ANALYTICAL ULTRASONICS FOR EVALUATION OF COMPOSITE MATERIALS RESPONSE

PART II: GENERATION AND DETECTION

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To evaluate the response of composite materials, it is imperative that the input excitiation as well as the observed output be well characterized. This characterization ideally should be in terms of displacements as a function of time with high spatial resolution. Additionally, the ability to prescribe these features for the excitation is highly desirable. This paper examines various methods for generating and detecting ultrasound in advanced composite materials. Characterization and tailoring of input excitation is considered for contact and noncontact, mechanical, and electromechanical devices. Type of response as well as temporal and spatial resolution of detection methods are discussed as well. Results of investigations at Virginia Tech in application of these techniques to characterizing the response of advanced composites are presented.

INTRODUCTION

Accurate characterization of mechanical performance of materials is crucial for engineering application. Destructive mechanical testing is capable of establishing a range of lower limit values for a limited number of states of stress. Generally this type of testing seeks to establish a uniform state of stress and to monitor the magnitude of load causing deformation or failure. Such testing is of little use for characterizing materials which are inhomogeneous by design or for materials which are created in a structural form. Modern tailored fiber reinforced composite materials fall into both of these categories. In that composites are being used frequently in high performance applications, appropriate means of mechanical characterization are a vital need.

Traditionally, in the engineering arena, ultrasonic techniques have been relegated to detecting flaws in components. In recent years, proponents of their use for characterizing material properties have been receiving greater attention. Rightly so, in that ultrasonic techniques possess the potential for local examination as well as incorporating a variety of parameters that are sensitive to subtle changes in material condition. These features are especially attractive for characterization of composite materials which may be composed of random or oriented reinforcement with varying conditions of reinforcement, matrix, reinforcement to matrix bonding, and layer to layer bonding.

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This paper is Part II of a pair of papers examining the application of ultrasound for characterizing composite materials. Part I has examined from a theoretical perspective the restrictions on the applications as well as provided insight into some yet unexplored areas. This paper examines the experimental methods of generating ultrasound in materials as well as detecting the associated resulting material response. A brief survey of existing methodologies is presented to serve as a basis for discussion with no attempt being made to fully review the extensive work in any of these areas. The primary objective here is to look to the future as regards new or improved methods of analytical ultrasonic evaluation of composite materials. In particular, the issue of characterizing materials of this class, which are constructed deliberately to be inhomogeneous, and those containing damage, is examined.

EXPERIMENTAL METHODS OF ULTRASOUND GENERATION

The prevailing philosophy in the generation of ultrasound has been to develop a generating device having an output ultrasound field with prescribed characteristics, these characteristics being a smooth -- either plane or curved -- wavefront; a specified amplitude, frequency spectrum, and duration. The subsequent interaction of the ultrasound field with the material was inferred from theory with recognition that problems with insertion, such as scattering and reflection, existed. Recently these difficulties although minimized, have still been seen as unacceptable. As a result, methods of creating ultrasonic disturbances within the material of interest, have begun to be explored. Some features of both types of approaches are presented, with attention to control and specification of the disturbance in the material being characterized.

METHODS OF EXTERNAL ULTRASOUND GENERATION

Piezoelectric Devices

Piezoelectric devices are used more frequently than any other for generation of ultrasound. They are simple in construction, rugged, and easy to use. Of these, piezoelectric ceramic materials are most prevalent; however, quartz, a naturally occurring piezoelectric material, does offer some advantages. These include good linearity of performance, little degradation with age, and pure mode generation, when appropraitely cut. Quartz is less active than its ceramic counterparts. Consequently, in most commercial devices, ceramics are used. Recently, the development of polymeric piezoelectric materials has provided some additional flexibility in structural and electronic configuration of devices. That is to say, that the response of the element at any point is constrained by its surroundings and the electrode configuration. Consequently, the element responds as a whole to imposed voltages but the response from point to point may not be the same. The sound field generated mimics this variation. A reduction in this variation can be achieved by shaping and mechanically coupling the element and by careful manufacturing control; neither problem can be completely eliminated. Frequently, the variation in the sound field is diminished by focusing the field into a smaller beam for application where the fine structure of the sound field is of little importance.

Through the use of electrode configuration or element arrays, it is possible to tailor the sound field (ref. 1). Claus and Zerwekh, in reference 2, for example, have used a single piezoelectric element and a concentric array of annular electrodes to develop a two-dimensional Gaussian field profile (as measured in water). Such development is nearly always demonstrated in water which is isotropic and homogeneous.

Spark Discharge Methods

Some work has been done with the use of shock waves created by the ionization of gases when a spark arcs a gap between two electrodes. The shock wave is directed at the surface of the material of interest. Little attempt is made as regards modifying the shock, as the primary objective of such methods is to create short duration disturbances which may be reproduced.

For all of these methods, the control and specification of the disturbance introduced in the material being examined is indirect. It is directly influenced by the surface condition, the differences in mechanical impedance between external media and that of the material, the isotropy, and homogeneity of the material. Of special significance, however, is the aspect of direction of propagation. The direction of incident wave propagation determines in large measure the subsequent direction of propagation in the material; additional wave modes that may not be desired will accompany non-normal incidence.

METHODS OF INTERNAL ULTRASONIC MECHANICAL WAVE GENERATION

It is possible to avoid the problems associated with creating an external ultrasound field and coupling it into a material. This may be accomplished by creating a mechanical disturbance within the material directly. Such an approach incorporates the advantages of avoiding problems related to coupling media and the constraints of the generating device mentioned above. OFten these advantages are offset by the fact that there is no way to characterize the resulting ultrasonic disturbance parat from the material being examined. Under ideal conditions it may be possible to experimentally charactrerize the disturbance caused by such a method. It should be noted, however, that the use of a characterized source does not necessarily mean that the ultrasonic disturbance it creates is characterized.

Electromagnetic Acoustic Transducers (EMAT)

The recognition that an eddy current induced in a conducting material would interact with an external magnetic induction to cause a Lorentz force on the particles of the conductor and thus an elastic disturbance lead to the development of electromagnetic acoustic transducers. Consequently, it is possible by appropriate choice of orientation of the electric and magnetic fields to induce a variety of different wave modes in conducting materials or materials on which a conducting layer has been deposited. EMAT induced ultrasonic disturbances are of course still influenced by the isotropy and homogeneity of the material, but now this includes both mechanical and electromagnetic considerations. A good review of work in this area has been made by Frost (ref. 3).

For these devices, the size does not control the frequency response; however, the electrical coil geometry does influence the overall response and it may not be varied arbitrarily. This limits somewhat the spatial variations that may be achieved in the induced ultrasound field.

Laser Generation

Rapid localized heating of the surface of a material may be accomplished using a pulsed laser. The associated rapid thermal expansion causes a mechanical disturbance which, upon cooling, is reversed, giving rise to ultrasonic waves within the material. It is suggested in reference 4 that since the surface is unconstrained in the normal direction, that the main resultant thermoelastic stresses are in-plane. The area of the beam can be in practice quite small, on the order of millimeters, and shaped as desired. Factors influencing the induced disturbance include the energy distribution of the laser beam, the isotropy of thermal conductivity and expansion, and homogeneity of the material.

In composite materials the thermal properties of the constituents are often different and the material is inhomogeneous on the scale of the beam diameter. This would certainly influence the ultrasonic waves created.

Impulsive Methods

A number of other methods which have as their basis mechanical impulsive loading of the material surface have been proposed and demonstrated. These include the use of a helium gas jet (ref. 5), tapping (or other forms of impact), pencil lead breaking (ref. 6), and glass capillary breaking (ref. 7). The advantage of such techniques is that the disturbances they cause are highly localized and often broadband in frequency content. The direction of propagation as well as the mode and frequency content are not controlled, but rather are determined by the response of the material to the impulsive load. It is imperative in the use of such methods that the impulsive source be mechanically characterized. This must be accomplished in a material in which the ultrasonic wave propagation is well characterized, which in general implies a homogeneous and isotropic material. The application of such sources to anisotropic, inhomogeneous materials is particularly useful for providing insight to efforts for modeling the wave propagation in such materials.

EXPERIMENTAL METHODS OF DETECTING ULTRASOUND

A number of methods have been developed for detecting ultrasonic mechanical waves in materials; however, not all of these methods provide information in a form that may be interpreted in terms of mechanical response. This limitation does not preclude effective application of these methods for imaging imperfections and other situations for which a precise description of particle displacement and velocity are not needed.

Piezoelectric Devices

Until very recently, the output electrical signal of piezoelectric transducers, although extremely sensitive to ultrasonic motion in materials, could not be closely related to the motion of the material. Proctor, building on the work of colleagues at the National Bureau of Standards, developed a piezoelectric device which, because of its configuration, provides an electrical output that may be shown to be related closely to the out-of-plane displacement of the material caused by the ultrasonic distrubance. Its sensing area is on the order of 2 mm^2 and is coupled to the surface of the material; more recently, development of a similar device for detecting in-plane displacements is underway. These devices are somewhat massive, making them difficult to utilize in many configurations, causing loading of the surface and thereby influencing the response of the material. They also suffer from all of the normal problems associated with coupling. Nevertheless, in application to the study of wave propagation in composites, they are capable of providing output information which, in conjunction with a well characterized input disturbance, provides the experimental data necessary to verify theoretical models of such behavior.

A special application of piezoelectric devices worth mentioning is that of the acoustic microscope (ref. 8). The construction of such a system is an enormous challenge, but the capabilities are powerful. It is possible with such systems to work at gigahertz frequencies which correspond to wavelengths of sound comparable to that of light. With appropriate design of the transmitter and receiver, extremely fine spatial resolution is possible. Application to composite materials has shown that images of mechanical reflectivity or transmissivity are possible (fig. 1); comparative quantitative evaluation is also possible.

Capacitance Displacement Measurement

A relatively simple application of the concept of a parallel plate capacitor may be used to detect out-of-plane displacements of a material caused by an ultrasonic disturbance. Such a device has been used to study wave propagation in composite plates; the details of this work are described in a later section. Such devices, although electrically capable of wide band response, are practically limited by their size at lower frequency if their gap is maintained by support on the material being examined. If support is independent of the material, the dynamic range of detectable displacements is limited since ideally for optimal sensitivity the separation of the "plates" should be similar to the size of the displacements. The size of such devices may be reduced, but the biasing potential must be increased to maintain sensitivity; the breakdown potential for arcing across the gap thus provides a limit. Such devices are insensitive to in-plane displacements.

Optical Methods

A number of interferometric methods have been developed with good success, although primarily development has been limited to the situation of out-of-plane displacement. A typical configuration finds the material acting as the mirror of one or, at times, both legs of a Michelsen Interferometer. Displacement of the surface causes interference to occur which may be determined precisely in terms of the wavelength of the laser light used. Such methods are normally sensitive to vibration of the material that may not be associated with the ultrasonic disturbance of interest. The area of examination is generally 1 to 2 mm^2.

A method of imaging the distortion of a reflecting surface caused by a continuous ultrasonic beam having passed through the material of interest has been developed and marketed by SonoScan, Inc. (ref. 9). The primary application is for detection of poor transmission of ultrasound within the material. Quantitative comparative interpretation of the wave propagation of the material from this method is possible. It is similar to the method of acoustical holography which in principal is similar to optical holography; this method also finds its principal applications to imaging of regions of imperfect ultrasound transmission.

Recently, Wagner (ref. 10) has utilized a pulsed laser holographic method for providing full field out-of-plane displacement images of a propagating ultrasonic disturbance caused by an explosive impulse, and by laser generation as well. Such a procedure is extremely beneficial for providing insight into the modeling of the material behavior in inhomogeneous anisotropic materials.

In general, full field visualization methods sacrifice temporal resolution because of the response of the recording media; however, technological advances are remedying this situation.

X-ray Measurement

Some work has been done with measuring ultrasonic amplitudes in small volumes of material by using X-ray measurements (ref. 11). In principle, this method relies on the fact that the ultrasonic wave decreases the diffracted X-ray beam intensity. For composites composed of crystalline constituents, this method would appear to have potential.

DATA ANALYSIS

Ideally, the decision regarding the method of generation and detection of the ultrasound disturbance should be made with a mind toward the intended physical interpretation of the results. Certainly there is no possibility of explaining directly a quantitative observation, in terms of material performance, if the cause is unknown. An indirect explanation may, however, be possible in specific situations. Although it is desirable to be able to prescribe the full displacement and velocity, at every point as a function of time arbitrarily, it is not presently possible. If one desires to evaluate the performance of the material without regard to a certain scale of inhomogeneity, it is presently possible. Velocity measurement for determining material constants is such a situation. The fact that the property determined may not be constant along the path, or across the beam of the ultrasonic wave, is generally not a concern unless the difference is severe. In such instances, a reflection due to an impedance discontinuity is often observed; gross changes could occur however without discontinuity. In such a fashion, considerable information may be determined experimentally through the use of a constant but uncharacterized source, if the homogeneity and isotropy of the material are known.

This approach may be extended and applied to advantage in characterizing the condition of composite materials in conjunction with other nondestructive and destructive methods. It, however, requires considerable effort as regards determining how the observed behavior is modified by various independently determined material conditions. Extension to other similar materials is of higher probability, the more similar the material. This type of approach, sometimes called adaptive learning, is not ultimately a substitute for an understanding of the actual materials response, and should only be used as a stepping stone to a more complete understanding. (From an engineering point of view, the advent of high speed computers makes this approach attractive for routine problems.)

If the assumption of a constant source is reasonable, considerable artificial data interpretation is possible in certain special cases. Such is the case with ultrasonic tomography and other methods of spatial data averaging.

The method of data analysis proposed by the National Bureau of Standards, which serves in part as the basis for their method of transducer calibration, is that of deconvolution (ref. 12). The approach supposes that the material, and its structural configuration, act as a linear invariant system. Then, using a well-characterized point source to create a white noise ultrasonic disturbance, which ultimately is detected at a point by a quantifiable detector, the influence of the material/structure can be quantified. This quantification is in the form of a Green's function which mathematically describes the material condition in some average way; it is <u>not unique</u> as regards the material condition. The technique is useful in certain limited situations for characterizing the source. This characterization is limited by the information obtained by the detector, i.e., if the detector measures only out-of-plane displacement, then the characterization of the source as regards in-plane displacements is not possible. Additionally, the process of calculating the Green's function is not trivial; however, recently Eitzen, et al., in reference 13, have suggested that by modifying the input source from the Dirac-delta function associated with a step force unloading at a point to an inverse Gaussian waveform, the calculation could be simplified.

Work employing finite difference methods or finite elements is underway; however, it is questionable as to whether, at this time, it is possible to properly pose this problem for analysis by these methods. It is certain that careful experimental investigation of this problem is needed to aid in these modeling processes.

EXPERIMENTAL INVESTIGATION OF WAVE PROPAGATION IN COMPOSITE MATERIALS

Composite materials are anisotropic and inhomogeneous. The inhomogeneity occurs on at least three scales:

i. on the scale of the fiber,
ii. on the scale of the laminae,
iii. on the scale of the laminate fiber orientation established by design.

Although during the fabrication of composite material structures manufacturing flaws occur, routine application of inspection methods is often sufficient for locating and sizing large flaws. On the other hand, during the fabrication, the material itself is created and its condition is often of concern. In general, the concern is with regard to the quality of the mechanical properties and their uniformity, where often the causes of poor properties are related to subtle variations in the material that are not detected by conventional flaw detection methods. Even if they were detected, the need is to characterize the performance, not to place the blame. Ultrasonic methods of determining materials constants are available. Unless the condition of concern is uniformly distributed, the "properties" measured reflect an integrated response that may, in fact, not represent any place in the material precisely. Furthermore, since the damage in fiber reinforced composite materials begins to occur at relatively low loads and is globally distributed, the interpretation of velocity measurements must be carefully undertaken. Quite often the properties of the composite formed may suffer substantial change. It might be contended that such changes are not changes in material but rather changes in structure. It is, however, this structure which synergizes the properties of the constituents into a unique material. The task of characterization therefore incorporates both material and structural features.

In 1979, Vary and Bowles (ref. 14) suggested a method which interrogated both the material and structural properties of the composite materials examined. This acousto-ultrasonic method employed an ultrasonic transmitting transducer and an acoustic emission type receiving transducer, both coupled to the same side of the material. This pitch-catch arrangement in the limit of zero transducer separation is the conventional pulse echo technique. Vary and co-workers subsequently have shown correlation of sound transmission measured in this way with tensile strength. In addition, regions of poor ultrasonic stress wave transmission, as measured in this way, were found to be at the location of final failure in uniaxial tension test coupons. Henneke et al. (ref. 15) have continued to explore the use, and develop the understanding of the method for characterizing composite materials.

As has been suggested above, in order to quantitatively describe the nature of wave propagation in composite materials resulting from a mechanical disturbance, it is imperative that the source of the disturbance be known. Further, in order to validate the prediction of any theory regarding the wave propagation resulting from a known disturbance, it is necessary to employ a detector which can be quantitatively interpreted in terms of mechanical response. As part of an overall effort to model the mechanical behavior of composite materials with and without mechanically induced damage, Rebello and Duke have utilized a point load with step function time dependence as a source (pencil lead break) and an out-of-plane displacement sensor (capacitive transducer) to study the behavior of laminated composite plates (ref. 16).

Plates of aluminum and graphite epoxy composite were examined with various boundary conditions. Figure 2 displays the experimental arrangement employed to study the response. Figure 3 is the spectrum observed for an aluminum plate simply supported on all four edges when subjected to a pencil lead break in the center of the plate. Table 1 shows the comparison between the frequencies predicted by an exact solution and a finite element solution. Figure 4 is the spectrum observed for a graphite epoxy plate simply supported on all four edges when subjected to a pencil lead break in the center of the plate. Table 2 is the comparison between the exact and finite element solution for this case.

In both cases, despite the broadband content of the source, resonances of the plate were observed. The conclusion drawn was that if the response is observed for a period of time much longer than the source event duration, or the distance from the source is such that interaction of the disturbance with the structure will occur, the spectral content of the observed response will be dominated by induced structural resonances; changes in structural resonances caused by damage might be observed. Further characterization of the source is possible only if the disturbance propagates directly to the detector and the period of observation is short enough to ignore portions of the disturbance propagating from other directions. Generally this is extremely difficult to achieve, however, material, rather than source, characterization is the objective.

Since the capacitive transducer is capable of detecting only out-of-plane displacement, development of optical methods for detecting dynamic in-plane and out-of-plane displacements are being developed. The primary effort is being directed at the in-plane measurements, with the method for out-of-plane measurement being adapted from other workers. The long range objective is to be able to introduce a known disturbance, predict the response at various positions in the structure, observe the actual response, and explain any difference from prediction in terms of the damaged material condition. Ideally this description would facilitate directly or indirectly the assessment of stiffness and strength or life.

In parallel with efforts to quantitatively measure displacements are efforts to study the influence of damage on the wave propagation in composites. This activity is utilizing the approach discussed above involving a constant but uncharacterized source. In particular, a conventional ultrasonic transducer is used to generate a disturbance in the material. At a fixed distance away on the same side of the material, another similar transducer is used to observe the disturbance (ref. 17). The material is at the same time subjected to mechanical loading which induces damage; independent means are employed to characterize the damage, including stiffness monitoring and penetrant-enhanced radiography. Figure 5 shows the spectrum of the observed disturbance at various stages of deformation. Of particular significance are the changes in the spectrum which appear to be related to the occurrence of particular damage mechanisms. This apparent frequency sensitivity raises the possibility of differentiating modes of damage by the observed spectral response. At the same time it appears to be advantageous to be able to influence the frequency content of the source in order to increase the range of damage development which may be monitored and to make possible the detection of damage that might interact with frequencies not already present.

By quantifying the observed response in a way related to the root mean squared energy, a correlation with stiffness degradation resulting during cyclic loading has been observed. This measure appears more sensitive than that of stiffness (fig. 6) but the reason is as yet unexplained.

Recently, experiments have been performed, replacing the receiving transducer with a Proctor out-of-plane displacement sensor (ref. 18). Figure 7 shows the spectrum of the observed disturbance caused by the same transmitting transducer used for the observations of Fig. 5. An extremely high resolution FFT has been performed; an explanation in terms of channeled plate waves (Lamb waves) is being sought.

FUTURE DIRECTIONS

Ultrasonic techniques, in that they are physically based on mechanical disturbances, possess the greatest potential for determining mechanical behavior of advanced materials. Consequently, in the future, efforts to understand the wave propagation in composites must be continued, as ultrasonic methods possess the potential for characterizing the mechanical behavior of these increasingly important engineering materials. Special emphasis must be given to characterizing the undamaged behavior of inhomogeneous materials, since conventional testing methods are inadequate. The ability to characterize, not simply identify, damage in composites must be a top priority, especially since there materials are very damage tolerant and may still perform satisfactorily even though severely damaged. At present the use of broadband ultrasonic disturbances appear to be most promising, but the need to measure quantitatively the displacement fields caused by such disturbances must be given priority. In addition, attention must be given to the means of creating such disturbance since the composites are inhomogeneous on a scale comparable to the area of the disturbance. A possible alternative to the broadband type of pulse disturbance which might lend itself to material characterization is to utilize a wide beam single frequency sound field, as is the procedure with the "acoustic microscope" of Sonoscan, but analyze the disturbance subsequent to additional interaction with the structure.

It should be anticipated that improvement of ultrasonic equipment and computer algorighms for data analysis will, in the future, lead to a greatly increased capability to image damage or regions of material property imperfection. However, for materials with complex or extensive damage, an image may afford little assistance in ultimately describing the anticipated performance of the material.

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TABLE 1

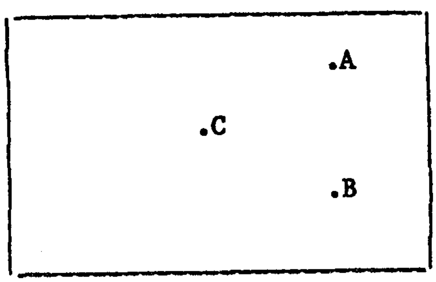
Aluminum Frequencies, SSSS

Frequency f_{ij}	Finite Element Hz	Exact Hz	Percentage Change in Frequencies	Experimental Observation (Source-Sensor)
f_{11}	0.2206	0.2170	1.6	(C,C), (A,C), (B,C), (A,A), (B,B)
f_{12}, f_{21}	0.5773	0.5425	6.0	(A,C), (B,C), (A,A), (B,B)
f_{22}	0.9284	0.8679	6.5	(A,A), (B,B)
f_{13}, f_{31}	1.2736	1.0849	14.8	(C,C), (A,C), (B,C)
f_{23}, f_{32}	1.6140	1.4104	12.6	(A,A), (B,B)

TABLE 2

Graphite-Epoxy Frequencies, SSSS

Frequency f_{ij}	Finite Element Hz	Exact Hz	Percentage Change in Frequencies	Experimental Observation (Source-Sensor)
f_{11}	64.3	61.7	4.0	(C,C), (A,C), (B,C)
f_{12}	99.1	93.6	5.6	—
f_{13}	197.4	167.8	15.0	(C,C), (A,C), (B,C), (A,A), (B,B)
f_{21}	256.8	239.2	6.9	—
f_{22}	271.3	252.0	7.1	—
f_{41}	326.1	281.7	13.6	(A,A), (B,B)
f_{23}	389.2	292.2	24.9	(C,C), (A,C), (B,C), (A,A), (B,B)
f_{24}	473.9	374.3	21.0	(C,C), (A,C), (A,A), (B,B)
f_{31}	629.7	535.4	15.0	(C,C), (A,C), (B,C)
f_{33}	637.9	567.0	11.1	—



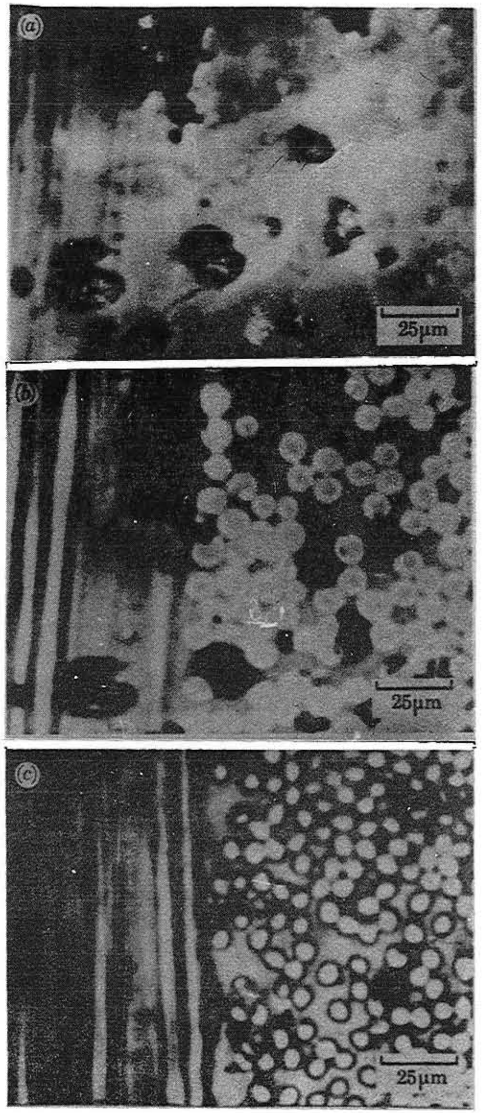


Figure 1 Comparison of Scanning Electron Micrograph (a) and Acoustic Micrograph (b focused), (c modest defocus) (from reference 8)

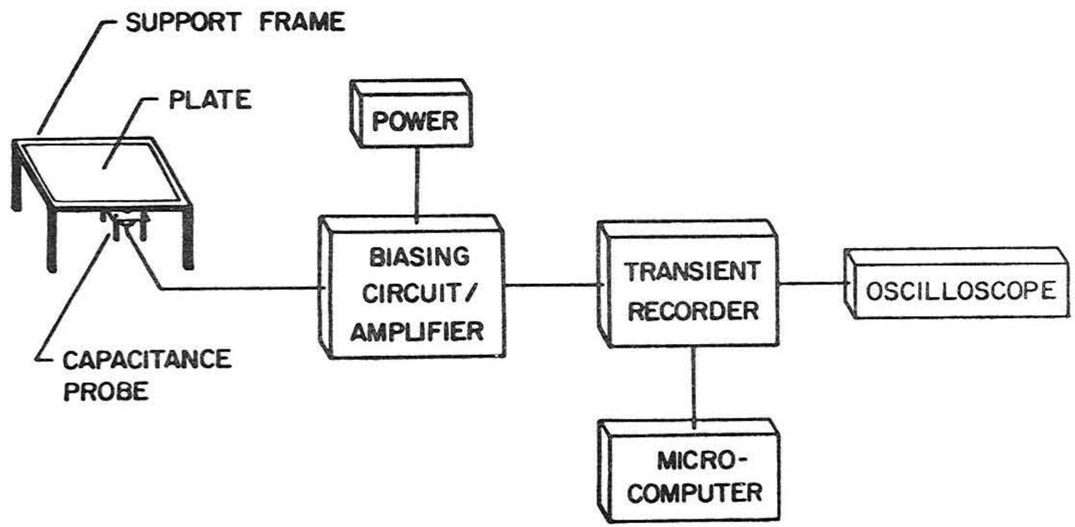


Figure 2 Experimental arrangement used to study the response of plates to point load with step function time dependence.

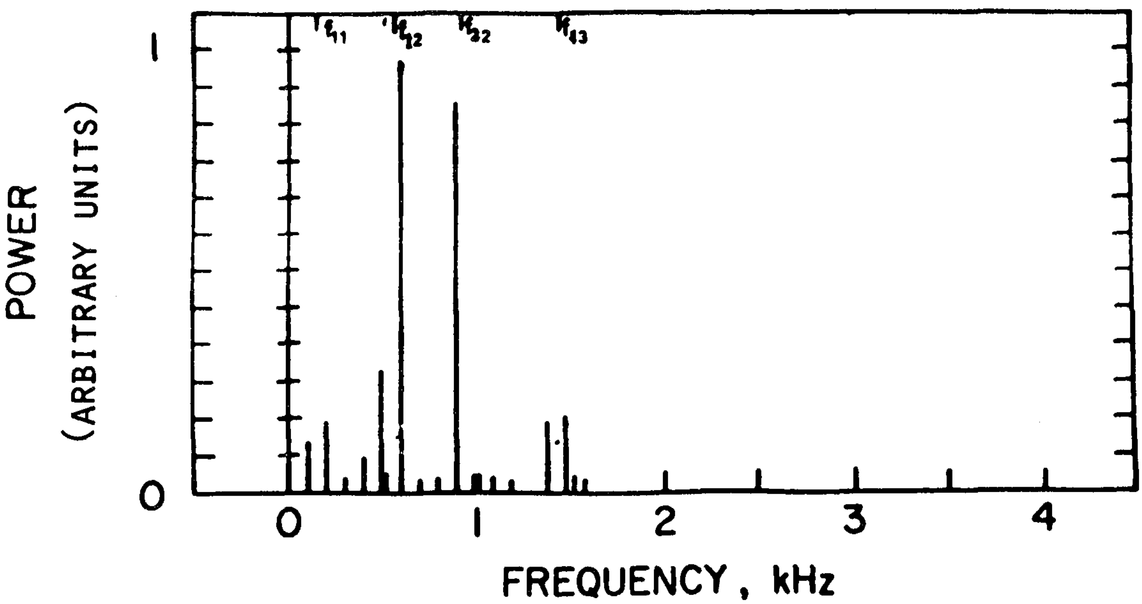


Figure 3 Frequency spectrum for an aluminum plate simply supported on all four edges when subjected to pencil lead break in the center of the plate.

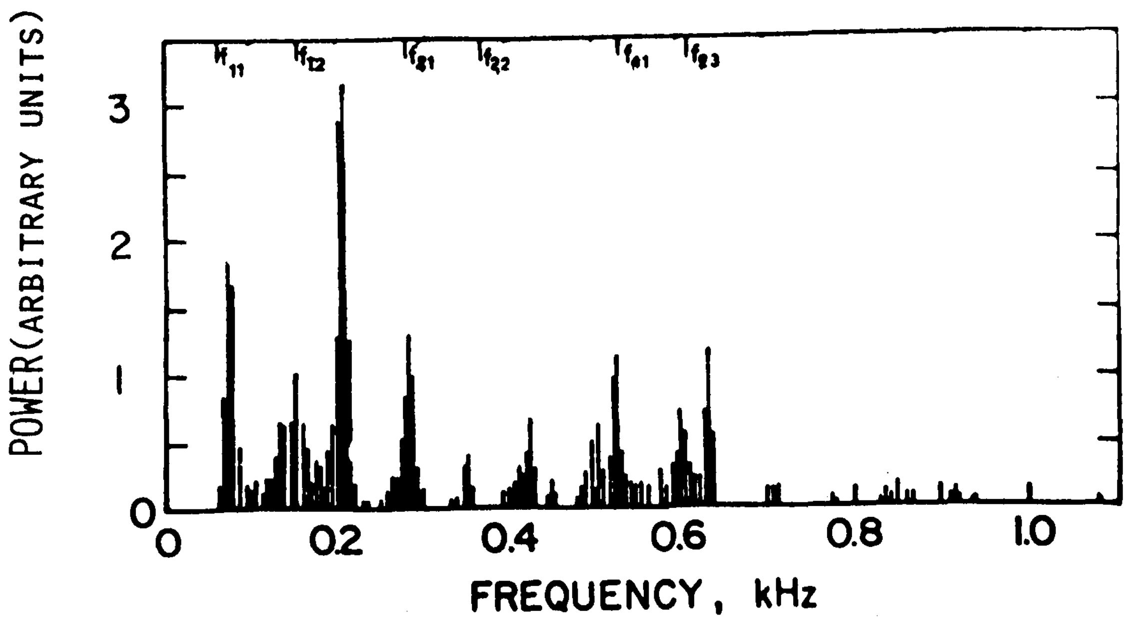


Figure 4 Frequency spectrum for a graphite epoxy plate simply supported on all four edges when subjected to a pencil lead break in the center of the plate.

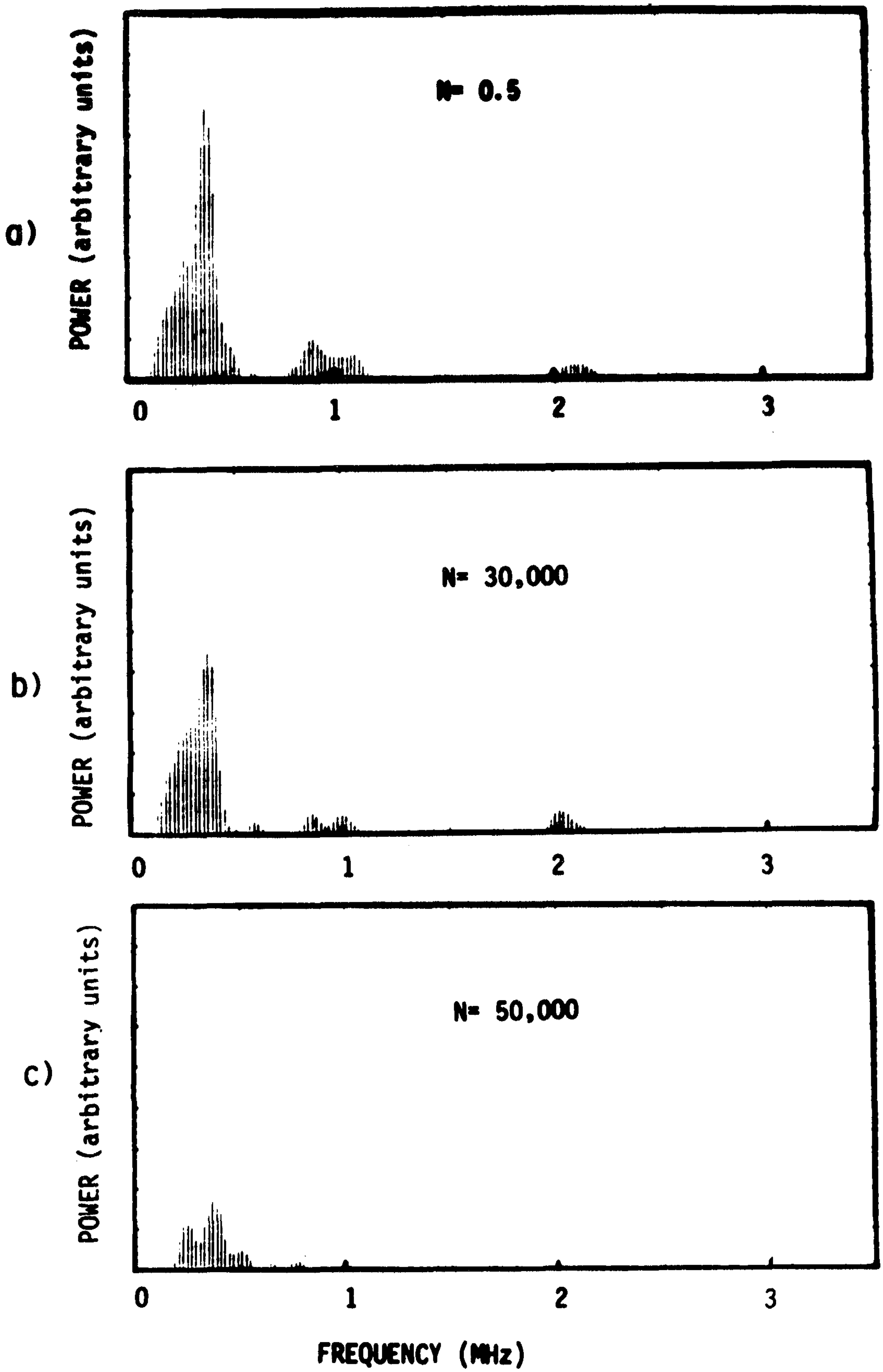


Figure 5 Frequency spectra at various stages of damage induced by cyclic loading.

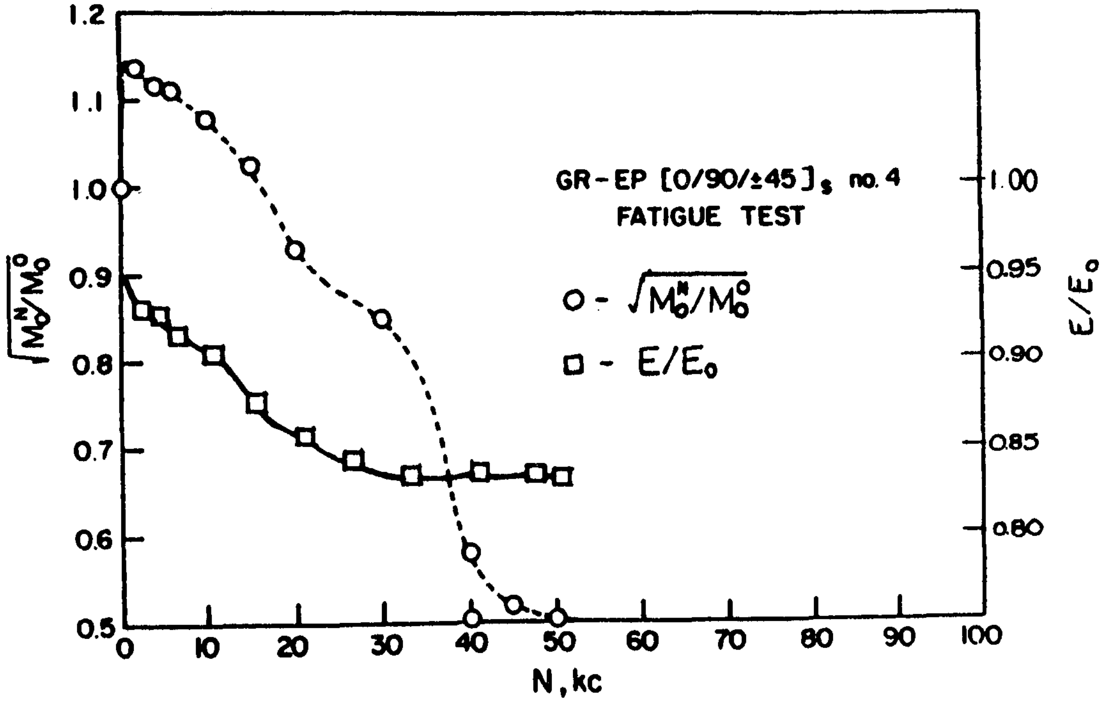


Figure 6 Change of normalized stiffness E/E_0 and the root of the normalized first spectral moment M/M_0 versus cycles of loading.

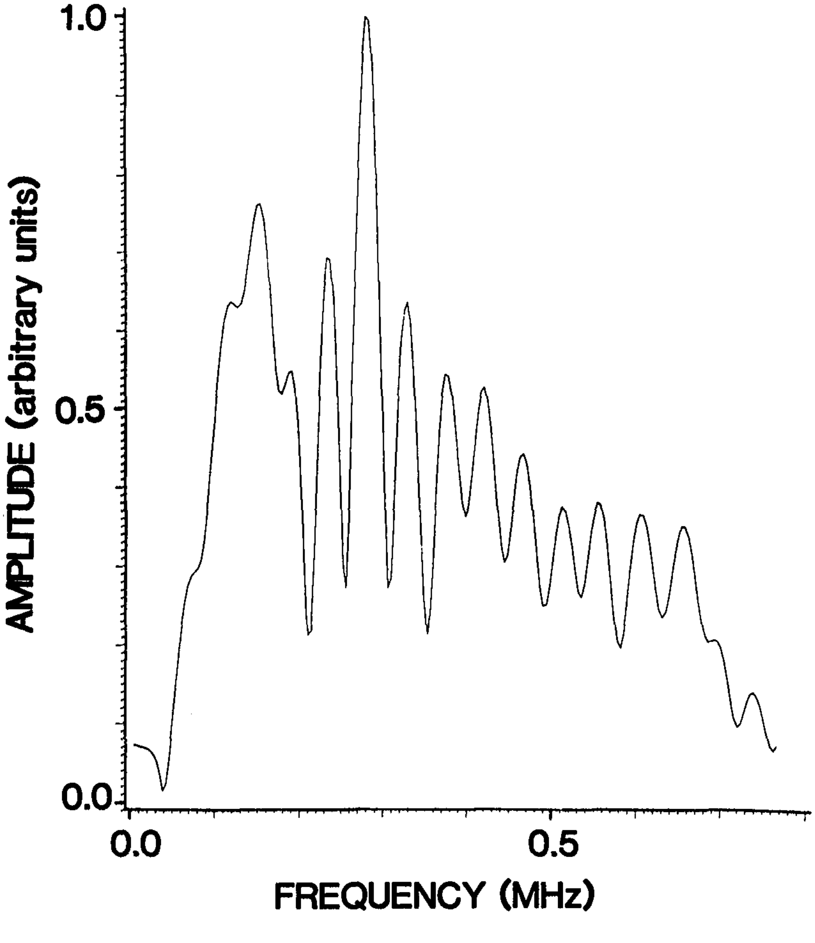


Figure 7 Output signal from a "Proctor" transducer used as a receiver in the acousto-ultrasonic measurement procedure.