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ULTRASONIC MEASUREMENT OF STRESS IN 2219-T87 ALUMINUM PLATE

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16. ABSTRACT

A nondestructive method based upon ultrasonic birefringence has been widely used for measuring stress level changes in laboratory specimens of anisotropic materials. However, only one component of three-dimensional stress fields can be determined this way. For this and other reasons, the method was found to be inadequate for practical, field type stress measurements. An exploratory in-house project was initiated to seek ways of overcoming the stated difficulty by developing techniques of nondestructively measuring orthogonal components of complex stress fields. This memorandum describes the approach taken to assess this measurement problem and illustrates a biaxial stress measurement method, which was subsequently developed, as well as an indirect method of determining a third stress component. Thus, the feasibility of nondestructively measuring principal components of complex stress fields has been demonstrated.

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SUMMARY

The basic relationship of ultrasonic signal velocity to directional subsurface stress is reviewed, and the inappropriateness of dependency on a single correlative value or "constant" for a three-dimensional stress field in metallic materials is discussed. The novel implementation of conventional ultrasonic nondestructive testing capabilities integrated to provide a composite technique for the measurement of orthogonal stress components is described, and the procedures for performing the preparatory calibration and subsequent stress field measurements are presented.

The principal concept employed in this investigation is that the prime effect of stress on ultrasonic signal velocity occurs only in the direction of material excitation or particle motion.

Laboratory investigation, performed utilizing cubes of 2219-T87 aluminum, demonstrated that six shear wave and three longitudinal wave stress constants exist for this material. However, only one longitudinal wave and two shear wave constants are required to define a three-dimensional stress field. The particular constants used in any application are dependent on the material anisotropy with respect to the accessible surface.

A less complex method for measuring the two principal stress components in such materials as in pressure vessels is also defined.

I. INTRODUCTION

Accurate methods of nondestructively measuring stress in metallic materials would provide the potential for building safer and more reliable engineering structures. This capability would be of great benefit to the Shuttle

Program, to nuclear industries, and to the construction industry in general. Of the candidate stress measurement methods that have been investigated, ultrasonic techniques show the most potential for measuring subsurface stresses. These ultrasonic techniques have been used for several years to measure stress and stress level changes in laboratory specimens [1-7]. The most utilized technique is based upon ultrasonic birefringence where time differentials of mutually perpendicular shear waves traveling through a specimen are related to stress. This technique works reasonably well on uniform laboratory specimens where only one principal stress exists. But stress is a three-dimensional force field and if two or more stress components in an engineering structure are near the same magnitude, the birefringent differentials may be near zero whereas large stress levels actually exist. An experimental study was initiated to assess this problem and, ultimately, to take ultrasonic stress measurement technology out of the laboratory and make it useful for evaluating stress in aerospace structures.

Difficulties with the birefringent technique in preliminary experiments furnished convincing evidence that a different approach was required to adequately define stress fields nondestructively. From these preliminary experiments, it was concluded that the principal effect of stress on ultrasonic velocity occurs only in the direction of material vibration or particle motion. This being true, longitudinal waves could be used to measure stress in the same direction as the wave is propagating, and shear waves could be used to measure stress transverse to the direction of propagation. A shear wave transducer can be rotated 360° to obtain a measure of stress at any orientation normal to the direction of propagation. Thus, theoretically, shear waves of two orientations and longitudinal waves of a different orientation could be used independently of each other to measure three orthogonal components of complex stress fields. Exploratory ultrasonic measurements necessary to develop this basic concept are described in a following section of this report. Practical biaxial and three-dimensional stress measurement methods developed from the concept are also described and illustrated.

II. EXPLORATORY ULTRASONIC MEASUREMENTS

A. Technique of Measuring Differential Velocity or Transit Time

The determination of stress magnitudes by ultrasonic techniques is essentially a measurement of ultrasonic velocity through the stressed material. The following expression depicts this velocity/stress relationship:

$$\Delta V(s) = \frac{-T\,(4\,u + n)}{8u\,Vp}$$

where

V = Velocity (m/s)

-T = Compressive stress (N/m^2)

u = Second order elastic constant (N/m^2)

n = Third order elastic constant (N/m^2)

p = Density (kg/m^3)

s = Shear waves.

In addition to stress, numerous material properties affect the velocity of sound in a medium; but, effects of these variations can be accounted for by adequate calibration. Thus, additional velocity changes can be attributed to stress.

One of the selected techniques of measuring velocity is basically a differential time measurement technique as depicted in part by Figure 1. Two ultrasonic transducers are simultaneously energized by a single pulse generator, one transducer being placed on a stressed specimen and the other on an unstressed reference block. Each of the reflected signals is put on a separate channel of a dual beam oscilloscope. The time base of the oscilloscope is expanded until each cycle of the narrow pulses can be observed. The distance or time between corresponding peaks of the two signals is proportional to stress in the specimen. An accurate value for the distance between peaks can be obtained by turning the Delay-Time Multiplier Knob on the oscilloscope until both signals are coincident (Figs. 2 and 3).

B. Determination of Ultrasonic/Stress Constants for Each Orthogonal Orientation in Aluminum

Ultrasonic/stress constants, or the change in ultrasonic wave propagation time per unit distance, per unit stress level change must be determined for each material type to obtain the understanding and specific values required to

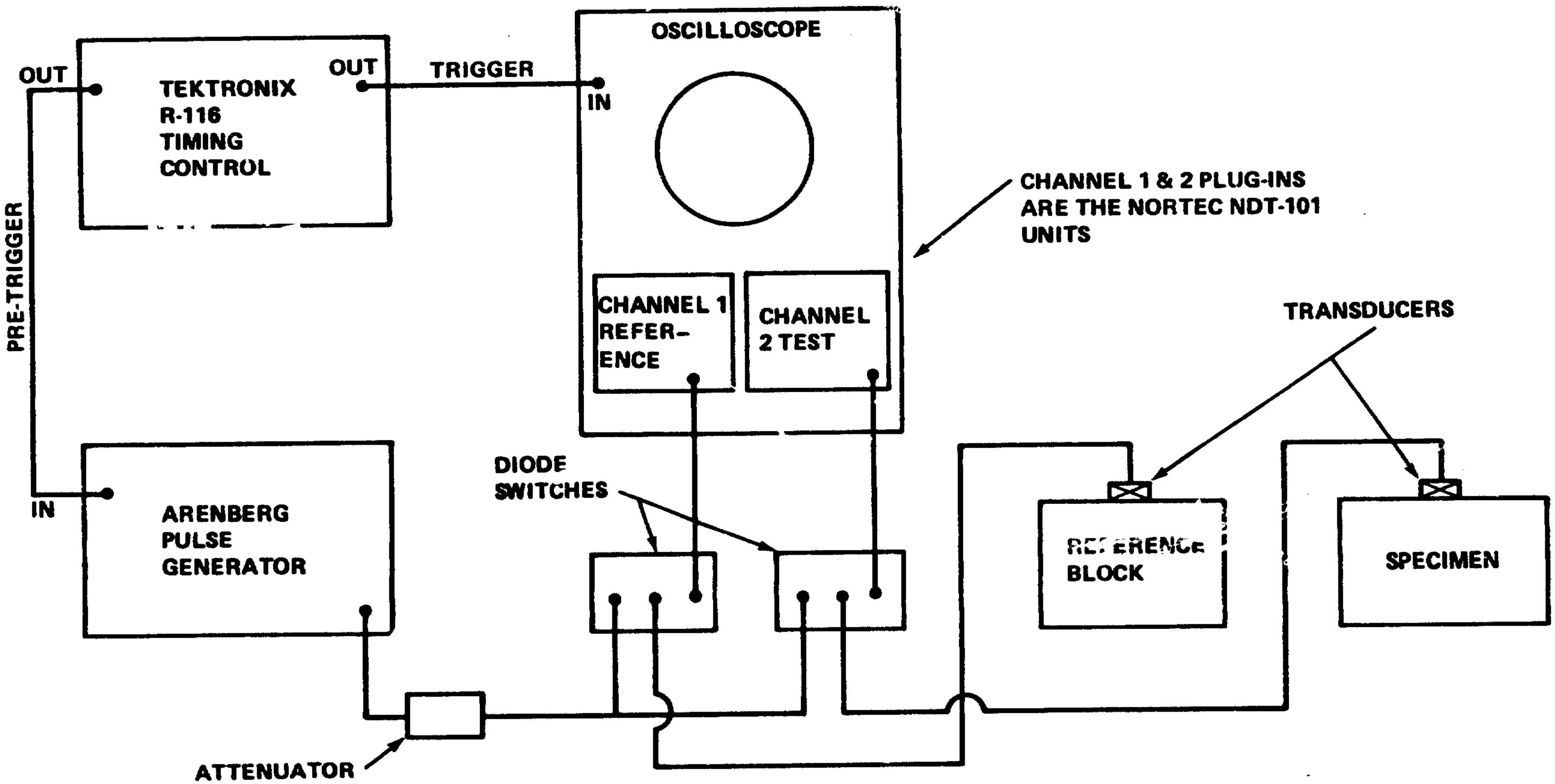

Figure 1. Block diagram of ultrasonic instrumentation.

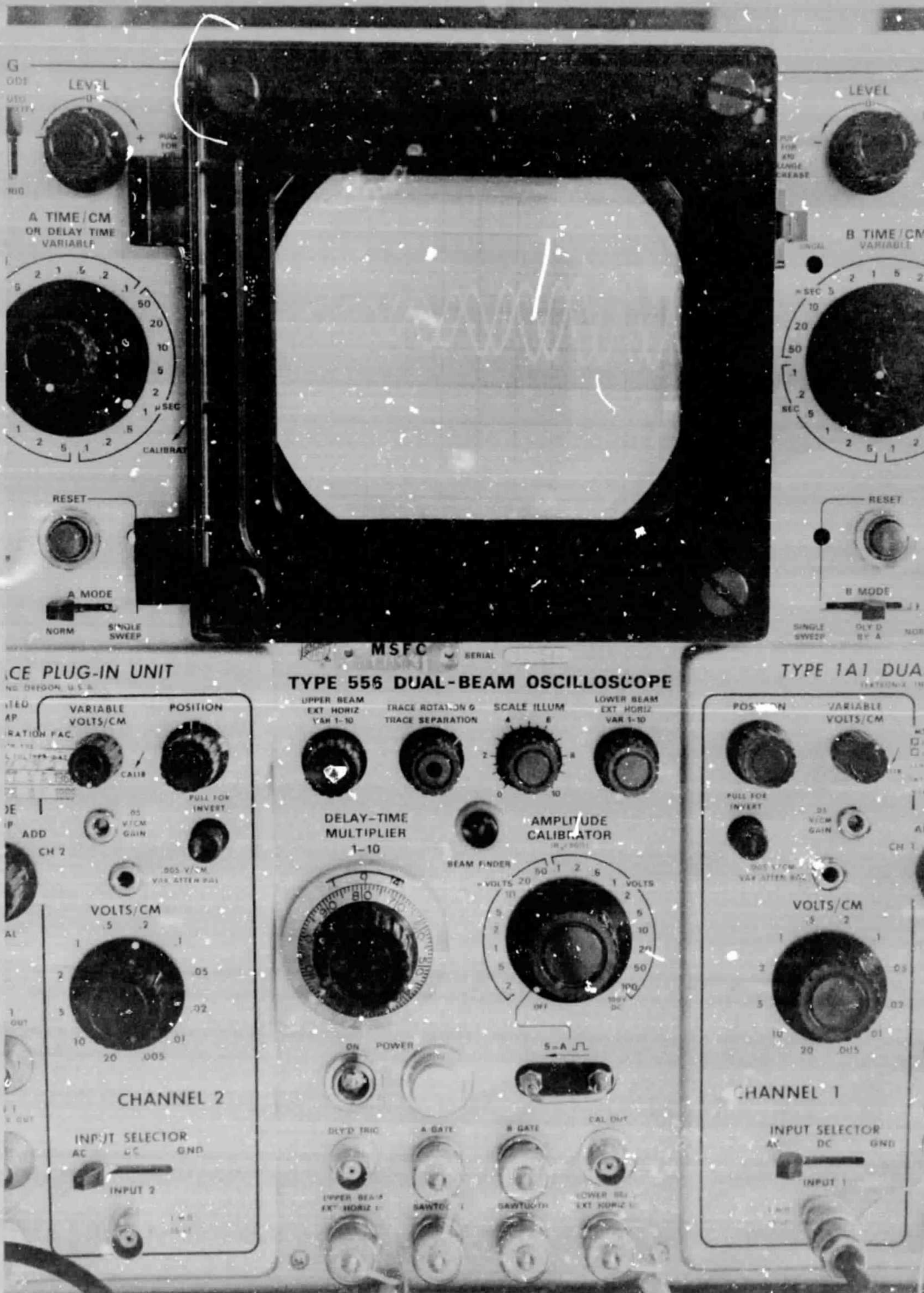

Figure 2. Time base expansion of reflected pulses from stressed and unstressed materials.

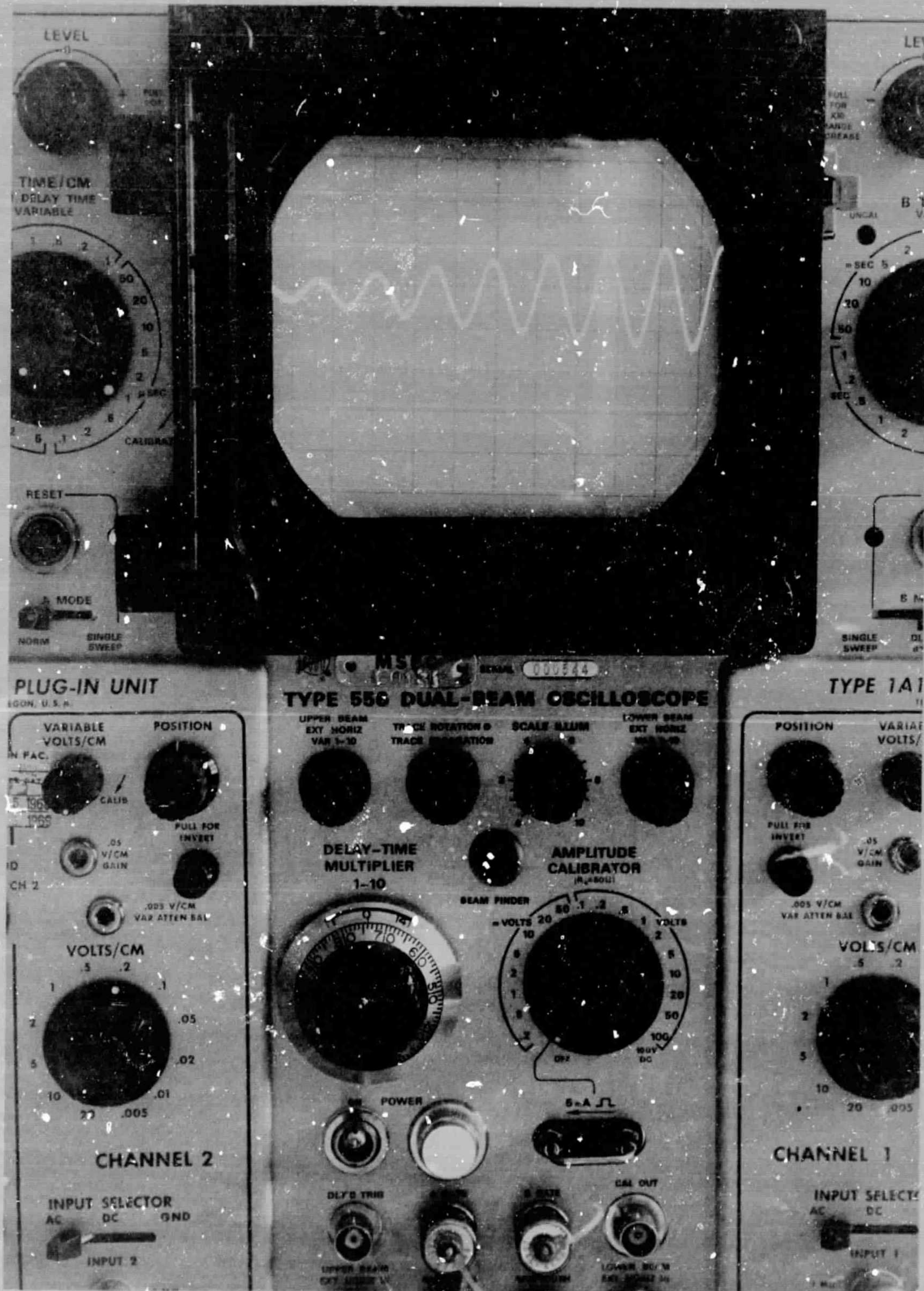

Figure 3. Time delay adjustment makes reference and measuring pulses coincident.

measure stress. This can be accomplished by making the necessary measurements on incrementally loaded laboratory specimens. Usually, only one constant is determined for each material and, subsequently, a single value representing the unknown stress level is obtained. However, stress is a three-dimensional force field and three orthogonal measurements are required to define it. Furthermore, anisotropic grain structure and the relationships of ultrasonic vibration to principal stress orientations affect the constants to varying degrees. Thus, if optimum stress measurements are to be made, several constants must be determined. In all probability, lack of consideration of these factors accounts for much of the wide variation in magnitude of published "constants" [1-7] for specific materials.

For this program, cube type specimens were selected to facilitate determination of the necessary ultrasonic/stress constants. Table 1 defines the measurement orientations utilized to determine shear wave constants and the symbols selected for each. Longitudinal wave stress constants are also needed. However, since propagation directions and particle vibrational directions are the same for longitudinal waves, only three constants are required. Namely, A, B, and C for the corresponding orientations as used for shear wave determinations. Transverse tensile loads generated by high compressive loads were used to determine the longitudinal wave constants since a transducer could not be satisfactorily placed on top of a loaded cube.

Thus, it becomes obvious that a total of nine constants are required to develop an optimum stress measuring capability. However, only three constants, two shear and one longitudinal, are required for each stress measuring problem. The longitudinal constant is utilized in measuring stress in the direction of ultrasonic wave propagation. Two shear wave constants are utilized for measuring stress levels in the major transverse orientations. The particular group of constants selected for each application is determined by the orientation of anisotropic grain structure with respect to accessible structural surfaces. Specific examples of shear and longitudinal wave constant determinations are shown in the following paragraphs.

An annealed aluminum specimen (number 1) was used as a reference block when shear and longitudinal wave stress constants were determined. A dual beam oscilloscope and the basic pulse "overlap" technique were used to measure time differentials between the reference block and incrementally loaded aluminum cubes. Shear wave measurements were obtained for each of the six particle vibrational/grain orientation relationships. The reference and measuring transducers were always oriented in corresponding directions, selected so vibrational motion would be in the loading direction. Ultrasonic/stress constants

TABLE 1. MEASUREMENT ORIENTATIONS FOR THE DETERMINATION OF SHEAR WAVE STRESS CONSTANTS

Cube Loading Direction[a]	Symbols for Constants	Propagation Direction
A. Rolling	A_1	Perpendicular to rolled surface
	A_2	Parallel with rolled surface
B. Long Transverse	B_1	Perpendicular to rolled surface
	B_2	Parallel with rolled surface
C. Short Transverse	C_1	In rolling direction
	C_2	Transverse to rolling direction

a. Place the transducer so the particle motion is always in the loading direction.

were calculated subsequent to correcting data for the effects of strain. For example, the "B" constant calculations for specimen number 2 are shown.

Experimental Data:

Average time change: 25.5 ns

Average load change: 5 ksi

$$\text{Transverse Strain} = \frac{\text{Stress}}{\text{Modulus}} \times \text{Poisson's Ratio} = \frac{5 \times 10^3 \times 0.33}{10.6 \times 10^6}$$

$$= 1.555 \times 10^{-3} \text{ in./in.}$$

For a 4 in. path length,

$$\Delta t_{\text{(Due to strain)}} = \frac{\text{Total Strain}}{\text{Velocity}} = \frac{4 \times 1.555 \times 10^{-3}}{1.22 \times 10^5 \text{ ips}} = 5.1 \times 10^{-8} \text{ s}$$

$$\Delta t_{(\text{Due to stress})} = 25.5 \text{ ns} - 5.1 \text{ ns} = 20.4 \text{ ns}$$

$$K = \frac{20.4 \text{ ns}}{4 \times 5 \text{ ksi}} = 1.02 \text{ ns/in./ksi}$$

A computerized program for making these calculations was prepared and utilized to obtain the shear wave constants shown in Table 2. These data depict in an effective manner the necessity of knowing all of the stress constants. Obviously, if the effects of material orientation are ignored, unacceptable stress measurement errors would occur.

TABLE 2. SHEAR WAVE STRESS CONSTANTS FOR 2 INCH 2219-T87 ALUMINUM CUBES

Constant Orientation	Stress Constant $ns/m/N/m^2 \times 10^{-6}$ (ns/in./ksi)
A_1	7.172 (1.256)
A_2	6.675 (1.169)
B_1	5.898 (1.033)
B_2	5.070 (0.888)
C_1	5.282 (0.925)
C_2	5.436 (0.952)

Note: These constants are corrected for strain.

The "A" orientation of specimen 2 is used as an example of longitudinal wave calculations. As previously stated, the load utilized in this case is the transverse tensile force generated by the applied vertical compressive load.

Experimental Data:

Average time change: 10.3 ns

Average load change: 2.64 ksi (Poisson's ratio times applied load)

$$\text{Transverse Strain} = \frac{\text{Stress}}{\text{Modulus}} = \frac{2.64\ \text{ksi}}{10.6 \times 10^6} = 0.249 \times 10^{-3}\ \text{in./in.}$$

$$\Delta t_{(\text{Due to Strain})} = \frac{\text{Total Strain}}{\text{Velocity}} = \frac{4 \times 0.249 \times 10^{-3}}{2.46 \times 10^5\ \text{in./s}} = 4.05 \times 10^{-9}\ \text{s}$$

$$\Delta t_{(\text{Due to Stress})} = 10.3\ \text{ns} - 4.05\ \text{ns} = 6.25\ \text{ns}$$

$$K = \frac{6.25 \times 10^{-9}\ \text{ns}}{4\ \text{in.} \times 2.64\ \text{ksi}} = 0.591\ \text{ns/in./ksi}$$

A computerized program was also written and utilized to make these calculations. Results shown in Table 3 are more nearly uniform, but smaller than those for shear waves. This shows that longitudinal waves are less sensitive to stress than shear waves, but it does not preclude their use as a stress measuring tool.

TABLE 3. LONGITUDINAL WAVE STRESS CONSTANTS FOR 2 INCH 2219-T87 ALUMINUM CUBES

Constant Orientation	Stress Constant $ns/m/N/m^2 \times 10^{-6}$ (ns/in./ksi)
A	3.460 (0.606)
B	3.068 (0.632)
C	3.169 (0.555)

Note: These constants are corrected for strain.

The existence of specified ultrasonic/stress constants for different material orientation/ultrasonic vibrational relationships has been clearly demonstrated. An apparent way of utilizing this knowledge to nondestructively measure complex stress fields in engineering structures is the direct velocimetric method. This means that absolute ultrasonic velocities for each orthogonal orientation in unstressed material would have to be measured with high accuracy as part of the necessary calibration procedures. Next, material thickness of the engineering structure would have to be measured with similar accuracy followed by the actual stress measurements involving shear and longitudinal ultrasonic waves. Finally, all of these data and the previously determined stress constants would be used in calculating the three orthogonal stress levels.

Theoretically, this direct method of measuring stress is sound, but with currently available instrumentation it is impractical. A major problem is the measuring of relatively long periods of time with adequate accuracy. Time required for an ultrasonic wave to make a round trip through an inch of material such as aluminum is of the order of thousands of nanoseconds. Our differential techniques of measuring time are suitable only for time periods ranging up to a few hundred nanoseconds. Thus, it is now impractical to obtain required velocity measurements, but when instrumentation is improved the method can be used.

Since the direct approach to measuring stress components is not currently useful, other techniques have been developed that overcome the stated difficulties. A relatively simple method of measuring biaxial stress and an indirect method of determining the third orthogonal stress component are described and illustrated in the remaining sections of this report.

III. BIAXIAL STRESS MEASUREMENT METHOD

Ultrasonic/stress constants are usually determined before attempts are made to ultrasonically measure stress. These constants are not required for measuring biaxial stress. However, a knowledge of the constants and the fact that different values exist for each orientation of anisotropic grain structure with respect to ultrasonic vibrational directions is necessary to understand and develop adequate calibration procedures. This biaxial stress measurement method is based upon the measurement of time differentials between ultrasonic shear waves and longitudinal waves propagating through stressed material. It utilizes a combination of the basic properties of longitudinal waves and of shear waves to overcome many of the problems previously discussed. More specifically, these problems can be resolved by measuring time differentials between the second longitudinal wave echo and the first shear wave echo for each biaxial orientation. An illustration of this approach as applicable to pressure vessels is illustrated in Figure 4.

The longitudinal wave serves as a reference, and shear waves sense stress values for each biaxial orientation. The velocity of longitudinal waves in

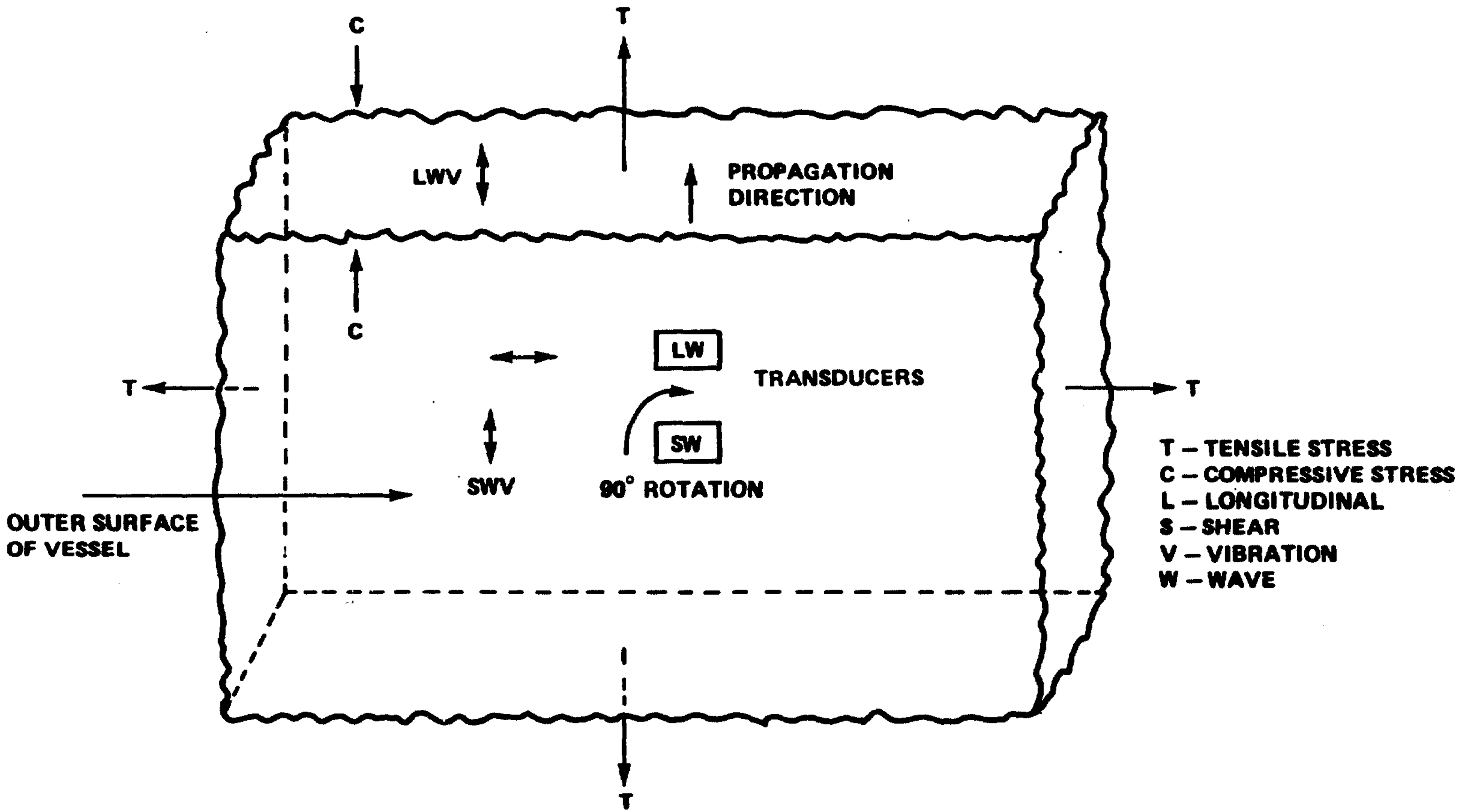

Figure 4. Biaxial stress measurement method as applied to a typical pressure vessel problem.

aluminum is approximately 6.25 × 10^5 cm/s (2.46 × 10^5 in./s) and for shear waves the velocity is 3.10 × 10^5 cm/s (1.22 × 10^5 in./s). Thus, the transit time for the second longitudinal wave echo is of the same order of magnitude as the time required for the initial shear wave echo. This fortunate relationship provides a time differential small enough to be readily measured with high accuracy. It eliminates the need for highly accurate material thickness measurements and provides biaxial sensing of stress components. Calibration and measurement procedures for utilizing this technique are described below.

An unstressed specimen of the same material, having the same thermal conditioning and the same grain orientation with respect to the accessible surface of an engineering structure, must be used for calibration. Calibration consists of the following steps:

a. Measure the time differential (ΔTL_2S) between the second longitudinal wave echo and the shear wave echo for each biaxial orientation as the calibration specimen is incrementally loaded.

b. Convert the time differentials to nanoseconds/inch for the ultrasonic path length and plot versus corresponding load values as depicted in Figure 5.

c. Good accuracy can be obtained as indicated in item b. However, improved accuracy should be obtained by making an indirect measurement of the low level of residual stress existing in a small calibration specimen. This can be accomplished by making the ΔTL_2S measurement on an annealed specimen of the calibration material, then correct the data for ultrasonic velocity changes resulting from modulus changes caused by annealing.

d. The small stress values determined by item c. can then be used to adjust values in graphs like that shown in Figure 5.

Tables 4 and 5 illustrate how data for calibration curves are obtained. Table 4 shows data taken by oscilloscope measurements and Table 5 depicts the reduction process. They also show why data taken transverse to the loading direction are not as useful when the biaxial stresses are not of like sign. There was no significant variation of ΔTL_2S with load for the 90° orientation since stress in this direction and in the direction of propagation were tensile in the compressively loaded cube. Since these transverse stresses were also of the same magnitude, no significant time differentials were obtained as a function of load. Thus, the cube must be rotated 90° and incrementally loaded a second time to obtain the second biaxial component calibration curve.

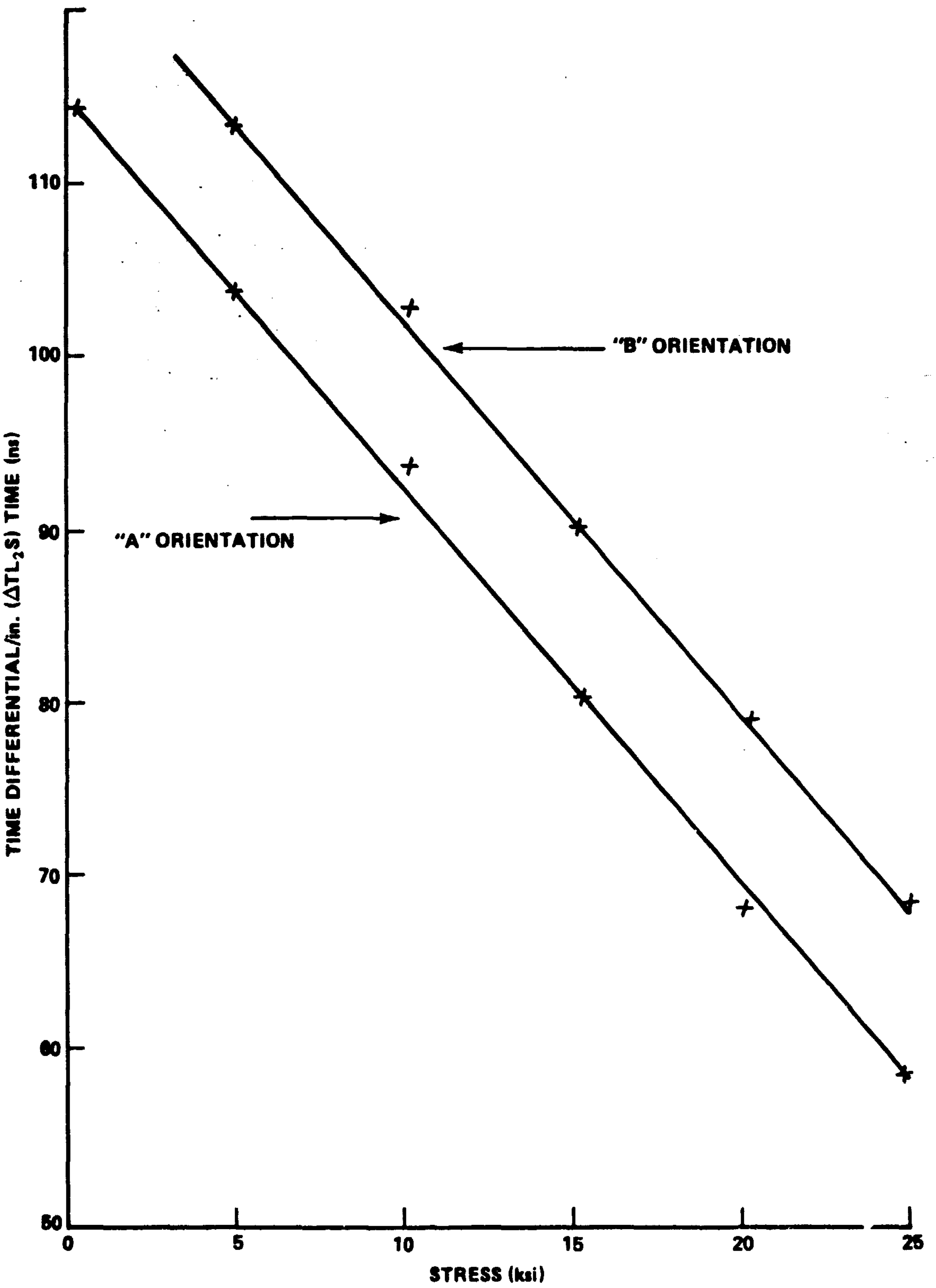

Figure 5. Biaxial stress calibration for 2219-T87 aluminum plate.

TABLE 4. CALIBRATION DATA FOR BIAXIAL STRESS MEASUREMENTS

Applied Load $N/m^2 \times 10^7$ (ksi)	Oscilloscope Indications (Divisions)		
	L_2	90°(s)	0°(s)
0 (0)	300.0	392.2	392.1
3.44 (5)	302.5	396.6	386.5
6.88 (10)	305.6	400.1	380.6
10.32 (15)	309.6	402.4	374.5
13.76 (20)	313.3	405.1	367.8
17.20 (25)	315.6	407.9	362.7

Notes: 1. 0° and 90° mean that ultrasonic vibration is in the loading and transverse directions, respectively.

2. L_2 indicates reflection times for second longitudinal wave echoes.

3. (s) indicates reflection times for initial shear wave echoes.

TABLE 5. DATA REDUCTION FOR BIAXIAL STRESS MEASUREMENTS

Applied Load $N/m^2 \times 10^7$ (ksi)	ΔTL_2S (Transit Time Differentials)			
	Divisions (90°)	Divisions (0°)	ns(0°)	ns/in. (0°)
0 (0)	92.2	92.1	460.5	115.1
3.44 (5)	94.1	84.0	420.0	105.0
6.88 (10)	94.5	75.0	375.0	93.7
10.32 (15)	92.8	64.9	324.5	81.1
13.76 (20)	91.8	54.5	272.5	68.1
17.20 (25)	92.3	47.1	235.5	58.8

Note: The 90° data are not useful and are not reduced.

Stress signs should not cause major problems when the Biaxial Technique is applied to pressure vessels. In most cases biaxial stresses will be tensile, and the radial or thickness stress will be compressive and of smaller magnitude than the other components. Furthermore, a compressive biaxial stress component is not harmful to a pressure vessel, and the fact that it is compressive can be confirmed. An ultrasonic transit time greater than that obtained for a corresponding orientation on a calibration block indicates tensile stress and a shorter time shows that the stress is compressive. It should also be stated that tensile specimens should be used when calibrating for pressure vessel stress measurements.

Measurement procedures are:

a. Measure the time differential between the second longitudinal wave echo and the shear wave echo of each biaxial orientation on the pressure vessel or other test article.

b. Convert the measured time differentials to nanoseconds/inch for the ultrasonic path length and use a graph like that shown in Figure 5 to determine biaxial stress levels.

IV. INDIRECT METHOD OF MEASURING THREE DIMENSIONAL STRESS FIELDS

As previously stated, the direct approach to three-dimensional stress measurement is impractical with currently available instrumentation. However, any technique of measuring stress in the direction of ultrasonic propagation used to supplement the biaxial method constitutes three-dimensional measurement. This has been accomplished with the aid of a quartz delay line or time reference.

A major problem in ultrasonically measuring stress is obtaining an adequate reference so differential time measurements can be made. Shear waves of two orientations are compared when the birefringent technique is used. The second longitudinal wave echo serves as a reference for biaxial stress measurements. In both of these cases, the stressed specimen or test article is utilized as a time reference device as stress levels are being determined. Consequently, effects of temperature and path length variations are minimized. The quartz delay line serves a similar purpose and is simply a stable external time reference used in obtaining calibration curves for the third stress component of complex stress fields. It is subsequently used in the actual stress measuring process. A cross section of a delay line is shown in Figure 6. A longitudinal wave transducer is permanently mounted on the quartz rod and shock supported with foam material. Since quartz has a thermal expansion coefficient of only $0.500 \times 10^{-6}/°C$, this provides a very stable time reference. The calibration procedures necessary to utilize this device are:

a. Display an echo from the back side of the quartz on an oscilloscope screen. Use maximum practical expansion of the time base.

b. Select a well defined peak within the echo and adjust delay control until it coincides with a line on the screen. Then, record the delay knob setting.

c. Disconnect from the quartz reference and connect to a second longitudinal wave transducer placed on the calibration block, utilizing the same oscilloscope channel to display an echo from the back side of the block. This calibration block must be material of the same type and alloy, and must have approximately the same thickness as the test article.

d. Repeat step b, and record the difference in these delay knob settings, which represents the time differential.

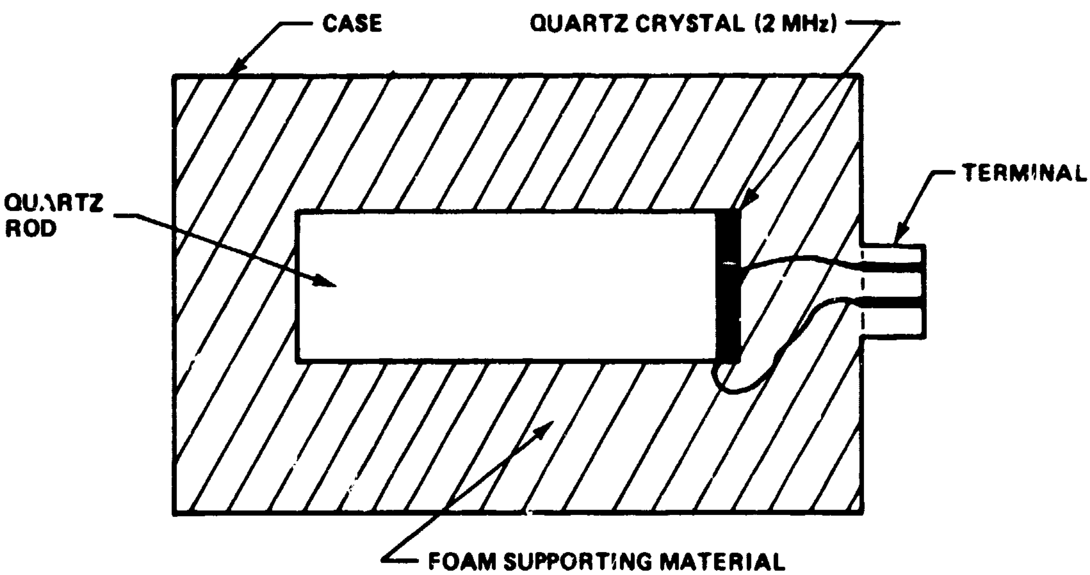

Figure 6. Cross section of a quartz delay line.

e. Repeat measurement procedure (steps a through d) at incremental load levels.

f. Plot graph of time differentials versus load levels.

g. Repeat calibration procedure for each material orientation of interest.

The calibration procedure is depicted quantitatively in Tables 6 and 7. Externally applied load levels, oscilloscope indications subsequent to the measurements, and differences between ultrasonic reflection time in the quartz rod and incrementally loaded specimens are shown in Table 6. Induced transverse loads and the corresponding time changes are shown in Table 7. These data were used to plot the calibration curve shown in Figure 7. It was necessary to use transverse loads since it is impractical to place a transducer on top of a compressively loaded cube and the longitudinal wave must be propagating in the same direction as the stress level being measured. Unknown stress levels can now be determined by:

a. Measuring differences between ultrasonic reflection time in the quartz reference and those times in stressed test article.

b. Using the calibration curve and time differentials to obtain corresponding stress values.

c. Correcting stress values for the effect of strain to obtain correct stress levels.

Although the indirect method of measuring three-dimensional stress fields may appear to be laborious and time consuming, it is not too difficult and can be made less so. Shear wave crystals of two orientations and a longitudinal wave crystal could be mounted in a single housing. Thus, such a single transducer could be placed on an unknown specimen and all three stress components quickly measured by adjusting electronic instrumentation. With some additional expense, this adjustment process could be automated.

V. CONCLUSIONS AND RECOMMENDATIONS

Based on the laboratory work performed and reported in this report, it is concluded that the orthogonal components of complex stress fields existing in metallic materials can be effectively measured, nondestructively, utilizing the principles described herein and state-of-the-art ultrasonic instrumentation.

TABLE 6. CALIBRATION DATA FOR AN INDIRECT METHOD OF MEASURING STRESS

Applied Compressive Load $N/m^2 \times 10^7$ (ksi)	Oscilloscope Indications (Divisions)	Specimen/Reference Time Differentials[a] (Divisions)
0 (0)	280.4	519.6
3.44 (5)	281.9	518.1
6.88 (10)	283.1	516.9
10.32 (15)	284.6	515.4
13.76 (20)	286.0	514.0
17.20 (25)	288.2	511.8

a. The initial oscilloscope indication for available quartz reference was 800 divisions.

TABLE 7. DATA REDUCTION FOR INDIRECT STRESS MEASUREMENTS

Induced Tensile Load[a] $N/m^2 \times 10^7$ (ksi)	Normalized Time Differentials	
	Divisions	ns/in.
0 (0)	19.6	25.6
1.13 (1.65)	18.1	22.7
2.27 (3.30)	16.9	21.2
3.42 (4.97)	15.4	19.3
4.55 (6.63)	14.0	17.5
5.68 (8.26)	11.8	14.8

a. Specimen was compressively loaded in the rolling direction. Thus, the induced load was of the "B" orientation.

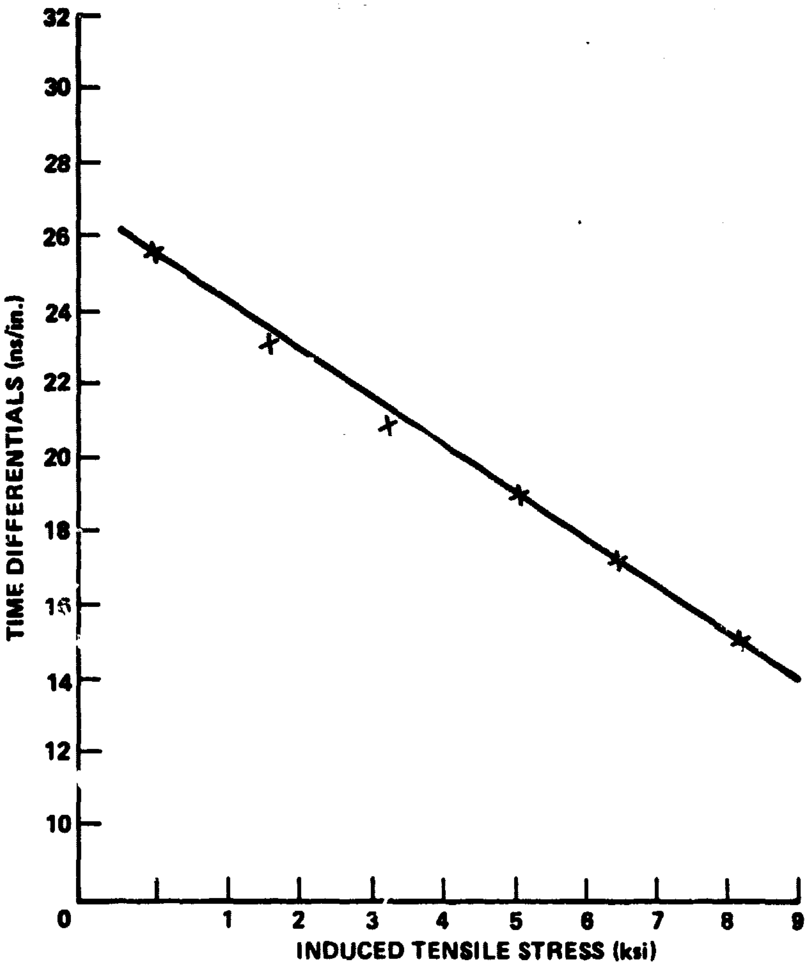

Figure 7. Calibration for the third ortho··onal stress component in 2219-T87 aluminu·· ..ate.

The utilization of such techniques can be considerably enhanced by refinement of the tooling employed in strategically positioning the transduce·· assemblies which must be placed in direct contact with the material under assessment. Thus, it is recommended that such tooling be given appropriate design consideration, recognizing the limitations of access which might be imposed by complex materials configurations if too large an assembly is evolved. In addition, redesign/packaging of the attendant electronics to specifically adapt to the requirements of this technique is also recommended.

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APPROVAL

ULTRASONIC MEASUREMENT OF STRESS IN 2219-T87 ALUMINUM PLATE

By W. N. Clotfelter and E. R. Risch

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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