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NASA Technical Memorandum 106158

Determination of Plate Wave Velocities and Diffuse Field Decay Rates With Broad-Band Acousto-Ultrasonic Signals

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Prepared for the
Second International Conference on Acousto-Ultrasonics
sponsored by the American Society for Nondestructive Testing
Atlanta, Georgia, June 24–25, 1993

NASA

DETERMINATION OF PLATE WAVE VELOCITIES AND DIFFUSE FIELD DECAY RATES WITH BROAD-BAND ACOUSTO-ULTRASONIC SIGNALS

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ABSTRACT

Lowest symmetric and lowest antisymmetric plate wave modes were excited and identified in broad-band acousto-ultrasonic (AU) signals collected from various high temperature composite materials. Group velocities have been determined for these nearly nondispersive modes. An algorithm has been developed and applied to determine phase velocities and hence dispersion curves for the frequency ranges of the broad-band pulses. It is demonstrated that these data are sensitive to changes in the various stiffness moduli of the materials, in agreement by analogy, with the theoretical and experimental results of Tang and Henneke on fiber reinforced polymers [1].

Diffuse field decay rates have been determined in the same specimen geometries and AU configuration as for the plate wave measurements. These decay rates are of value in assessing degradation such as matrix cracking in ceramic matrix composites. In addition, we verify that diffuse field decay rates respond to fiber/matrix interfacial shear strength and density in ceramic matrix composites.

This work shows that velocity/stiffness and decay rate measurements can be obtained in the same set of AU experiments for characterizing materials and in specimens with geometries useful for mechanical measurements.

INTRODUCTION

The acousto-ultrasonic (AU) configuration has been shown useful in assessing mechanical properties in composite structures [1-7]. In particular, plate wave analysis has been shown useful [1,8,9], for characterizing composites in terms of the various stiffness moduli. Similarly, diffuse field decay rate measurements have been shown sensitive [10,11] to other mechanical conditions. These two types of measurement are generally associated with different types of specimen geometries. In this work we examine the practicality of doing both in the same AU experiments on the same useful specimen geometry. With this combination of measurements available, a more complete NDE characterization might be achieved.

THEORETICAL

Plate Wave Analysis

When the distance a wave travels between reflections is short, or at least comparable to the wavelength, interference between propagation path segments will be important. This is realized, for example, in CMC and MMC tensile specimens when frequencies in the range of 1 MHz are employed. Here plate waves dominate the signal. Tang and Henneke [1] present dispersion curves for several situations with graphite polymer systems measured under conditions that produce plate waves. Figure 1, reproduced from Ref. [1], shows a typical case for AU propagation in a [0] oriented unidirectional panel. Certain features can be generalized for other composite

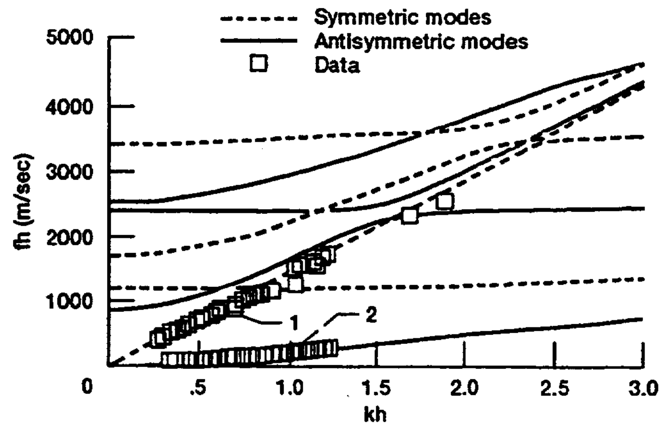


Figure 1.—Theoretical Lamb wave geometrical dispersion curves for propagation parallel to fiber direction of a unidirectional graphite/polymer laminate. The curves are constructed using the approximate theory in ref. f = frequency, k = wave number (= $2\pi/\lambda$), and h = plate thickness. Arrows 1 and 2 point to nondispersive Lamb curves.

systems. With plate thickness h, and wave number k, comparability of free path length and wave length occurs in the vicinity of:

$$kh = 2\pi.$$

At sufficiently low values of the product: fh, (slightly below 1000 m/sec in Fig. 1), only the two lowest plate modes, the lowest symmetric and lowest antisymmetric, will be excited. These two modes are of special interest because they are nearly nondispersive and hence support pulse propagation. Measurements can be performed to determine their group velocities and to then relate them to the mechanical state of the specimen under study. In Ref. [1] it is shown that the differential wave equation for the first symmetric mode is a function of the axial modulus in the propagation direction. At the same time, the wave equation of the first antisymmetric mode is a function of shear and flexure moduli.

Diffuse Field Decay Rate

The acousto-ultrasonic configuration has recently been applied to the measurement of attenuation in materials by means of diffuse field decay analysis [10,11]. Diffuse field decay might be thought of as a refinement of the ringdown count. The power spectrum is partitioned. The log of time segments of these partitions are fitted to decay curves to calculate characteristic constants as a function of frequency.

The differences between "true" and "apparent" attenuation associated with these time decay constants is discussed in Ref. [10]. True attenuation is the conversion of energy, by internal friction, from ultrasonic to other forms such as heat. Apparent attenuation is the scattering of ultrasound out of the sender to receiver path. It can be expected that, through correct interpretation of their source, both types of attenuation can be utilized in material and structure assessment. While internal friction may be sensitive to microstructural condition, scattering will be effected by acoustic impedance discontinuities such as cracks, pore densities and interface bonds.

Ultrasonic attenuation is measured in nepers/centimeter. Precise measurements of this can be made by the pulse-echo technique providing properly shaped specimens can be employed [12-14]. The diffuse field technique determines a decay coefficient in nepers/microsecond. In a nondispersive medium the relationship between the two is straight forward. The relationship between nepers/centimeter and nepers/microsecond is not well defined for an AU signal in a composite. Dispersion makes it ambiguous. However, the diffuse field decay technique presents less severe geometry and surface quality restrictions than pulse-echo. For this reason it is of value to study the diffuse field technique and the use of nepers/microsecond as a monitor of ultrasonic attenuation.

The diffuse field is ideally a totally incoherent field [10]. This is in contrast to plate wave analysis discussed above where one depends upon coherent pulses. Diffuse fields might be expected to occur for the acousto-ultrasonic configuration when coherent pulses are lost. For example highly disperse plate modes arising from a broad-band source will produce incoherent signals.

It has been shown [11] that diffuse field decay is sensitive to fiber/matrix interface bond strength as well as impact damage in SiC/SiC composite.

EXPERIMENTAL

In this work we consider tensile specimen geometries useful for mechanical tests in important high temperature composites. We will find that on these, useful measurements can be obtained with commonly available transducer frequencies.

Acousto-ultrasonic data collection and processing has been described earlier [4,8,9]. Figure 2 shows the AU configuration for plate wave excitation with the tensile specimen oriented with transducers coupled to the wide surface. For plate wave excitation, 0.5 and 1.0 MHz broad-band transducers were employed. Diffuse field measurements were performed under slightly different geometric conditions designed to discourage the propagation of coherent plate mode pulses. To this end, tensile specimens were placed such that the transducers were coupled on the sample thickness edge rather than the faces. In this configuration the wave free path between surface reflections was on the order of the width of the specimen rather than the thickness. In this case, 2.25 MHz broad-band transducers were used. In Fig. 1, taken from Ref. [1], this shift to higher frequency is a shift to a higher range of the product fh and thus higher plate modes. The diffuse field transducer separation, either 2.0 or 3.81 cm, and the signal sweep time were chosen to exclude end reflections of pulses.

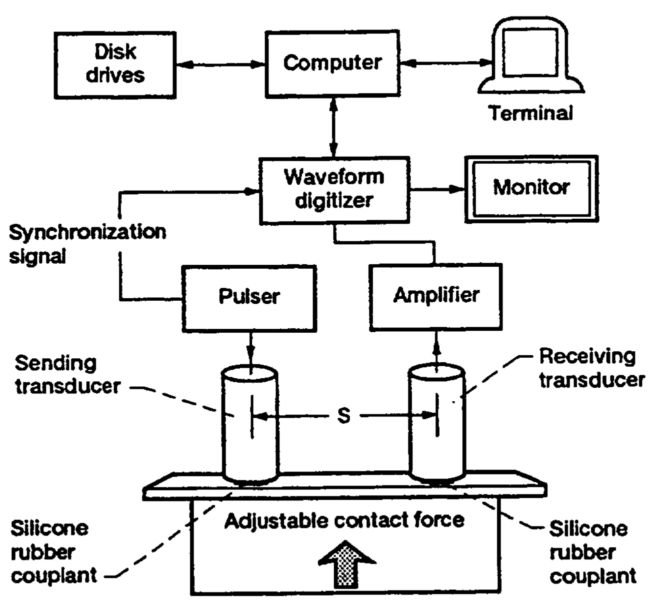


Figure 2.—Acousto-ultrasonic configuration employed for collecting data. s is the centerline spacing between the transducers. s is varied in these experiments.

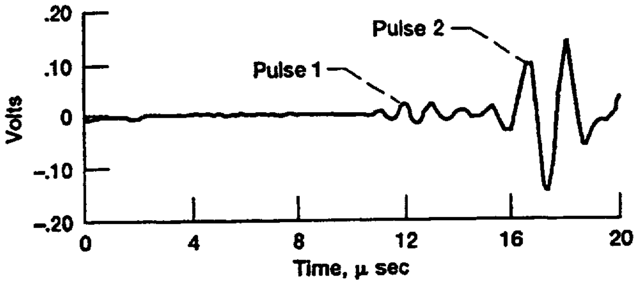


Figure 3.—Waveform collected on a typical composite tensile specimen employing two 1.0-MHz transducers in the plate wave configuration.

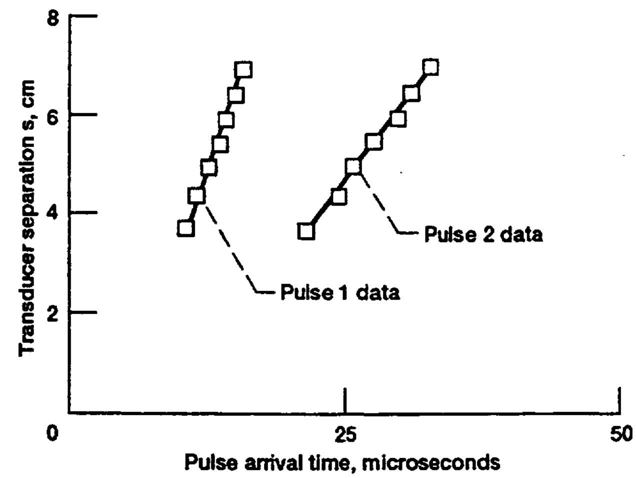


Figure 4.—Typical plots for determining pulse 1 and pulse 2 group velocity, V_g from regression slope.

All acousto-ultrasonic measurements were performed with pairs of broad-band immersion-type piezoelectric transducers. Some diffuse decay data was obtained with the wear plates coupled to specimens through gel couplant. However, in most diffuse decay and all plate wave measurements ultrasonic coupling was with elastomer pads.

Diffuse field decay rates were determined by the methods outlined in Refs. [10] and [11]. The digitized waveform was first partitioned into equal time intervals. The diffuse decay waveform, being a "classical" AU signal, first exhibits a rise to a maximum amplitude followed by a ringdown. This ringdown is the region of interest. Time domain partitions are Fourier transformed. The power spectrum of these partitions is next integrated over selected frequency ranges. The natural log of these integrals are then plotted as a function of the position of the time partition in the original signal. We assume a linear relation between this log function and time. With this assumption one can take the slope of a linear regression fit as the decay constant appropriate for the given frequency range.

RESULTS AND DISCUSSION

Group Velocity for Plate waves

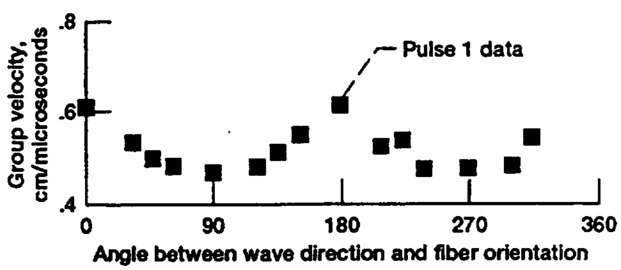
When broad-band transducers were coupled to thin specimens in the AU configuration, waveforms could be recovered such as in Fig. 3. This waveform was collected using two 1.0-MHz transducers with elastomer couplant pads. Two pulses are evident. These pulses can be identified as nearly nondispersive plate wave modes. Pulse 1 is associated with the lowest symmetric plate mode, curve 1, in Fig. 1. Pulse 2 is associated with lowest antisymmetric (Curve 2).

By noting the change in arrival time of these pulses as the transducer separation, s, is varied one can determine group velocities. This is illustrated in Fig. 4. The approximate theory developed in Ref. [1] shows that the group velocities of these modes can be useful in NDE of materials. It was mentioned earlier that the lowest symmetric mode is sensitive to axial modulus and the lowest antisymmetric is sensitive to shear and flexure stiffness. These sensitivities have been illustrated in Refs. [1], [8], and [9] and are shown in Figs. 5 and 6. Figure 5 shows the summary of a study [8] performed with CMCs of various fabrication parameters and treatments. The lowest symmetric group velocity was found to behave as axial modulus. Concomitantly, the lowest antisymmetric velocity behaved as fiber/matrix interfacial shear strength.

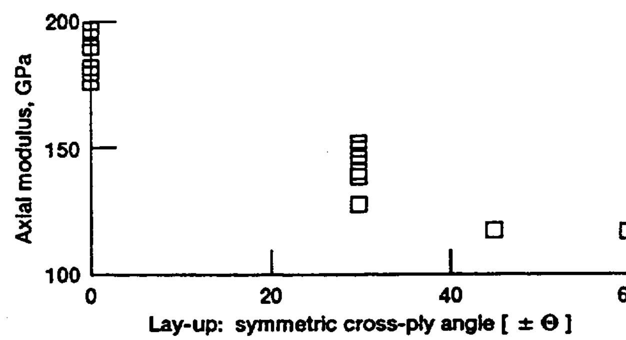
Change from SCS-6/RBSN to:	Axial modulus	Velocity "VL"	Interfacial shear strength	Velocity "VS"
SCS-6/RBSN HIPed	Increases	Increases	No change	No change
SCS-0/RBSN	No change	No change	Increases	Increases
SCS-6/RBSN thermally degraded	Decreases	Decreases	Decreases	Decreases

Correlation between plate wave velocity and mechanical properties of CMCs.

Figure 5.—Summary of results from reference 9 relating changes in plate wave group velocities to change in mechanical properties for SiC/RBSN composite.



(a) Group velocity for unidirectional panel.



(b) Axial modulus for [±0] lay-ups. This data is from destructive tensile tests.

Figure 6.—Variation of pulse 1 group velocity and of axial modulus with angle between fiber direction and measurement direction in SiC/Ti15-3 MMC.

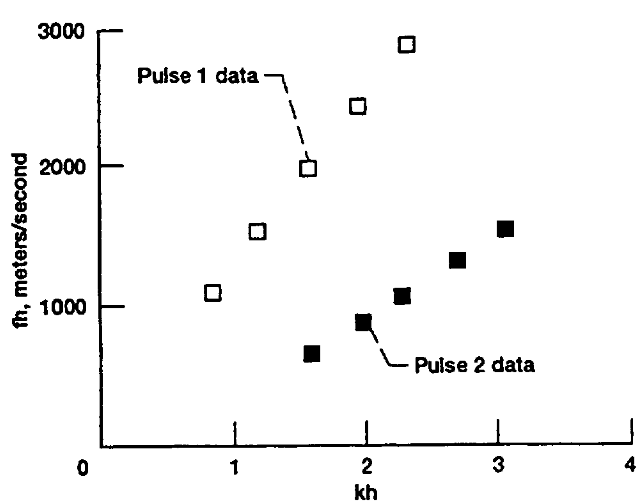


Figure 7.—Experimental Lamb wave dispersion curves calculated for a [0] SiC/RBSN CMC tensile specimen. Calculations were made from broadband transducer acousto-ultrasonic data.

Figure 6(a) shows how the two velocities vary with orientation on a unidirectional SCS–6/Ti 15–3 MMC panel. This can be compared with destructive test verification in Fig. 6(b) of the behavior of axial modulus as a function of fiber layup. The comparison shows that the symmetric mode group velocity strongly follows the same orientation dependence as does the axial modulus.

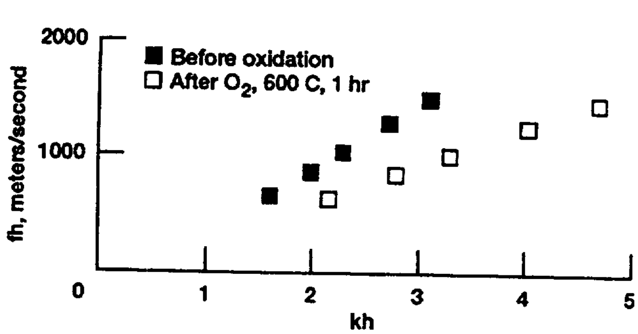
Dispersion Curves for Plate waves

As expected with broad-band transducers, the magnitude spectra exhibit significant width. Over this width, the phase spectrum contains the information on the relation between the phases of the frequency band that produce the pulse. Reference [9] details the technique for using this phase relationship, as it changes with transducer separation, to determine phase velocity as a function of frequency. This in turn allows construction of dispersion curves like Fig. 1.

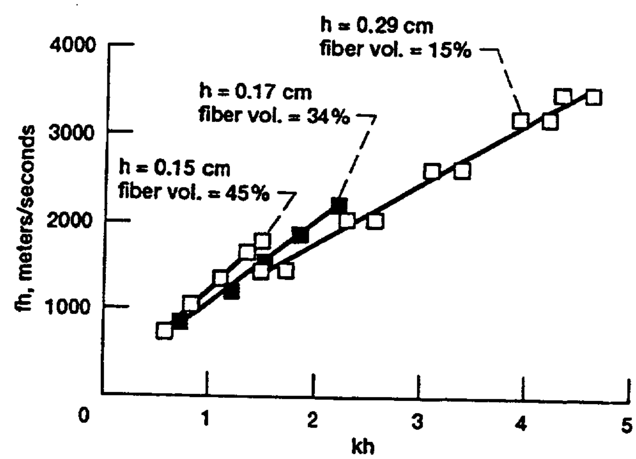
Figure 7 shows a dispersion diagram determined for [0] oriented CMC tensile specimen by the method of Ref. [9]. Curve 1 shows an intercept near the origin, indicating nondispersion. Curve 2 exhibits the unique-negative intercept of the lowest antisymmetric mode. These results agree with the Ref. [1] results presented in Fig. 1.

Examples of the effect changing mechanical properties have on dispersion curves is presented in Ref. [15] and also here in Fig. 8. In Fig. 8(a) the lowest antisymmetric curve for a [0] oriented CMC is shown before and after 600 °C oxidation for 1 hr. The oxidation has degraded fiber/matrix interfacial shear strength. This degradation is reflected in the dispersion curves.

In Fig. 8(b) the lowest symmetric curves are shown for SCS–6/Ti 15–3 MMC [0] oriented panels of different fiber fraction and thickness. Different fiber fractions yield different axial modulus which is reflected in the slopes of the curves. Different thickness causes the curves to fall on different parts of the diagram.



(a) Variation of pulse 2 dispersion curve with thermal degradation in SiC/RBSN CMC.



(b) Variation of pulse 1 dispersion curve with panel thickness and fiber volume percent in SiC/Ti 15-3 MMC.

Figure 8.—Experimentally determined dispersion curves for high temperature composites.

Diffuse Field Decay

Two 2.25-MHz transducers were coupled to CMC tensile specimens as described earlier. The waveform shown in Fig. 9 is typical of the data collected. This is a 1024 point array obtained by appending two 512 point arrays. This waveform was partitioned into ten 10-μsec partitions. It is obvious that the 0- to 10-μsec partition must be discarded because it contains the characteristic initial rise portion of the AU signal. It also seems evident that if a waveform such as this is followed too far to the right noise dominates the signal.

Diffuse field decay measurements were performed on three types of [0] oriented unidirectional SiC fiber/ RBSN CMC tensile specimens. They were:

(1) SCS–6/RBSN as fabricated

(2) SCS–6/RBSN raised to 100 percent density by hot isostatic pressing, [HIPing]

(3) SCS–0/RBSN as fabricated with high fiber/matrix interfacial shear strength (ISS) compared to the SCS–6 reinforced specimens

These same three conditions were referred to earlier in the results with plate wave measurements.

Figure 10 is a plot of the calculated decay rates as a function of frequency. Note that the HIPed SCS–6 reinforced specimen and SCS–0 reinforced specimen, with high ISS had much reduced diffuse field decay rate from the as fabricated SCS–6 specimen. This result is in agreement with reported results with SiC fiber reinforced SiC composite [11].

Two sources of attenuation, and hence diffuse field decay, were noted earlier. Figure 10 may show both. Differences in true attenuation may be manifesting between the SCS–6 and SCS–0 reinforced composite. There is likely to be much less internal friction at the SCS–0/RBSN fiber-matrix bond. On the other hand, HIPing of the SCS–6/RBSN causes a decrease in porosity and hence a decrease in apparent attenuation due to scattering.

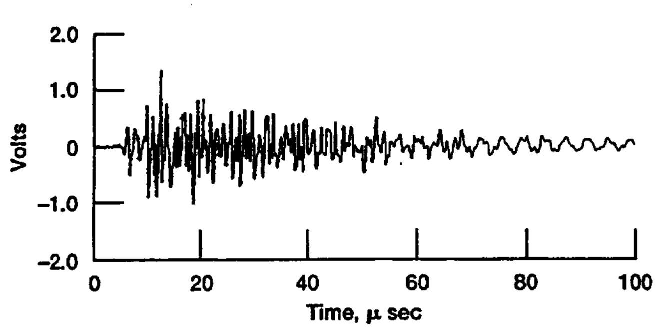


Figure 9.—Typical diffuse field waveform collected on [0] unidirectional CMC tensile specimen with two 2.25 MHz transducers.

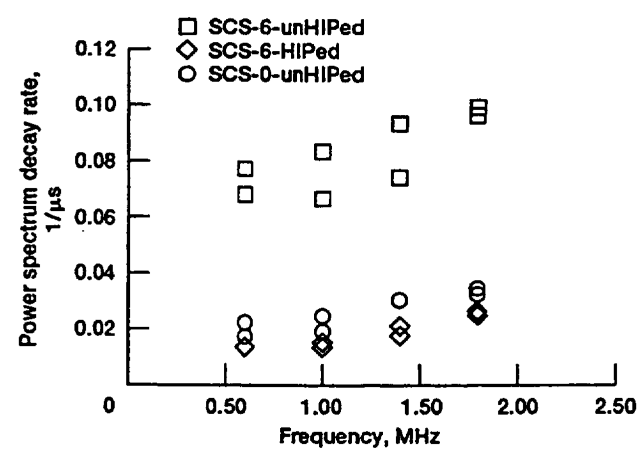


Figure 10.—Diffused field decay rate as a function of frequency for three fabrication conditions on [0] unidirectional SiC/RBSN composites. Two trials were performed for each specimen.

CONCLUSIONS

It has been demonstrated that both AU techniques: plate wave and diffuse field decay rate measurements, can be performed successfully on the same specimen materials and geometries. All these measurements can be done in the same set of experiments and with the same equipment. The materials are important high temperature composites presently under development for aerospace application. The geometries are typical tensile specimens designed for mechanical test in this development program.

It has been demonstrated for CMCs, and indicated for MMCs, that these AU techniques can provide, nondestructively, information on axial modulus, fiber/matrix interfacial shear strength, density, i.e., porosity, and the degradation effects of oxidation at high temperature.

What is needed is more detailed correlation of these AU parameters with results of mechanical tests and metallography. Such correlations can be used as bases for assessing the ability of the AU parameters to predict strength and reveal defect densities.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1993	Technical Memorandum

4. TITLE AND SUBTITLE

Determination of Plate Wave Velocities and Diffuse Field Decay Rates With Broad-Band Acousto-Ultrasonic Signals

5. FUNDING NUMBERS

WU–510–01–50

6. AUTHOR(S)

Harold E. Kautz

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
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Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–7844

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–106158

11. SUPPLEMENTARY NOTES

Responsible person, Harold E. Kautz, (216) 433–6015

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 38

12b. DISTRIBUTION CODE

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14. SUBJECT TERMS

Nondestructive tests; Ultrasonics; Ultrasonic tests; Ceramics; Ceramic matrix composites; Metal matrix composites; Mechanical tests

15. NUMBER OF PAGES

10

16. PRICE CODE

A02

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

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