2233	2275	2
5	SH	8	1549	1661	7	1579	1678	6

A* : Experimental
B* : Theoretical
C* : % Difference

$$\%Difference = \frac{|\,Theoretical - Experimental\,|}{Theoretical} \times 100\%$$

Table 3 Experimental and theoretical values of arrival times for SV shear waves output voltage signals.

Energy Flux Direction θ (Degree)	Deviation Angle Δ_e (Degree)	Group Velocity V_g (m/s)		Arrival Time (μs)	
		Experimental	Theoretical	Experimental	Theoretical
30	13	2453	2659	4.782	4.412
	28	1778	2275	6.600	5.157
	-18	2229	2456	5.264	4.777
45	32	2852	2983	5.038	4.817
	41	2528	2744	5.684	5.237
	-18	2182	2266	6.584	6.341
64.77	57	4137	4166	5.760	5.722
	-13	2120	2076	11.244	11.482

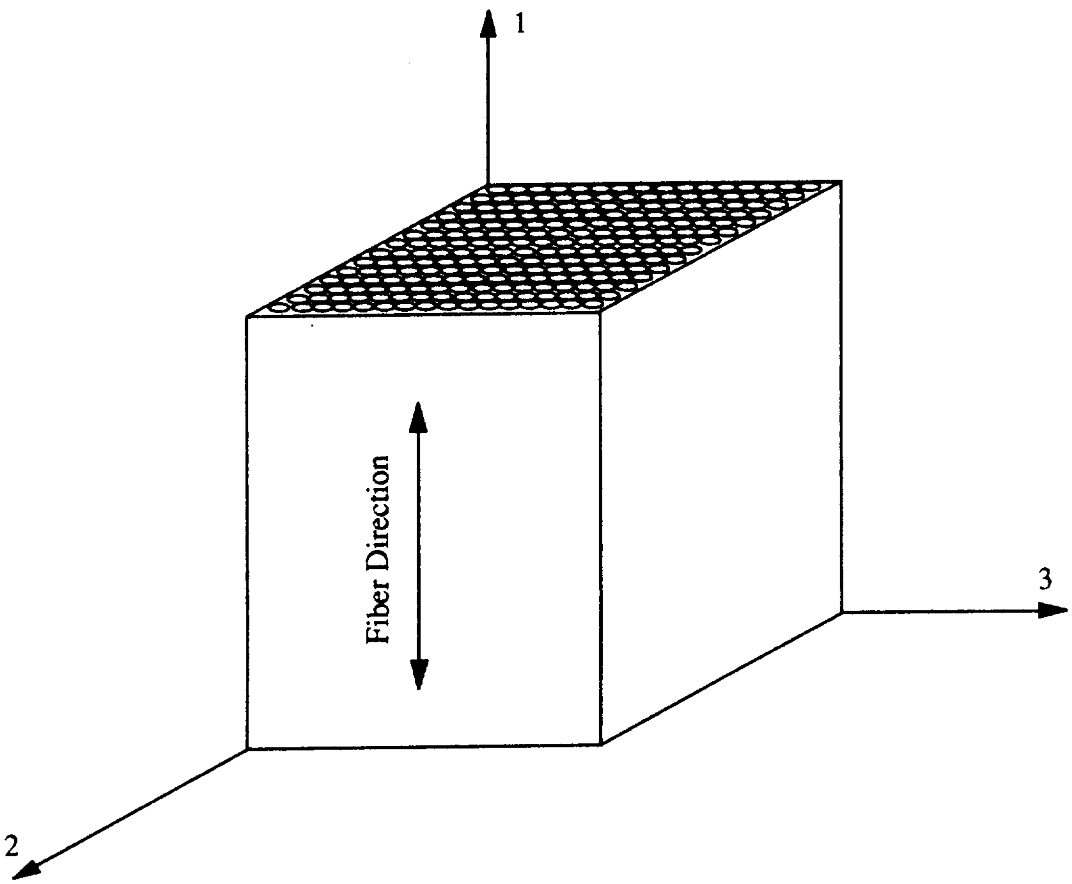


Fig. 1 Material axes for unidirectional graphite fiber reinforced composite.

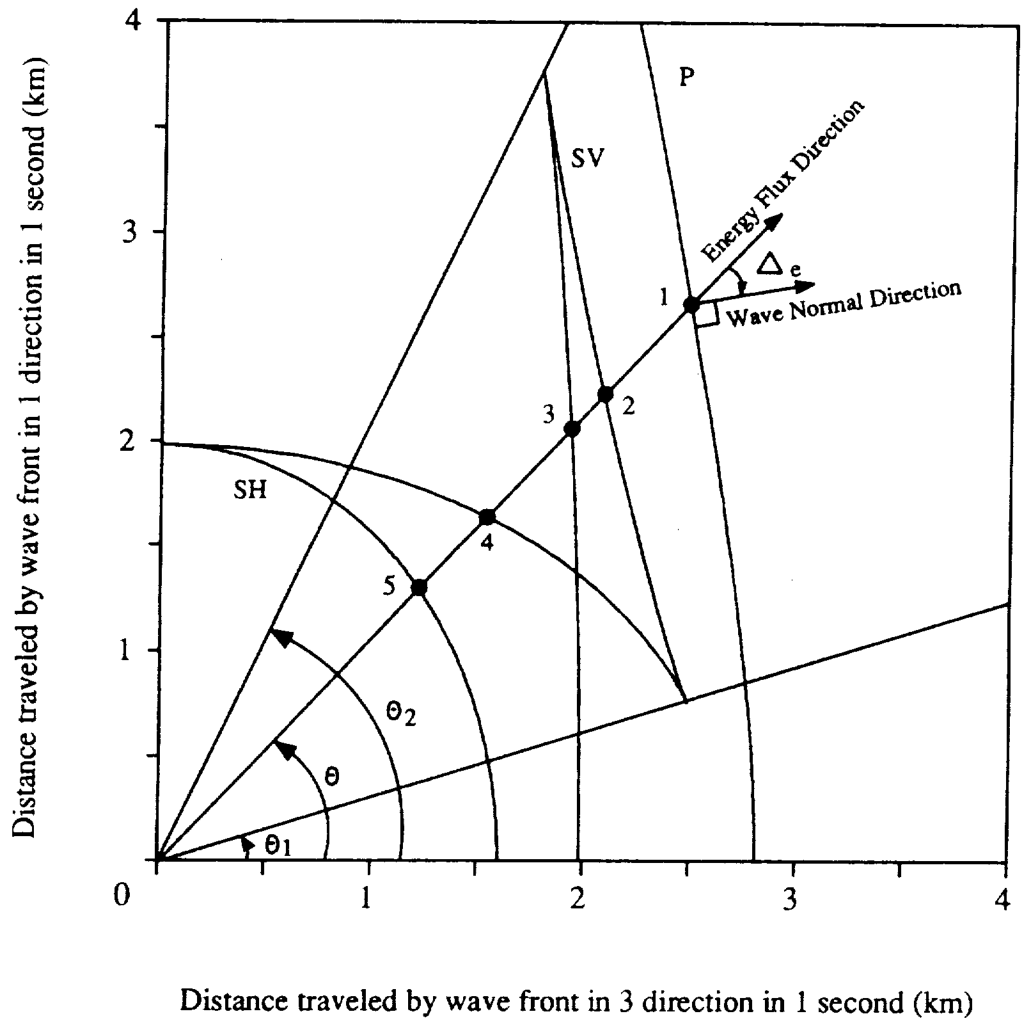


Fig. 2 Wave surfaces of composite in 1-3 plane.

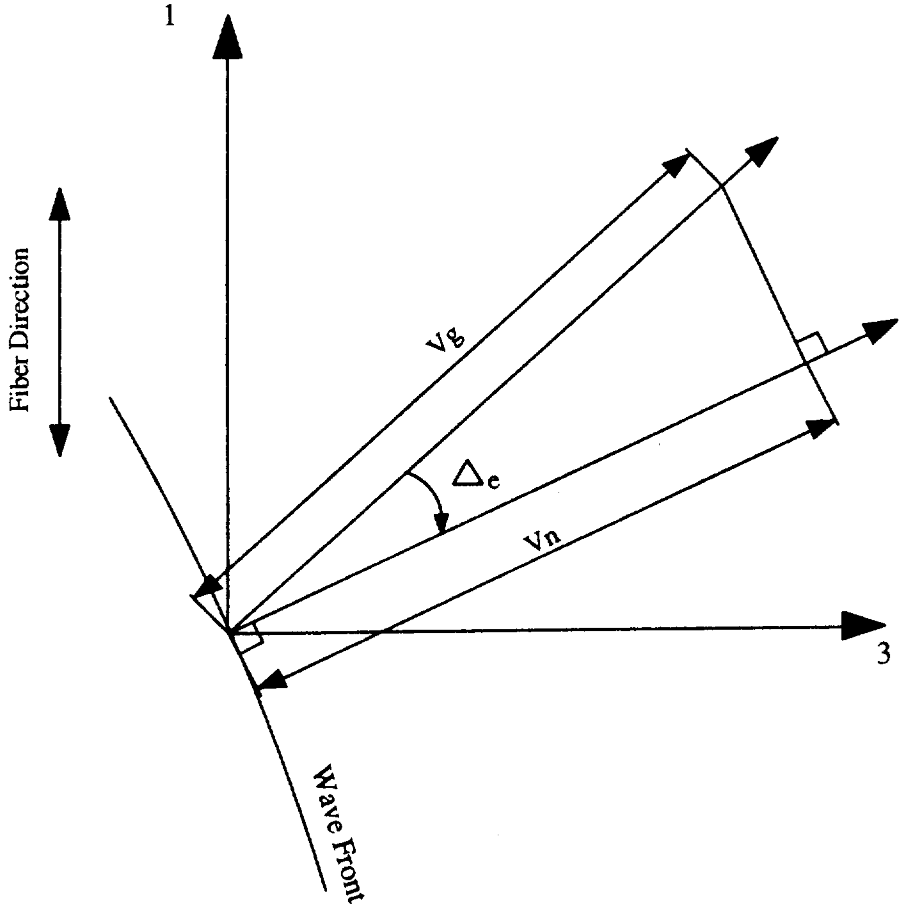


Fig. 3 Geometrical relation between group velocity vector Vg and phase velocity vector Vn.

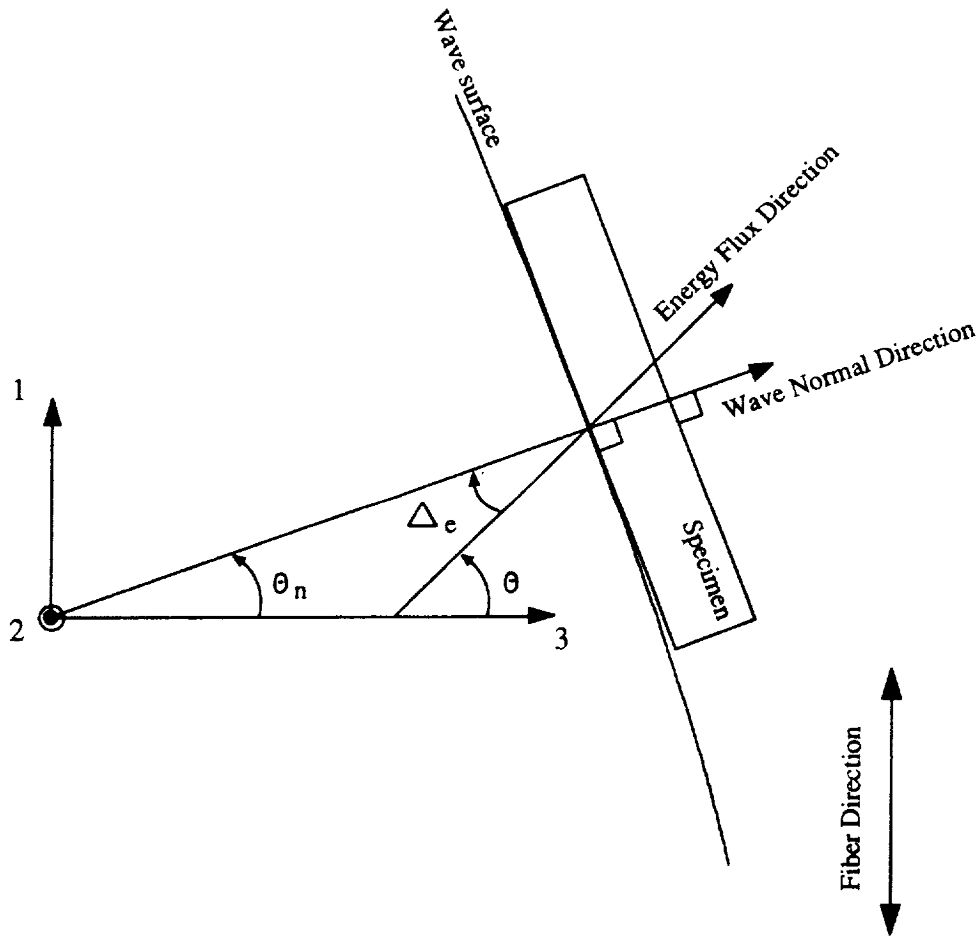


Fig.4 Relation of energy flux direction, wave normal direction and specimen orientation for Method I.

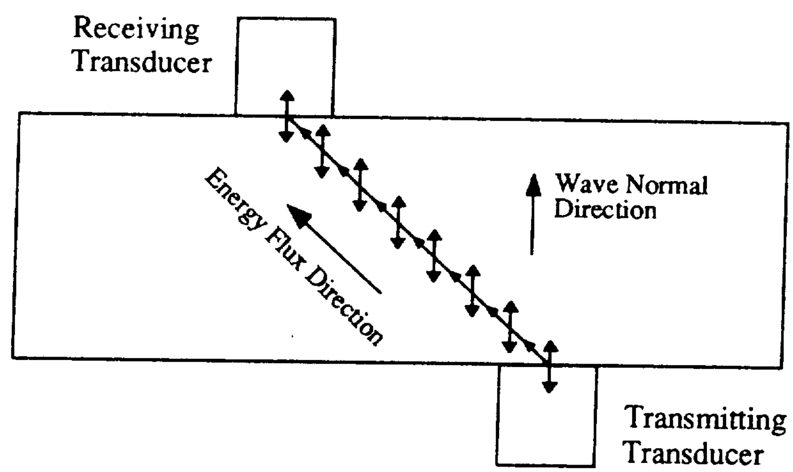


Fig. 5 Transducer arrangement for maximum output voltage amplitude.

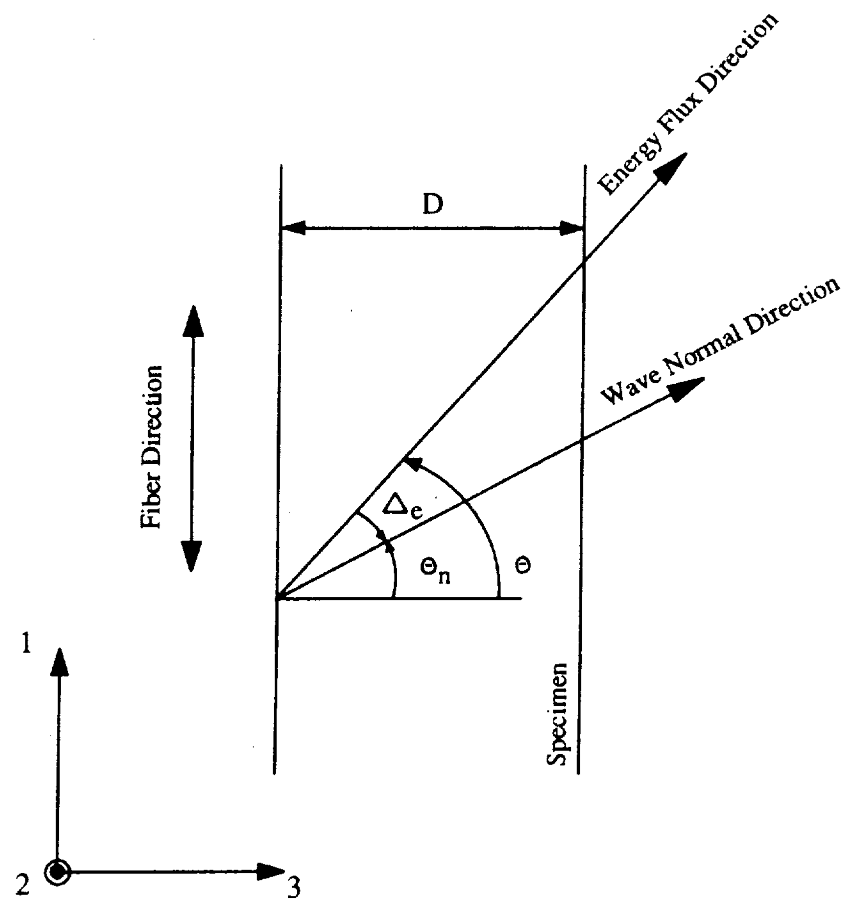


Fig. 6 Geometrical relation between specimen surface, wave normal direction and energy flux direction.

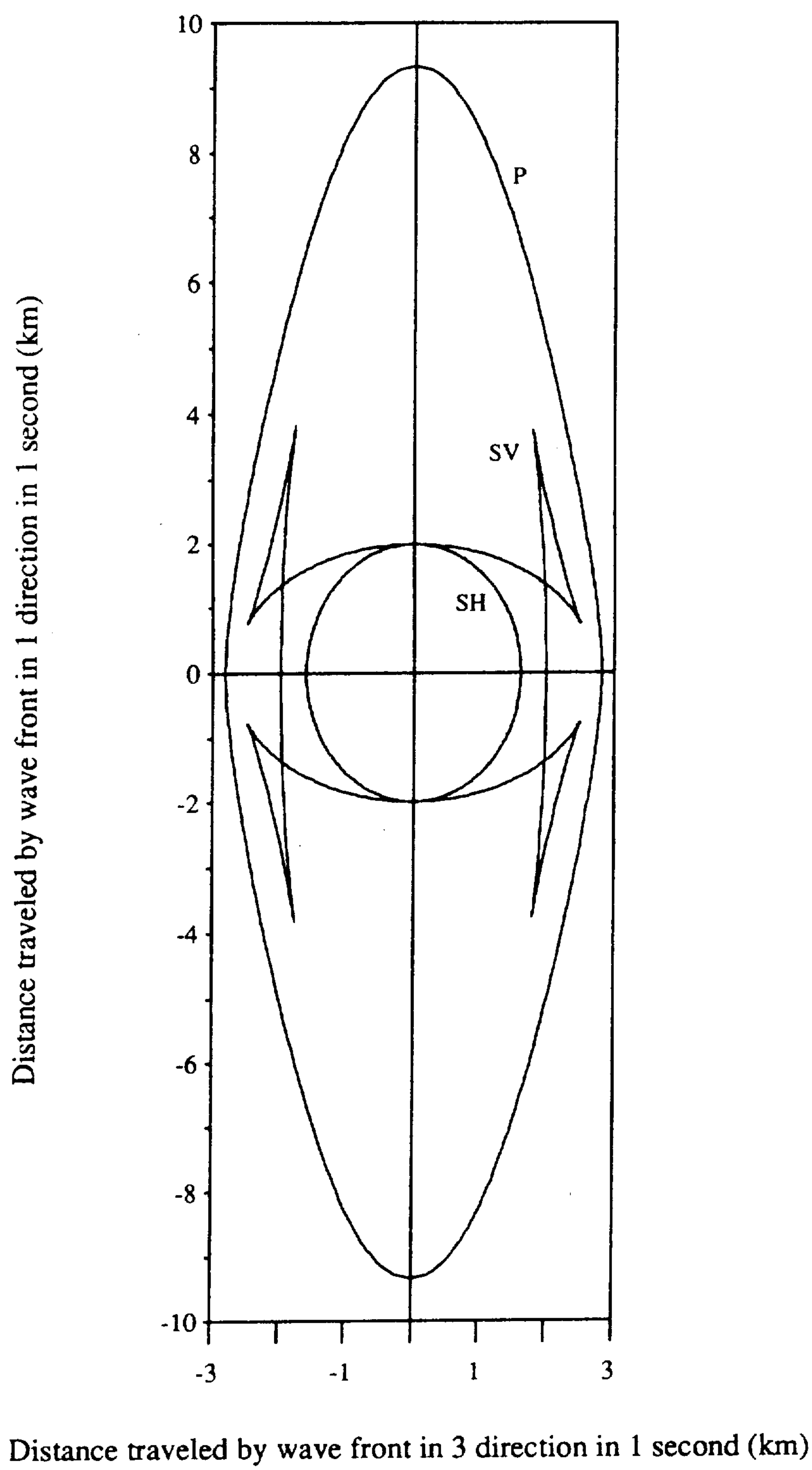


Fig. 7 Wave surfaces for unidirectional graphite epoxy composite in 1-3 plane.

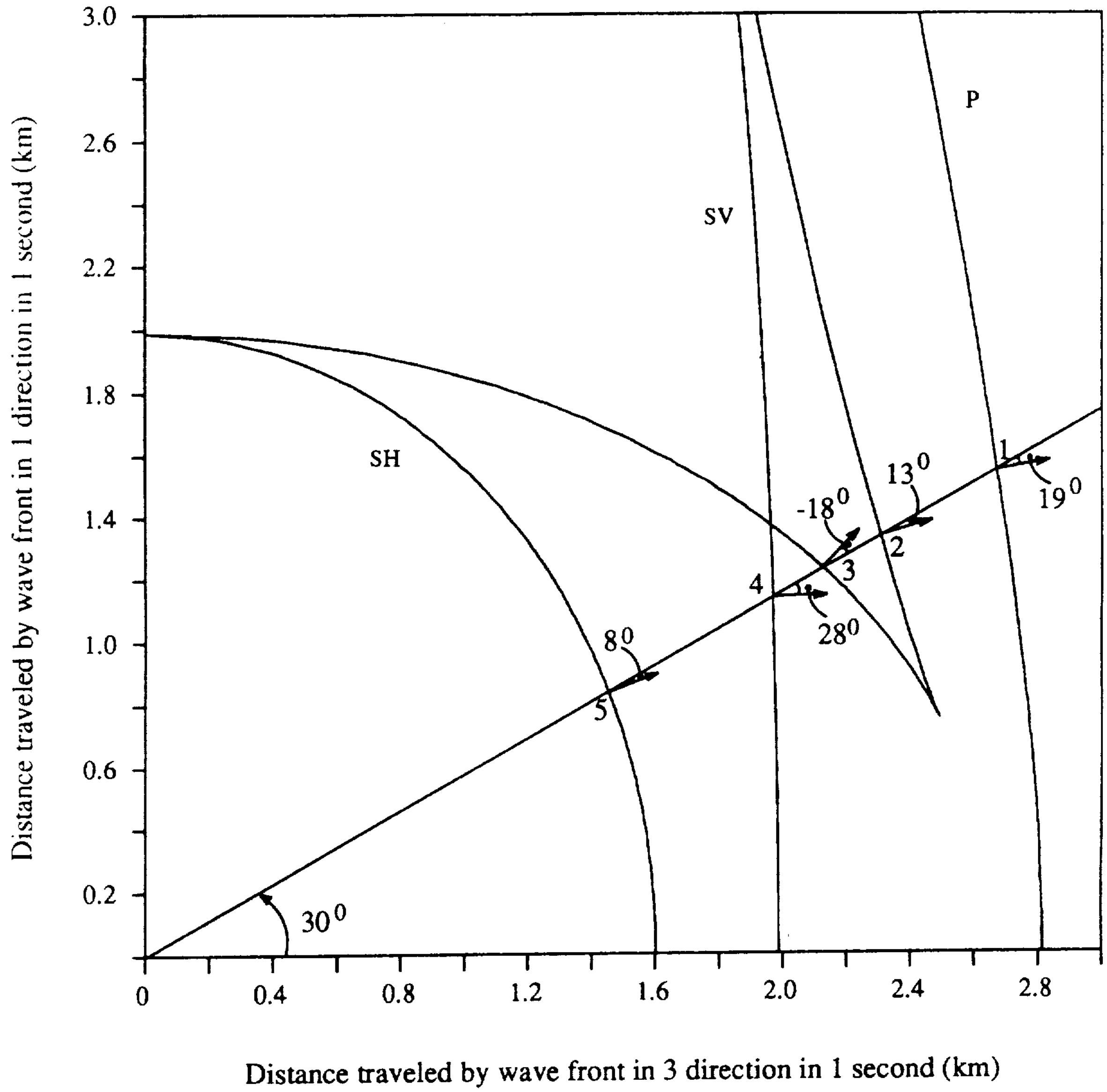
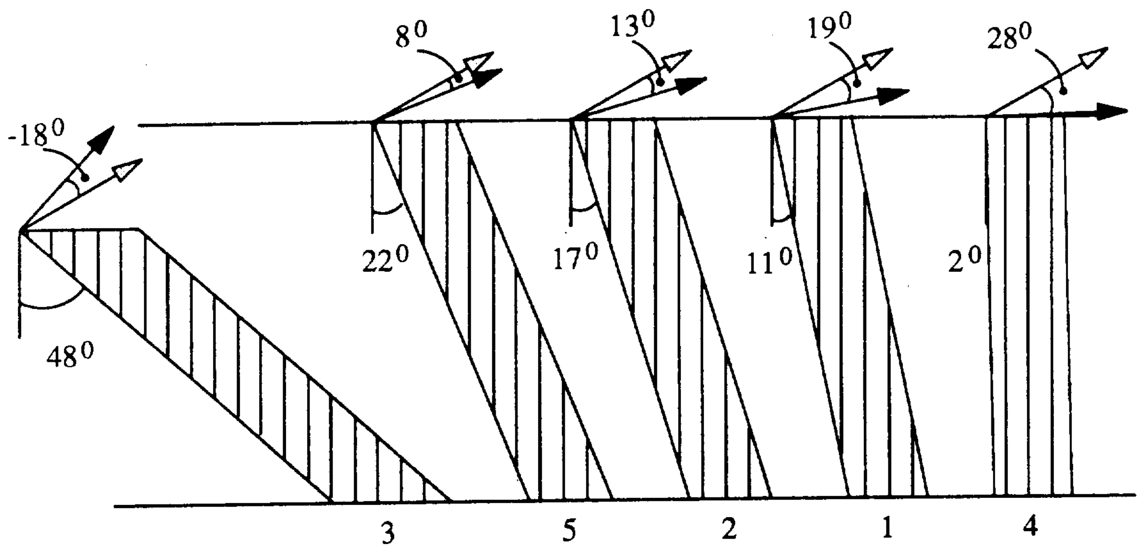
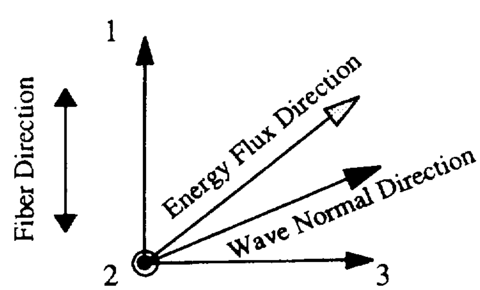


Fig. 8 Wave surfaces for graphite epoxy composite in 1-3 plane with energy propagating at 30^0 with respect to 3 axis, showing devation angles.





Specimens :

no. 1 for P wave phase velocity measurement
no. 2 for SV wave phase velocity measurement
no. 3 for SV wave phase velocity measurement
no. 4 for SV wave phase velocity measurement
no. 5 for SH wave phase velocity measurement

Fig. 9 Specimen configurations.

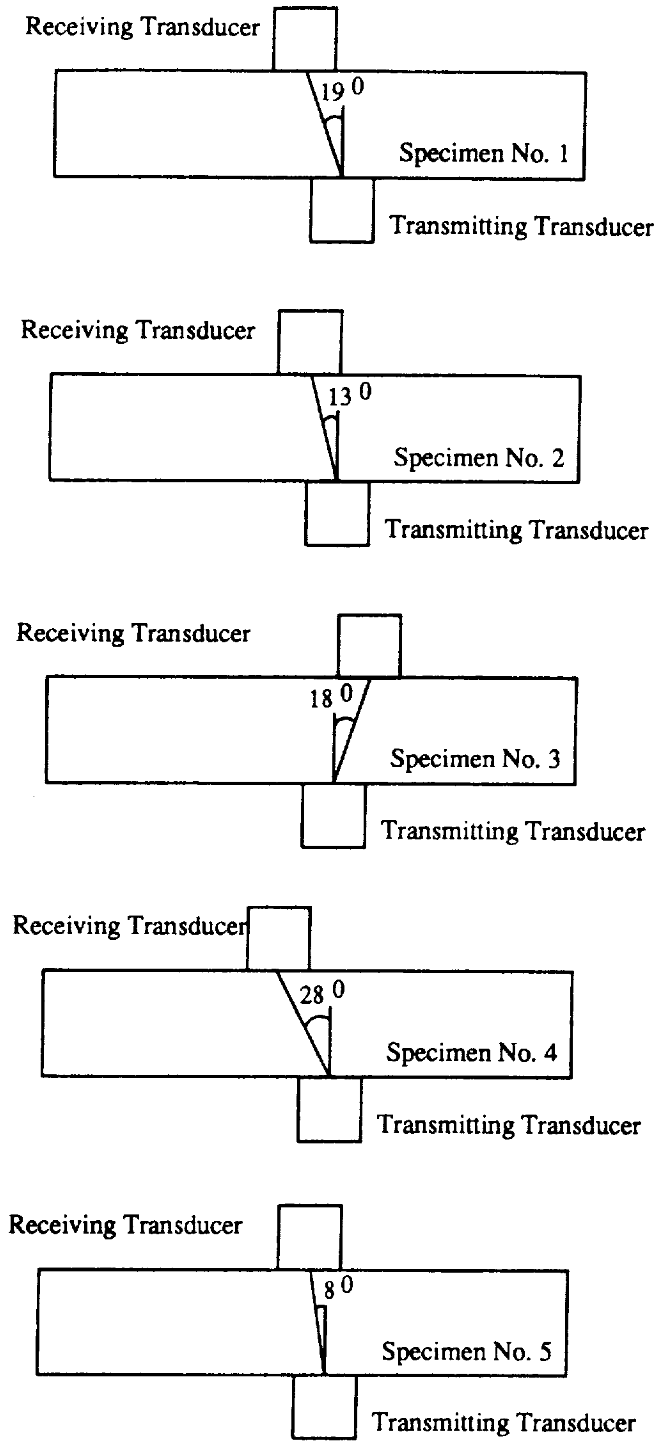
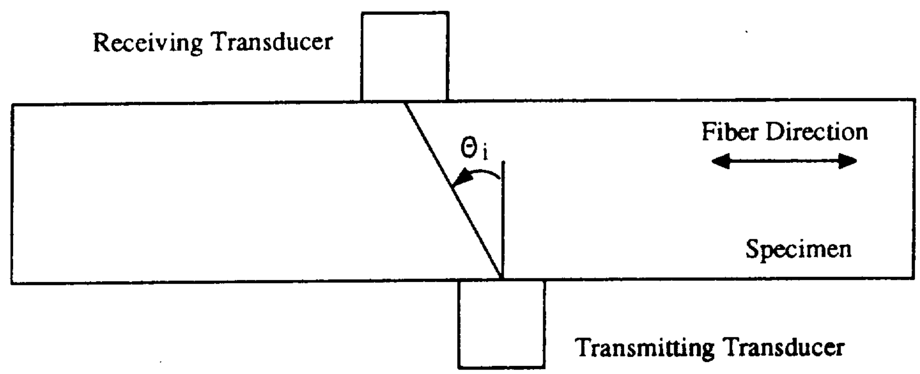


Fig. 10 Through transmission offset transducer arrangements for measuring input-output signals in experimental method I.



Experiments are conducted at three different transducer offset angles.
$\Theta_i = 30^0, 45^0$ and 64.77^0.

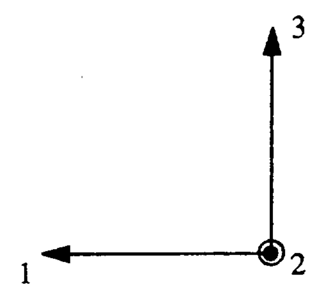


Fig. 11 Through transmission offset transducer arrangements for measuring input-output signals in experimental method II.

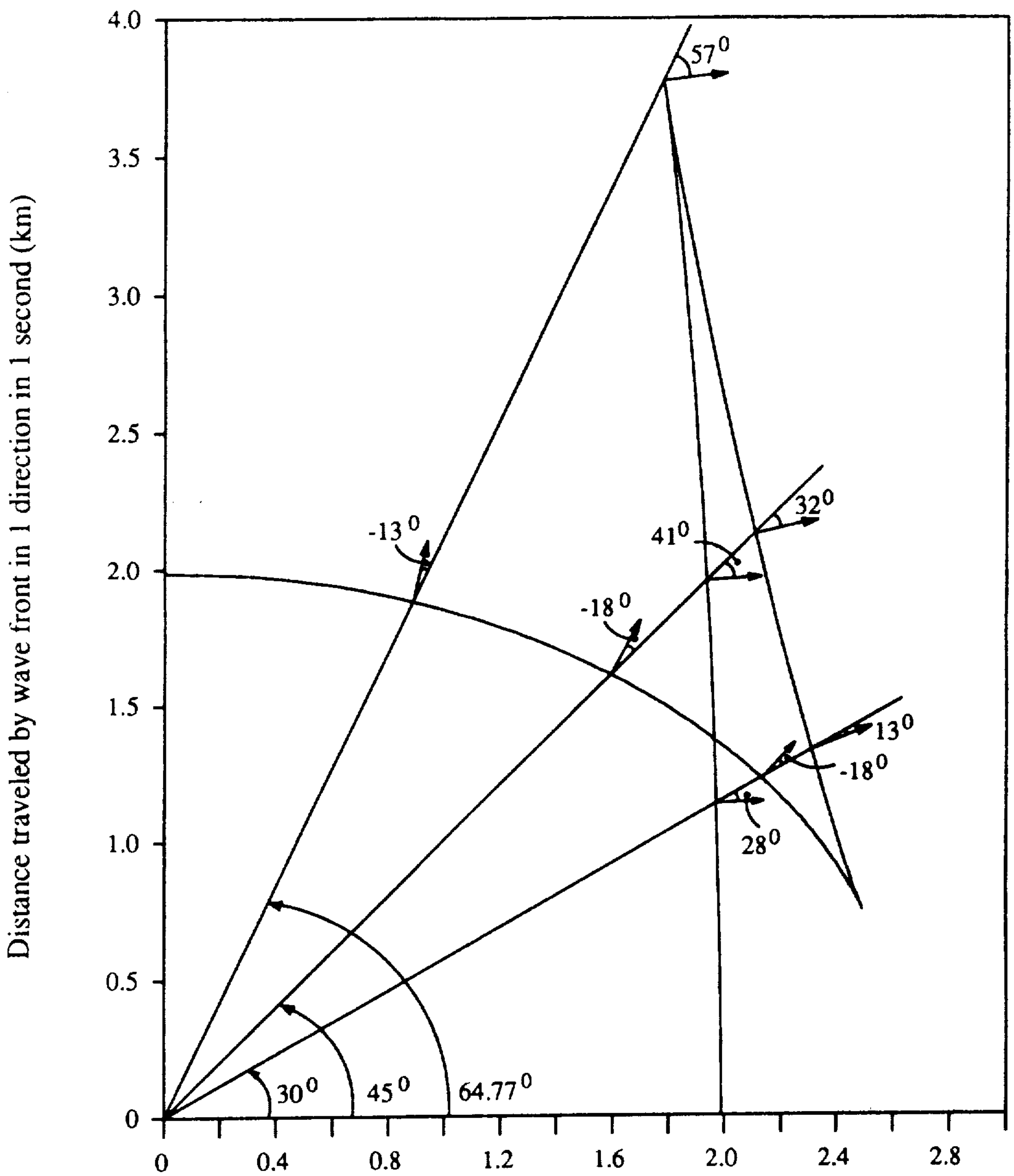


Fig. 12 SV wave surface for graphite epoxy composite in 1-3 plane with energy propagating at various angles with respect to 3 axis, showing deviation angles.

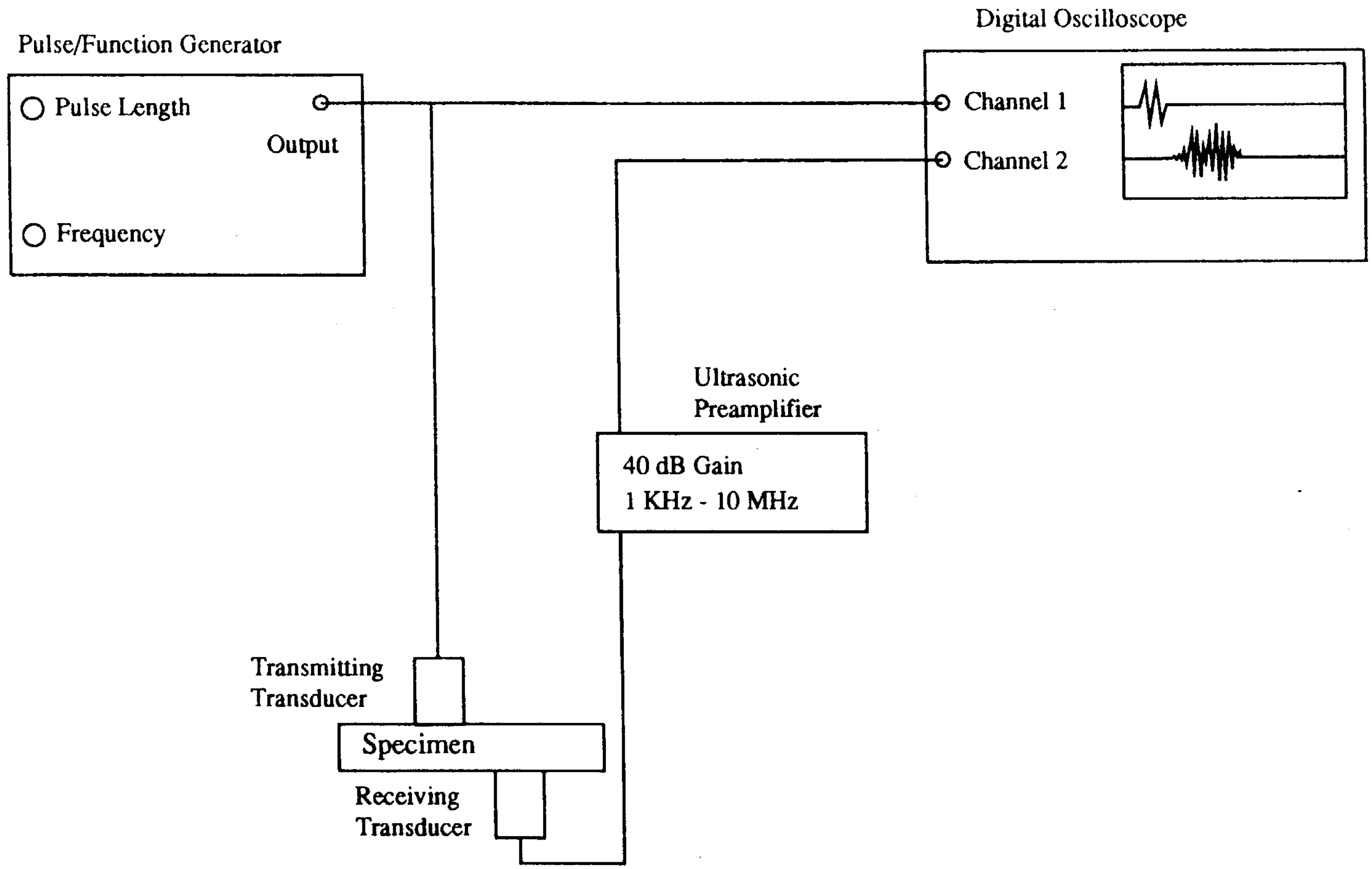


Fig. 13 Schematic of experimental system for through transmission measurements .

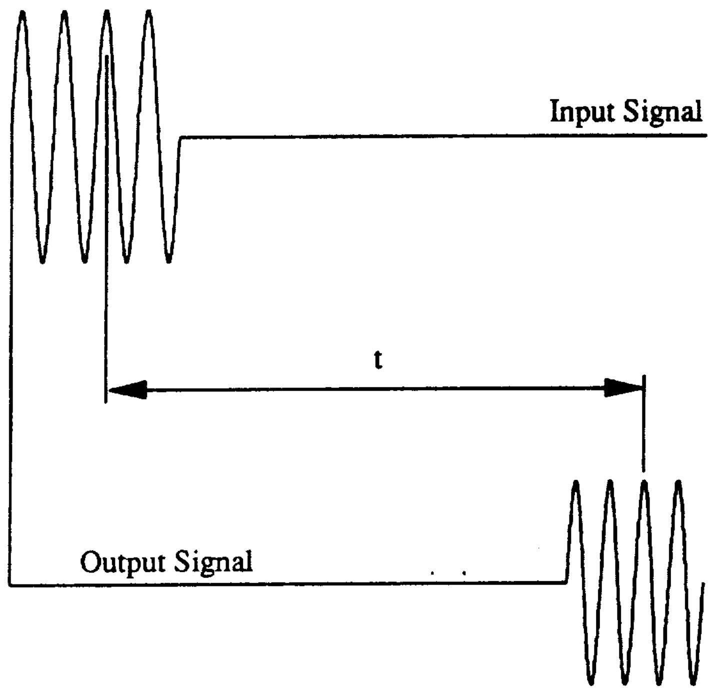


Fig. 14 Time shift between corresponding input-output signals.

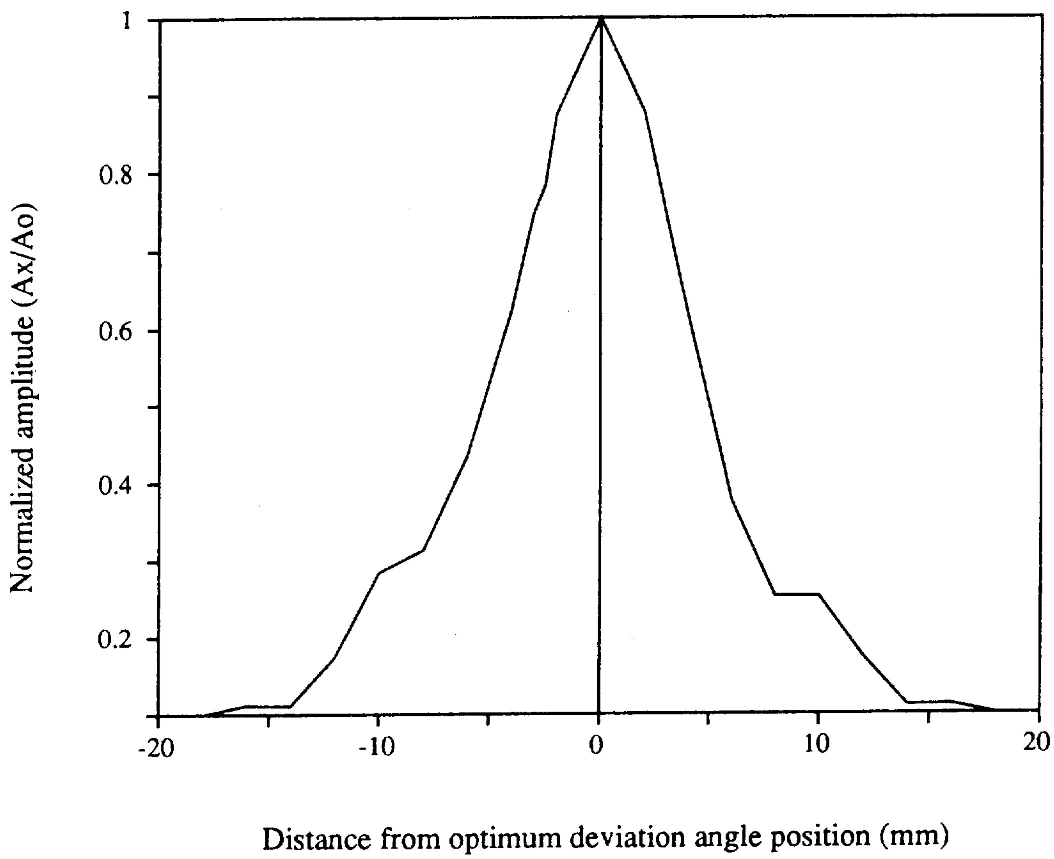


Fig. 15 Normalized output amplitude for longitudinal wave P
propagating in specimen no. 1.

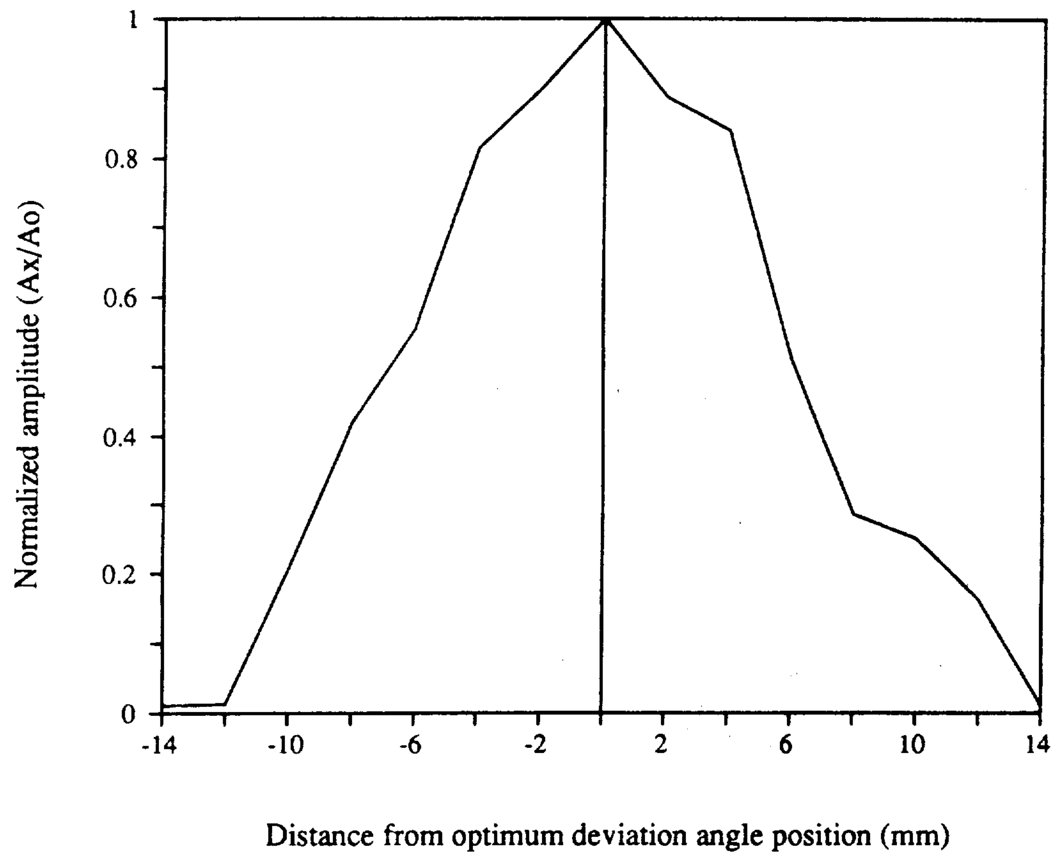


Fig. 16 Normalized output amplitude for shear wave SV propagating in specimen no. 2.

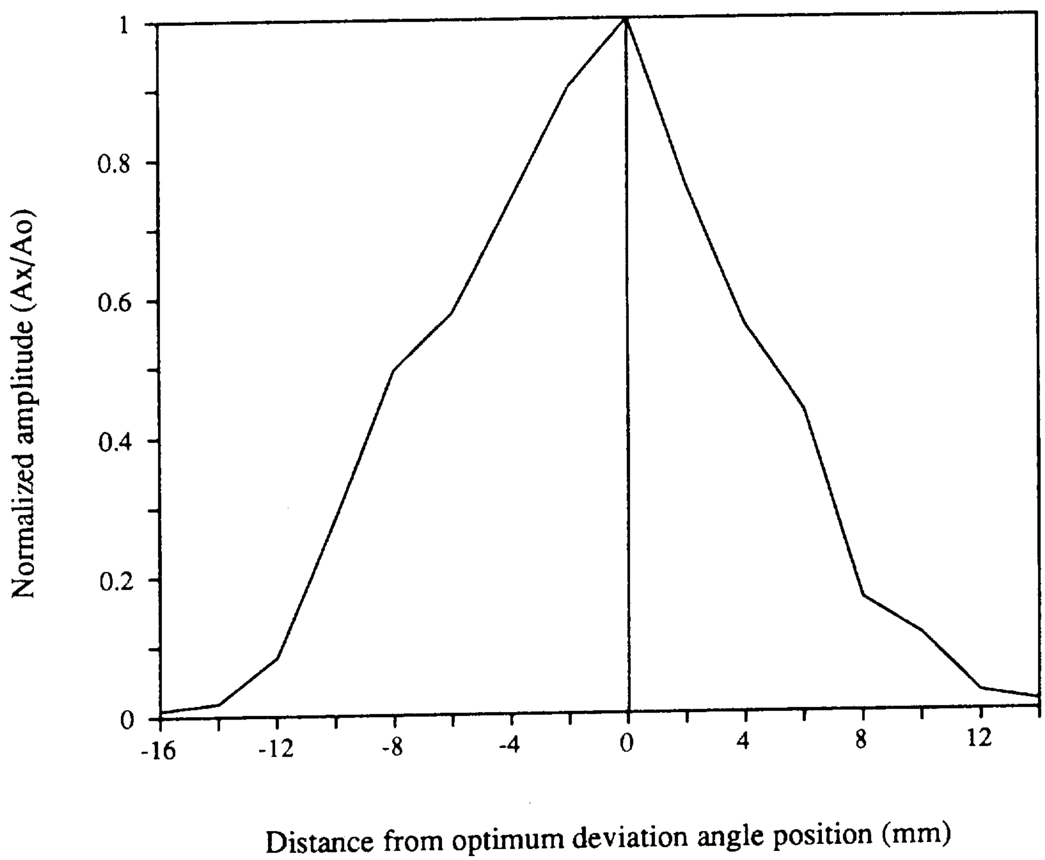


Fig. 17 Normalized output amplitude for shear wave SV propagating in specimen no. 3.

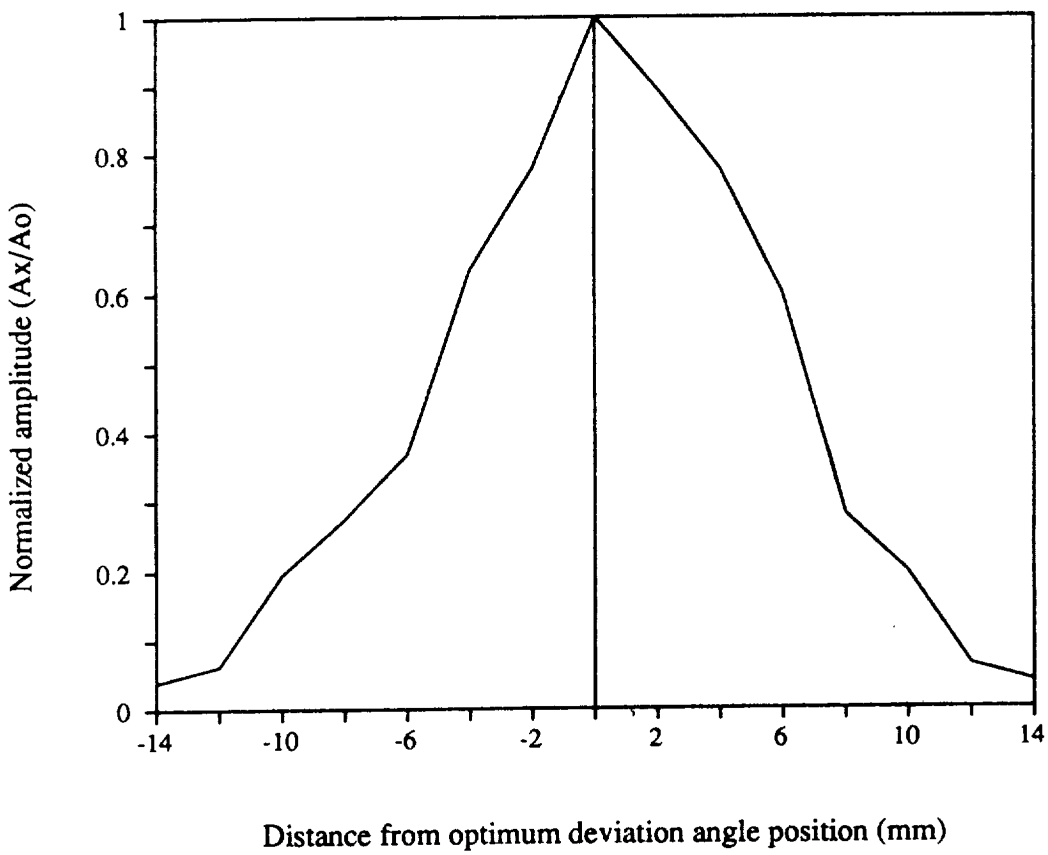


Fig. 18 Normalized output amplitude for shear wave SV propagating in specimen no. 4.

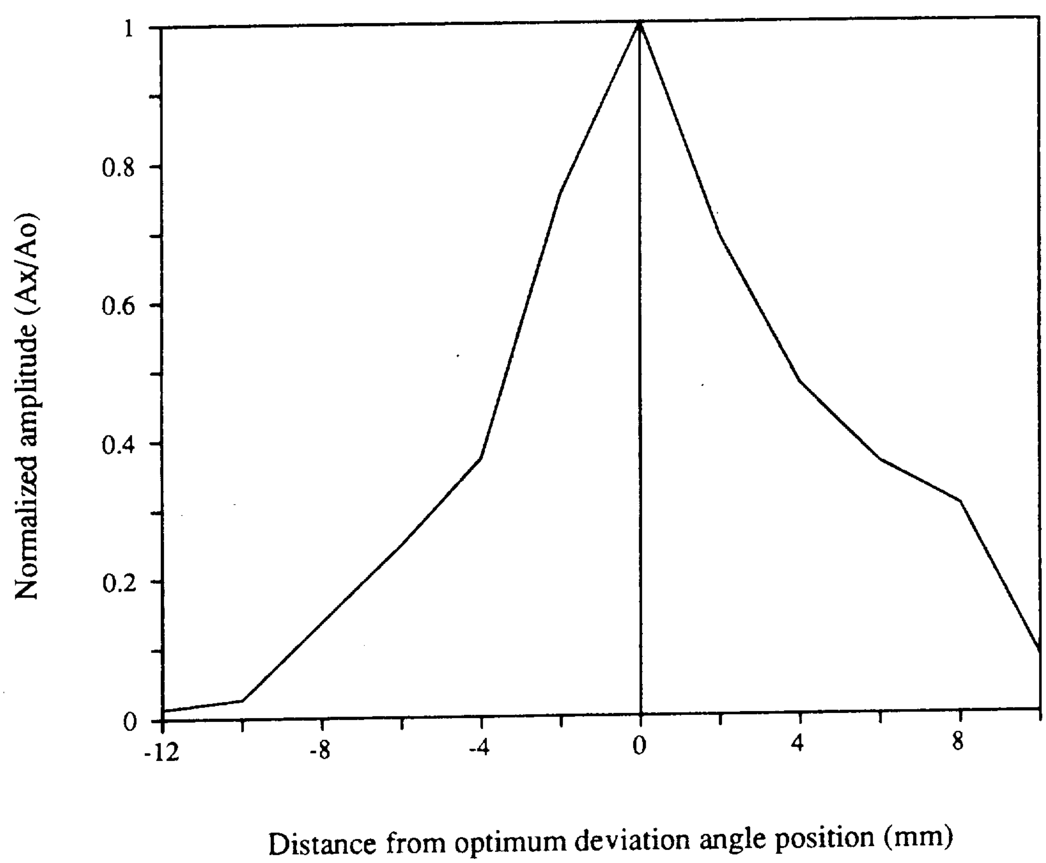


Fig. 19 Normalized output amplitude for shear wave SH propagating in specimen no. 5.

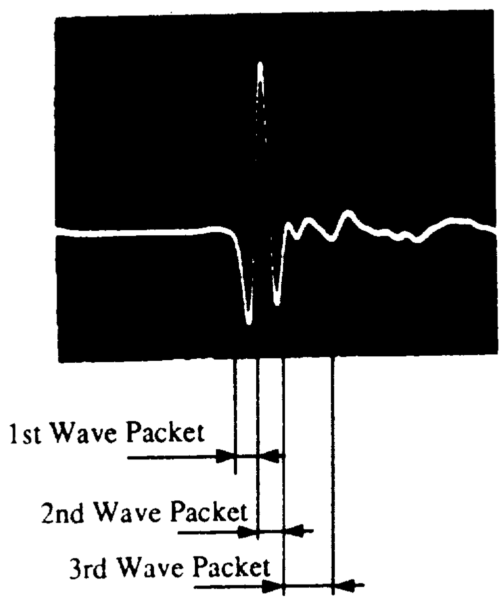


Fig. 20 Output signal from SV wave receiving transducer at an offset angle of 30^0.

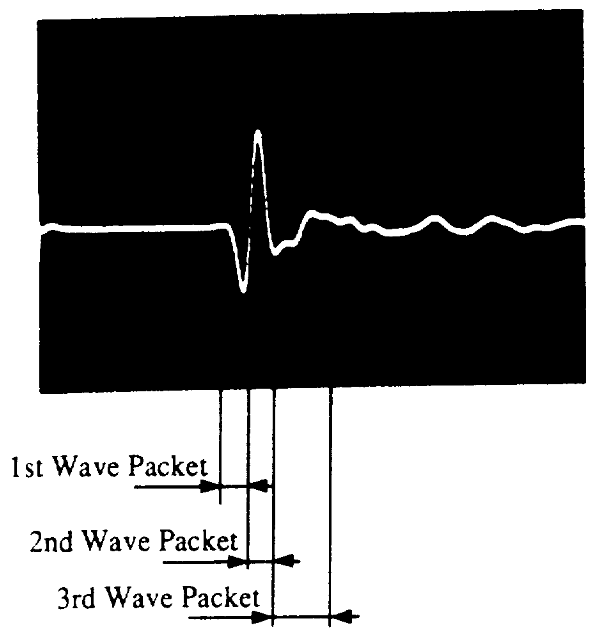


Fig. 21 Output signal from SV wave receiving transducer at an offset angle of 45^0.

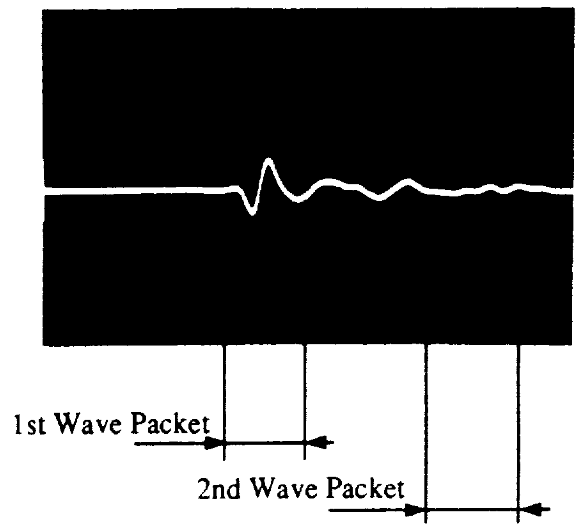


Fig. 22 Output signal from SV wave receiving transducer at an offset angle of 64.77^0.

Appendix A

SV Shear Wave Output Voltage Signal Verification

Ultrasonic nondestructive evaluation techniques consist of wave generation, wave propagation and wave detection. Many factors contribute to the final shape of the detected signal. Thus, to analyze the output voltage signal accurately, the effects of these factors on the output signal must be taken into consideration. In this appendix, two cases of potential error in ultrasonic signals are examined.

Theoretical Analysis

Case 1 :

When the transmitting and receiving transducers are in direct contact, the output voltage signal received by the receiving transducer is composed of four stress wave signals [1A]. Two stress waves T_C and T_D propagate directly from the transmitting transducer to the receiving transducer and two stress waves T_A and T_B reach the receiving transducer after being reflected from the far (back) face of the transmitting transducer. The superposition of these four stress wave signals produces the wave that becomes the output voltage signal, sometimes having two distinct wave packets. Fig. A-1 shows the typical input and output voltage signals when the transducers are in direct contact and the arrival times of the first and second wave packets are t_{CD} and t_{AB}, respectively. If the transmitting and receiving transducers are coupled to the opposite faces of a specimen, the arrival times of the two distinct wave packets in the output voltage signal due to the direct transmission of stress waves T_C and T_D and the reflected stress waves T_A and T_B are

$$t_1 = t_S + t_{CD}$$

$$t_2 = t_S + t_{AB}$$

for

$$t_S = \frac{D}{V_n(\theta)\cos\theta} \tag{1A}$$

where t_s is the time delay for the stress waves to propagate through the specimen, D is the specimen thickness, θ is the wave propagation angle and $V_n(\theta)$ is the directionally dependent phase velocity of the specimen. The typical output voltage signal for the case where the transmitting and receiving transducers are coupled to opposite faces of the specimen is shown in Fig. A-2.

Case 2 :

Reflections from the boundaries of the specimen may also affect the shape of the output voltage signal significantly. Consider the case where the transmitting and receiving transducer are coupled to the opposite faces of the specimen and the wave signal is detected by the receiving transducer after one reflection from the top face and one reflection from the bottom face of the specimen as shown in Fig. A-3. The total distance L_T traveled by the multiply-reflected wave is

$$L_T = 3\sqrt{\frac{L^2}{9} + D^2} \tag{2A}$$

where L is the spacing between the transducers. If the angle of incidence for the wave to propagate in the specimen with one reflection from the top face and one reflection from the bottom face of the specimen is θ_1 and the phase velocity is $V_n(\theta_l)$, the time delay t for the stress wave to reach the receiving transducer is

$$t = \frac{L_T}{V_n(\theta_1)}. \tag{3A}$$

Discussion and Conclusions

The SV shear wave output voltage signal for the case where the transmitting and receiving transducers are in direct contact is shown in Fig. A-4. The arrival times of the first and second wave packets t_{CD} and t_{AB} are 0.002 μs and 9.224 μs, respectively. Using the offset through transmission technique, the output voltage signal for an SV wave to propagate through a unidirectional graphite fiber reinforced epoxy composite with the transmitting and receiving transducers offset at three different angles (30°, 45° and 64.77°) are shown in Fig. A-5. From the first wave packet arrival time t_l, the time delay t_s and the arrival time of the second wave packet t_2 for the three measurements are calculated from eqn. (1A) and tabulated in Table A-1. For all cases, the arrival times of the second wave packet due to the stress waves T_A and T_B from the back of the transmitting transducer are greater than 14μs, which is also greater than the duration observed in the output voltage signals shown in Fig. A-5. Thus, the output signals received by the receiving transducer are from the direct transmission of the stress waves T_C and T_D and are not affected by the reflected stress waves T_A and T_B .

Table A-2 shows the theoretical time delays calculated from eqn. (3A) for SV shear waves to reach the receiving transducer after one reflection from the top face and one reflection from the bottom face of the specimen. The arrival times of all wave packets observed in Fig. A-5 are also listed in Table A-2. The multiple times given in the column labeled B* correspond to the multiple wave fronts. The (direct transmission) experimental arrival times are smaller than the calculated time delays for the multiply-reflected waves. These indicate that all the wave packets observed from the output voltage signals are from the direct through transmission (Fig. A-3).

To detect the possible reflection of stress waves from the side faces of the specimen, a composite is bonded to the specimen (Fig. A-6) and the output voltage amplitudes and arrival times of wave packets with the transmitting and receiving transducers offset at angles of 30° and 64.77° are recorded and compared with the output voltage amplitudes and arrival times of wave packets observed in Fig. A-5, where measurements are performed on the specimen without the added composite. The output voltage amplitudes of the SV wave packets and their arrival times observed from the specimen that is bonded to the composite and from the specimen alone are tabulated in Table A-3. Only a small difference in arrival times is observed between the two measurements. This disparity is likely due to the misalignment of transducers with respect to their correct offset angle position. The output voltage amplitudes received at the transducer offset angle of 30° appear to be approximately the same for both measurements. However, at the transducer offset angle of 64.77°, the output voltage amplitudes received by the receiving transducer from the specimen that is bonded to the composite are approximately 30% lower than the output voltage amplitudes recorded from the specimen alone. With the composite bonded to the specimen, the propagating stress waves that reach the side face of the specimen will either propagate into to the composite (if bonding is perfect) or be partially transmitted and partially reflected from the side face. Without the added composite, all the stress waves that reach the specimen side face will be reflected back into the specimen. If these reflected stress waves are detected by the receiving transducer, the output voltage signal will consist of the reflected stress wave signal and the directly transmitted stress wave signal. Thus, the lower output voltage amplitudes received by the receiving transducer from the specimen that is bonded to the composite at the transducer offset angle of 64.77° indicates that some (or all) of the stress waves that reach the specimen side face are being transmitted into the composite.

Reference

[1A] J. H. Williams, Jr. and B. Doll, "A Simple Wave Propagation Analysis of Piezoceramic Ultrasonic Transducer Response", *Materials Evaluation*, Vol. 40, December 1982, pp. 1374-1381

Table A-1 Arrival times of first and second wave packets due to direct and reflected stress waves propagating through the specimen.

Energy Flux Direction	Experimental Time Delay t_s (μs)	Arrival Time (μs)	
		First Wave Packet t_1	Second Wave Packet t_2
30°	4.780	4.782	14.094
45°	5.036	5.038	14.260
64.77°	5.758	5.760	14.982

Table A-2 Time delays for SV shear waves to reach receiving transducer after direct transmission and after one reflection from top face and one reflection from bottom face of the specimen.

Incidence Angle θ (Degree)	Incidence Angle θ_1 (Degree)	Arrival Time (μs)	
		A*	B*
30	10.89	12.68	4.782
			6.600
			5.264
45	18.44	12.38	5.038
			6.684
			6.584
64.77	35.28	15.03	5.760
			11.244

A*: Theoretical prediction of first wave packet arrival times for wave propagating at an incidence angle of θ_1

B*: Experimental arrival times of all wave packets for wave propagating at an incidence angle of θ.

Table A-3 Time delays and output voltage amplitudes for SV shear waves packets to reach the receiving transducer when measurements are performed on the specimen alone or on the specimen that is bonded to an extra composite.

Incidence	Arrival Time (μs)		Output Voltage Amplitude (mV)	
Angle θ	C*	D*	C*	D*
30	4.813	4.782	105.564	103.225
64.77	5.761	5.760	15.609	22.016
	11.234	11.244	2.356	4.009

C*: Specimen bonded to an extra composite.
D*: Specimen alone.

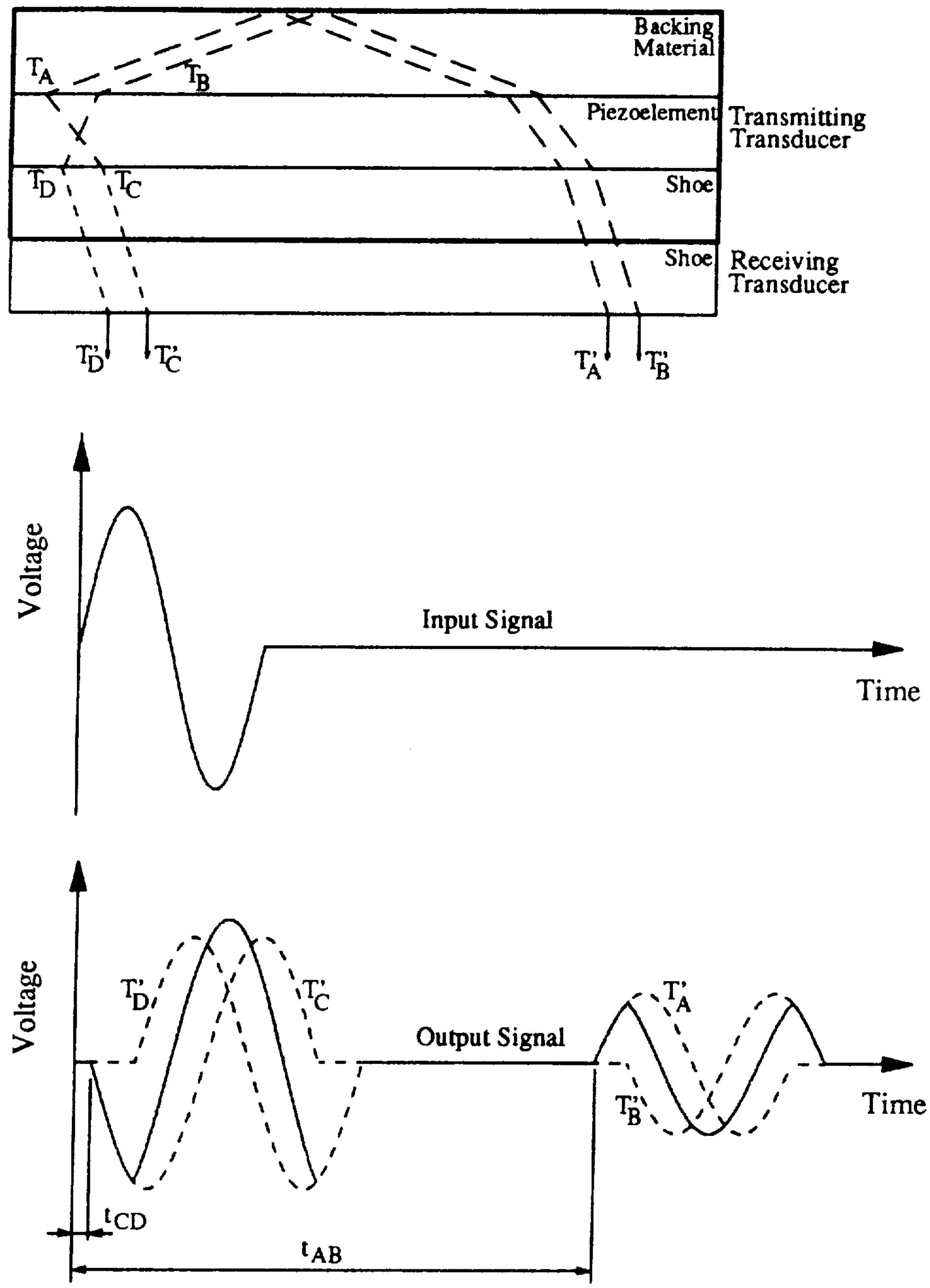


Fig. A-1 Input and output signals for two transducers in direct contact.

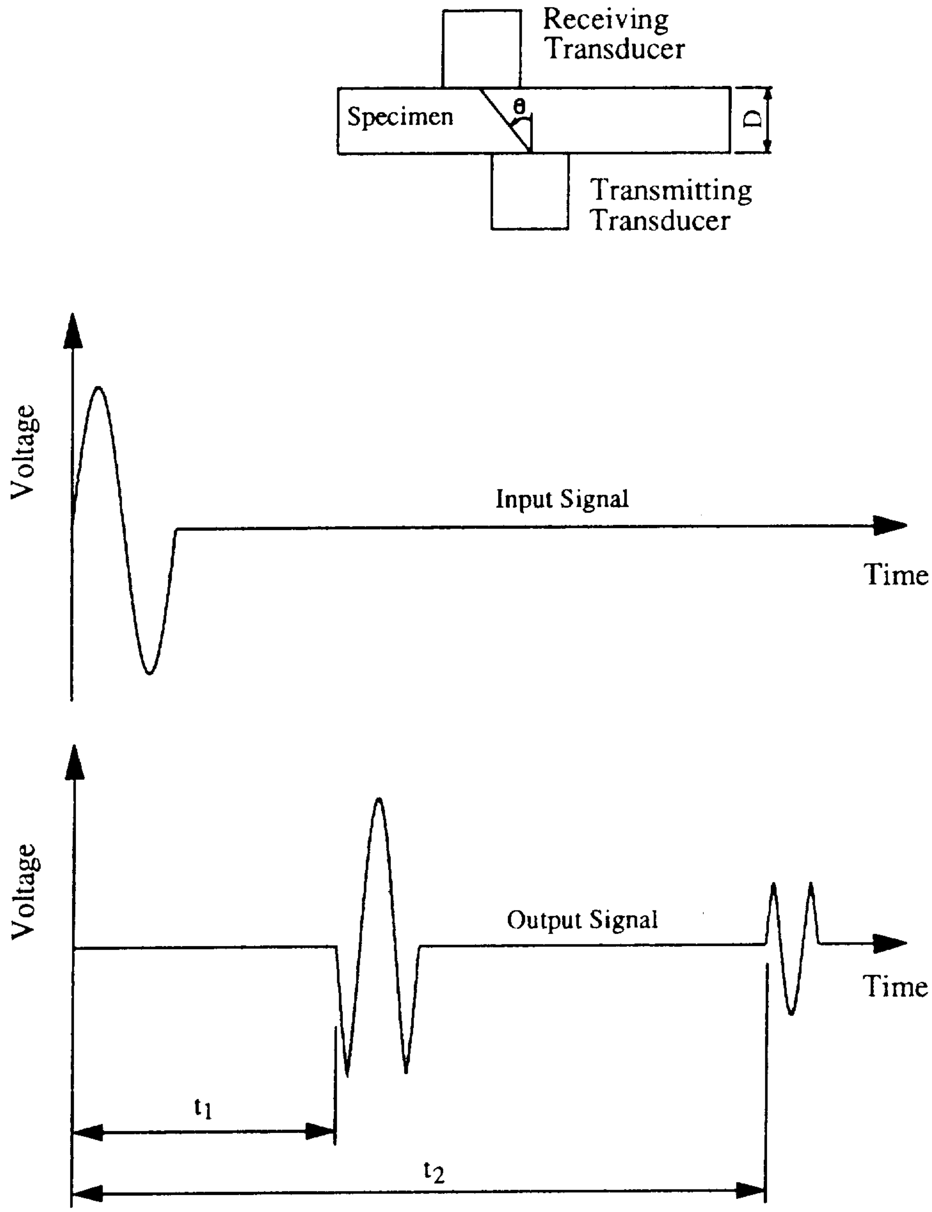


Fig. A-2 Input and output signals for through transmission measurement.

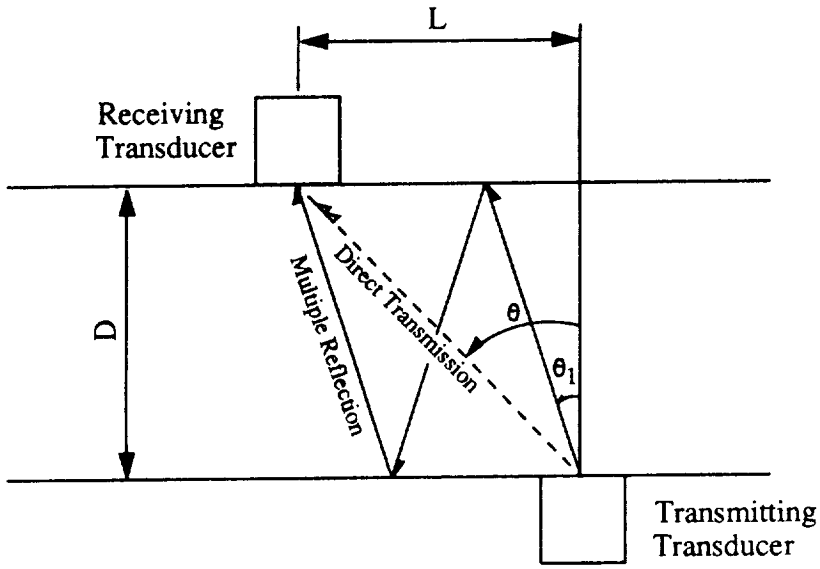


Fig. A-3 Direct transmission and multiply-reflected waves.

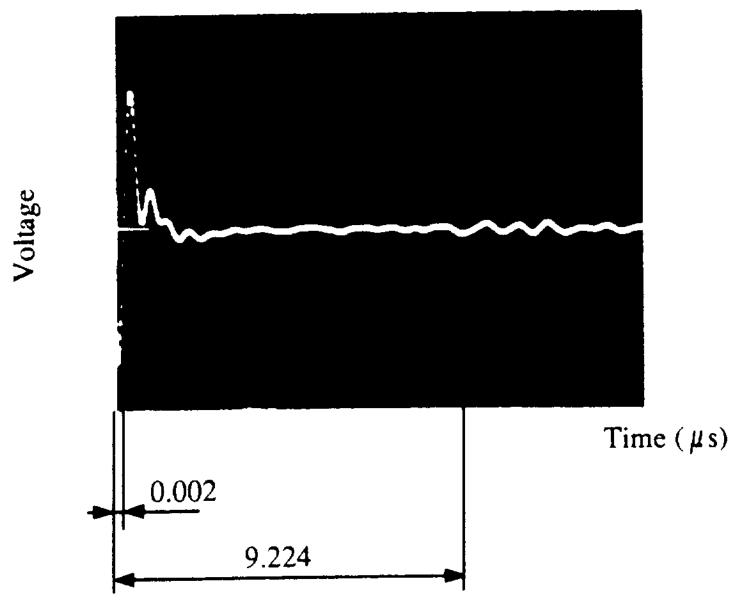
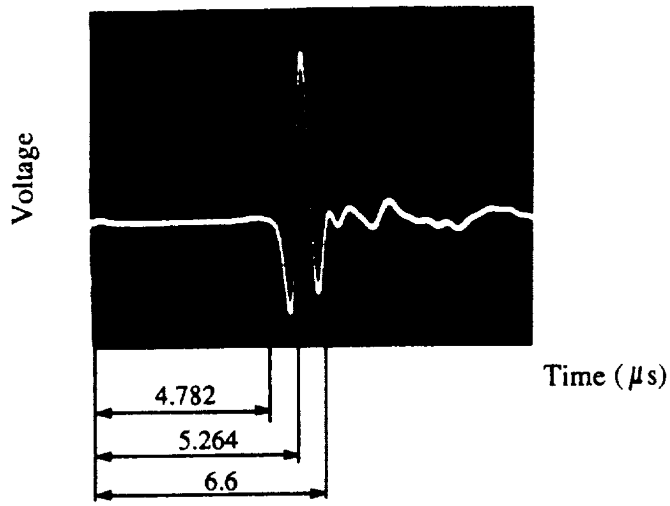
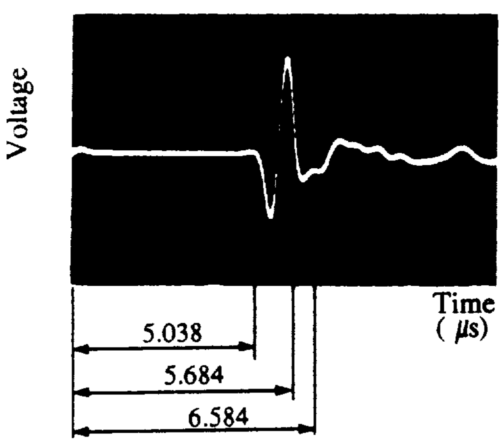


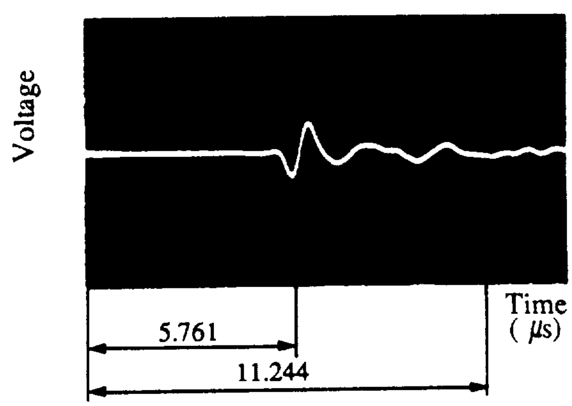
Fig. A-4 Output signal for two SV wave transducers in direct contact (duration of input signal is $0.002 \mu s$.



(a) 30^0



(b) 45^0



(c) 64.77^0

Fig. A-5 (a) 30^0, (b) 45^0 and (c) 64.77^0 transducer offset angles output voltage signals from through transmission measurements.

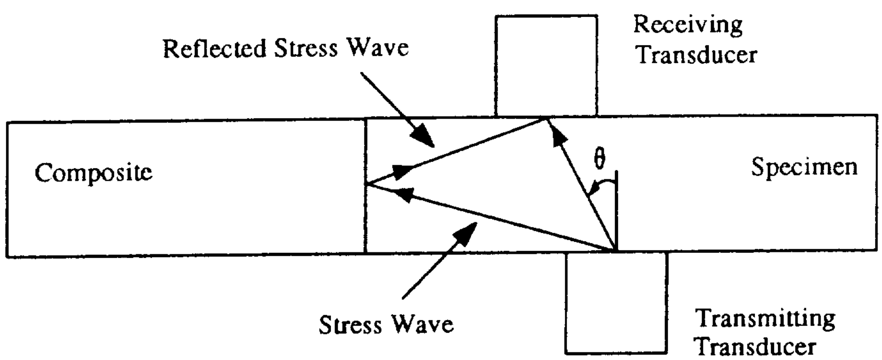


Fig. A-6 Stress waves received by receiving transducer after being reflected from side boundary of specimen.

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16. Abstract

The existence of five different waves fronts in a unidirectional graphite fiber reinforced epoxy composite with energy flux propagating at an angle of 60° with respect to the fiber direction is verified by measuring their corresponding group and phase velocities of longitudinal and shear waves using the through transmission technique. The experimental and theoretical values of phase velocities show excellent agreement for all three modes of wave propagation. It is also verified that the maximum output voltage amplitude is obtained when the line joining the centers of the transmitting and receiving transducers is parallel to the energy propagation direction defined by the deviation angle.

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