The Lucchi Elasticity Tester

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Summary

The values of Young's Modulus obtained using the Lucchi Elasticity Tester have been compared with published values for some common materials and also compared with the results of other test methods. Agreement was obtained for the common metals. The Tester gave values higher than published figures for the plastics tested and higher values for wood compared with those from a static method. Care is needed in the interpretation of the Young's Modulus measured in transverse directions in wood as shear deformation appears to be significant in some test methods.

Introduction

The single most important parameter of soundboard material for musical instruments is the radiation constant. This should be as high as possible to give maximum sound output. This constant is obtained by dividing the velocity of sound in the material by the density. The latter is readily obtained from the weight of an accurately prepared rectangular prism, cut from the waste part of the soundboard, and the volume from the dimensions. The velocity of sound can be found from the resonant vibration of a beam of the material or the transit time for an ultrasonic wave to pass through the material. The Lucchi Tester measures the latter and is the subject of this study.

Sound wave propagation in homogeneous materials is considered to be well understood. Propagation in composite materials is not well understood. Wood is thought to behave like a layered composite material. This idea is supported by its microstructure and the orthotropic nature of its physical properties. It has been suggested that very high frequency sound waves travelling along the grain see the structure as a waveguide and when travelling across the grain, as a band pass filter. Bedford et.al. (1) summarise the present understanding on composite materials. To a first approximation, when the wavelength is long compared with the structural periodicity in the direction of propagation, dispersion does not occur and the phase (wave) and group velocities are equal. This means that the signal remains unchanged during its passage through the material and valid results can be obtained.

The measurement of sound velocities and hence elastic constants in spruce and maple, has been done by Bucur (2) in recent times using MHz frequencies.

1. Bedford A. Drumheller D.S. and Sutherland H.J., Mechanics Today, Vol 3, ed. S. Nemat-Nasser, Pergamon, 1976.
2. Bucur V., CAS Newsletter #47, May 1987, 42.

The present study was aimed at determining the signal frequency of the Lucchi Tester and evaluating its use on various materials and comparing the results with those from static and resonant vibration methods.

The Lucchi Elasticity Tester

The Tester allows the average velocity of a sound pulse to be determined over a distance in the sample being tested. It is localised to a specified direction in the sample.

The Tester emits an ultrasonic pulse from a transducer placed in contact with the sample and the pulse is detected by a receiver placed at another position on the sample. The transit time is displayed on a digital readout. Coupling with the sample surface is achieved at the transmitter by a thin layer of soft rubber glued to the transmitter. A certain pressure is required between the transmitter/sample/receiver and is found with the aid of a calibration bar of Perspex and a known transit time. This pressure is maintained for all subsequent readings. The transmitter and receiver are manipulated while maintaining the desired pressure to achieve a steady minimum reading of the time.

The time is expressed in microseconds (us) so that:

Sound velocity (km/s) = Length (mm)/Time (us),

and with the calculated Density (kg/m^3), the elastic modulus in the direction of propagation can be calculated using the equation:

Young's Modulus (N/m^2) = Velocity^2 (m/s)^2. Density (kg/m^3)

The Tester has rechargeable Ni-Cd batteries and a charger making it portable.

Experimental Details

Surface preparation was found to be important in that a smooth plane surface was necessary for proper transmission of the signal and its detection. A rough sawn surface on wood as typically found on tonewood billets, particularly on the endgrain, was unsatisfactory. The surface had to be planed smooth or fine sanded. Difficulty in obtaining a consistent reading is the result of a rough surface.

Two holders were made for the transducers, the one holding the receiver was spring loaded so that the holding pressure could be reproduced and maintained easily during successive readings. They were turned from solid plastic; the position of the receiver could be marked during calibration. These were used for all readings.

The signal from both the transmitter and the receiver were recorded on a digital storage oscilloscope and subsequently plotted. Figure 1 shows both signals for the perspex calibration bar; the transmitted signal above that received. The received signal was much weaker than that transmitted. The scaling for the former was 200 times that for the transmitted signal. The time in 0.1 microseconds is counted from the initial onset of the transmitted signal until detected by the receiver. The waveform of the transmitted signal was remarkably reproducible in every detail in all the tests done. The signal at the receiver was different in form and amplitude but showed a general similarity with different materials.

The two signals in figure 1 were analysed to determine their frequency content. The result is shown in figure 2. The plot for Tx is at the bottom of this figure. In all other figures it is at the topl3 The starting spike on the transmitted signal was excluded as shown and the analysis yielded two main frequency bands centered around 60 kHz and 120 kHz. The width of the bands is partly accounted for by the small number of sample points. The same applies to the band in the analysis of the received signal which is also centered at 60 kHz and is a well defined peak.

The result for mild steel is shown in figure 3 where the vertical scaling for the receive signal is 10 times indicating lower damping than in perspex.

Signal traces are shown in figures 4,5 and 6 for the three orthogonal directions in a rectangular block of spruce. The vertical scaling is the same as that for perspex. The block was 242 mm (L direction), 60.5 mm (R direction) and 23.5 mm (T direction). The traces are similar in all three directions with some overlapping of the first reflected signal in the L direction.

Measurement of Sound Velocity in a Range of Materials

Some common materials in rod form were selected for sound velocity measurement. The ends were prepared in most cases by fine turning in a lathe. Table 1 shows the results obtained with comparison values taken from Kaye and Laby (3).

Table 1

Sound Velocity in Common Materials

Material	Density, d (kg/m^3)	Velocity of Sound, c (m/s)		Young's Modulus, E (x10^{10} N/m^2)	
		(K & L)	Expl.	(K & L)	Expl.
Brass 60:40	8400	3500-3650	3598	10.0	10.9
Mild Steel	7860	4700-5200	5137	20.0	20.7
Hi C Steel	7840		5227	20.9	21.4
Aluminium	2700	5100	5140	7.05	7.1
Glass (soda)	2500	5000-5300	5226	6.5-7.8	6.8
Perspex	1190		2195	0.3*	0.57
HD Polythene	950		1449	0.1*	0.2
Calibration Bar			2277	0.3*	0.62

* from Materials Data Book: E.R.Parker, McGraw-Hill, 1967.

(3) Kaye G.W.C. and Laby T.H. Physical and Chemical Constants, Longmans, Green and Co. 1944.

It can be seen that for the common materials and glass, the experimental values of the velocity of sound fall within the accepted ranges, and the calculated elastic moduli agree well with published data as would be expected. These materials would be considered to have homogeneous structures on a microscopic scale.

No sound velocity values have been found for the plastics quoted and the values of Young's Modulus given in the literature are about half those calculated from the sound velocities measured.

Comparison of Elastic Moduli Determined by Three Methods.

A further comparison of elastic moduli was made using two other experimental techniques; (a) the static deflection of a simply supported beam with centre loading, and, (b) the resonance frequency determination for the same beam in its lowest vibration mode.

The equation for Young's Modulus from the deflection of a flat rectangular section beam of the materialm simply supported and loaded at the centre, is given by:

$$E = (M.g.l^3)/(48.I.y) \qquad \text{Pascals } (N/m^2)$$

where E is Young's Modulus
M is the load, (kg)
g is acceleration due to gravity ($9.81\ m/s^2$)
l is the distance between supports
I is the section modulus ($bd^3/12$) (m^4), and
y is the deflection due to Mg.

The distance between supports was 0.135 m; the beams were 0.040 m wide and 0.001- 0.002 m thick for the metals and 0.003-0.004 m thick for the non-metals. Masses up to 1 kg in small increments were used to determine the deflection curve, the slope of which gave Mg/y.

The resonance method involved the same beam which was suspended over a speaker on string supports at 0.224xbeam length, from each end. A small magnet (0.15 g) was mounted in the centre of the beam and a coil placed over it and connected to a C.R.O. via a preamplifier to monitor the vibration amplitude. The frequency was read from a counter connected across the signal generator/amplifier output. An equation given by Haines (4) was used to calculate the elastic modulus, thus:

$$E = 0.946.d.f^2.l^4/t^2$$

where d is the material density
f is the resonant frequency
l is the length of the beam, and
t is the beam thickness.

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(4) Haines D.W. CAS Newsletter #33 May 1980. 19.

Finally, the same beams were used for velocity measurements with the Elasticity Tester. The recommended calculation was applied and the results calculated using the equation:

$$E = c^2.d$$

where c is the velocity of sound in the material (m/s)
d is the density of the material (kg/m^3).

Since the beams had been accurately dimensioned, they were weighed and the density calculated from the measured volume. The results from these three techniques are shown in table 2.

Table 2

Elastic Moduli by Three Methods

Material	Density	Young's Modulus (x10^{10} N/m^2)		
	(kg/m^3)	Static Bending	Resonant vibration	Sound velocity
Aluminium	2746	7.48	7.95	7.3
Mild Steel	7932	22.65	21.8	22.0
Perspex (3 mm)	1192	0.335	0.504	0.679
Perspex (6 mm)	1192	0.309	0.516	0.663
Spruce (L)	467	0.995	1.41	1.45
Spruce (R)	473	0.043	0.0565	0.067
Spruce (R)	473	0.049	0.065	0.072
Maple (L)	553	0.818	0.946	0.946
Maple (R)	570	0.135	0.151	0.165

Discussion

The discussion centres around three things; the frequency used to determine the velocity of sound, the comparison of experimental Young's Modulus with published values and with other methids of determination.

In the Elasticity Tester the sound waves are presumably longitudinal compressional. Interaction is possible when the wavelength is of the same order as the spacing between growth rings. For the frequency of 60 kHz used, the wavelength is more than 10 times the spacing for most sound velocities and spacings encountered in acoustic soundboards. The relation, wavelength = c/f, leads to the following values in table 3 for the approximate wavelength as a multiple of ring spacing, for typical values of ring spacing and sound velocities.

Table 3

Velocity (c) (m/s)	Number of rings equal to the Wavelength at a ring spacing of 1 mm	2 mm	4 mm
4250	60	30	15
3250	50	25	13
2250	35	15	7
1250	20	10	5
750	12	6	3

For comparison, at a frequence of 1 MHz used in ultrasonic studies of elastic constants, a velocity of 4250 m/s gives a wavelength of 4 mm, and at 1250 m/s a wavelength of 1 mm. A wavelength of about 10 times the ring spacing would be considered desireable.

In looking at the elastic moduli, the agreement is good between values published for some common metals e.g. aluminium and mild steel, and the experimentally determined values shown in table 1. However, in the same table, the values for Perspex and HD Polythene show a large discrepancy between published and experimental results. The lower values for the static tests may be related to relaxation whereas relaxation would not be expected in the dynamic tests. An explanation is not possible without further study.

In the case of Spruce and Maple, the results from the static test are also lower than for the other two tests. In the longitudinal direction agreement is good between the two dynamic tests, but is less good in the case of the crossgrain samples, and the static test results are again lower. Kollmann and Cote (5) in their table 7.3 quote values for Young's Modulus for Spruce found by static and viabration methods.These are given below in table 4 together with values corrected for shear. They state that frequency did not significantly influence the measurements.

Table 4

Property of Spruce	Young's Modulus ($\times 10^{10}$ N/m^2) (as measured)	(corrected for shear)
Density 501 kg/m^3		
E (static bending)	1.485	1.68
E (transverse vibration)	1.587	1.75
E (longitudinal vibration)	1.771	not applicable

These values show a similar trend to the results of this study. It appears that a correction for shear is required for the non metallic materials in this study.

An attempt to measure the shear modulus of spruce was made using a torsion

(5) Kollmann F.P. and Cote Jr. W.A. Principles of Wood Science and Technology, George Allen and Unwin, 1968.

pendulum. The specimen was about 0.65 m long and 4 mm square. It was made the suspension on which hung the inertia bar. The specimens were cut with the long axis in the longitudinal and transverse (radial) directions respectively. The shear modulus is given by the equation:

$$G = 8(pi).I.l(f/r^2)^2$$

where I is the inertia attached to the specimen
l is the specimen length
r is the specimen radius, and
f is the frequency of oscillation.

Values of the shear modulus, G, for spruce and perspex were found as shown in table 5. Those for spruce were of the same order as values determined by Haines (6) and Bucur (7). The variability of wood can account for differences. There is a need with wood to be quite specific with regard to direction and which elastic constant is being considered.

Table 5

Determination of Shear Modulus

Specimen (axis)	Shear Modulus ($x10^{10}$ N/m^2) This study	Haines (6)
Spruce (L)	0.096	0.084
Spruce (R)	0.029	0.0054
Perpex	0.183	

The difference in results for spruce (R) could be connected with the elastic constants acting.

While for spruce and maple the static bending method gave lower values for Young's Modulus, the resonant beam and sound velocity method gave very good agreement as shown in table 2. However there was significant disagreement between the resonant beam and sound velocity method for transverse measurements. The difference was about 10%. For these transverse specimens with the length in the radial direction, the width in the longitudinal direction and the thickness in the transverse direction, shear may account for these differences.

Conclusion

Within the limits of accuracy set by the operating conditions in terms of surface preparation and the manipulation of the transducers to obtain the lowest steady transit time, it would appear that useful measurements of Young's Modulus may be made with the Lucchi Elasticity Tester. The choice of signal frequency, 60 kHz, not

(6) Haines D.W. CAS Newsletter #31, May 1979,23.
(7) Bucur V. ibid.

far above the high acoustic region would appear to avoid the risk of serious wave dispersion effects. Being longitudinal compressional waves, shear effects are avoided and a Young's Modulus value under near operating conditions for tonewood would seem to be obtained.

It would appear that for wood and plastics, the determination of Young's Modulus by bending methods requires that shear deformation be taken into account.

For spruce and maple good agreement was obtained for longitudinal specimens between the dynamic tests, transverse vibration and sound velocity measurement. With transverse specimens sound velocity measurements, which give the higher value, are probably more useful in the context of the action of soundboards.

Appendix

Determination of Transit Times from figures 1,3,4,5, and 6.

The information stored in the oscilloscope was obtained with x10 probes. In all the figures the time scale was 20 mm equal to 50 us; the scale of the ordinate for Tx; 20 mm was equal to 1 V. The vertical axis for Rx was 20 mm equal to 5 mV except in figure 3 where 20 mm was equal to 0.1 V. The transit times and the measured specimen distances are as shown below:

Figure	1	3	4	5	6
Distances (mm)	168	394	242.5	60.6	23.5
Time (us)	75.7	76.7	46.5	30.7	19.5
Distance (mm) in the figures, to first negative deflection in Rx					
	28.8	29.0	19.0	14.0	7.0
Calculated distances from us value					
	30.28	30.68	18.6	12.28	7.8

The perspex calibration bar was used for figure 1 and the calibration time set by the maker was 74 us. This was used to set the pressure to be applied when taking a measurement.

Lucchi Elasticity Tester

Figure 1. Waveform of Transmitted, Tx, and Received, Rx, signal for Perspex.

Figure 2. Frequency analysis of waveforms in figure 1.

Figure 3. Waveform of Transmitted and Received signals for Mild Steel.

Figure 4. Waveform of Signals for Spruce in L direction.

Figure 5. Waveform of Signals for Spruce in R direction.

Figure 6. Waveform of Signals for Spruce in T direction.

perspex 75·7

20mm = 50μS

TX channel 1 20mm = 1V

RX channel 2 20mm = 5 m

x 10 probes

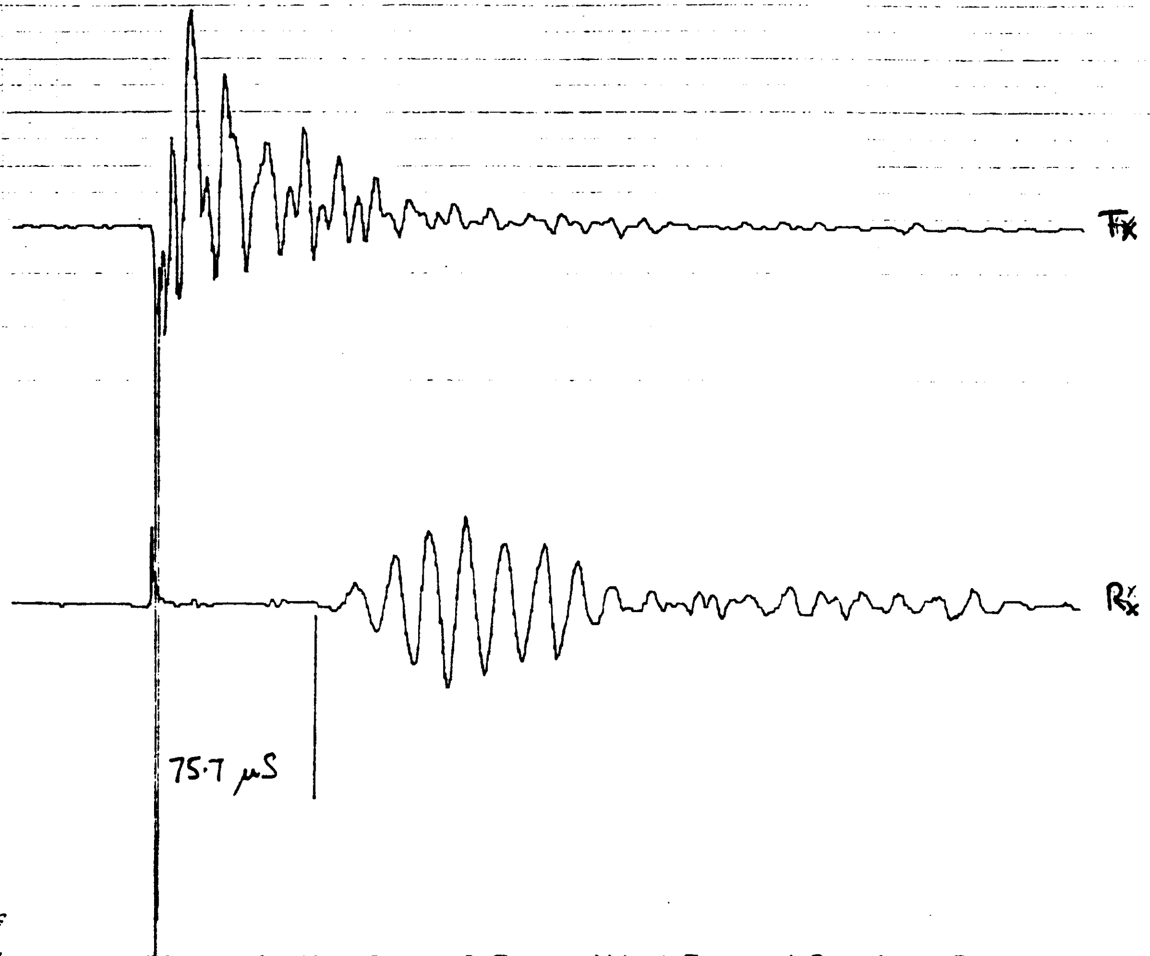

Figure 1. Waveform of Transmitted,Tx, and Received,Rx, signal for Perspex.

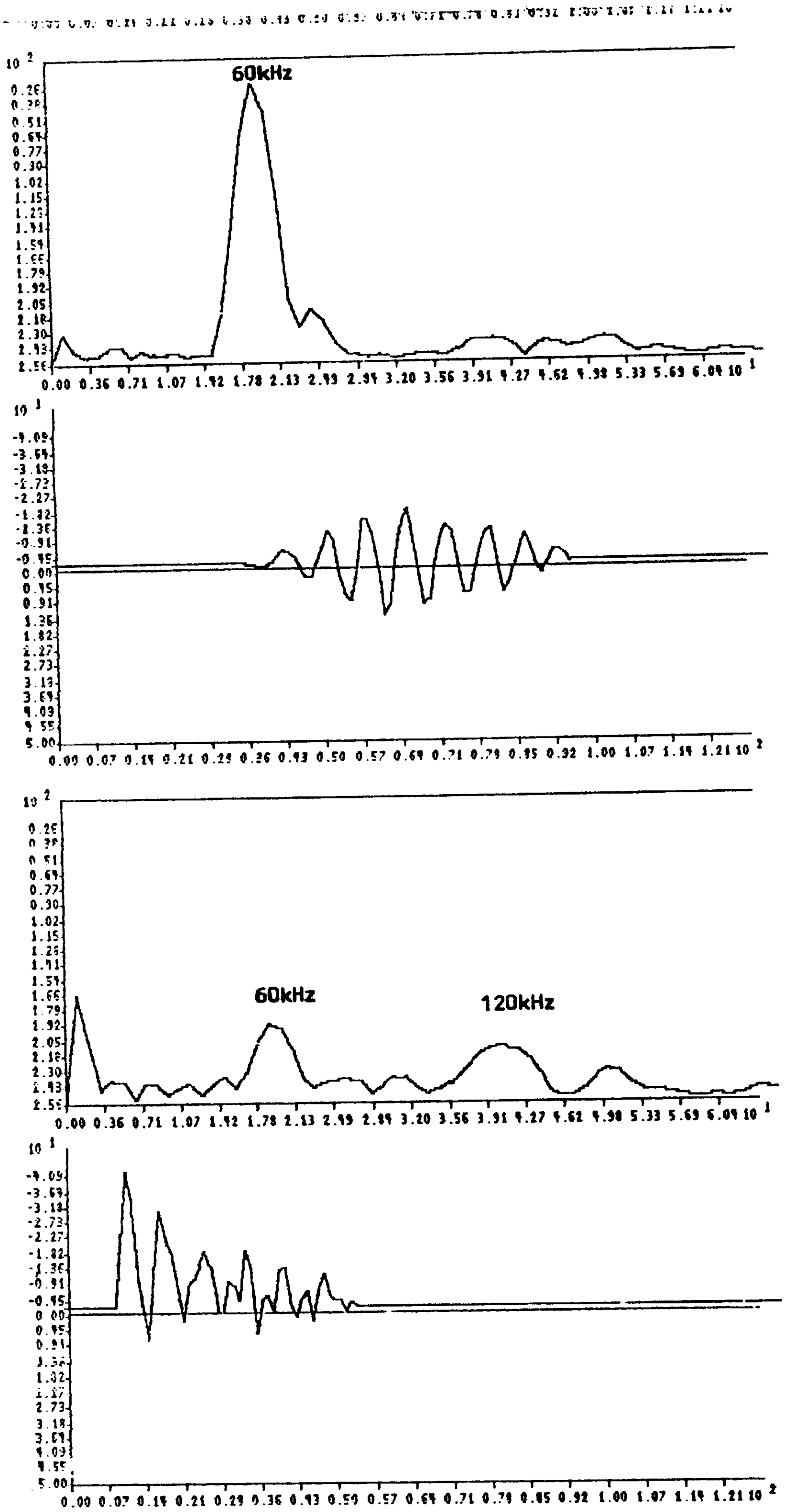

Figure 2. Frequency analysis of waveforms in figure 1.

Mild Steel

T_x Ch1 20 mm = 1V
R_x Ch2 20 mm = ·1
Hozizl 20 mm = 50/
Transit dist. 394 m
Transit time 76·7/

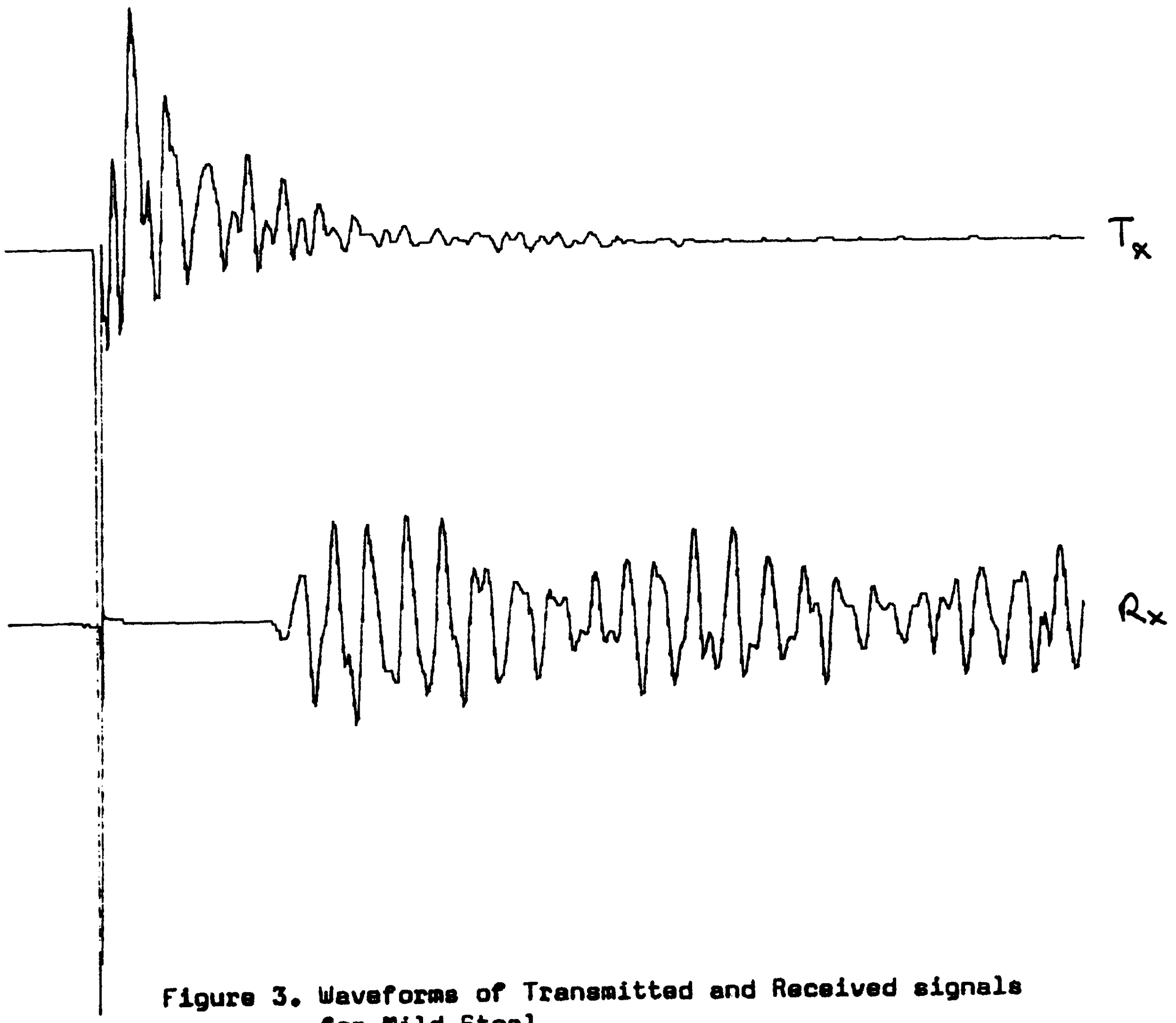

Figure 3. Waveforms of Transmitted and Received signals for Mild Steel.

Spruce block
L direction

T_x Ch 1 20 mm = 1V
R_x Ch 2 20 mm = 5
Horiz'l 20 mm = 50

Transit distance 242.5
Transit time 46.5

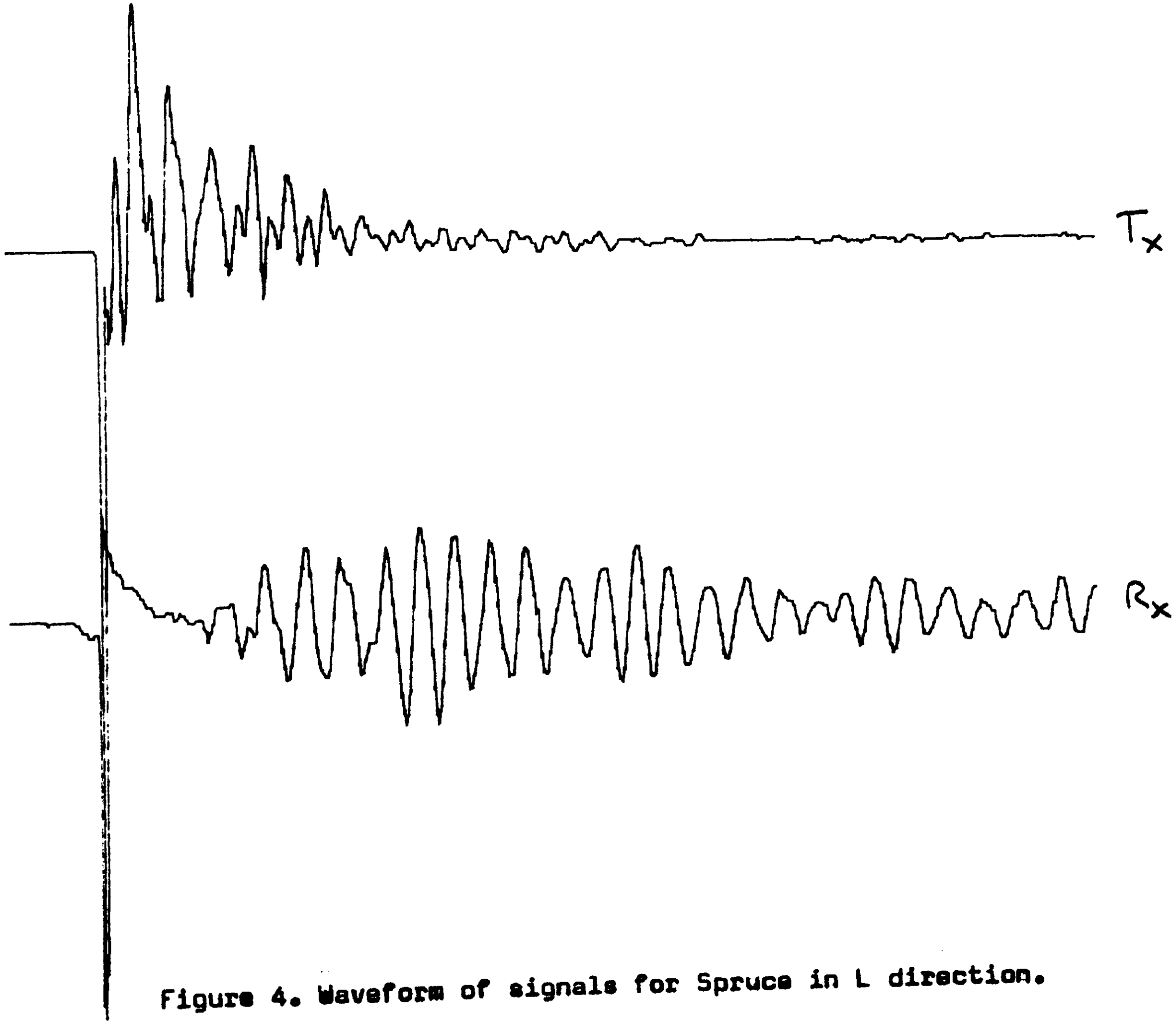

Figure 4. Waveform of signals for Spruce in L direction.

Spruce block
R direction

T_x Ch1 20 mm = 1
R_x Ch2 20 mm = 5m
Horiz^{l} 20 mm = 50

Transit dist. 60.6
Transit time. 30.7

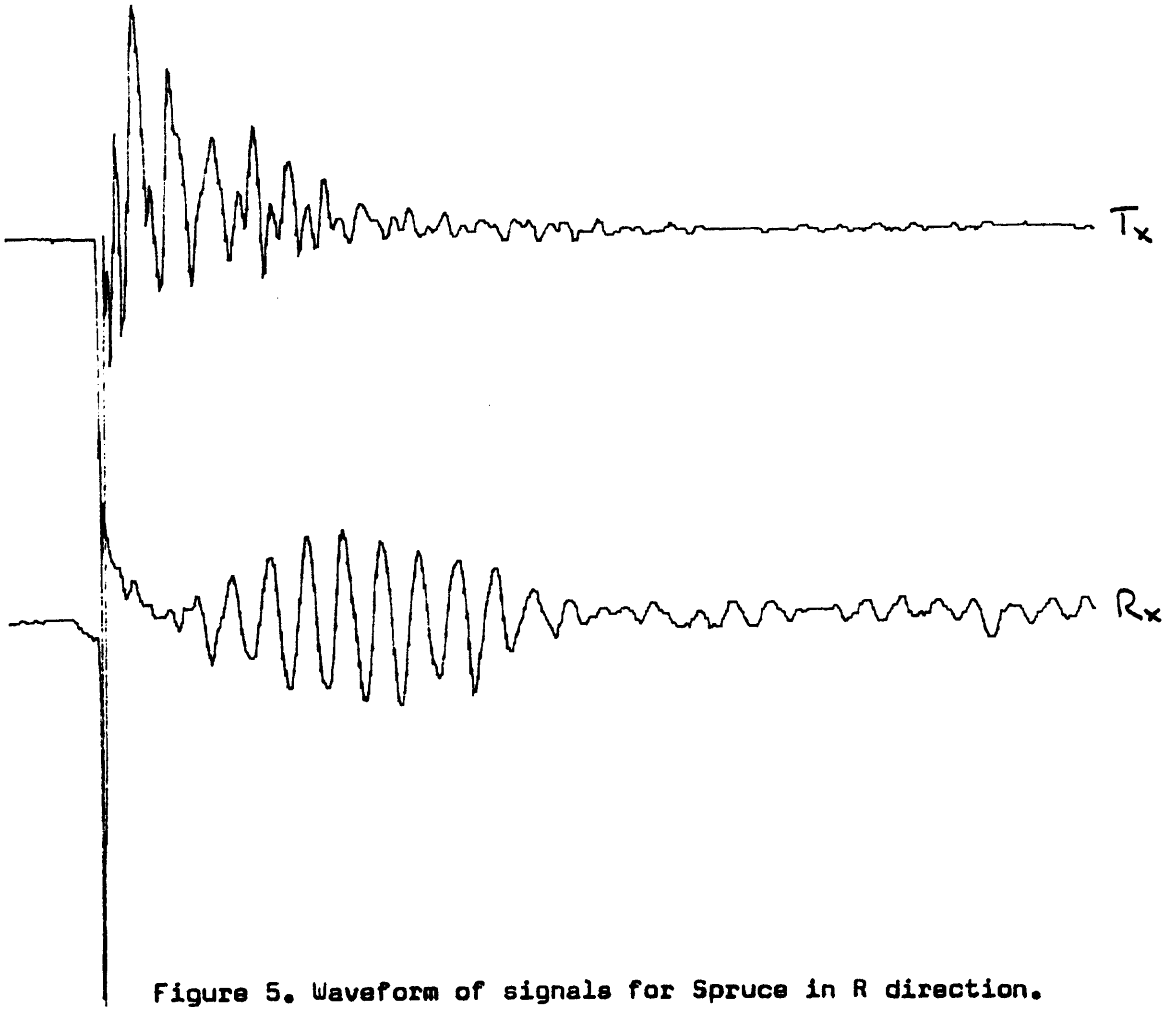

Figure 5. Waveform of signals for Spruce in R direction.

Spruce block
T direction

T_x Ch1 20mm = 1V
R_x Ch2 20 -- = 5m
Horiz'l 20mm = 50

Transit dist. 23.5'
Transit time 19.5

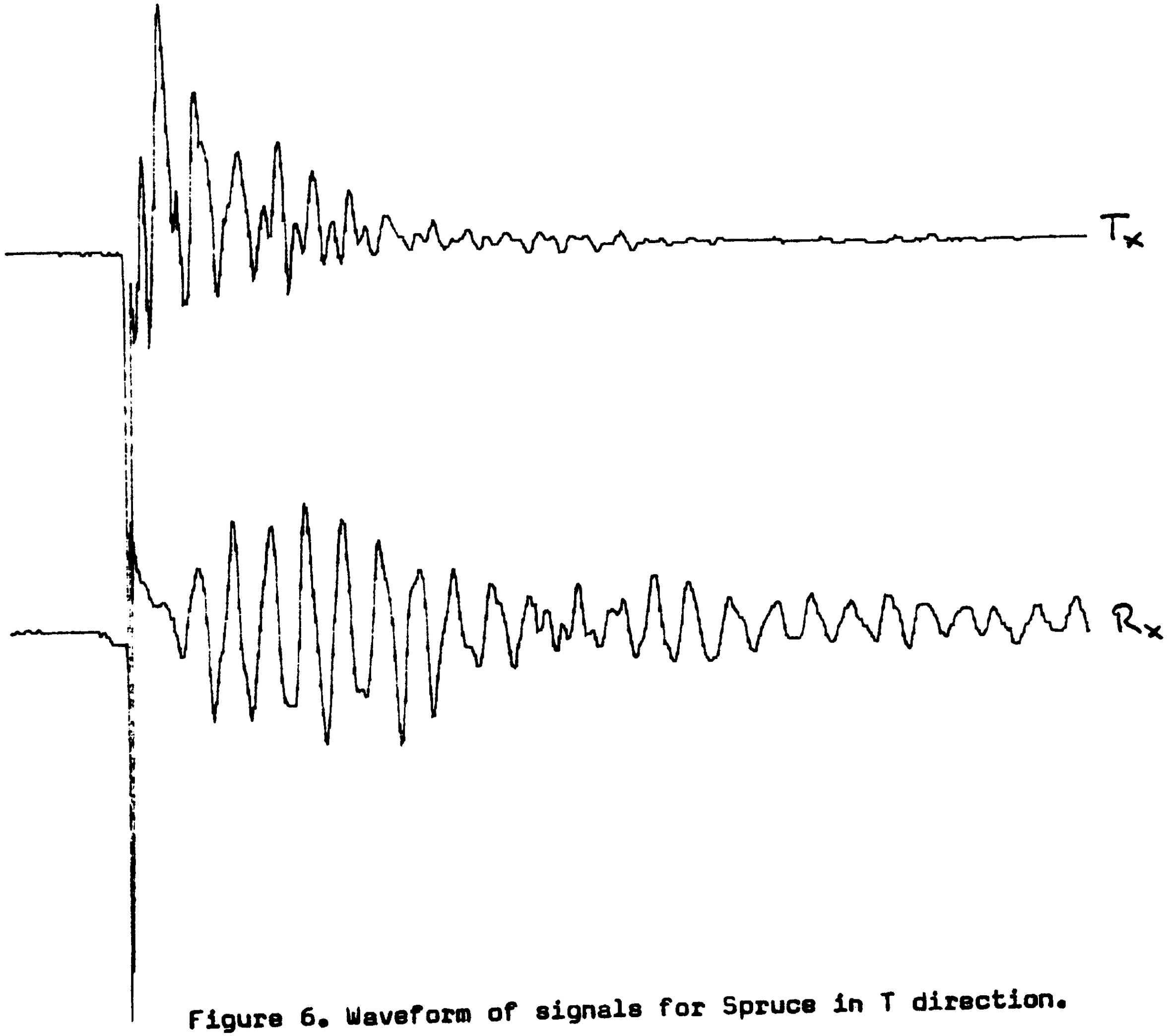

Figure 6. Waveform of signals for Spruce in T direction.