AN EXPERIMENTAL INVESTIGATION ON THE ACTIVE-DAMPING CHARACTERISTICS OF A CLASS OF ULTRA-ADVANCED INTELLIGENT COMPOSITE MATERIALS FEATURING ELECTRO-RHEOLOGICAL FLUIDS

by

S.B. Choi*, B.S. Thompson+, and M.V. Gandhi†

Intelligent Materials and Structures Laboratory
Composite Materials and Structures Center
Michigan State University
East Lansing, MI 48824

*(517) 355-9886, +(517) 355-2179, †(517) 355-1744

ABSTRACT

A new generation of revolutionary multi-functional, dynamically-tunable, intelligent, ultra-advanced composite materials featuring electro-rheological fluids is proposed herein for the active continuum vibrational-control of structural systems. This paper reports on a pioneering proof-of-concept experimental investigation focused on evaluating the elastodynamic transient response characteristics of cantilevered beams fabricated in this new class of materials. The results of this investigation clearly demonstrate the ability to dramatically change the vibrational characteristics of beam-like specimens fabricated in ultra-advanced composite materials by changing the electrical field imposed on the fluid domains. The capability of these materials to interface with modern solid-state electronics can be exploited by extending the fundamental phenomenological work presented herein by the successful incorporation of intelligent sensor technologies and modern control strategies in order to significantly accelerate the evolution of these composite materials for military and aerospace applications.

PREFACE: BACKGROUND ON ELECTRO-RHEOLOGICAL FLUIDS

Electro-rheological (ER) fluids are typically suspensions of micron-sized hydrophilic particles suspended in suitable hydrophobic carrier liquids, which undergo significant instantaneous reversible changes in material characteristics when subjected to electrical potentials. References [1-12] provide a flavor of the research activities in ER fluids. The most significant change in the material characteristics of an ER fluid is associated with the energy dissipation characteristics of the suspension which varies dramatically upon applying an electrical field to the fluid. The tailoring of this rheological property by the imposition of a suitable electrical potential can be usefully exploited in vibration-suppression applications.

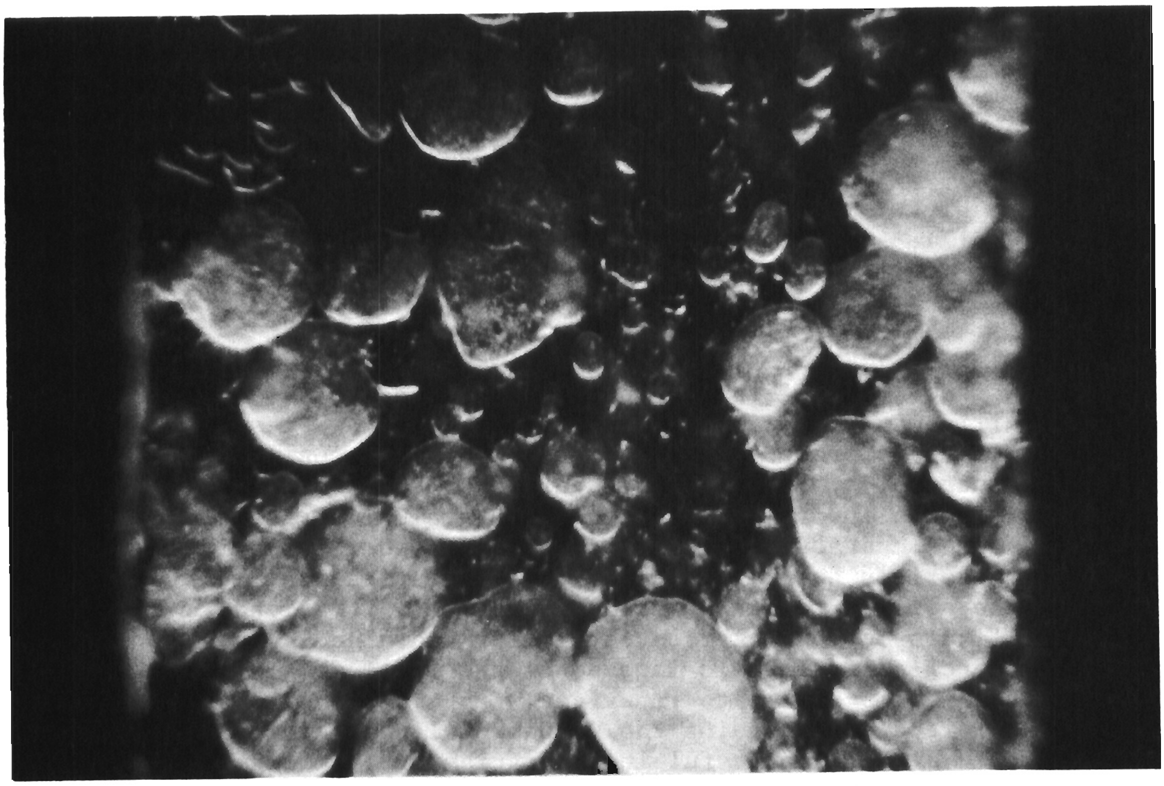

Figure 1. Photomicrograph of an Electro-Rheological Fluid with and Electric Field Strength of 0 kV/mm

Figures 1 and 2 present photomicrographs of an electro-rheological fluid subjected to electrical field intensities of 0 kV/mm and 2 kV/mm respectively. The photomicrographs were taken in the Biothermal Sciences Laboratory at Michigan State University using a Zeiss universal phase-contrast microscope with a X40 magnification and a Chinon camera. The black regions at the sides of the photographs are images of the electrodes employed to generate the electrical field in the ER fluid. Figure 1 clearly shows the random structure of the suspension when a potential difference is not generated between the electrodes. This structure imparts nominally isotropic global mechanical properties to the suspension. Figure 2 clearly shows the truly dramatic change in the structure of the suspension upon developing a potential difference between the electrodes of magnitude 2 kV/mm. Under these conditions, the particles in the suspension orientate themselves in relatively regular chain-like patterns to form a mixture with globally anisotropic mechanical properties. These columnar structures increase the energy-dissipation characteristics of the suspension, they increase the stiffness of the global suspension/electrode structure, and they are also responsible for re-orientation of the mass distribution of the suspension. Thus, by imposing an electric field upon an ER fluid, the mass, stiffness and energy-dissipation characteristics of the electro-viscous suspension are changed. When the field returns to a zero potential upon switching off the electrical energy supplied to the electrodes, the particles return to a state of random orientation in the carrier fluid as shown in Figure 1.

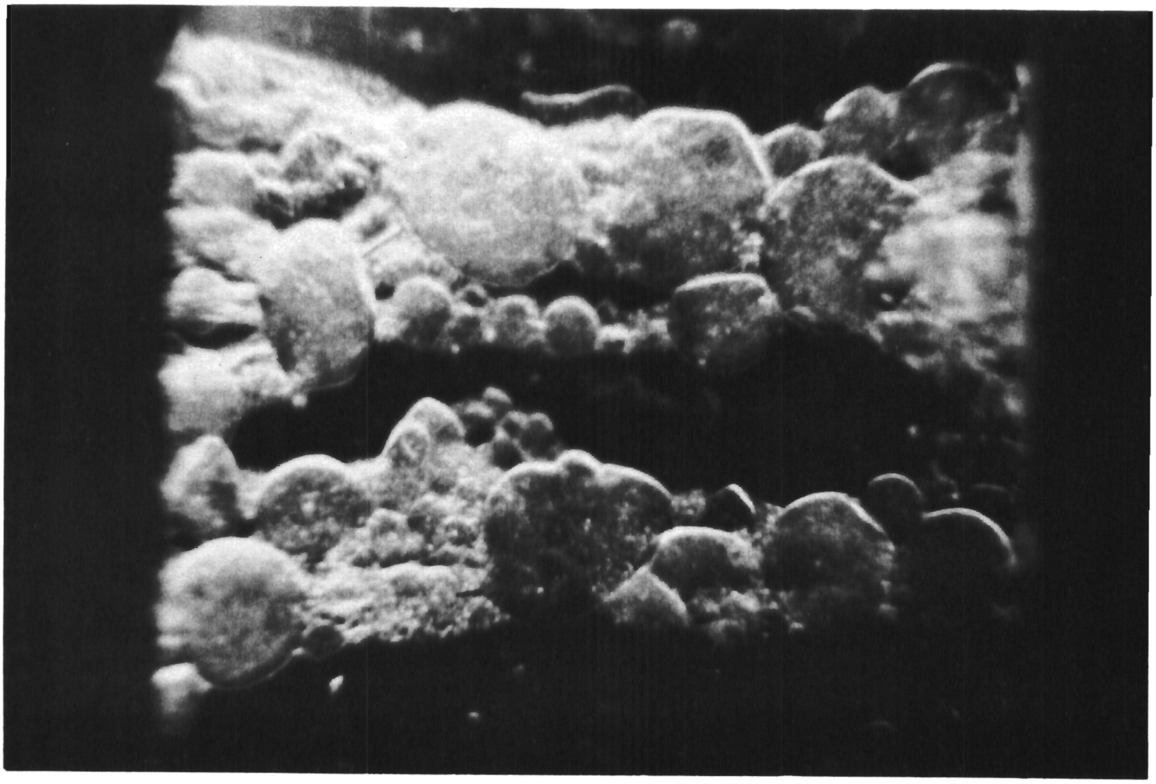

Figure 2. Photomicrograph of an Electro-Rheological Fluid with an Electric Field Strength of 2 kV/mm

INTRODUCTION

The insatiable demand in the international marketplace for high-performance structural and mechanical systems for the aerospace and defense industries has triggered the evolution of advanced composite materials technologies. These diverse high-performance applications have mandated that designers tailor the materials and the material microstructural characteristics in order to provide optimal performance of the structural systems under various service conditions and unstructured environments. [13,14]

With traditional advanced composite materials, the optimization strategies result in an optimal design which is passive in nature and cannot respond to unstructured environments. For instance, the vibrational characteristics of a helicopter rotor fabricated in an advanced composite material are clearly dependent upon several factors such as the rotational speed, aerodynamic loading, payload and the ambient hygrothermal environment. An optimally-tailored rotor designed in a traditional advanced composite material is passive in the sense that it cannot actively respond to changes in the rotor speed and aerodynamic loading, for example. It is clearly evident, therefore, that the elastodynamic response of the rotor is sub-optimal for all service conditions except the one for which the rotor was optimally designed.

In order to overcome this limitation, a new generation of revolutionary, intelligent, ultra-advanced composite materials featuring ER fluids is proposed herein which will enable the response characteristics to be continuously varied in order to achieve the optimal performance under varying service conditions. These ultra-advanced composite materials capitalize on the superior characteristics of advanced composite materials which are interfaced with dynamically-tunable ER fluids contained in voids in the advanced composite structure. Changes in the electrical field imposed upon the ER fluids dramatically alter the rheological characteristics of the fluids and hence the global mass, stiffness and dissipative characteristics of the ultra-advanced composite structure. A methodology for synthesizing this class of smart materials is presented in Figure 3.

The instantaneous response-time of the ER fluids and the inherent ability of these materials to interface with solid-state electronics and modern control systems provides designers, for the first time, with a unique capability to synthesize ultra-advanced intelligent composite structures, whose continuum electro-elastodynamic response can be actively controlled in real-time. An application of this philosophy to control the vibrational response of an aircraft wing is schematically represented in Figure 4.

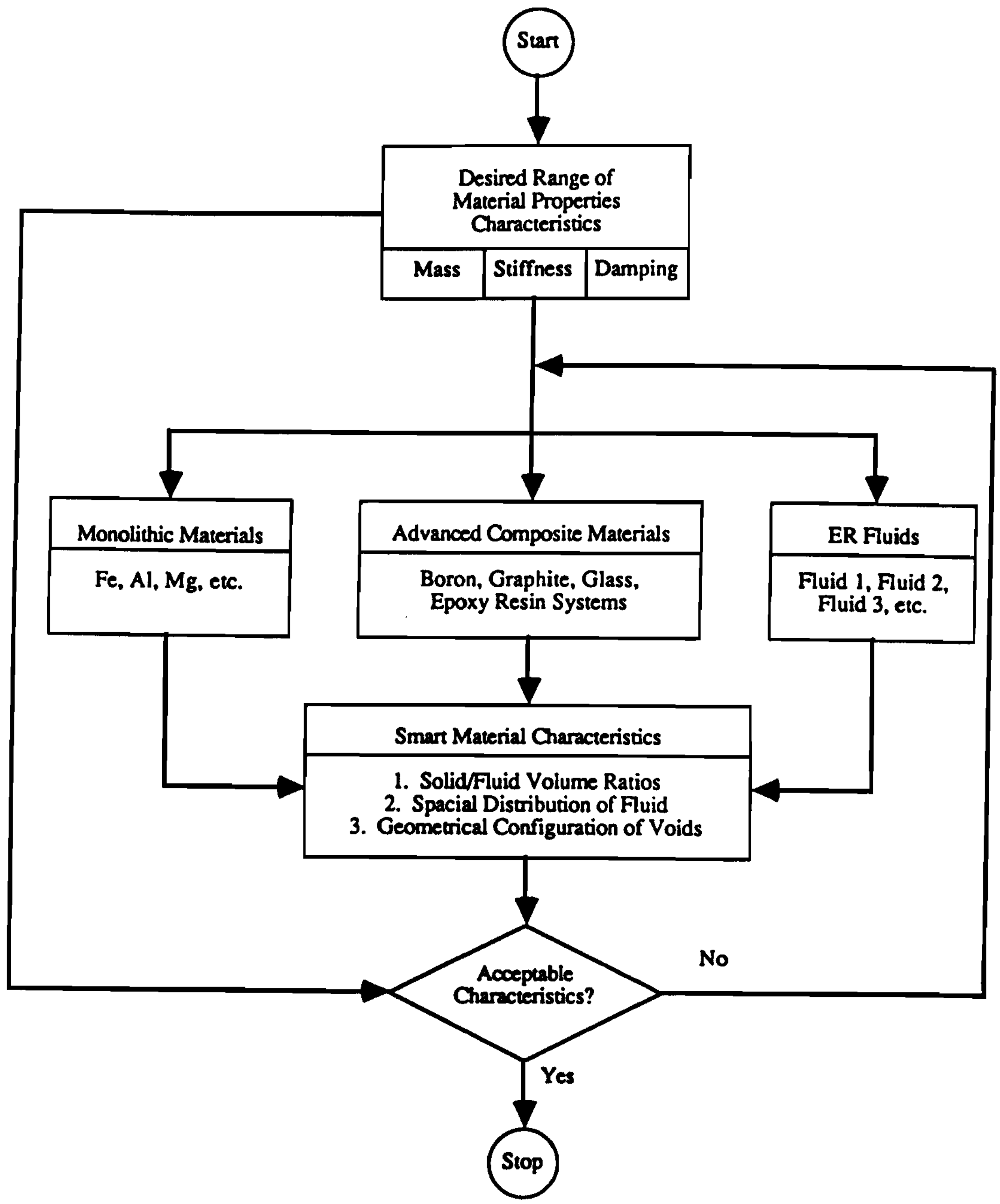

Figure 3. A Methodology for Synthesizing Materials Incorporating ER Fluids

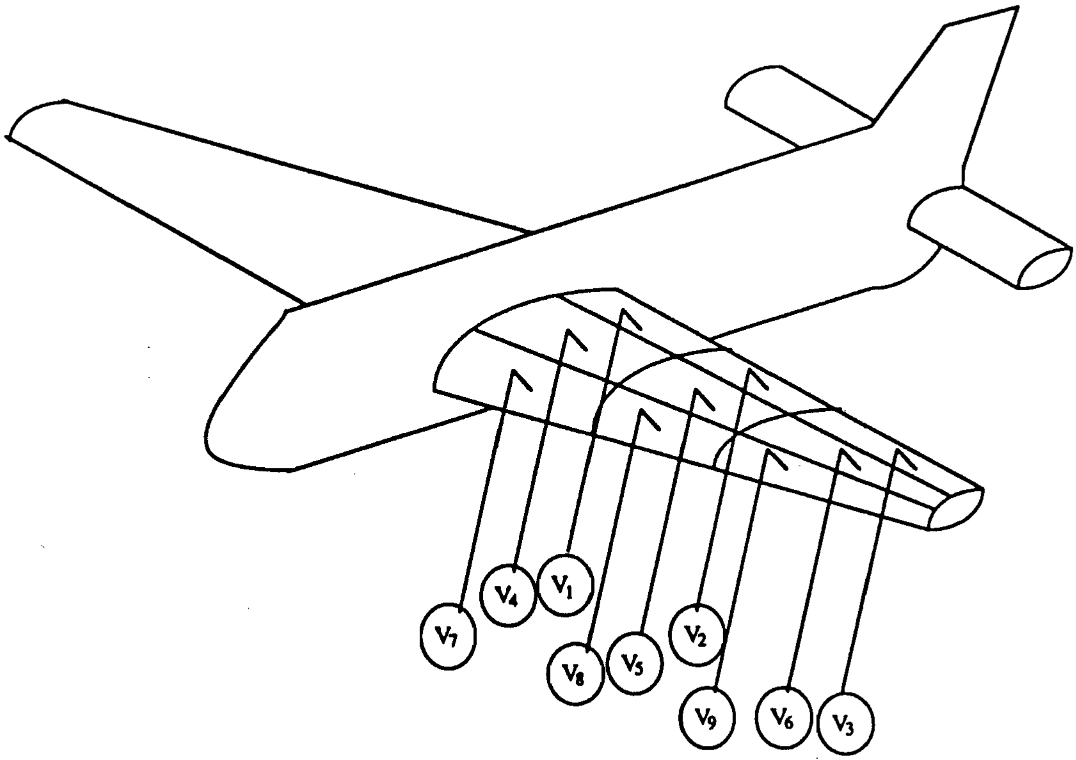

Figure 4. A Schematic Diagram of an Aircraft with a Wing Fabricated from an Ultra-Advanced Intelligent Composite Material

This class of innovative materials derive their intelligence from the merger of sensors, built into the finite element control segments of the ultra-advanced composite material continuum, microprocessors, and dynamically-tunable electro-rheological fluids as shown schematically in Figure 5. The sensors monitor the elastodynamic behavior of the ultra-advanced composite structure, and the signals from the sensors are fed to the appropriate microprocessor which evaluates the signals prior to determining an appropriate control strategy in order to synthesize the desired elastodynamic response characteristics. This is typically accomplished by controlling the rheological characteristics of the ER fluid domains in the finite element segment associated with the particular sensor. This change in the rheological characteristics of the ER fluid in a typical finite element control segment, in turn alters the global mass, stiffness, and damping characteristics of the ultra-advanced composite structure in order to achieve the desired vibrational response.

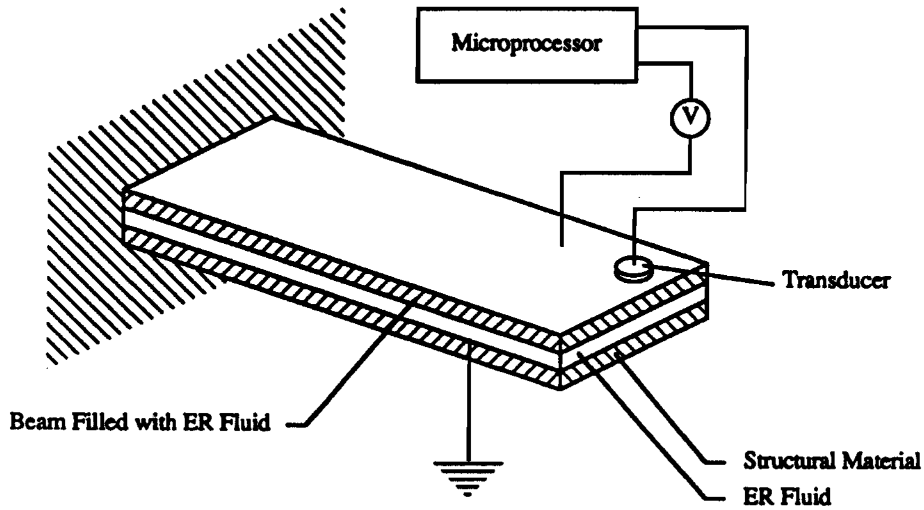

Figure 5. Schematic of a Cantilevered Beam Fabricated in an Ultra-Advanced Intelligent Composite Material Showing Sensor and Date-Processing Components

This paper reports on a pioneering proof-of-concept experimental investigation focussed on evaluating the elastodynamic response of cantilevered beams fabricated from ultra-advanced intelligent composite materials. The preliminary results of this investigation clearly demonstrate the ability to dramatically change the transient elastodynamic response characteristics of beam-like specimens fabricated in the ultra-advanced composite materials by changing the electrical field imposed on the ER fluid domains.

EXPERIMENTAL PROGRAM

The objective of the experimental program was to investigate the transient response characteristics of various cantilevered beam specimens fabricated in smart ultra-advanced composite material in a variety of different operating conditions in order to provide a basis for evaluating the controllability of these structures in real-time. The experimental investigation focussed on evaluating the responses of AS4/3501-6 graphite-epoxy beams featuring various stacking sequences, and containing various ER fluids. The subsequent investigations focussed on evaluating the transient behavior of ultra-advanced composite beams subjected to sudden changes in the electrical field intensity as a first step towards evaluating the controllability of this innovative class of structures.

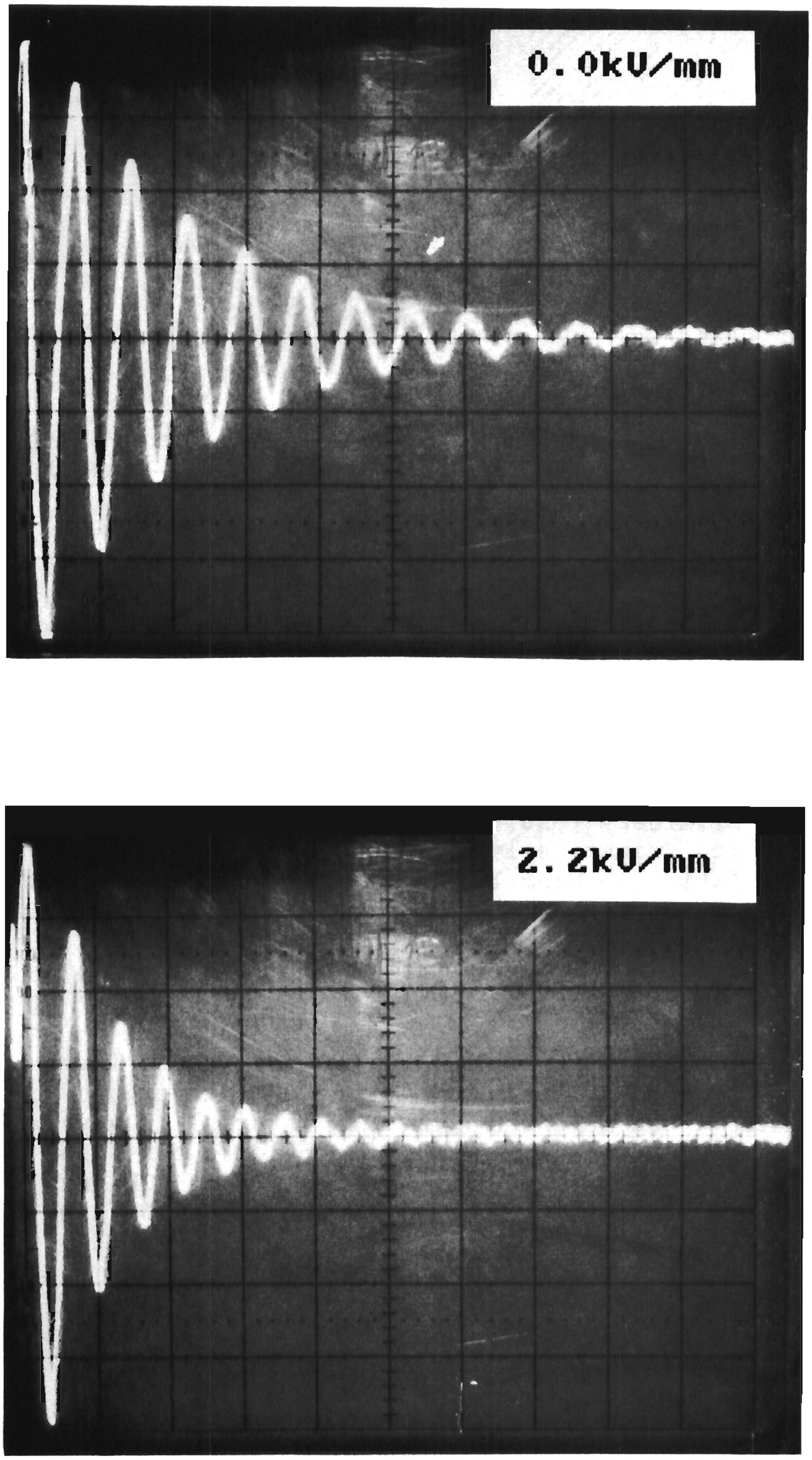

Figure 6. Transient Response of a Cantilever Beam Speciment With and Without Electric Field at Room Temperature

DISCUSSION OF EXPERIMENTAL RESULTS

Figure 6 presents polaroid photographs of the oscilloscope traces of the transient elastodynamic responses of a cantilever beam specimen at room temperature at two discrete, different, voltage stages. It is evident from these results that the frequency of the response and also the damping ratio of the signal are strongly dependent upon the voltage applied to the beam. Thus as the electrical field intensity increases, the damping increases monotonically and the fundamental natural frequency of the beam also increases.

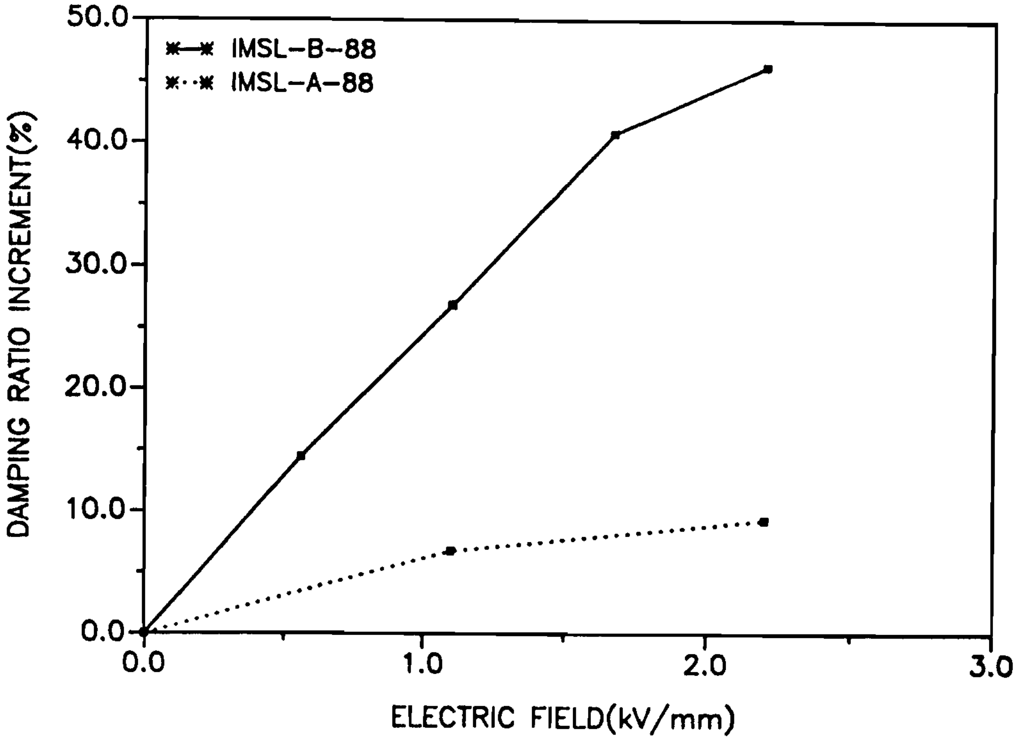

Figure 7. Comparison of the Relative Damping Ratio Increment Between AS4/3501-6 Specimens Featuring Different ER Fluids at Room Temperature

Figure 7 presents a comparison of the damping ratio increments between different specimen classifications as a function of the applied voltage. The relative increment in the damping ratio of each ultra-advanced composite beam specimen in the presence of an electric field is defined with respect to the corresponding magnitude in the absence of an electric field, which is employed as the datumn. Thus, in the context of Figure 7 and the damping ratio increment, when the fluid domain in the beam specimen is not subjected to an external voltage, the damping ratio increment is zero, however, the beam naturally has a non-zero damping ratio due to the energy-dissipation characteristics of the structural and fluid components of the ultra-advanced composite material. The results presented in Figure 7 were obtained from specimens with the same structural properties and geometries but one specimen featured ER fluid type IMSL-B-88 and the other featured ER fluid type IMSL-A-88. These results indicate that the type of ER fluid has a major impact on the change in damping and hence controllability of the elastodynamic response of the material.

Figure 8 presents the experimental results for the damping ratio increment as a function of the applied electrical field for two classes of beam specimens. The specimens contained the same ER fluid and they were fabricated with identical geometries, but the layups of the graphite pre-preg AS4/3501-6 were different. A consequence of these different layups is that the stiffness and damping properties of the specimens are quite different, thus the properties of the ER fluid and the properties of the encasing structional material are crucial parameters in the synthesis of this class of dynamically-tunable smart materials.

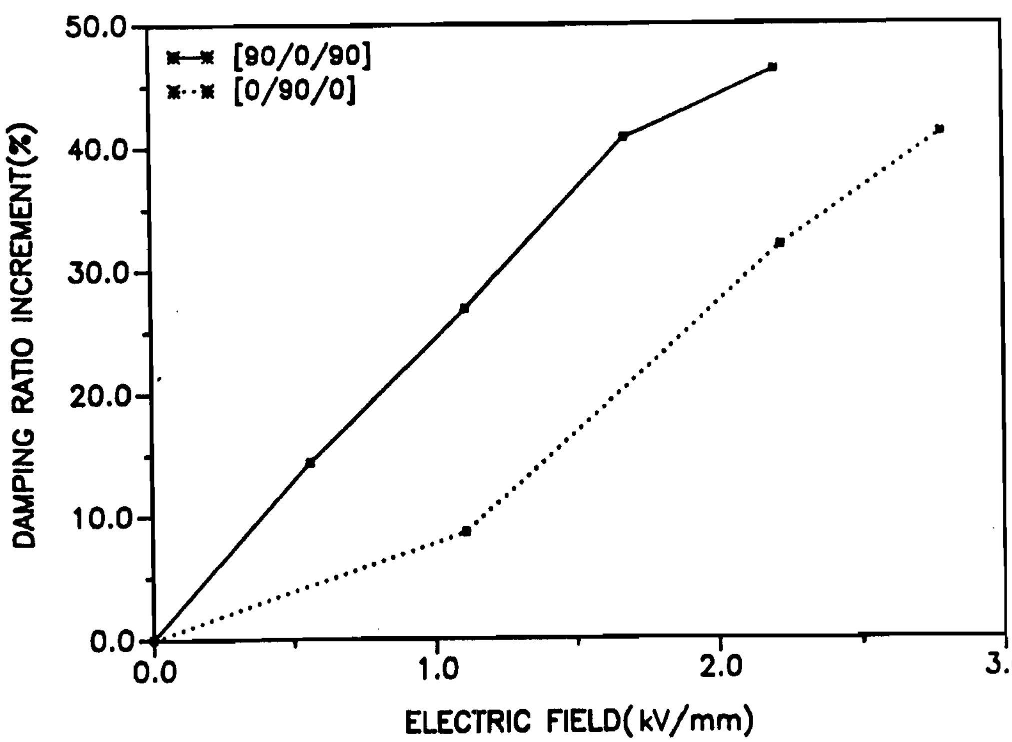

Figure 8. Comparison of the Relative Damping Ratio Increment Between Specimens Featuring Two Different Lay-ups of AS4/3501 at Room Temperature

Figure 9 presents the polaroid photographs of the oscilloscope traces of the controlled transient elastodynamic response of a cantilever beam specimen at room temperature. The transient response of the specimen for zero applied voltage is presented in Figure 9a). Figure 9b) presents the transient response of the identical specimen subjected to the same initial conditions, namely the same initial tip transverse deflection and an electrical field intensity of 0 kV/mm. This field intensity was maintained for the first 0.37 seconds of the response profile, prior to instantaneously generating a field intensity of 2.5 kV/mm. These two piecewise-constant discrete voltage inputs represent the active-control inputs based on a bang-bang control strategy. A cursory review of the response profiles presented

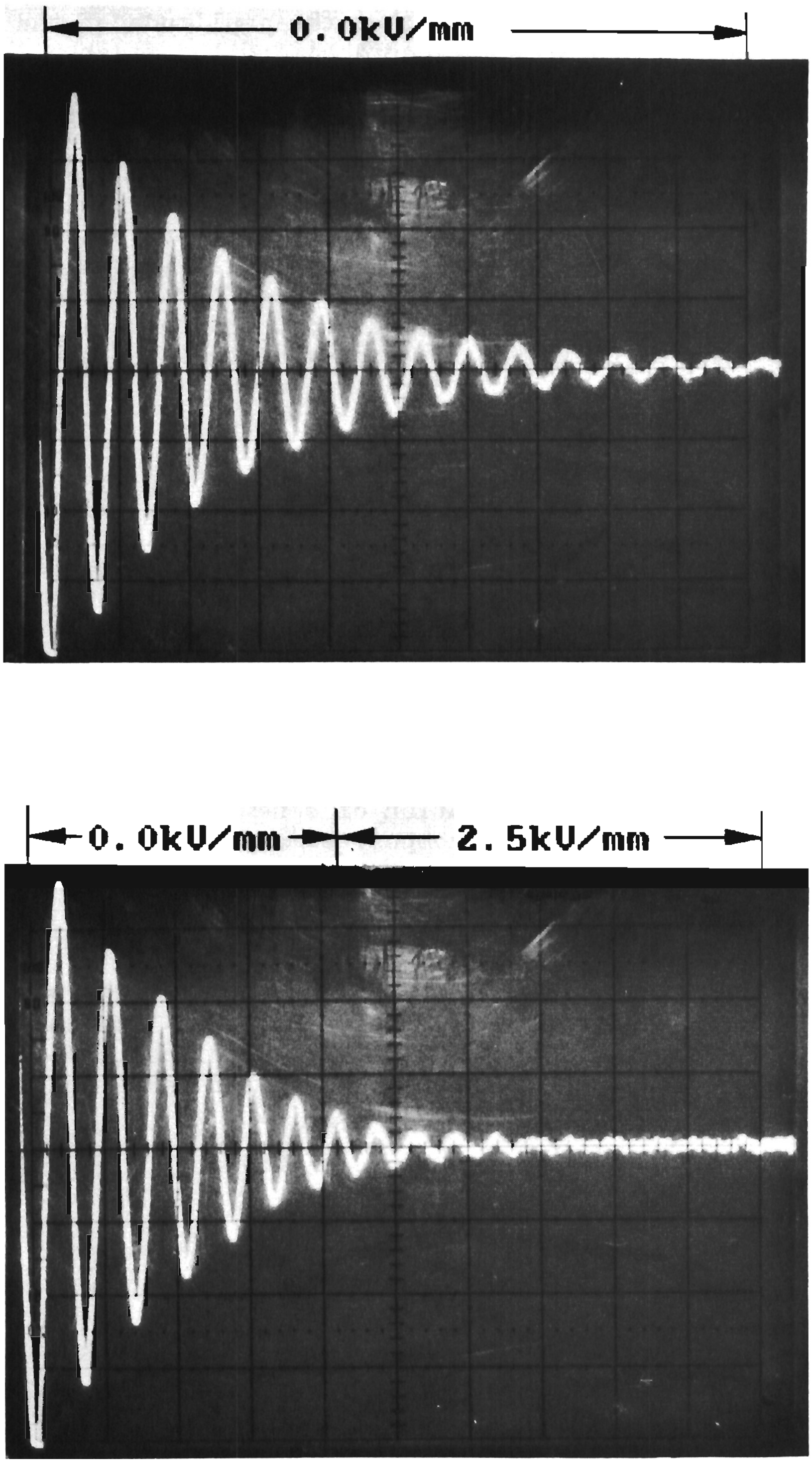

Figure 9. Controlled Transient Response of a Cantilever Beam Specimen at Room Temperature

in Figures 9a) and 9b) clearly indicates that the amplitude of the vibrational response in the two profiles is identical for the first 0.37 seconds. Subsequently, the amplitude of vibration presented in Figure 9b) is substantially attenuated upon imposing the 2.5 kV/mm electrical field strength.

It is clearly evident from these proof-of-concept results that the elastodynamic response characteristics of structures fabricated from ultra-advanced composite materials can be actively controlled in real-time in order to obtain desired performance characteristics of the structure by altering the applied voltage. Naturally, advanced control algorithms and sensors must be employed to realistically implement this philosophy in practice.

CONCLUDING REMARKS

A new generation of innovative, ultra-advanced, intelligent composite materials featuring ER fluids has been proposed herein. A proof-of-concept investigation focussed on evaluating the elastodynamic response characteristics of beam-like specimens has been undertaken. The results of these investigations clearly demonstrate for the first time the feasibility of actively controlling in real-time the continuum vibrational characteristics of structures fabricated upon ultra-advanced composite materials by altering the voltage applied to the structure. It is anticipated that the successful integration of the fundamental phenomoneological work presented herein with modern control strategies and intelligent sensor technologies will significantly accelerate the evolution of a new generation of innovative ultra-advanced intelligent composite materials for the defense and aerospace industries.

ACKNOWLEDGEMENTS

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