NINETEENTH EUROPEAN ROTORCRAFT FORUM

Paper n° N6

DEVELOPMENT OF A SMART ROTOR

by

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September 14-16, 1993
CERNOBBIO (Como)
ITALY

ASSOCIAZIONE INDUSTRIE AEROSPAZIALI
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

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Abstract

This paper reviews the status of smart structures technology development at the University of Maryland for application to rotor systems. Though a large component of research is focussed to the minimization of helicopter vibration, the methodology is equally applicable to other problems such as aeromechanical stability augmentation, handling qualities enhancement, stall alleviation, reduction of acoustic signatures, minimization of blade dynamic stresses and rotor head health monitoring. More than any other system, the structural, mechanical and aerodynamic complexity and the interdisciplinary nature of rotorcraft offer many opportunities for the application of smart structures technologies with the potential for very substantial payoffs in system effectiveness. Two types of Froude-scale smart bearingless rotor models (diameter six foot) were built: controllable twist blades with embedded piezoceramics and blades with trailing-edge flaps actuated with piezo-bimorphs. Both rotor models were tested in hover at 300, 600 and 900 RPM (operating speed) and piezo-actuation was carried out at 1, 2, 3, 4/rev. At the operating speed with 4/rev excitation, a tip twist of .1 deg was achieved with the first model and flap deflection of 2 deg was achieved with the second model. Though these amplitudes are much smaller than target values (2 deg and 8 deg respectively), both techniques show promise for further work. To implement the trailing-edge flap system in a full-scale vehicle, an alternate actuation concept of using extension-torsion coupled composite tube in conjunction with a magnetostrictive actuator is investigated. An optimum design showed that kevlar-epoxy tube with a ply angle of 30 deg gave the maximum induced twist for a prescribed axial force. Using the induced strain actuation with embedded shape memory alloys, it became possible to reduce the bending frequency of a solid cantilevered beam by over 25% with a 1.3% volume fraction of SMA wires. This concept can be exploited to design a variable speed rotor. For application to rotor problems, the currently available analytical bending-extension beam models were extended to include torsional deflection for single or multi-actuators oriented at an angle with respect to beam axis. Validation studies using experimental data showed good correlation for bending response but showed poor correlation for torsional response. Torsional beam model needs further refinements before it can be includes in comprehensive rotor code

Introduction

Helicopters are susceptible to high vibratory loads, aeromechanical instabilities, excessive noise levels, poor flight stability characteristics, and high dynamic stresses. Compared to fixed-wing aircraft, helicopters suffer from high operating cost, poor ride quality, low fatigue life of structural components, less reliability, inferior handling qualities and a restricted flight envelope. To reduce these problems to an acceptable level, numerous passive and active devices, and many ad hoc design fixes, are resorted to with resultant weight penalties and reduced payloads. The primary source for all these problems is the nonsteady and complex aerodynamic environment in which the rotor must operate and the complex coupled structural and mechanical system comprised by the rotor, body, transmission system and engine. To counter some of these deficiencies, and also to further expand the flight capabilities of military and civilian helicopters, many new design modifications and devices are being contemplated. These appear to show incremental and modest gains in terms of performance improvement and reduction in operating costs. If the objective is to achieve *'a jet smooth ride'* with helicopters at a comparable operating cost, for example, one has to try revolutionary ideas. One innovative idea that may give a substantial jump in performance at a small price is to apply the technology of smart structures to rotorcraft. For such an application, numerous light-weight sensors and actuators are embedded or surface-mounted at different stations on the blades, and optimal distributed forces applied with the help of modern control theory. At this stage, the technology of smart structures is primitive and requires a focused basic research effort that will help clarify the projected gains. This paper will review the state-of-the-art on the application of smart structures technology to the rotor systems.

Smart Structures

A smart structure involves distributed actuators and sensors, and one or more microprocessors that analyze the responses from the sensors and use distributed-parameter control theory to command the actuators to apply localized strains. A smart structure has the capability to respond to a changing external environment (such as loads and shape change) as well as to a changing internal environment (such as damage or failure). Many types of actuators and sensors are being considered, such as piezoelectric materials, shape memory alloys, electrostrictive materials, magnetostrictive materials, electro-rheological fluids and fiber optics. These can be integrated with main load-carrying structures by surface bonding or embedding without causing any significant changes in the structural stiffnesses of the system. Among these, piezoelectrics are the most popular. They undergo surface elongation (strain) when an electric field is applied across them and produce voltage when surface strain is applied, and thus can be used both as actuators and sensors. These materials however generate very low strain but cover a wide range of actuation frequency. The most widely used piezocermics (such as lead zirconate titanite) are in the form of thin sheets which can be readily embedded or attached to composite structures.

Among other materials, shape memory alloys (SMA) are gaining rapid recognition as actuators because of the possibility of achieving large excitation forces and displacements. These metals undergo phase transformation at a specific temperature. When plastically deformed at a low temperature, these alloys recover to their original undeformed condition if temperature is raised above the transformation temperature. This process is reversible. The most common SMA material is Nitinol (nickel titanium alloy) and is available in the form wires of different diameters. Though heating is carried out internally (electrically), response is very slow (about 1 Hz). Electrostrictive materials are quite identical to piezoelectric materials, with slightly better strain capability, but very sensitive to temperature. Magnetostrictive materials such as Terfenol-D elongate when exposed to a magnetic field. These materials generate low strains and moderate forces over a wide frequency range. Because of coil and magnetic return path, these actuators are often bulky. Fiber optics are becoming popular as sensors because they can be easily embedded in composite structures with little effect on the material integrity. Piezoelectric and electrostrictive materials are also available in the form of 'stacks' where many layers of materials and electrodes are assembled together. These stacks generate large forces but small displacements, in the direction normal to the top and bottom surfaces. Bimorphs or bending actuators are also available commercially where two layers of these materials are stacked with a thin shim (typically of brass) between them. If an opposite polarity is applied to two plates, a bending action is created.

Potential Applications to Rotorcraft

The multidisciplinary nature of rotorcraft offer many opportunities for the applications of smart structures technologies with the potential for very substantial payoffs in system effectiveness. The rotor is the key subsystem, setting the current limits on vehicle performance, handling qualities and reliability. Since the rotor is also a flexible structure, changes in shape, mechanical properties and stress/strain fields can be imposed upon it. These in turn will alter the vibratory modes, aeroelastic interactions, aerodynamic properties, and dynamic stresses of the rotor and fuselage. Smart structures technologies will enable these imposed changes to be tailored to conditions sensed in the rotor itself. Furthermore, because the smart actuators and sensors can be distributed over each individual rotor blade, control can be imposed over a much larger bandwidth than with current swashplate-based controls which are limited to N/rev for an N-bladed rotor. This opens up a hitherto unavailable domain for vibration control, aeromechanical stability augmentation, handling qualities enhancement, stall alleviation, and reduction of acoustic signatures. The use of smart structures also offers the prospect of sensing structural damage in the rotor structure and in other critical components. The pilot can then be alerted, enabling him/her to take load alleviation action. There also exists the potential for altering the stress field following damage, using smart materials. This could provide a degree of self-repair. A further very promising application of smart structures is to control the critical frequency of drive shafts.

State of the Art

Recently, there has been an increase in smart structures research activities. Much of this work is focused on the application of piezoelectric technology to space related systems, such as the control of vibration of large space structures [1-2], and for stable bases for precision pointing in space (telescope, mirrors, etc., see Ref. [3]). Also, there are a few preliminary applications to the field of fixed-wing aircraft, such as controlling wing twist and camber for wing divergence and flutter suppression [4-5] and for controlling structure-borne noise [6]. To date, only limited work has been conducted on the use of smart structures for rotorcraft applications.

At the University of Maryland, work in this field was focused on the building of dynamically-scaled smart rotor models. Two types of Froude-scale models were built: controllable twist models incorporating embedded piezoelectric crystals, and trailing-edge flap models actuated by piezoelectric bending bimorphs. Barrett [7] built a six-foot diameter rotor and conducted rotating tests in a vacuum chamber. To actively and independently manipulate bending and twist distributions of the blades, directionally attached piezoelectric (DAP) crystals were embedded. Using a simple proportional feedback control system with crystals as sensors, it was shown that flapwise vibration response at resonance frequencies (with tip amplitudes of approximately 10% of the radius) could be suppressed (up to 70% reduction in amplitude). A refined form of this concept was used to build a six-foot diameter two-bladed Froude scaled bearingless rotor model, where each blade was embedded with banks of specially-shaped piezoelectric actuators at +/- 45 degree respectively on the top and bottom surfaces [8]. When the same potential was applied to the top and bottom banks, it cause pure twisting of the blade. The rotor was tested on a hover stand and tip twisting of the order of .1 degree was achieved at the operating speed of 900 RPM for a 4/rev excitation. Though this dynamic twist amplitude is an order of magnitude lower than needed to suppress vibration, it shows the potential for further research. The concept of trailing-edge flaps was initiated by Spangler and Hall at MIT [9] who conducted non-rotating tests of large fixed-wing sectional models. The extension of this concept to a smart rotor of the correct dynamic scale began at Maryland where rotor blades with bimorph piezo actuators have been investigated in free-jet wind tunnel tests in a fixed-wing mode and as a rotor in hover flight on a hover tower [10]. Significant oscillatory flap deflections have been sustained in both fixed-wing testing and in rotation (up to 2 degrees at 900 RPM). This concept appears more promising.

Straub [11] carried out a feasibility study of using smart structures technology for primary and active control of a full-scale vehicle. For this study, the AH-64 helicopter was selected. It was concluded that the concept of twist and camber control using embedded actuators is not practical with the available smart materials. Servoflap control system using smart actuators appears feasible. There are other papers [12-15] which have also discussed the application of smart structures technology to rotorcraft systems.

So far there has been limited research towards the development of analytical tools for a smart rotor. Current methods for predicting the static and dynamic response of anisotropic beams [1-2] are limited to bending and extension of beams using paired crystal actuation (via actuators bonded to the top and bottom surfaces of the beam). Continued research at the University of Maryland is expanding these theories to include the coupled torsion/bending/extension of beams with single or multiple crystals not aligned along the beam axis and bonded on one or both surfaces of the beam [16].

These are clearly just a very limited beginning to the research necessary if we are to develop this highly promising technology. The objective of this paper is to assess the smart structures technology developments at the University of Maryland for application to the rotor systems. Though a large part of this research is focussed to minimize vibration, these developments are equally applicable to other problems. In this paper four different topics are covered: trailing-edge flap concept, controllable twist concept, shape memory alloy actuation and analytical modeling of smart rotors.

Smart Rotor with Trailing Edge Flap

This section presents the development of a Froude scaled model of a typical hingeless rotor with smart trailing edge flaps to minimize vibration. Each blade consists of a plain flap, located near the tip. By oscillating the flap, the lift on the blade is varied, which in turn actively minimizes vibration at its source. This trailing edge flap concept (lift control) is different from servo flap concept (moment control) since for the latter case the flap motion causes change of torsional moment resulting in twisting of torsionally flexible blades. For the present approach, the flaps are driven using smart materials actuators placed inside the blade, and small displacements of actuators are amplified using leverage arrangement. Such a system provides an individual blade control (IBC) capability, which can be used for other purposes such as to minimize blade dynamic stresses, ensure aeromechanical stability, reduce acoustic levels, enhance handling qualities and improve rotor performance.

At the University of Maryland, a six foot diameter, two-bladed, 1/8-th Froude scale bearingless rotor (ITR-Boeing) was built with flaps actuated using piezo-bimorphs. Two separate sets of blades, one for testing as a wing in the open-jet wind tunnel and second for testing as a rotor on the hover stand were fabricated. Blades were constructed out of rigid foam, covered with fiber-glass prepreg fabric, embedded with a spar made of unidirectional glass-epoxy prepreg. The spar was located near the quarter chord to carry blade centrifugal load in rotation. To minimize the possibility of flutter in rotation, the sectional center of gravity of the blades was located at the quarter chord point by adding tantalum weights near the leading edge. Both blade sets used NACA0012 airfoil section and were of 3.0 inch in chord length. The trailing edge flap consisted of 4.38 inch length, 0.6 inch wide (20% chord) plain flap located at the trailing edge. For wind tunnel testing, the wing span was of 22 inch in length, with the flap located at the center of the blade span while for rotor blades, the flap was located near the tip of the blades between 85% to 97% of the rotor radius (Fig. 1).

MAIN ROTOR BLADE WITH FLAP ACTUATOR
Fig. 1

Trailing edge flap was actuated by three 1.5 inch long , 1.0 inch wide and .021 inch thick piezoelectric bender elements (bimorphs). The bender elements were made of two sheets of G1195 piezoelectric material, glued together with a brass shim in the middle. These bender elements are available commercially. These elements were rigidly anchored to the blade spar so that they formed 1.0 inch long cantilever beams. When actuated, these beams bend upward or downward depending on the applied voltage field and produce force when they are restrained at the tip. The bender elements were connected to the flap through a common hinge. A system of mechanical hinges and linkages were used to amplify the bending of the elements at the tip to cause larger flap rotation (Fig. 2). This flap rotation was measured by a Hall Effect transducer system with the flux inducing permanent magnet mounted along the flap hinge line which rotates with the flap.

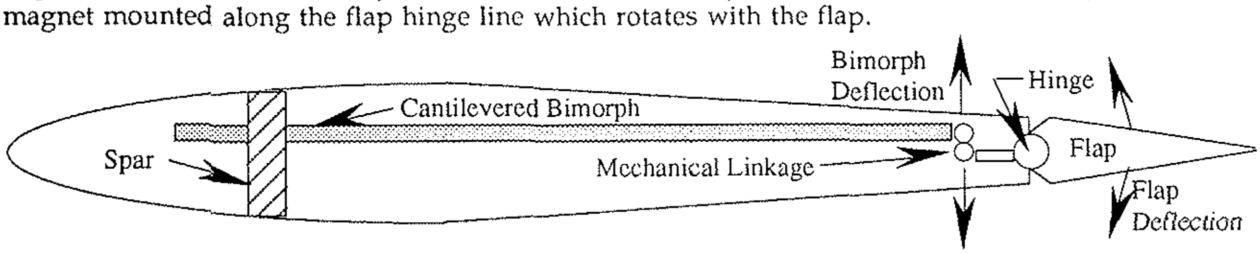


Fig. 2: Bimorph Flap Actuation System

The piezoelectric sheets in the bender element were connected to a special circuit through a power amplifier that energizes them individually. This circuit modifies input sinusoidal signal and applies unequal voltage to both sheets so that when the applied signal has the same polarity as the polarity of the sheet, a significantly higher voltage was impressed (as high as coercive field limit of the material) in comparison to when applied signal has the opposite polarity. This enables application of higher alternating voltages without degrading the piezoelectric material performance.

The wing and rotor models were tested extensively, respectively in the open-jet wind tunnel and on the hover tower. The wing model was tested up to the maximum tunnel speed of 110 ft/sec, angle of attack of 4 and 8 deg and with flap actuation frequencies of 5, 10 and 15 Hz. The two-bladed rotor was tested on our hover stand using our model rotor rig at rotational speeds of 300, 600 and 900 RPM (operating speed) and flap was actuated at 1, 2, 3 and 4/rev. Two collective blade pitch of 4 and 8 deg were used. Figure 3 shows flap angles at different rotational speeds. From these studies [10], the following conclusions were drawn:

i) For the wing model, the flap deflection decreases with higher speed, but does not change much with the excitation frequency at a given angle of attack and wind speed.

ii) For the rotor model, the trailing flap deflection decreases rapidly with rotational speed. With all the improvements incorporated for the actuation system, a maximum flap deflection of 2 deg was achieved at the operating speed of 900 RPM.

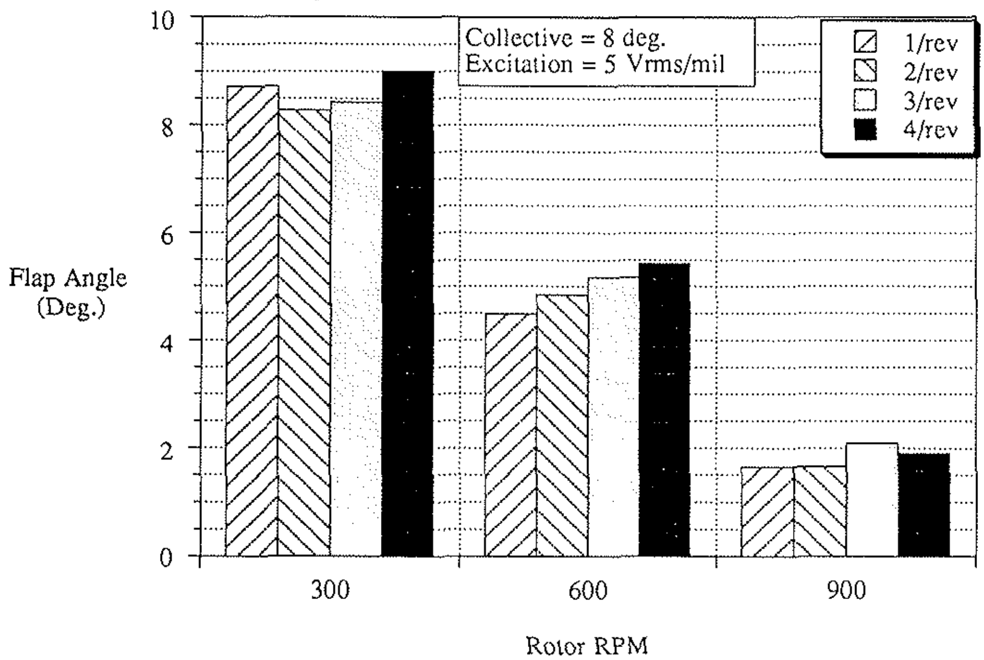


Fig. 3: Flap Deflection at Different Rotor RPM and Actuation Frequency in Hover

To minimize rotor vibration, the targeted trailing-edge flap deflection is 8 deg at excitation frequency of 4/rev. So, the current research is focussed to improve the design of actuation system by changing arrangement of flap hinges, resizing flap dimensions and increasing the number of bimorphs. From the above testing with two layer bimorph actuators, it became clear that the actuators need to have higher force capability. Thus, the four layer bending actuators were built. The comparison of measured cantilevered bimorph bending results with predicted Euler-Bernoulli beam model [14] values showed that the analysis is inadequate for extremely thin baseline beam (in comparison to piezo thickness). Then parametric studies were carried out to match the displacement and force characteristics of actuators with flap aerodynamics. Figure 4 shows flap force and displacement requirements to obtain 5% flap authority (additional lift with flap deflection/ steady blade lift) at a collective pitch of 8 degrees with a 20% flap chord and for different flap span. The four layer actuator shows a decrease in the free displacement (zero force condition) but an increase in block force (zero displacement condition) than the two layer actuator. The four layer actuator has more authority than the two layer actuator, however the desired 5% flap authority could not be achieved with the current design. Using this matching scheme, a six layer actuator is being designed to meet the desired flap authority.

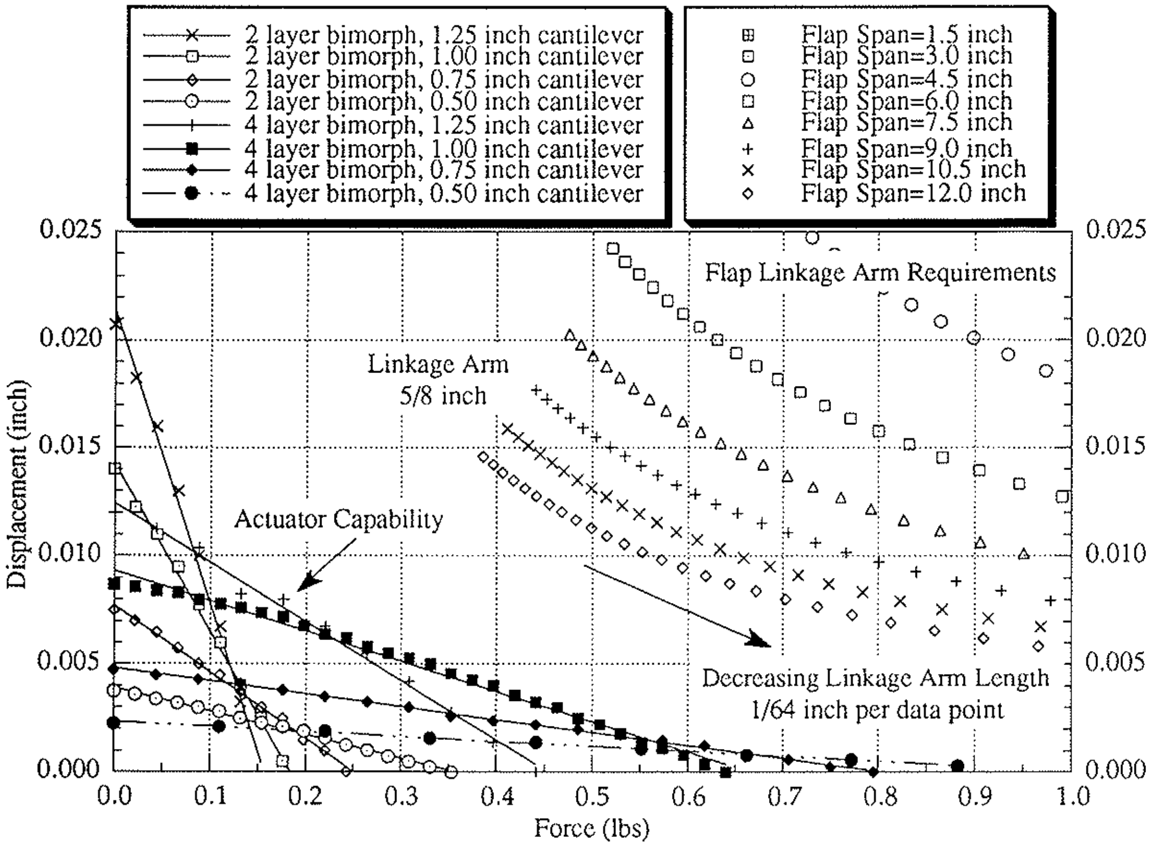


Fig. 4: Comparison of Linkage Arm Requirement and Bimorph actuator Capability

A second rotor model with longer flap span and multi-layered actuators is being built. Again, blade models will be tested in hover to check flap effectiveness at different rotational speeds and actuation frequencies. In parallel, analytical tools are being refined to calculate blade response with trailing-edge flap excitation. Analysis will be validated using experimental data. Finally, when the desired flap authority is obtained, the rotor model will be tested in the Glenn L. Martin wind tunnel to evaluate the performance of trailing-edge flap actuation at different forward speeds.

Full-Scale Actuation Development: Extension-Torsion Composite Tube with Magnetostrictive Actuators

For a full-scale trailing edge flap system, the force requirement of actuators become very substantial. At the same time, the blade can also accommodate larger size actuators. An alternate concept of using extension-torsion coupled composite tube in conjunction with magnetostrictive actuator is investigated to cause twisting of trailing edge flap. Figure 5 shows a schematic of this concept. The extension-torsion composite coupled tube is subjected to axial force generated by a magnetostrictive actuator resulting in twisting of the tube. An extension-torsion composite beam is built by wrapping angle plies resulting in an anti-symmetric ply layup with respect to the beam axis.

Thin beam analysis developed in Refs [17-19] is specialized to predict the induced twist of an extension-torsion coupled composite cylindrical tube due to axial force. The essence of this analysis is that two-dimensional stress and displacement fields associated with any local plate segment of the tube are reduced to the global one-dimensional beam displacements and forces (Vlasov theory). Nonclassical effects such as cross-section warping, transverse shear and warping restraint at edges are included. The objective is to determine the design of the composite tube that best utilizes the prescribed force and displacement characteristics of the magnetostrictive actuator to generate maximum torsional motion. To understand the influence of ply layup, number of plies and tube diameter on the induced twist, extensive parametric studies were carried out. Three different composite materials, graphite-epoxy, kevlar-epoxy, and glass-epoxy were examined. Figure 6 shows that for a prescribed axial force, the maximum induced twist occurs for kevlar-epoxy tube with a ply angle of approximately 30 deg. Then an optimization study was carried out to Calculate the best tube design keeping in view first ply failure and buckling instability.

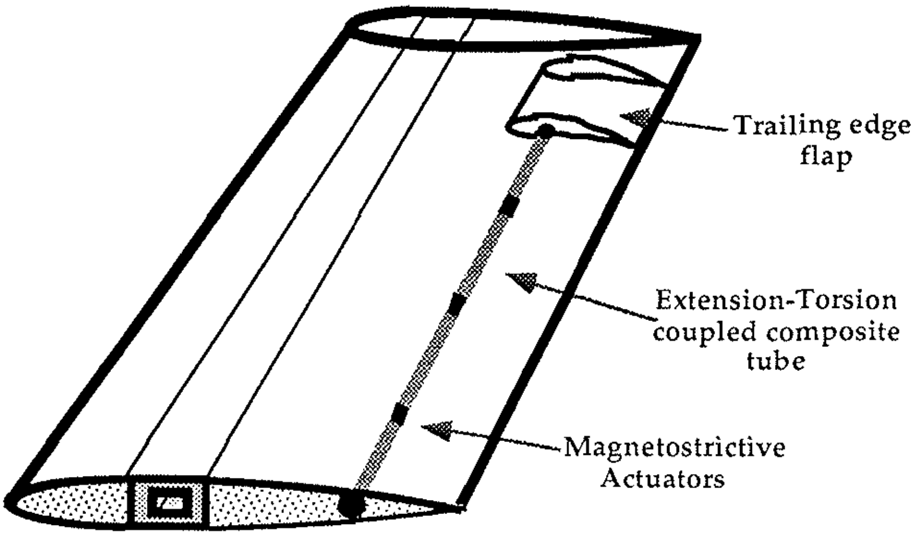


Fig. 5: Schematic of rotor blade trailing edge flap actuated by extension-torsion coupled composite tube and magnetostrictive actuators

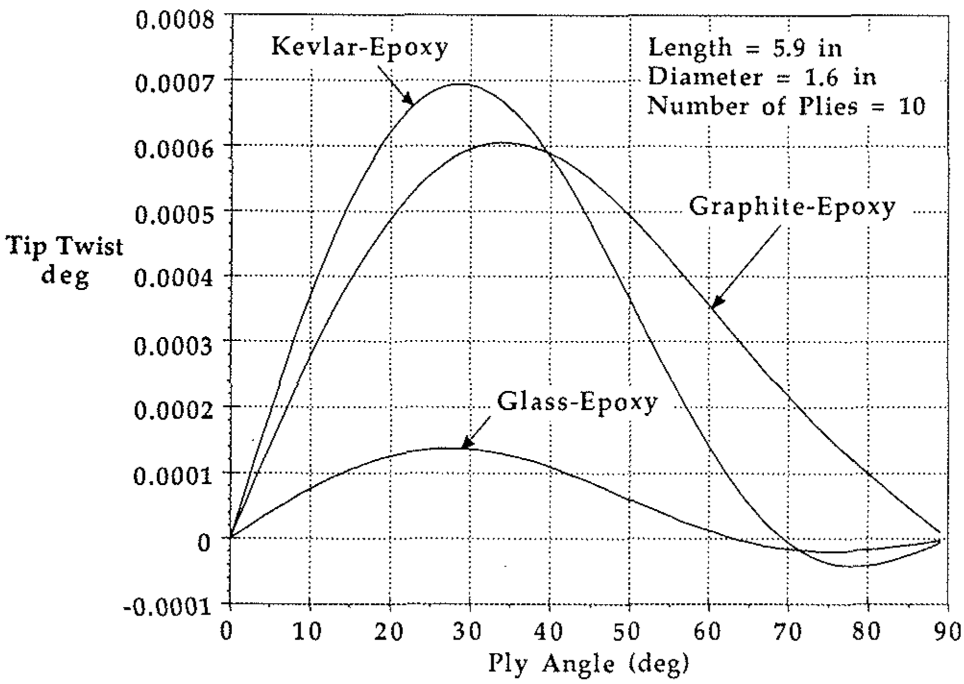


Fig. 6: Induced Twist vs. ply angle for extension-torsion composite tube for a Prescribed Axial Load

The magnetostrictive actuator was selected because of its superior characteristics (force, displacement and size) as compared to electrostrictive and piezoelectic stacks. For the present study, a commercial available magnetosrictive actuator (100/6-MP Etrema) was chosen. The composite tube was fabricated using an autoclave molding technique. In order to utilize the extension-torsion coupling characteristics of the composite tube, the magnetostrictive actuator must be attached to the tube in such a way that both twist and axial strain are permitted. Figure 7 shows the schematic of the tube and actuator assembly. A series of tests will be performed to check the performance of this torsional actuation device for different loading.

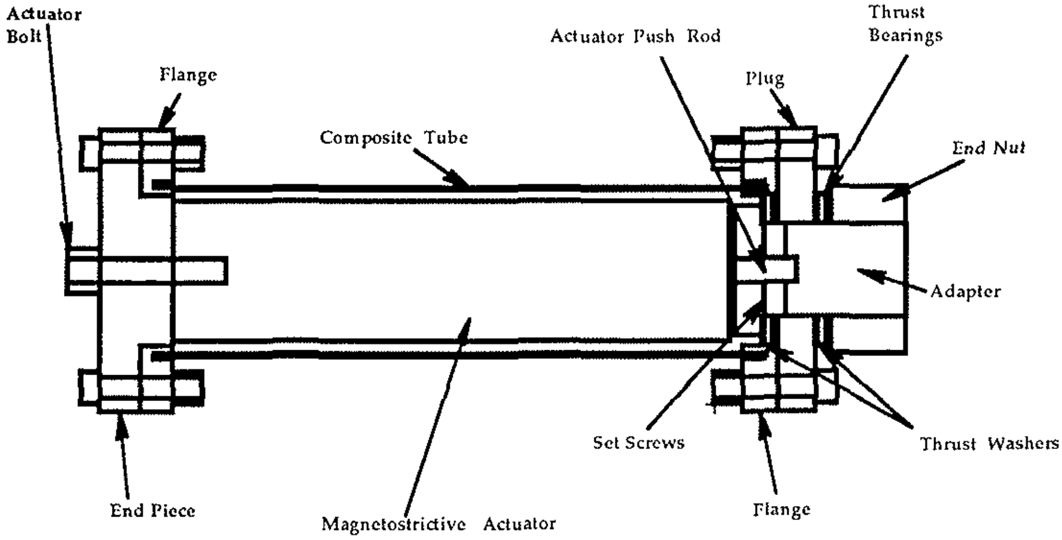


Fig. 7: Schematic of composite tube and actuator assembly

Smart Rotor with Controllable Camber and Twist

This section presents the development of a Froude scaled rotor model where blade camber/twist is controlled using distributed embedded actuators. Specially-cut piezoelectric actuators are attached under the skin at certain orientation so that a pure twisting of blade occurs when a potential is applied to both top and bottom actuators. Again, this will provide an individual blade control (IBC) capability.

The smart rotor model under development is a six-foot diameter, 1/8-th Froude scale, two-bladed bearingless rotor (Boeing-ITR). The blade is constructed by laminating 10 mil pre-preg fiberglass cloth plies around a foam core which is cured in a NACA 0012 airfoil mold (Fig. 8). The overall blade length is 26.58 inches from tip to root and the chord is 3.0 inches.

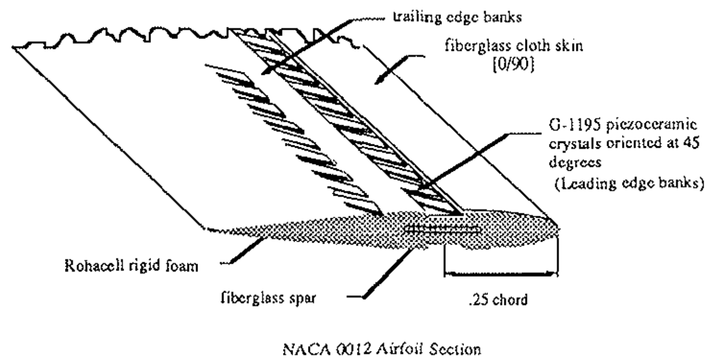


Fig. 8: Piezoceramic Blade Cross Section Details

Structural integrity is achieved through a mahogany wood root section and a continuous longitudinal 10- mil fiberglass spar with ply angles of [0/90] degrees, which is embedded at the quarter chord location. Inertial coupling between the flap and pitch modes is reduced by placing the airfoil section center of gravity at quarter chord. To activate blade motion independently in bending and torsion and to sense blade deformations, specially shaped 9.5 mil thick piezoceramic elements are embedded under the fiberglass skin in banks of five discrete crystals at angles of +/- 45 degree on the top and bottom surfaces of the blade. Wires extend from each bank to the root of the blade, allowing for independent actuation or sensing from each bank. The crystals used for this study are G-1195 lead zirconate titanate (PZT) piezoceramics manufactured by Piezo Electric Products [20].

The structural properties of the piezoceramic blade were experimentally determined by measuring the spanwise bending and twist distributions along the blade. A laser beam was reflected off mirrors mounted at the elastic axis along the span of the blade and several tip loadings were used to determine average values for the structural stiffness. The measured flapwise and chordwise bending stiffness were satisfactory, however the torsional stiffness of the smart blade was about three times the desired Froude-scale value. This large torsional stiffness adversely affected the performance of piezo-actuation. Since the objective is to cause dynamic twist in the blade at different frequencies, the torsional stiffness of the blade is a key factor which limits the induced twist by piezo actuators.

Then, the static response of the piezoceramic blade as determined by tip deflections was measured. The blade was clamped at the root and a voltage potential was applied across the thicknesses of each two adjacent banks of crystals located at 10, 20, 30, 40, 50, 60, 70 and 80 percent blade span. A minimum of two bank pairs were actuated for each measurement in order to achieve twist deflections within the resolution limits of the laser/mirror apparatus used to determine twist amplitudes. All of the leading edge banks were then energized at the same DC voltage potential and the corresponding tip twist was measured. A maximum tip twist of the order of .15 deg was achieved. This value however is an order of magnitude lower than needed to suppress vibration. Comparison with predicted simple beam theory results showed poor correlation. A dynamic test followed which determined the non-rotating torsional responses of the blade to dynamic actuation for frequencies ranging from 5 to 100 Hz. The blade was cantilevered at the root and the tip deflections were measured using a laser/mirror apparatus. The crystal banks at the leading edge are actuated at voltages of 70, 80, 90, 100 and 110 volts RMS to excite the torsional modes of the blade. Because of the limitations of the existing power supply system, excitation was limited to lower voltages at higher frequencies and also only to the leading edge banks. To test the effectiveness of the smart blade in the rotating condition with aerodynamic forces, the blades were then tested in a bearingless rotor configuration on a hover stand where the rotor was rotated at two speeds (300 and 400 RPM). The blade was excited at different frequencies and the changes in oscillatory lift was measured using 4-component balance in rotating frame. Also, the flapping response from gages mounted on flexbeams were recorded. Figure 9 shows the flap response due to distributed twist actuation at 400 RPM at different excitation frequencies for collective pitch angles of 4 deg. and 6 deg.

The following conclusions were made from these tests [8].

i) Embedded piezoelectric actuators were able to excite pure bending and pure torsional modes of the blade. Response amplitude grew dramatically near resonance condition.

ii) The simplified uniform strain theory of the static torsional blade twist did not show good correlation with experimental results. However, trends with number of crystals and excitation voltage were predicted well.

iii) A dynamic tip twist of the order of .1 deg was achieved at 4/rev excitation.

Research in HHC has shown that tip twist on the order of 1-2 deg. at 4/Rev is needed in the rotating condition to significantly affect the lift distribution and vibratory forcing of the blade. This relatively large twist angle was unattainable with the above blade design scheme where the dynamic twist response at non-resonant frequencies is approximately 20 times less than what is desired. However, with lower torsional stiffness of the blade, better actuators and improved fabrication techniques, it may be possible to build a dynamically scaled rotor model with desired actuation to suppress vibration.

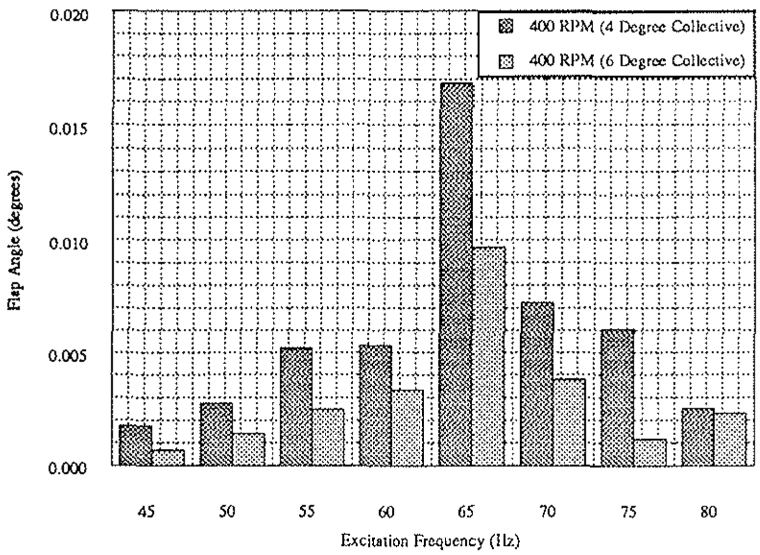
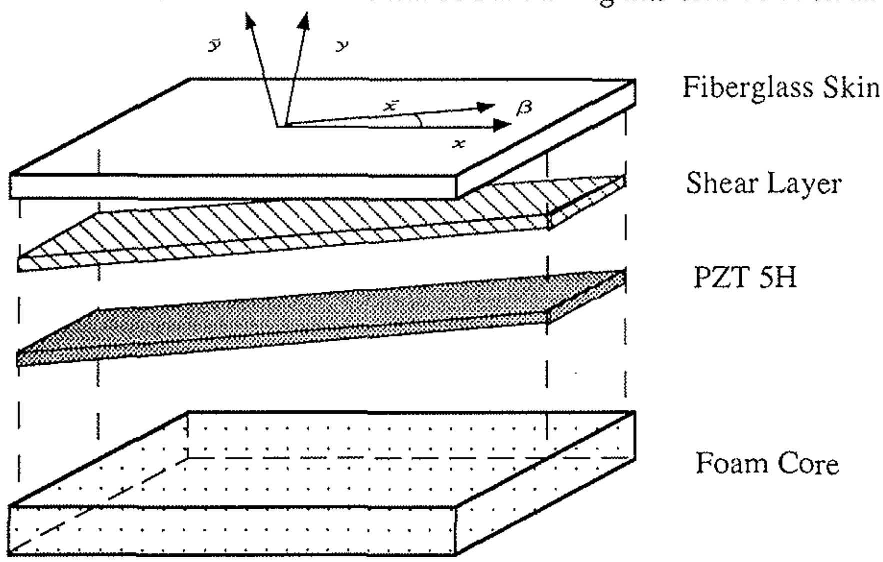


Fig. 9: Blade Flapping Response Due to Torsional Piezo-Actuation (400 RPM)

The performance of the above piezoceramic blades showed that continued research into this smart rotor with distributed actuators is warranted. The lessons learned from this prototype blade indicated many areas for improvement in construction. Delamination of the fiberglass skin from the crystal layer during the curing process might be a source of disparity between the predicted and measured twist. The bond thickness between the crystals and the substrate is another critical factor where a thick layer renders the crystal less effective in transferring shear as well as increasing the torsional stiffness. These bonds contribute significantly to the structural properties of the blade where the stiffness of the components such as the skin, spar, and foam are smaller in magnitude than a thick bond layer. A substantial reduction in adhesive thickness in future models may significantly improve the response of the blades. The next rotor model will be built taking into consideration all these points.



Note: Laminate Symmetric About Foam Core; Only Upper Plies Shown

Fig. 10: Laminate layup sequence

Most of the existing analytical beam models with peizo-actuation are developed for surface-mounted piezoceramics. Uniform strain model including shear lag effects due to adhesive layer is reformulated for embedded piezo-actuators at an arbitrary orientation with respect to beam axis to predict bending and torsional responses. The theory was validated using experimental data from simple rectangular section sandwich beam specimens. Beams were comprised of a rigid foam core, three equidistant embedded piezoceramics, bond layer and fiberglass skin (Fig. 10). Several specimens were built with varying bond thickness, actuators orientation and beam thickness. Figure 11 shows the correlation of predicted and measured bending slope and twist for a beam with a shear layer thickness of 0.020 inch for different orientation of piezoceramics. Once the analysis is perfected, then it will be used to optimize the design (number, size and orientation) of piezo-actuators to maximize blade twist.

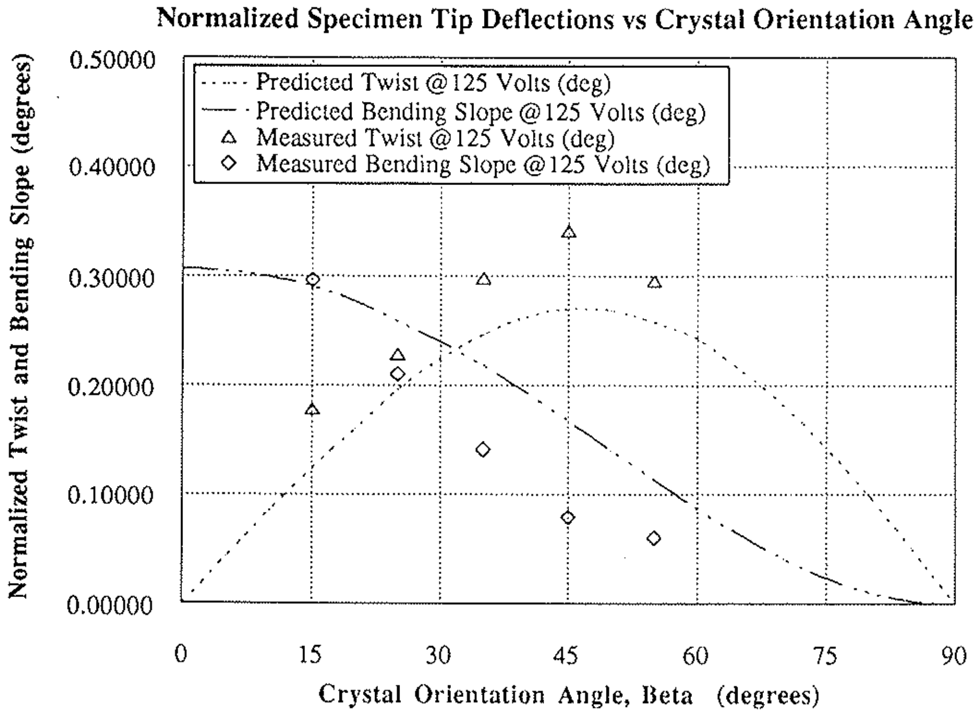


Fig. 11: Twist and Tip Bending Slope for Different Piezo Orientation

Then static and vibration tests will be repeated, and later on, model will be tested on the hover stand in the Glenn L. Martin wind tunnel using model rotor rig. Measured resulted will be correlated with calculated results obtained using refined analytical models.

Shape Memory Alloy Actuators

Shape memory alloys such as Nitinols undergo phase transformation at a specific temperature. When temperature is reduced, they recover to their original shape. It is well established that SMA actuators result in high strains and high forces, but at a very low frequency (less than 1 Hz).

Using induced strain actuation with embedded shape memory alloys, there is the potential of designing variable speed rotor, supercritical tail-rotor shaft and collective pitch control system(without swashplate). To accomplish these goals, an accurate modeling of open-section and closed section thin-walled composite beams, which form essential structural elements of rotor blades, with embedded SMA fibres is needed.

Rogers, Liang and Jia [21-22] analytically studied the behavior of shape memory alloy reinforced composite plates. They demonstrated the structural control characteristics and authority with the SMA reinforcement for four different plate problems; plate bending, free vibration, buckling analysis, and acoustic transmission loss through the plate. It was shown that the first bending frequency of a simply supported composite plate increased by about 100% at activation for 10% SMA reinforcement (by volume). Rogers and Barker [23] presented an experimental study of active strain energy tuning of composite beams with embedded SMA. They showed the fundamental bending frequency of a clamped-clamped beam increased by about 300% with 15% nitinol volume fraction. These studies showed the potential of controlling static and dynamic characteristics of beams and plates using embedded SMA fibers.

An accurate structural modeling of composite beams under mechanical loading is a prerequisite to modeling of beams with embedded SMA. Above studies related to SMA actuation are all confined to plates and solid beams. For application of the SMA technology to rotor systems, it is essential to model thin-walled composite beams. Chandra et al [17-19] developed general thin-walled composite beam analyses for box beams, I-beams (open-section) and multi-cell blades (airfoil section) under mechanical loading and validated these using experimental data. These analyses based on Vlasov theory are being modified to include the effect induced strain actuation with SMA [23]. Non-classical effects such as section warping and transverse shear are included. SMA fibers under heat-activation induce significant longitudinal forces in the host structure. The state of stress in an SMA-composite layer is obtained using a micromechanical model [21-22]. SMA composite layer refers to the composite lamina formed out of SMA fibers as reinforcement and laminating resin as matrix (Fig. 12) and the constitutive relations are dependent on initial strain of the SMA fibers, volume fraction of SMA, recovery temperature and stiffness matrix.

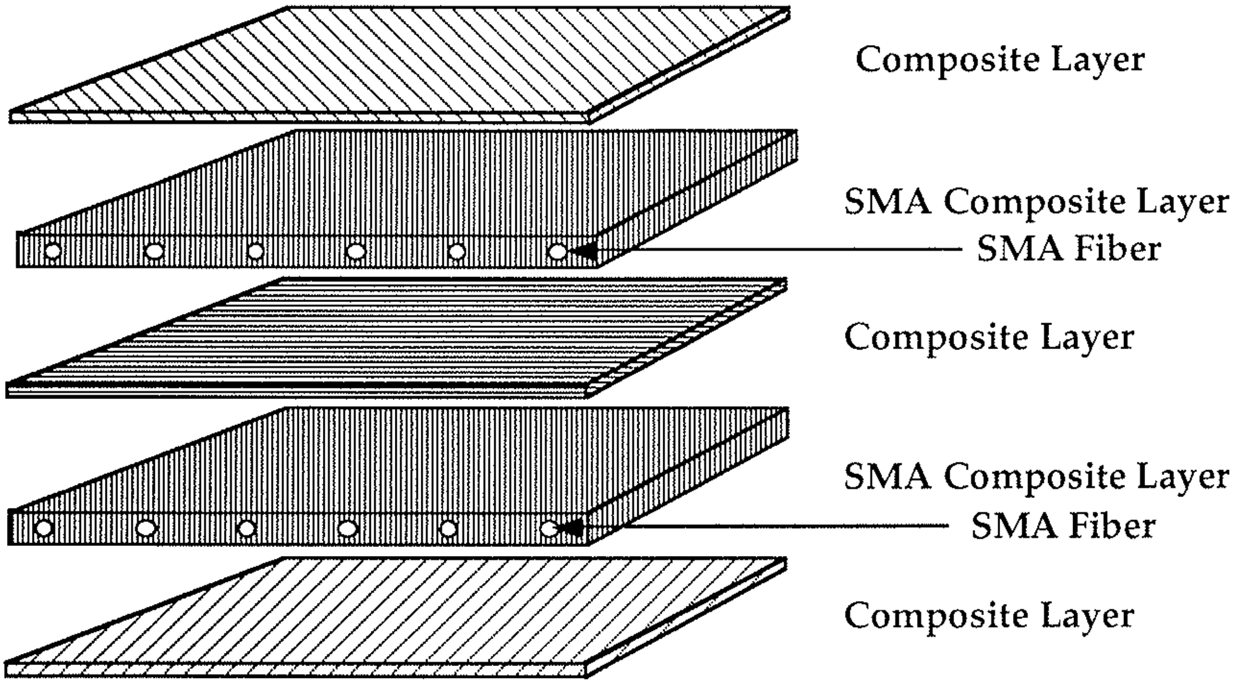


Fig. 12: Plate segment of composite beam showing SMA-composite layers.

There are two important considerations for embedding SMA fibers in composite beams. The first one is that the matrix of composite material should withstand the prestrain of the SMA fibers. This requirement does not permit the use of normal composite materials and calls for the use of materials with superior interlaminar shear strain at failure. IM7-8552 from Hercules satisfies this requirement. The second consideration is that the SMA fibers must be constrained during the manufacturing, so that these do not return to their original position at curing temperatures which are higher than the phase transformation temperature of the SMA. Figure 13 shows the schematics of composite I-beam with SMA fibers. It is to be noted that 36 SMA wires (18 on each flange) were embedded in composite I-beams. In order to ensure uniformity of induced forces by these wires, the following procedure was used. The wires were electrically heated to remove the prestrain given during the manufacturing. These were then given a known prestrain; 5 mil diameter wires were stretched by 200 grams of weight whereas 10 mil diameter wires were stretched by 900 grams of weight.

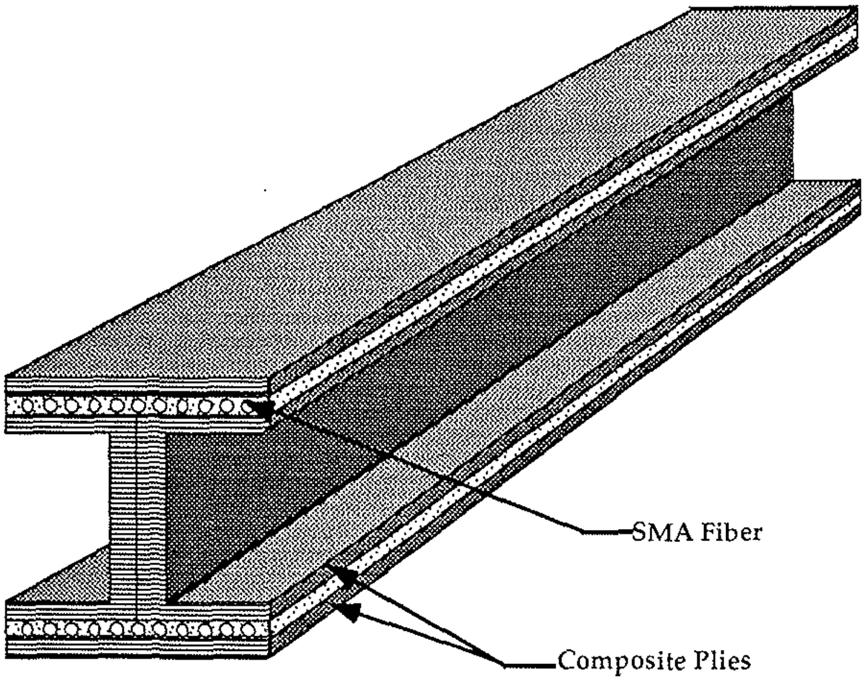


Fig. 13: Schematic of composite I-beam with SMA fibers.

In order to avoid the problem of curing at high temperature, composite solid beams with SMA fibers were built using room temperature curing adhesive and cured glass-epoxy sheets. This did not need the device to constrain the SMA fibers as the phase transformation temperature of SMA (158^{O}F) was above the curing temperature (70^{O}F) of the adhesive. Figure 14 shows the schematic of such solid beams with SMA fibers.

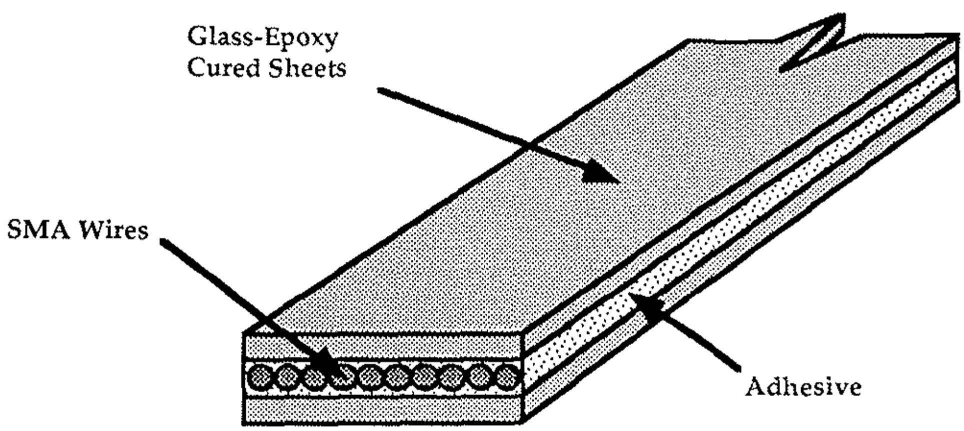


Fig. 14: Schematic of composite solid beam with SMA fibers.

Transient testing was used to measure the natural frequencies of composite beams with SMA activation in 'off' and 'on' conditions (Ref 23). An instrumented hammer was used to apply an impulse loading on the beam and an accelerometer was used to measure the response. Natural frequencies were determined from the FFT plot obtained using a spectrum analyzer. Test showed that there was a reduction of 26% of fundamental bending frequency with activation of SMA fibers for the cantilevered solid beam (volume fraction 1.3%). For a clamped-clamped boundary condition, the reduction of frequency was 34%.

Currently, research is directed to refine and validate mathematical model of beams with SMA actuators. Also, fabrication techniques to build composite beams with embedded SMA wires of different cross-sections are being improved. Several different types of thin-walled coupled (bending-torsion and extension-torsion) composite beams of open section (such a I-beam and cruciform section beams) and closed section (such as box beams) are being built with embedded SMA. These beams will be tested under static and dynamic loadings and results will be compared with predictions. It is important to develop proper analytical tools and refine fabrication techniques to exploit SMA for the development of a variable speed rotor.

Modeling of Blades with Induced Strain Actuators

To fully exploit the application of smart structures technology in the rotor system, it is necessary to develop analytical tools to model blades with strain actuation. At this time, available structural models of beams with embedded or surface-attached piezoceramic actuators are few and limited. For the comprehensive aeroelastic analysis of a rotor system, it becomes essential to treat the blade as one-dimensional beam undergoing extension, bending and torsion deformation.

Crawley and de Luis [1] formulated a uniform strain bending model of a beam with strain-induced piezo-actuation. A pair of piezoceramic actuators aligned along the beam axis were assumed, and the shear lag effects of the adhesive layer between the piezoceramic and the beam were included. Predicted response of the first two bending modes of a cantilevered beam was verified experimentally. Crawley and Anderson [2] formulated a Bernoulli-Euler model and compared it with uniform strain model, detailed finite element model and experiment. It was shown that for thin beams, Bernoulli-Euler model is more accurate than uniform strain model. These as well as few other studies were all confines to plates and solid section beams. Chandra and Chopra [24] developed a formulation for coupled composite thin-walled beams with distributed actuators and then validated analysis with experimental data. Analysis is based on Vlasov theory where two-dimensional stress and displacement fields associated with any local plate segment of the beam are condensed to one-dimensional generalized forces and moments. Correlation with experimental data from a cantilevered graphite-epoxy beam with surface mounted piezoelectric actuators (Fig. 15)showed that the including of chordwise bending is essential to accurately predict beam's coupled response (Fig. 16).

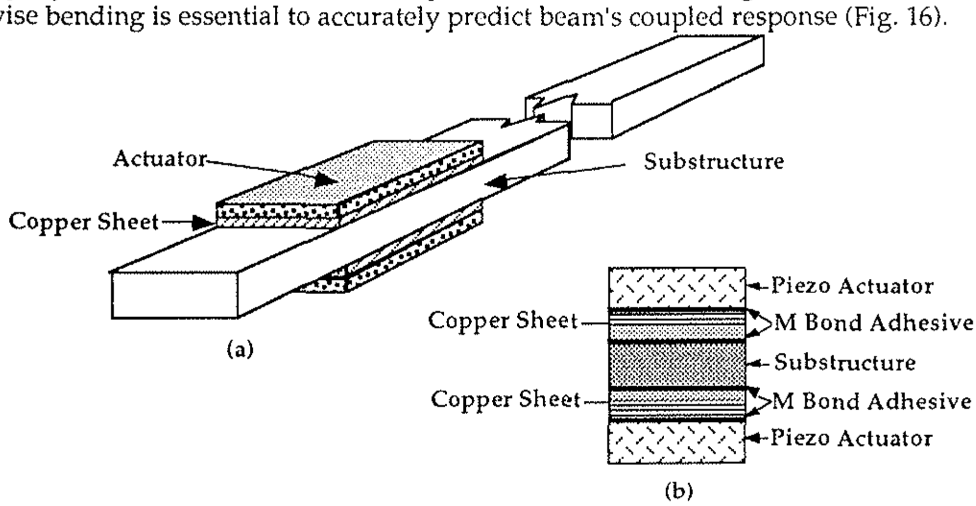


Fig. 15: Solid Beam with Piezoelectric Actuators

Above analytical models are developed for a pair of piezoceramic actuators, one on each surface aligned along the beam axis. If the same voltage is applied to both piezoceramics, it will result in pure extension for an isotropic beam and if opposite voltage is applied it will result in pure bending. If the piezoceramic actuator is attached at an arbitrary orientation with respect to the beam axis, it will cause extension, bending and torsional deformation. Park et al [16] formulated one-dimensional analytical model of a beam actuated by single piezoceramic surface-mounted at an arbitrary orientation with respect to the beam axis (Fig. 17). Both uniform strain and Bernoulli-Euler models were developed and shear lag effects due to a finite thickness of adhesive layer between the piezoceramic and beam were included (Fig. 18). Analysis is also applicable to distributed actuators on both top and bottom surfaces. Experimental tests on response of cantilevered beams with piezoceramic actuators were carried out to evaluate the accuracy and limitations of the models. The bending and coupled bending and extension models showed acceptable correlation with static test results (Fig. 19) whereas the combined extension, bending and torsion model showed poor correlation (Fig. 20).

Consequently, the coupled model was modified to include effects of section warping. It improved prediction of torsional response somewhat, but it is still not satisfactory for larger orientation angle of actuator with respect to beam axis.

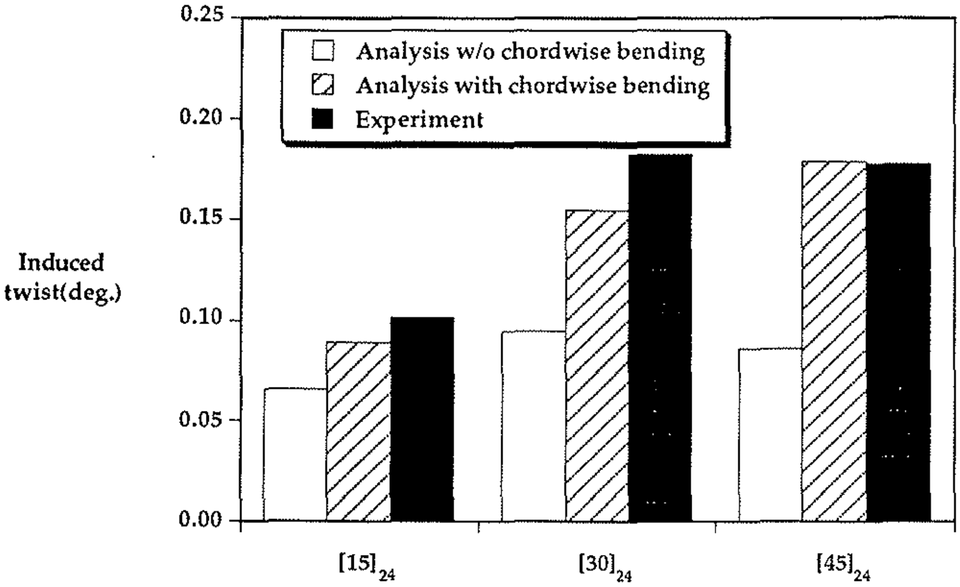


Fig. 16: Induced twist of graphite-epoxy solid beams under piezoactuation, free actuator strain=240 microstrain

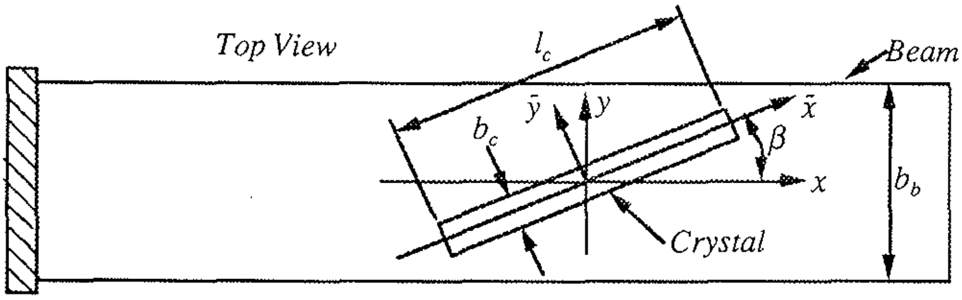


Fig. 17: Crystal Axis offset from beam axis

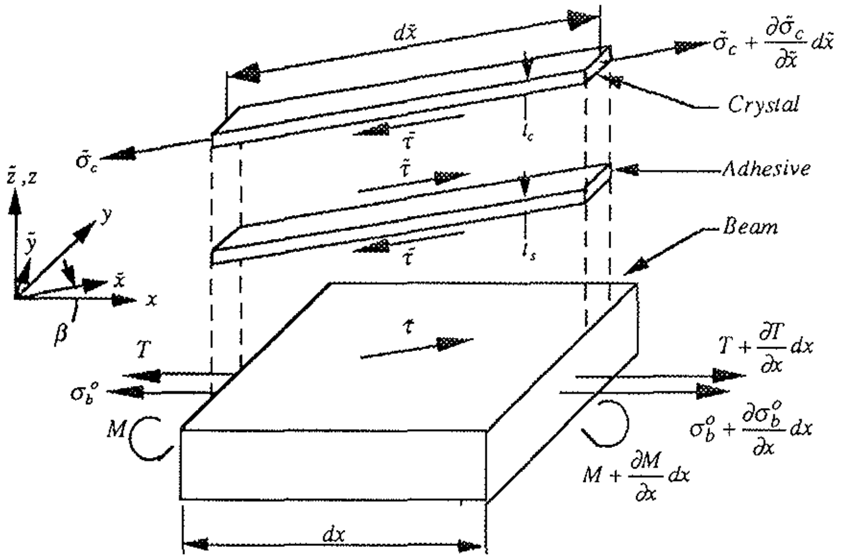


Fig. 18: Components of the differential element

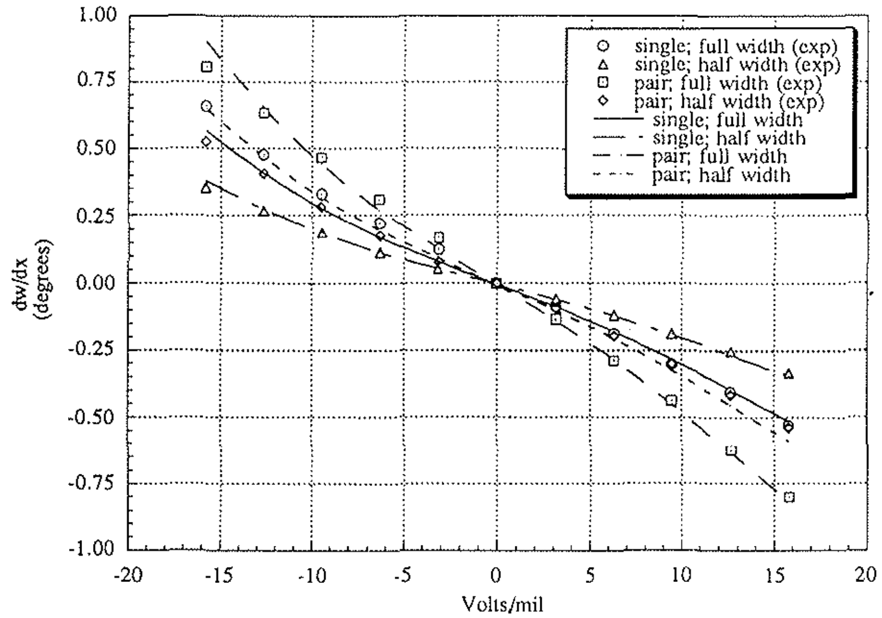


Fig. 19: Bending slope data for 1/32 inch thick aluminum cantilevered beam

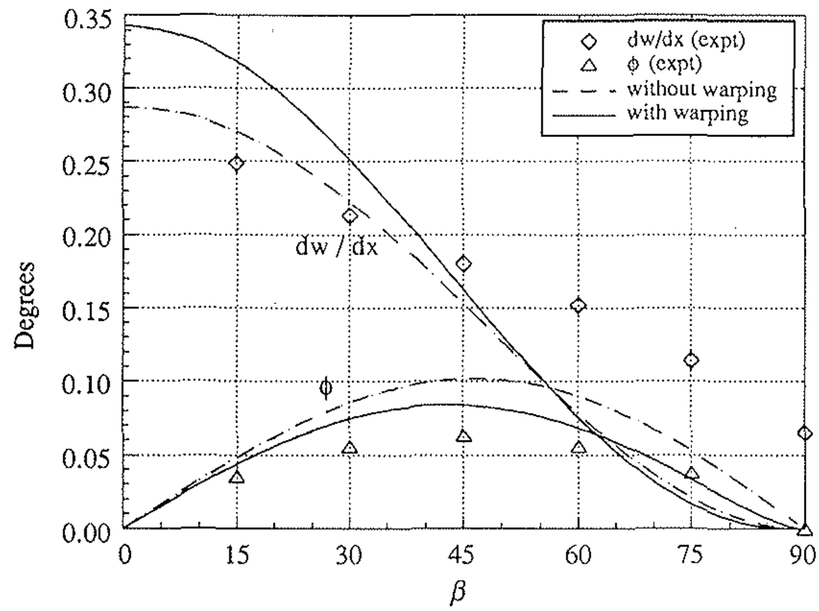


Fig. 20: Bending slope and twist results of a Cantilevered Beam (Tip)

In a parallel effort, analytical tools are being developed for coupled extension-bending-torsion beams with embedded piezo-actuators at arbitrary orientation.

Conclusions

This paper reviewed the developments in smart structures technology at the University of Maryland for application to rotor systems. Two types of Froude scale rotors were built: trailing-edge flap models and controllable twist models. Both models were actuated using piezoceramics and these were tested in hover at different rotational speeds. Some exploratory work on building a variable speed rotor using shape memory alloys was initiated. Analytical tools to model a smart rotor undergoing bending, extension and torsion were formulated. The following conclusions are drawn:

1. Trailing-Edge Flap Concept: At the operating speed in hover, flap actuated by piezo-bimorph was able to deflect about 2 deg. at 4/rev. To achieve the target flap deflection of 8 deg., flap and actuation system needs redesigning. To implement the trailing-edge flap concept on a full-scale vehicle, a kevlar-epoxy extension-torsion coupled tube with a magnetostrictive actuator was designed to the achieve the desired actuation force and displacement.

2. Controllable Twist Concept: At the operating speed in hover, a maximum tip twist of .1 deg. at 4/rev was achieved using embedded piezoceramics at +/- 45 deg. on the top and bottom surfaces. To achieve the target tip twist of 2 deg., new models are being built with thinner bond layers and lower blade torsional stiffness.

3. Shape Memory Alloys Actuation: The bending frequency of a solid beam with embedded SMA wires (volume fraction 1.3%) was reduced by 26% upon actuation. To exploit this concept to build a variable speed rotor, it is necessary to develop proper analytical tools and refine fabrication techniques.

4. Analytical Modeling: Validation of newly formulated one-dimensional beam model undergoing bending, extension and torsional deformation with experimental data showed an acceptable correlation for bending response and a poor correlation for torsional response. This beam model needs further refinements before it can be included in a comprehensive rotor code.

Acknowledgments

This work is supported by the Army Research Office under the grant DAAL 03-92-G-0121 with Dr. Gary Anderson as Technical Monitor.

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