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Subject: Final Report of project entitled, "Dynamic Behavior of Fiber and Particle Reinforced Composites", ONR Grant No. N00014-91-J-1297 (CU # 153-1744)

Date: March 12, 1993

As per our telephone conversation today I am sending a copy of the report that was sent to the Office of Naval Research in December 1991 along with the renewal request for the grant. I hope that this will satisfy the requirements. Please make necessary copies and send to the appropriate people at ONR.

cc: Pam J. Treggo

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FINAL REPORT OF RESEARCH ACCOMPLISHMENTS

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Project Title: Dynamic Behavior of Fiber and Particle Reinforced Composites

Grant No.: N00014-91-J-1297

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OBJECTIVE

The goals of our research program can be described as follows.

1. Ultrasonic Characterization of Composite Materials

Develop models for wave propagation in a particle or fiber reinforced composite material in order to describe its dynamic anisotropic and dispersive properties. Compare model predictions with experimental results for inversion of anisotropic properties of the constituents. Also relate measured properties with the microstructure. Study by the modelling technique the effects of interface/interphase on the effective properties in order to characterize interface/interphase.

2. Guided Waves in Laminated Composite Plates

Analyze the characteristics of guided waves in fiber reinforced laminated plates and shells for the characterization of anisotropic properties of a lamina. Also investigate the effect of the properties of the interface material layers (bond layers) between the laminae on the dispersion and dynamic response of guided waves. In addition, for thick laminated composites it is of interest to investigate the dispersion of guided waves in order to model them as homogeneous anisotropic media.

3. Impact Response of Composite Plates

Study the transient response of laminated composite plates due to impact. Of particular interest is the dependence of the response on the duration of impact. Analyze the maximum inter-laminar stresses for damage development.

4. Scattering by Cracks and Weldments

Investigate scattering of guided waves by matrix cracks and

Investigate scattering of guided waves by matrix cracks and delaminations for the purpose of ultrasonic nondestructive characterization of these defects (lengths and depths). Also study simulated acoustic emission fields in a plate for the inverse characterization of the emission source.

APPROACH

1. Ultrasonic Characterization of Composite Materials

Use a multiple scattering formulation to derive effective wave speeds and attenuation in a medium containing a random distribution of particles or fibers (with or without interface layers).

2. Guided waves in Laminated Composite plates

Develop a numerical procedure based on the Rayleigh-Ritz method for the derivation of the dispersion equation governing guided waves in a multilayered anisotropic plate. Use the solutions to the approximate dispersion equation in order to determine accurately the roots of the complex transcendental exact equation corresponding to the guided modes (propagating, nonpropagating, and evanescent).

3. Impact Response of Composite Plates

Develop a robust numerical integration scheme for the study of guided transient waves in composite laminated plate when there is time-dependent load is applied on the plate.

3. Scattering by Cracks and Weldments

Investigate the scattering problem using two different approaches: local finite element formulation coupled with the (guided) modal representation of the scattered and incident fields, and Green's function boundary integral representation of the scattered field coupled with the local finite element formulation.

ACCOMPLISHMENTS

1. Dispersion of elastic waves in composites

A. Model calculations of, and measured, velocities in fiber reinforced composites have led to the determination of the (often unknown) elstic stffnesses of the fibers. It is found that ultrasonic waves provide accurate material characterization of composite systems. This has been shown not only for fiber reinforced composites, but also for particle or whisker reinforced systems, where the orientation and distribution of particles or whiskers influence the properties significantly.

B. Interface effects on the velocities and attenuation of plane waves in particle reinforced composites have been shown to depend on the interface properties, geometry of particles, and frequency. Thus experimental work on metal matrix or ceramic matrix systems coupled with these model calculations should provide information on the interface characteristics, as in the case discussed in item A.

C. Guided waves in a transversely isotropic fiber (graphite) with an interface layer in a homogeneous matrix material show changes in the dispersive behavior that are measurable particularly near the cutoff frequencies of the guided modes. So an investigation using certain frequency bands should provide quantitaive information on the interface.

2. Guided waves in laminated composite plates

A. Dispersion of guided waves in a cross-ply graphite-epoxy plate has been used to inversely calculate the properties of each lamina. Similarly, comparison of predicted and measured dispersion of guided waves in a three-layer (Al/Aramid/Al) plate leads to the determination of the thickness and the anisotropic properties of the aramid layer.

B. Dynamic response of a thick multilayered laminated plate has been studied and it is shown that the plate can be modelled as homogeneous. This is significant for the characterization of anomalies or defects in thick composites.

C. Interface layers in a cross-ply plate influence the dynamic response in a manner that depends critically on the layer properties and the frequency. It is shown that the frequency response can be exploited to characterize interfaces.

3. Impact Response of Composite Plates

A. Response of a multilayered cross-ply composite plate due to line impact load has been studied. It has been found that for a long pulse the response is predicted well by a homogenized plate model when there is a sufficiently large number of layers. This is consistent with the finding that the dispersion in this case can be predicted well by a homogenized model.

B. Although the response to long pulses can be modelled by homogenization, the time dependence for a short pulse contains features that cannot be captured by this model. For this case it is necessary to take into account the individual layer properties.

C. The response is also critically modified due to interface soft layers. As the interface layer softens the response at low frequencies becomes amplified and contains resonances that are related to the cutoff frequencies.

3. Scattering by cracks and weldments

A. Scattered fields measured by an array of sensors on a composite plate with a delamination have been modelled. It is shown that the depth and length of delamination can be estimated by using the time and frequency response measured by the sensors. Similar study for a homogeneous plate with a vertical crack shows characteristic changes in the response corresponding to the length and depth of the crack.

B. Reflection and transmission coefficients of guided waves in a welded plate change significantly in some ranges of frequency. Their dependence on the length of a vertical crack in a weldment indicates that certain modes are affected more than others and this effect is quite pronounced in some ranges of frequency. Thus careful choice of the frequency band and selective modes can be used to characterize both the weldment and the defects in it.

Evolution of the ONR supported project work

The work that we have completed in the last five years has progressed through the following stages.

1. Development of a multiple scattering model to predict ultrasonic wave velocities and attenuation in a composite medium. The model incorporates constituent properties, distribution, and interfaces. Model results together with experiments have been used to determine constituent properties. Effects of the interfaces on attenuation and velocities have shown the possibility of ultrasonic characterization of interfaces.

2. Development of analytical and numerical techniques to study dispersion of guided waves in a multilayered anisotropic plate. The numerical technique is quite unique in that arbitrarily anisotropic lamina or layer properties as well as interfaces can be studied. Model results coupled with experiments using leaky Lamb waves and contact variable-angle-wedge transducers have been used to determine layer or lamina properties.

3. Numerical modeling of impact response of both composite and isotropic plates has shown the feasibility of inverting source characteristics. Experiments have complemented this study.

4. Development of hybrid techniques to model scattering of guided waves in a composite plate. Two techniques have been developed. In one we use the finite elements with guided modes to predict the reflection and transmission coefficients of guided modesdue to flaws. In the other we use the Green's function representation with the finite elements to predict the scattered full field. Experiments on glass plates with cracks have shown excellent agreement with predictions. It has been shown also that it is possible to size delaminations in a plate using array sensors.

5. Currently we are developing numerical techniques to study three dimensional guided waves. Work is also in progress to calculate Green's functions in three dimensions using the modes.

6. The work is in progress to study guided wave interaction with kink bands.

7. A laser ultrasonic facility is being developed which will be operational by the end of August.

LIST OF PUBLICATIONS/REPORTS/PATENTS/GRADUATES

1. Papers published in refereed journals:

   W. M. Karunasena, A. H. Shah, and S. K. Datta, "Scattering of Plane Strain Waves by Normal Edge Cracks in Laminated Composite Plate", ASCE Journal of Engineering Mechanics, Vol. 117, 1991, pp. 1738-1754.

2. W. Karunasena, A. H. Shah, and S. K. Datta, "Wave Propagation in a Multilayered Laminated Crossply Composite Plate", Journal of Applied Mechanics, Vol. 58, 1991, pp. 1028-1032.

3. W. M. Karunasena, R. L. Bratton, S. K. Datta, and A. H. Shah, "Elastic Wave Propagation in Laminated Composite Plates", Journal of Engineering Materials and Technology, Vol. 113, 1991, pp. 413-420.

4. P. C. Xu and S. K. Datta, "Characterization of Fiber - Matrix Interface by Guided Waves: Axisymmetric Case", Journal of the Acoustical Society of America, Vol. 89, 1991, pp. 2573-2583

5. T. H. Ju and S. K. Datta, "Pulse Propagation in a Laminated Composite Plate and Nondestructive Evaluation", Composites Engineering, Vol. 2, 1992, pp. 55-66.

6. S. K. Datta, T. H. Ju, R. L. Bratton, and A. H. Shah, "Transient Response of a Laminated Composite Plate: Results from Homogenization and Discretization", International Journal of Solids and Structures, Vol. 29, 1992, pp. 1711-1721.

7. S. K. Datta, T. H. Ju, and S. K. Datta, "Scattering of an Impact Wave by a Crack in a Composite Plate", Journal of Applied Mechanics, Vol. 59, 1992, pp. 596-603.

8. N. Rattanawangcharoen, A. H. Shah, and S. K. Datta, "Wave Propagation Laminated Composite Circular Cylinder", International Journal of Solids and Structures, Vol. 29, 1992, pp. 767-781.

9. T. Kohl, S. K. Datta, A. H. Shah, and N. Rattanawang-charoen, "Mode-Coupling of Waves in Laminated Tubes", Journal of Composite Materials, Vol. 26, 1992, pp. 661-682.

10. H. Ledbetter and S. Datta, "Cast-Iron Elastic Constants: Effect of Graphite Aspect Ratio", Zeitschrift fur Metallkunde, Vol. 83, 1992, pp. 195-198.

11. T. Kohl, S. K. Datta, and A. H. Shah, "Axially Symmetric Pulse Propagation in Semi-Infinite Hollow Cylinder", AIAA Journal, Vol. 30, 1992, pp. 1617-1624.

2. Books (and Sections thereof) Published:

1. T. H. Ju and S. K. Datta, "Pulse Propagation in a Laminated Composite Plate and Nondestructive Evaluation", in Enhancing Analysis Techniques for Composite Materials, eds. L. Schwer, J. N. Reddy, and A. K. Mal, NDE Vol. 10, pp. 23-34, The American Society of Mechanical Engineers, New York, 1991.

2. S. Datta, H. Ledbetter, and M. Lei, "Elastic Properties of Uniaxial Fiber-Reinforced Composites: General Features", in Nondestructive Evaluation and Material Properties of Advanced Material, eds. P. K. Liaw, O. Buck and S. M. Wolf, pp. 23-28, TMS, PA., 1991.

3. H. Ledbetter and S. Datta, "Elastic Properties of Al_2O_3/Al Composites: Measurements and Modelling", in Damage and Oxidation Protection in High Temperature Composites, eds. G. K. Haritos and O. Ochoa, AD Vol. 25-2, pp. 83-88, The American Society of Mechanical Engineers, New York, 1991.

4. S. K. Datta, T. Kohl, W. Karunasena, and A. H. Shah, "Guided Waves and Scattering in Laminated Plates and Shells", in Modern Theory of Anisotropic Elasticity and Applications, eds. J. Wu, T. C. T. Ting, and D. M. Barnett, pp. 263-279, SIAM, Philadelphia, 1992.

5. S. W. Liu, S. K. Datta, and A. H. Shah, "Transient Scattering of Rayleigh-Lamb Waves by Surface-Breaking and Buried Cracks in a Plate", in Review of Progress on QNDE, eds. D. O. Thompson and D. E. Chimenti, Vol. 11, pp. 73-80, Plenum, New York, 1992.

6. S. K. Datta, T. H. Ju, R. L. Bratton, and A. H. Shah, "Transient Response of a Laminated Composite Plate", ibid, pp. 145-151.

7. R. Bratton and S. K. Datta, "Analysis of Guided Waves in a Bilayered Plate", ibid, pp. 193-200.

4. A. Conference Presentations

1. S. K. Datta, T. H. Ju, R. L. Bratton, and A. H. Shah, "Ultrasonic Scattering by Cracks in a Laminated Compoiste Plate", presented at the ASNT 1991 Fall Conference, September 15-18, 1991, Boston, MA.(invited)

2. T. H. Ju and S. K. Datta, "Pulse Propagation in a Laminated Composite Plate and Ultrasonic Nondestructive Evaluation", presented at the Symposium on Enhancing Analysis Techniques for Composite Materials, ASME Winter Annual Meeting, December 1-6, 1991, Atlanta, GA.(invited)

3. W. Karunasena, A. H. Shah, and S. K. Datta, "Wave Propagation in a Multilayered Laminated Cross-Ply Composite Plate", presented at the ASME Winter Annual Meeting, December 1-6, 1991, Atlanta, GA.

4. S. K. Datta and R. Paskaramoorthy, "Effect of Membrane Stress and Material Properties at the Interface Layer on the Dynamic Response of a Laminated Composite Plate", ONR Workshop on Adaptive Structures with Active Materials, May 18-19, 1992, Tyson's Corner, VA.

5. S. K. Datta and T. H. Ju, "Inversion of Source, Material and Defect Characteristics using Guided Waves", presented at the IUTAM Symposium on Inverse Problems in Engineering Mechanics, May 11-15, 1992, Tokyo, Japan.

6. R. Paskaramoorthy and S. K. Datta, "Three Dimensional Response of a Cross-Ply Composite Plate with Imperfect Interfaces", Review of Progress in QNDE, July 19-24, 1992, La Jolla, CA.

4. B. Seminar Presentations

1. "Guided Wave Scattering in a Laminated Composite Plate", October 23, 1991, The Johns Hopkins University, Baltimore, MD.

2. "Use of Guided Elastic Waves for Material and Defect Characterization in Composites", October 24, 1991, The David Taylor Research Center, Annapolis, MD.

3. "Guided Elastic Waves in Composite Plates: Material and Defect Characterization", November 21, 1991, University of California, Los Angeles, CA.

4. "Dynamics of Composite Laminates", March 9, 1992, Brown University, Providence, RI.

5. "Dynamics of Composite Laminates", May 6, 1992, Tokai University, Shimizu, Japan.

6. "Dynamics of Composite Laminates", May 8, 1992, Tohoku University, Sendai, Japan.

7. "Inversion of Material and Defect Characteristics in Laminated Composite Plates using Guided Waves", August 20, 1992, The Ohio State University, Columbus, OH.

6. <u>Degrees Granted (name, date, degree)</u>:

T. H. Ju, <u>Transient Pulse Propagation and Dynamic Analysis of Fracture in Composite Plates</u>, Ph. D. Thesis, University of Colorado, Boulder, CO, 1991.