ACTIVE TWIST CONTROL OF SMART HELICOPTER ROTOR - A SURVEY

Dipali Thakkar* and Ranjan Ganguli**

Abstract

Helicopter vibration and blade-vortex interaction (BVI) noise are major problems restricting the wider use of helicopters in civil and military applications. Traditional methods based on vibration isolators and absorbers and passive designs of the rotor blade to reduce BVI noise have reached the point of diminishing returns and are increasingly unable to meet the stringent requirements of next generation helicopters. The advent of smart materials such as piezo-ceramics, has opened the possibility of actively twisting the rotor blade using control algorithms in a manner such that new higher harmonic forcing is developed which cancels the existing unsteady higher harmonic aerodynamic forces that are the main sources of vibration and noise on the rotor. Since the main rotor of a helicopter is the principal source of vehicle vibration, active twist control offers possibility of a low vibration helicopter. This paper reviews the literature in active twist rotor control using smart materials.

Keywords: Helicopter, active twist, smart materials, vibration, control, rotor

Introduction

Significant vibration and noise levels occur in helicopters because of strong aeroelastic interactions between a highly unsteady aerodynamic environment and rapidly rotating flexible blades. Other sources of vibration are asymmetry of the rotor disk aerodynamics, blade-vortex interaction, retreating blade-stall, high advancing blade Mach numbers, low aerodynamic lag damping, and out-of-track blades. High noise causes discomfort to passengers, limits operations inside the residential areas, increases detectability in defense applications and causes poor ride quality. High vibration levels limit helicopter performance and reduce the structural life of components, require expensive maintenance, cause fatigue in rotor system components and increases the likelihood of damage to critical avionics components in the helicopter. Significant research is being dedicated towards vibration reduction of helicopters. Moreover, the traditional approaches to vibration reduction based on vibration isolators and absorbers lead to large weight penalty and show severe degradation in performance for flight speeds that are away from the design condition. Since the rotor is a primary source of helicopter vibration, efforts are being directed towards controlling a rotor in such a way that new unsteady loads are generated that cancel out existing loads. Active control technology and smart materials being explored to design rotors with reduced vibration levels towards pursuit of the long-term goal of 'jet- smooth-ride' for a helicopter [1]. While conventional methods based on vibration absorbers and isolators have reached a point of diminishing returns, the advent of smart materials has opened up exciting research opportunities in the area. Comprehensive reviews on applications of smart materials are available [1-9]. Reviews on aerospace applications are given by Chopra [1], Giurgitiu [2] and Loewy [3]. The application of smart structures to helicopters is given by Chopra [4]. Other reviews on structural and vibration control are provided by Irschik [5] and Valliappan [6]. Trindade and Benjeddou [7] review work on active damping using piezoelectric materials. For reviews on the materials aspects of smart materials see [8] and for a comprehensive review on piezoelectric materials see [9]. There is no comprehensive review on active twist control of smart helicopter rotors in the literature though many research papers have been published in this area. This paper addresses this gap in the literature and discusses in detail research on the area of active twist control of helicopter rotor vibration and noise using smart materials.

* Ph.D. Student ** Associate Professor
Department of Aerospace Engineering, Indian Institute of Science, Bangalore-560 012, India
Manuscript received on 05 Jan 2005; Paper reviewed, reivsed and accepted on 18 Aug 2005

Higher Harmonic Control and Individual Blade Control

For an N-bladed rotor with a rotational speed of Ω, the primary vibration transmitted by the rotor to the fuselage is the NΩ or N/rev component. For example, for a 4-bladed rotor with a rotational speed of 300 rpm (5Hz), the primary cause of vibration is at the 20Hz (4*5) frequency. The vibration at 4/rev harmonic in the fixed frame is caused by 3/rev, 4/rev and 5/rev harmonics in the rotating frame. The basic principle of HHC (higher harmonic control) is that by generating new airloads in the rotating frame at 3, 4 and 5/rev, the 4/rev vibrations in the fixed frame can be reduced. HHC was implemented by giving a 4/rev motion to the swashplate using actuators which led to 3/rev, 4/rev and 5/rev motion in the rotating system. HHC thus used active root pitch control using swashplate oscillations. HHC methods were successfully demonstrated using numerical simulations [10-13], wind tunnel tests and full scale flight tests producing reductions in vibrations from 25 to 90 percent [14-17].

Unfortunately, higher harmonic control needed high actuation power and involved large weight penalties. The IBC (individual blade control) methods allowed each blade to be controlled separately at a desired frequency. HHC works in the frequency domain while IBC works in the time domain. While exciting the swashplate at 4/rev allowed only 3/rev, 4/rev and 5/rev oscillations in the rotating frame for a 4-bladed rotor, IBC could also be used to generate 2/rev and any other harmonics. IBC was implemented on a BO-I05 helicopter using hydraulic pitch-link actuators [18]. These hydraulic actuators were controlled by servovalves. While the results of these tests were encouraging, amplitude limitations of the control system prevented the demonstration of the full capability of the IBC technology. IBC also suffered from the problems of large weight penalties and needed complex hydraulic devices.

Besides vibration, noise is also an important problem in helicopter rotors and restricts helicopter usage in both civil and military applications. Impulsive noise is the most irritating because the human ear is highly sensitive to pressure changes that occur over very small time periods. Helicopters have two main types of impulsive noise: blade-vortex interaction (BVI) noise and high- speed impulsive (HSI) noise [19]. HSI noise is caused by compressibility effects. In high speed forward flight a phenomenon known as delocalization may occur. This is characterized by the supersonic region on the blade extending to the far-field beyond the rotor. This results into impulsive noise. Passive design features have been used to minimize this effect.

BVI noise occurs at low speed descent which a helicopter undergoes before landing and is caused by large velocity gradients caused by trailed tip vortices. The rapid changes in the induced velocity field leads to large, time-varying fluctuations in blade loading. The strongest BVI occurs on the advancing blade where the axis of the trailing vortex is nearly parallel to the rotor blade leading edge. BVI noise is difficult to predict accurately because the unsteady airloads and aeroacoustics require prediction of the wake location and the strength of the vertical elements with good accuracy. Research has been done on passive designs of the rotor blade to reduce the BVI noise. The methods used include (1) advanced blade tip designs and tip air mass injection [20-22], (2) increasing the size of the vortex core or instigating vortex bursting using spoilers or stub wings [23] and (3) altering the blade planform. Unfortunately, these methods have not been very successful and the active control approach has emerged as the preferred method. It has been found that 2/rev forcing is quite effective in reducing BVI noise. However, the optimal values of phasing for minimizing BVI noise may result in an increase in rotor vibration. A particular advantage of the use of active control in BVI noise reduction is that BVI occurs in low speed descent where excess power is available for the smart materials actuators as the rotor power requirement is reduced compared to forward flight.

Smart Rotor Concept

Among the active control solutions to solve the helicopter vibration problem, rotor blade trailing edge flaps and actively twisted rotor actuated using smart materials are undergoing active investigation. In the trailing edge flap-approach vibration control is achieved by exciting the flap at a combination of frequencies to produce incremental change in rotor lift and pitching moment such that, if correctly phased, can cancel out unwanted vibrations. This has a high frequency bandwidth and a minimum of moving parts of compact size. Another approach is to actively twist the entire rotor blade. This can be achieved by actively controlling the blade angle of attack distribution by creating a time varying and controllable elastic twist, which as a result reduces helicopter vibrations by influencing the aerodynamic disturbances at its source. In this approach, there is an advantage of avoiding the profile drag penalty associated with trailing edge flaps. Nevertheless, the drawback is that it requires increased actuation for twisting the entire blade, compared to relatively small flaps.

Though HHC and IBC technology has been around for some time, what has caused new research interest in the area of active vibration and noise control is the emergence of smart materials such as piezoceramics [1]. Piezoceramics have found increasing use in applications and are an integral part of the smart structures systems [5]. In piezoelectric materials, electrical energy is converted to mechanical energy and vice versa. When an electric field is applied to a free layer of piezoelectric material, the particles of the layer exhibit displacements from their original position in a manner similar to thermal expansion of a freely heated elastic strip. If the piezoelectric layer or patch is bonded to some non-piezoelectric structure such as a helicopter rotor blade, without completely constraining the free displacement, the converse piezoelectric effect will actuate the structure (Fig.1). On the other hand, piezoelectric materials can also be used to sense deformations because an electric field is actuated due to strains because of the direct piezoelectric effect. When a piezoelectric is used for both sensing and actuation, it is called a self sensing layer. According to Irschik [5], the ability of structures with bonded piezoelectric patches and automatic control algorithms to react to external disturbances in a manner similar to human beings results in their being called "smart" or "intelligent" structures.

Piezoelectric materials are the main candidates for active twist rotor because they can operate over a wide bandwidth of frequency and can be placed in a manner such that they are removed from the primary flight control path. The active twist concept using smart structures offers the advantages of IBC, requires lower actuator power, higher range of frequencies not necessarily linked to harmonic motions and eliminates the need for a hydraulic slip ring. Piezoelectric actuators can also be used to generate unsteady aerodynamic loads on the same time scale as caused by BVI.

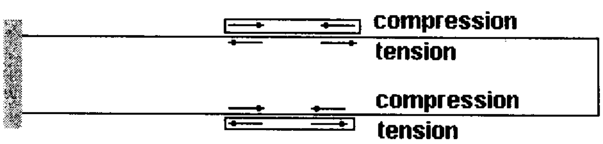

Fig. 1 Bending actuation on application of equal and opposite voltage

Literature Survey

The objective is to reduce the vibration or BVI noise in helicopter rotor blade using active twist approach; this approach has gained popularity over the past decade. There is substantial material available for the proof of this concept in the literature. The existing literature is classified into the following sections: (1) Early studies (2) Smart active blade tips (3) Active fiber composites (4) NASA/MIT/Army active twist rotor (5) Active composite beams and (6) Induced shear strain mechanisms. The classification is for convenience and there is overlap between these areas. Finally, we discuss some of the conclusions from the literature survey and identify areas requiring further research.

Early Studies

These studies are mostly experimental in nature with simple modeling and were undertaken to prove the concept of active twist control using piezoceramic materials. The key idea was to check if the required 1-2 degrees of twist needed for suppressing vibration dramatically could be obtained with minimum consumption of power. The first works in this area were published in 1996.

Chen and Chopra [24] built a Froude-scale model rotor and concurrently developed an analytical model to predict the behavior of the rotor blades with embedded piezoceramic actuators. For this, a uniform strain theory was formulated to predict the static torsion and bending response of rectangular section beams and rotor blades, followed by experimental validation.

Experiments were conducted on a 1.83m diameter, $1/8^{th}$ Froude scale model of a two-bladed bearingless rotor. The blade cross-section was NACA 0012. Total blade length was 67.51cm from tip to root and chord was 7.62cm. Piezoceramic elements that were 11.5 mil thick were embedded under the fiberglass skin in banks of discrete actuators at angles of ± 45 degrees on the top and bottom (Fig.2). The first configuration had 55 pairs of actuators spaced 0.254 cm apart and the second configuration had 12 pairs of actuators spaced 3.81cm apart. Both these rotors were assessed in order to find out the optimum configuration in terms of piezoceramic actuators. Bending and extension were also discussed in this paper. An analytical model was developed for a beam and then applied to a rotor and the results were compared with experimental data.

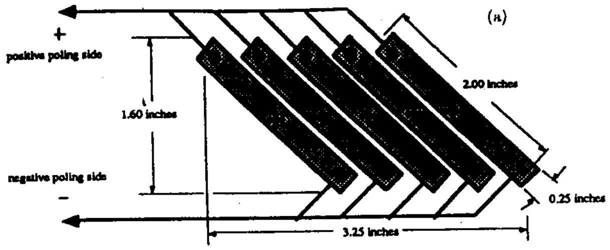

Fig. 2 Active plies oriented at 45 degrees

The first set had 80% more actuators than second set. It was observed that an increase in the number of torsion actuators resulted in increase in the torsion stiffness of rotor blade and the 'interference effect', which reduces the twist. However, reducing the number of actuators reduces the stiffness and increases the twist. Rotating response of the rotor blade was evaluated at various speeds with a Froude-scale operating speed of 900 rpm. The rotor collective was set at 4, 6 and 8 degrees and the piezoceramic actuators were actuated at 100 V rms to manipulate blade twist motion at -frequencies from 10-100 Hz. In general, the response was observed to decrease in amplitude with increasing rpm for all collectives.

Uniform strain theory correctly predicts the trends of the torsion and bending responses of the rectangular beam specimens, except that it shows discrepancy at very high voltage. This theory was able to predict static torsion response with an accuracy of approximately 80 percent. Blade testing showed that structural stiffness of the blade decreased as the actuator spacing was increased.

In [25, 26], the work done in [24] was extended and it was found that actuator geometric parameters have significant effect over structural properties and hence twist performance of the blades. Blade twist performances in static and rotating modes differ due to the presence of large external loads at high rpm. By generating new unsteady airloads, blade twist is capable of altering the aerodynamic characteristics of the rotor. *In this study (experiment) a blade twist 010.5 degrees was attained at 900 rpm with dual layer actuators*. But for viable vibration reduction, a blade tip twist of 1-2 degrees is required at 900 rpm. The twist achieved here being small, only partial reduction was possible. The maximum tip twist values at resonance frequencies (50Hz and 90 Hz) were 0.35° and 1.1° respectively. At non-resonance frequencies, the response was less than 0.5° at 4/rev excitation.

In another study in 1996, Derham and Hagood [27] used smart materials to achieve main spar twist. This method is called Inter-Digitated Electrode Piezoelectric in Fiber Composite (IDEPFC), and was jointly applied by MIT and Boeing to rotor blades (Fig.3). It uses active materials embedded in the composite plies of rotor blades actuated through applied electric fields. Active twist for a 1/6th Mach scale CH-47 rotor blade was demonstrated and a preliminary design for a 1/6 scale active twist blade was presented (Fig. 4). Blades were made of composite materials and had a built in pre-twist of 12 degrees. The rotor was three bladed and fully articulated. Feasibility of applying this concept to rotorcraft was discussed in terms of performance including economic merit, weight and power consumption.

IDEPFC is a variation on traditional PFC (peizo-fiber composites). These incorporate active material fibers in a composite ply lay-up. The PFC's are actuated by digitated electrodes and hence are known as IDEPFC. A structural analysis was performed to assess the structural integrity of this active blade configuration and strength parameters were calculated. Design loads consistent with full-scale blade requirements and practices, including the effects of added actuator mass and inertias were developed using Boeing's TECH-01rotor aeroelastic analysis. TECH-01 is

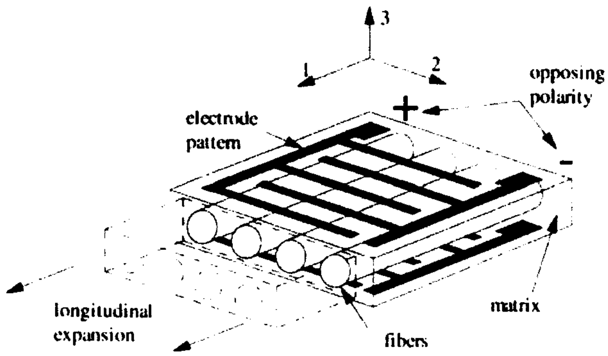

Fig. 3 Interdigitated Piezo Fiber Composites (IDEPFC)

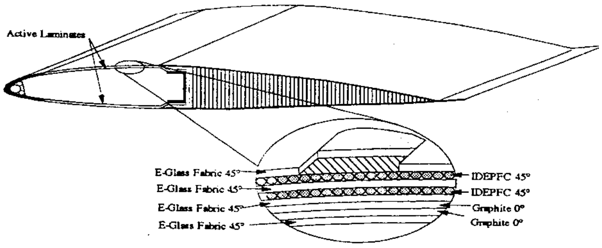

Fig. 4 Structural layout of 1/6 scale active twist blade

a comprehensive rotor analysis considering unsteady aerodynamic forcing and associated elastic blade response caused by the complex flow and wake patterns around a rotor in edgewise flight.

A 1/16 Froude-scale CH-47 helicopter blade was manufactured with IDEPFC actuators embedded. The blade was bench tested for twist actuation performance to verify both an MIT developed mathematical model for predicting actuator performance and the manufacturing process for active blades. Predictions for the actuated torsional capabilities of the 1/6 Mach scale blade were made using the model that was correlated to the 1/16 Froude scale experiment. It was observed that 3/rev and 4/rev induced twist had the greatest impact on 3/rev vertical shear. *A 70% reduction in vibratory vertical shear was achieved over the baseline (no actuation) case with a penalty of 2.5% in required power*. A 40% reduction was obtained with a 2/rev actuator without a penalty in power.

The main conclusion from [27] was that substantial vibration reduction could be obtained using the active twist concept. But, the studies by Chen and Chopra [24-26] found that the amount of twist generated was not sufficiently high with current day actuators to completely suppress vibration.

Smart Active Blade Tips (SABT)

Bernhard and Chopra [28] worked on the development of an active on-blade vibration-reduction system using smart active blade tips (SABT), which are driven by piezo-induced, bending-torsion coupled actuator (Fig. 5). The beam was designed specifically to fit within the rotor blade profile and was essentially used as a pure torsional actuator. The actuator was located lengthwise in the box-beam cavity and was supported only at the root and at the tip of the main blade. The inboard end is directly mounted on the blade root and the outboard end is connected to the SABT via a shaft, supported in a radial bearing. The bearing is capable of carrying lift, drag, flapwise and chordwise bending moments of the blade tip whereas the centrifugal and torsional loads were transferred to the actuator beam. Beam layup was selected as [-45, 0, 45]. The actuator beam applied a torque at the tip, which thereby induced the blade to twist. By actively pitching the tips, new unsteady airloads were generated. Correctly phased, they could be used to reduce the dynamic rotor hub shears and moments. The advantage here is that the large centrifugal force imposed by the moving tip on the beam is eliminated, improving the twist performance. The

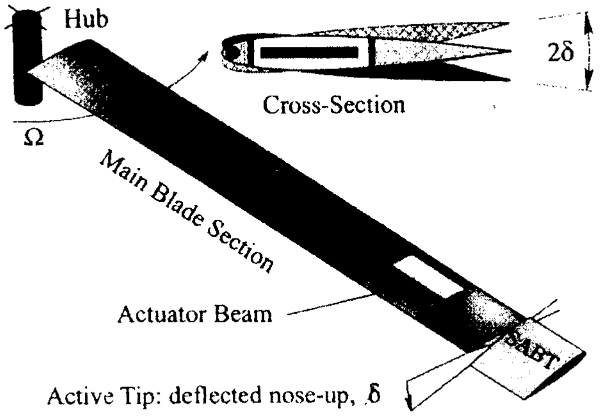

Fig. 5 Smart Active Blade Tip (SABT)

span-wise segments were differentially energized such that, the induced-strain bending curvatures cancelled out, while the induced-strain twist curvatures added up to a net tip rotation.

These SABT have distinct advantages at the expense of a few drawbacks. First, the entire blade can be used for actuation. The required twist can be achieved without any amplification mechanisms. Second, the need for the tip thrust beam is eliminated via the actuator beam. Third, the moving tip is hinged at the aerodynamic center to minimize the pitching moments. For analysis, an extension of the induced-strain composite-beam model presented by Chandra and Chopra [29] was used. This was based on Vlasov-theory [30], in which the structure is modeled in two phases. First, on the local cross-sectional level, a two-dimensional (thin walled) plate-analysis was used. Second, this was reduced to a global one-dimensional bar analysis, using principle of virtual work. The fabrication of these SABT blades was carried out at the Maryland rotorcraft center for a 1/8th Froude scale bearingless rotor hub. The nominal diameter was 1.83 m with a root cutout of 31% and a nominal operating speed of 817 rpm. The main rotor blade was a rectangular, untwisted NACA 0012 blade, with a 76.2 mm chord. Structural integrity tests, non-rotating tests and hover tests were performed on this rotor.

The rotating twist amplitudes with SABT are similar to tip twist amplitudes reported by Chen and Chopra [24]. However, in this case, the blade twist is achieved with half the power, because the actuator beam used a surface area of 206.45 cm^2 of 0.0254 cm thick PZT-5H elements, compared to the 412.90 cm^2 of 0.0254 cm PZT-5H used by Chen and Chopra [25]. It is to be noted that the SABT blades were 25% heavier then the blades used in Reference [24]. Hover, tests at 875 rpm produced blade twist results from 0.30 at 1/rev through 0.50 at 5/rev excitation frequencies.

In another paper [31], a Vlasov based bar analysis was used to derive a specialized, computationally efficient, one dimensional finite element, to model non-rotating actuator beam. This was a two-node, 12 degree-of-freedom element with bending, torsion and in-and out-of-plane warping degrees of freedom and induced strain capability. Results obtained by FEM were validated by experiments for two cases. Good correlation was obtained with experimental data. In one case, a reverse bending region was observed between the plate cantilever root and the first bank of piezo actuators. This was captured in the analysis with the help of specialized continuous in-plane warping mode. The predicted dynamic blade-tip pitch deflection was approximately 10-20% below the measured values. Later, a Mach-scale active twist rotor was fabricated [32] and tested with the above mentioned SABT. This suggested that the concept to be capable of achieving twist distribution throughout the blade.

While the SABT concept was demonstrated by wind tunnel tests and Mach scale models, tip twist amplitudes were similar to those obtained by Chen and Chopra [24] and below the 2 degrees needed for full vibration suppression. The primary disadvantage of SABT is that this is a localized active system, consulting a single-input single-output control devise. In contrast, distributed active blade systems, such as multiple trailing edge flaps, offer a greater flexibility for simultaneously achieving vibration and noise reduction.

Active Fiber Composites (AFC)

The objective of the study by Rodgers and Hagood [33] was to develop an integral twist-actuated rotor blade for helicopter individual blade control. Active fiber composites (AFC) are integrated within a composite rotor blade to induce a twisting moment. AFC are active plies oriented at a 45 degree angle to the blade span in order to induce shear stresses and a distributed twisting moment along the blade. They consist of a laminated structure of fiberglass plies and PZT-fiber plies. The PZT-fiber plies have continuous, aligned, PZT-fibers in an epoxy layer, and polymid/copper electrode films. The electrode films are etched into an inter-digitated pattern that affects the electric field along the fiber direction, thus activating the primary d_{33} piezoelectric effect. The AFC has a number of advantages; it is a conformable actuator, which could be integrated with a passive structure. The actuators are distributed throughout the structure providing redundancy in operation. The active blade requires no articulating components, thus eliminating the need of amplification mechanisms and does not increase the profile drag of the blade like servo-flap actuators.

Design, manufacture and testing of this rotor were investigated thoroughly in [34]. A $1/6^{th}$ Mach-scale CH-47D blade was designed, fabricated and tested in a hover test stand facility. The span of the blade was 153.97 cm and the chord was 13.68 cm. The blade was used on a fully articulated hub. The blade had a built-in linear twist of 12 degrees and taper of a VR7 airfoil at 0.85R to a VR8 airfoil at the tip. A configuration with three diagonally placed active plies in the spar laminate was selected for the integral blade. These active plies were uniformly distributed between 0.27R and 0.95R and were divided into 7 spanwise AFC segments. Activation of the diagonally placed fibers induced shear in the spar skin, which generated blade twist. *Bench tests performed at frequencies up to 67.5 Hz demonstrated that a maximum twist of 1 to 1.5 degrees peak-to-peak (± 0.5 - ± 0.75° amplitude) could be obtained*. However, full span sections resulted in a twist performance relatively below design targets. But half-span sections successfully demonstrated twist at full authority. Moreover, excellent correlation with model predictions was achieved. Even with the reduced twist, the hub load generation at all blade loading conditions and rotor speeds was consistent and near predicted levels, suggesting that the integral twist actuation concept is feasible and worthy of further investigation.

The studies in [33-34] proved the feasibility of the active twist rotor concept when active fiber composites were used. In general, AFC are much less fragile compared to monolith piezoelectric patches and can be more easily implemented into practical structures. However, the AFC's are more difficult to manufacture and much more costly than equivalent monoliths.

NASA/Army/MIT Active Twist Rotor

The so-called NASA/Army/MIT Active Twist Rotor (ATR) is the most ambitious project in the area and has lead to several publications. This work [34-35] uses the active fiber composites for actively twisting the blades using both analytical simulations and wind tunnel tests. Wilbur et. al [35] describe aeroelastic-modeling procedures and use them in the design of a piezoelectric controllable twist helicopter model rotor for wind tunnel testing. Two numerical active twist rotor approaches were developed. First, a code named PETRA (Piezoelectric Twist Rotor Analysis) was developed and was specifically intended for fundamental studies of active twist rotor designs with embedded actuators. The code PETRA was used for control law and design optimization studies. The blade equations were simplified to a linear out-of-plane bending-torsion model by using an ordering scheme. A sectional analysis was used to determine the blade structural properties and piezoelectric terms. The resulting piezoelectric terms were applied to the right hand side of the final equation of motion as a force term along with all aerodynamic forcing terms. The aerodynamic loads were derived using strip theory and a finite-state unsteady aerodynamics formulation, which includes the ONERA model of dynamic stall. A uniform inflow model, with a linear variation across the rotor disk in forward flight was used.

The second approach is based on the CAMRAD II comprehensive rotor analysis package, which can be used for more detailed analytical studies [36]. The commercially available CAMRAD II software package has more extensive rotorcraft modeling capabilities. *Forward flight simulations using CAMRAD II indicate that large reductions in 4P vertical hub shear may be achievable with significantly less than the maximum twist actuation authority of the active twist rotor*. However, it should be noted that [35] modeled the smart structure using applied loads and the piezostructure was not included in the aeroelastic equations through constitutive relations.

In another study by the same group [37], a four-bladed, aeroelastically scaled, active twist rotor (ATR) model was designed and fabricated to be tested in the heavy gas medium of a transonic wind tunnel. Active fiber composites (AFC) were utilized in fabricating the rotor blades. Each ATR blade consisted of 24 active fiber composite (AFC) actuators to implement the active twist control. The AFC's were placed in four layers through the thickness of the blades and were oriented such that the active strain is applied at ±45 degrees relative to the blade spanwise axis to permit maximum torsional control on the blades. They were actuated using separate high-voltage, low-current power channels for each blade, The pretwist was linear with a twist of -10º from the center of rotation to the blade tip. NACA-0012 airfoil section was used. Hover testing was conducted to determine the basic frequency response characteristics of the ATR blades under active twist control. Tests were carried out for a wide range of frequencies. In forward flight tests, both low (μ=0.14) and high (μ=0.333) advance ratio cases were considered. Results show that for both low and high-speed forward flight, active control was capable of generating significant variations in both rotating and fixed system loads, and that large reductions in fixed-system vibratory loads were achievable. *Both rotating and fixed system loads could be dramatically affected by changes in active twist control phase and a reduction in fixed-system loads of 60-95% was obtained*. An active twist control frequency of 3P was found to be most effective in reducing fixed-system loads for both the low-speed and high-speed conditions. *Active twist amplitudes of 1.1º to 1.4º were obtained for 3P to 5P twist actuation, with 1000V*. Although the 4P blade loads were reduced using 4P active twist control, there was a significant increase in the 4P pitch link loads, tending to counter the affect in the fixed-system. The power necessary to operate the four ATR blades is, at most, less than 0.9% of the maximum rotor power required during testing.

In [38], acoustic aspects of the ATR blade were studied and it was found that the largest BVI noise reduction was provided by 5P control inputs. For rotor operating conditions where BVI noise is dominant, active twist control provided a reduction in BVI noise of about 3dB. However, the operating conditions for minimum BVI noise lead to an increase in low frequency noise of upto 7dB and also adversely affected vibration levels. In general, these studies showed that there was a tradeoff between BVI noise, low frequency noise and vibration levels which need to be addressed during design of an active twist rotor. Recently, a review regarding the rotorcraft investigation in the Langley Transonic Dynamics Tunnel which summarizes some of the wind tunnel test results conducted on the active twist rotor was published [39].

In another work, Shin et. al [40] describes system identification and closed loop control of the ATR system. They found that the ATR rotor system could be treated as linear and time invariant and the periodic effects can be neglected. For the ATR rotor, it was also found that the transfer functions did not vary much for level flight conditions. Therefore, a single control law could be used to effectively control the rotor over a wide range of advance ratios. The closed loop control tests were performed using the T-matrix approach recast as a continuous time formulation. The objective was to reduce the 4/rev normal shear. The collective mode of blade actuation was found to be useful for controlling 1/rev vibrations due to rotor tracking and was less effective for hub normal shear, whereas effect of cyclic actuation was found to be much more. For closed loop analysis vibration at each time step was measured and fed back through the control law to adjust the swashplate input to cancel the vibration. Different gain constants were investigated. Since it is possible for the controller signal to exceed the voltage limit of individual actuators, an anti-windup mechanism was added to each feedback structure. *Results showed that in some flight conditions, 4P vibration was almost eliminated (40 db reduction).* The other components of the fixed system loads at 4/rev were also reduced, except for the negligible change in yawing moment.

The studies [35-40] clearly show the potential of active fiber composites in helicopter vibration reduction. The wind tunnel results with heavy gas medium allow the matching of full scale Mach number leading to more realistic results. Studies also showed that considerable vibrations could be obtained even if tip twists were less than the target 1.5-2 degrees.

Smart Composite Rotor Modeling

The studies discussed until now were more focused towards experiments and limited in terms of modeling. Addressing this issue, some researchers discussed detailed modeling of smart composite rotors. Chattopadhyay et. al [41] presented numerical results for a four-bladed bearingless model rotor with self-sensing piezoelectric actuators mounted at 45 degrees on the top and bottom walls of the composite box-beam blade. The composite box beam consisted of Graphite/epoxy in stacking sequence of $[-45/45]_{2S}$ in horizontal walls and $[45]_8$ in vertical walls. The box-beam dimensions were: length = 7.92m, width = 0.18m and height = 0.05m. The thickness of PZT was 0.196 mm and the blade had a rectangular planform with a linear twist of -10 deg.

First, a comprehensive ana1ysis technique was developed for the analysis of rotor dynamic loads using a composite rotor blade built around an active box beam. Second, the model was used to investigate reduction in hub dynamic loads using closed-loop control. A higher order theory based approach was used to model the smart composite beam [42]. In this theory, higher order displacement field was developed to model the individual walls of arbitrary thickness, in the presence of eccentricity (Fig. 6). The theory approximates the elasticity solution so that the beam cross-sectional properties are not reduced to one-dimensional beam parameters. It considers inplane and out-of-plane warping. Because the relationships between the induced strain due to actuation and the applied electric field are nonlinear at high voltages, the formulation in-

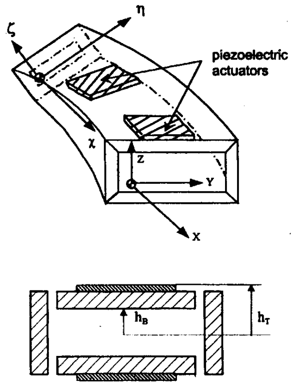

Fig. 6 Modelling composite plate with eccentricity

cludes these nonlinear induced strain effects. For the rotor analysis, an unsteady aerodynamic model was coupled with a rotor blade dynamic model to develop an integrated rotor vibratory load analysis procedure. The rotor dynamic analysis accounted for deformations in the flap, lag and torsion directions. A finite-state induced flow model was used for predicting the aerodynamic loads. The 4P dynamic forces and moment at rotor hub were calculated in forward flight. Parametric studies were also done to assess the influence of number and location of actuators on the vibratory load reduction at the hub.

Strain rate feedback was used for structural vibration control. The feedback actuator voltage was defined with the help of the current developed from the electric charge. A finite element formulation was used to implement the coupled theory. After the induced-velocity coefficients were obtained, the aerodynamic, inertial, and centrifugal forces along the blade span were integrated to calculate the rotor vibratory loads.

For maximum efficiency, the distribution of the actuator locations must be closely related to the region of high strain rate of the vibration modes. Elements 1 (root area where maximum strain rate occurs) and 5 represent optimal actuator locations for the control of the second flapping mode and elements 1, 3, 4, 9 and 10 (Fig.7) represent the most effective locations for the third flapping mode. Because seven modes are involved in the rotor loads analysis, it was difficult to predict the optimal locations of the actuators for the control of all hub loads. Thus, two different cases were studied here. First configuration involved 10 pairs of self-sensing PZT actuators surface bonded to the horizontal walls of the box beam (elements 1-10) and the second configuration involved 4 pairs of self-sensing PZT actuators placed on elements 1, 3, 5 and 7. Blade natural frequencies were calculated for both the

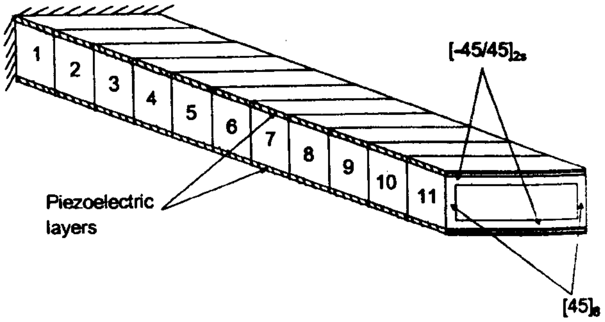

Fig. 7 Composite box beam configuration

configurations. Differences were observed in the modal frequencies and mode shapes of both the configurations, because of the variation in stiffness, arising due to the different number of actuators in both cases.

Significant reductions were observed in all hub forces and moments using active control. *A reduction in vertical shear force of about 50 percent was achieved.* In general, among all six dynamic hub loads, the pitching moment and the rolling moment contribute most significantly to vehicle vibration. *A reduction of about 33% was obtained in the pitching moment and 30% in the rolling moment*. On comparing both the configurations, a reduction of about 50% in vertical shear force was achieved in the first configuration (10 pairs) and about 30% in the second configuration (4 pairs). The power consumed was found to be 60% lower in the second configuration. This indicated the existence of a nonlinear tradeoff between actuator power and vibration reduction.

In another set of important studies on smart composite rotors, Cesnik and Shin [43] performed detailed modeling of the active twist rotors with active fiber composites. The analysis was based on an asymptotic formulation for the two-cell thin-walled anisotropic active beam [43, 44]. This formulation stems from shell theory, and the displacement field (including out-of-plane warping) is not assumed a priori, but results from an asymptotical approach. It was observed in case of two celled box beams that increasing the stiffness in the active members always decreased the actuation. Two cases were analyzed (Fig. 8); one had a symmetric distribution of active layers (top and bottom) and other had an asymmetric distribution. For the asymmetric distribution; adding passive stiffness at wall 3 decreased the twist actuation, which supports the common view that twist actuation will decrease with an increase in torsional stiffness. A change in the stiffness of wall 2 did not affect the twist actuation. However, by adding passive stiffness at wall 1, the twist actuation was found to increase. But, for symmetric distribution, twist actuation was found to be insensitive to the change in stiffness in walls 1,2 and 3. For both these cases, significant coupling of active and passive components between both cells was seen. This coupling was noted to diminish for a single- ell section. Hence, the behavior in case of two-cell was complex and more realistic than of single cell because of coupling effects. To illustrate this, two possible single-cell derivatives of the real airfoil-shaped beam were considered. One is the configuration in which trailing edge (fairing) was of very low or zero stiffness, which is known as D-spar single-cell beam. The other possible model is one without web, and it is simply called the outer-shell beam. It was observed that in none of these cases, comparable results with a full (two-section) model were obtained. Either over-or under-prediction was observed in these cases. By adding plies at the nose and the web, the twist actuation increases, while it decreases when the passive plies are added at the active region and fairing. The torsional stiffness was proportional to the variation in the wall thickness and the bulk active twist moment increased on increasing the stiffness in walls, except in the active regions.

In case of a more representative two-cell active beam with a NACA 0012 airfoil-shape cross- section (Fig. 9), active regions were the front spar skins with embedded AFC layers, and all other parts of the blade were passive. An electric field of 1.795 MV /mm was applied in all cases. By adding or removing E-glass plies at each region of the cross-section, the stiffness was varied and a parametric

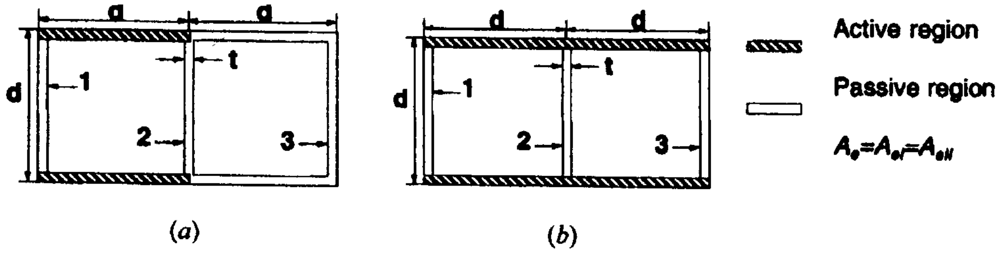

Fig. 8 Configuration of two cell box beams: (a) asymmetric case (b) symmetric case

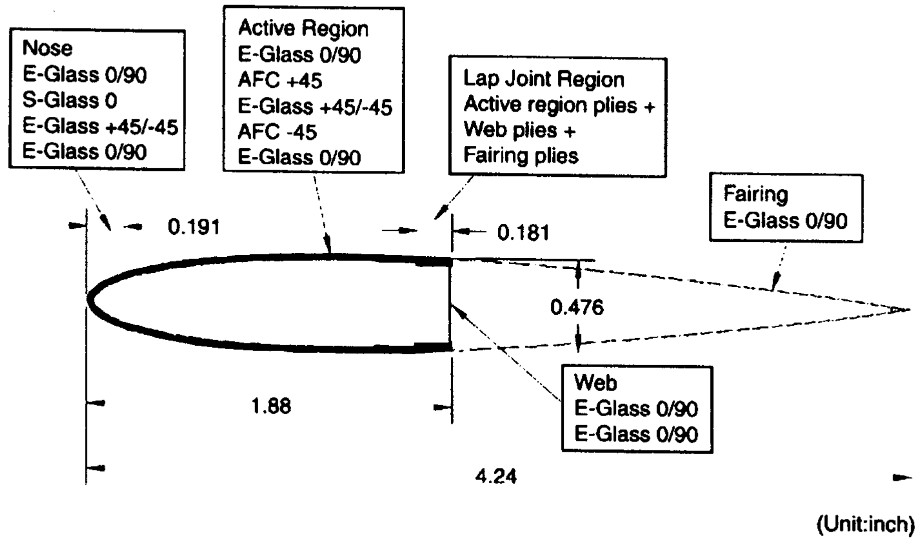

Fig. 9 Configuration of a two-cell airfoil shape beam

study was performed. They found that there was a possibility of obtaining an increase in twist actuation in the two-cell model, on adding passive plies at regions other than the active one (web and nose).

An important conclusion of the study [43-44] was that the net change in twist actuation in the two- cell active beam depends. on the local stiffness variation in the active or passive region. Conventional design belief that torsional stiffness must be reduced to increase twist actuation was not found to be true. It was shown that torsional stiffness can be increased up to 20% with an increase in twist actuation of about 5%. The authors mention that the single-cell cross-section model is incapable of capturing the interaction between active and non-active cross-sectional walls and hence is insufficient to predict the performance of multi-cell beams.

In another paper, Cesnik et. al [45] have investigated dynamic characteristics of active twist rotor (ATR) blades analytically and experimentally. This paper presents a general framework to analyze and design active composite blades with distributed anisotropic piezoelectric strain actuators, investigates the frequency of an active twist rotor blade for both non-rotating and rotating conditions and then correlates the theoretical model with experiments on the bench and under hover conditions. AFC's were used to obtain the required actuation in the experimental model. This experimental model is discussed in [35, 36]. Overall, the active model was found to be in good agreement with the experiments and therefore could be used to design and analyze future active helicopter blade systems.

In another study, Buter and Breitback [46] investigated the active twist concept using an actively controlled tension-torsion-coupling of the structure at the DLR (German Aerospace Laboratory). Tension-torsion coupling is an anisotropic behavior which appears in structural components. It can be realized by properly orienting the blade stiffnesses. The anisotropic material behavior has to be separated from the anisotropic structural behavior resulting from structural elements like ribs or stringers. The actuator was integrated inside a composite helicopter rotor blade. The rotor blade was represented by a tension-torsion coupled thin-walled rectangular beam similar to the BOI05 model rotor with a scaling factor of 2.54. A piezoelectric stack actuator was found to be suitable for twisting the blade and a deformation of $\pm$ 1.5 degrees was achieved. However, a disadvantage of the actuator was the high spanwise stiffness of the rotor blade spar. The adaptive twist was achieved using only the outer part of the blade resulting in a comparatively small control effect. An advantage of the actuation at only the outer part of the rotor blade was that the aerodynamic forces were the largest at that location and it was possible to compensate disturbances induced by the flowfield. The active use of blade deflections also allows the possibility of reducing dynamic stall at the retreating blade.

Kube and Kloppel [47] discuss the role of predictive computer programs for the development of smart helicopter rotor. Accurate aeroelastic simulations were suggested to speed up the development of an adaptive rotor system, since the number of design iterations during the development process needs to be minimized. The key contributions of this research project were (1) reduce rotor induced vibrations by 90 percent (2) reduce BVI noise by 6 dB and (3) expand the helicopter flight envelope by 5 percent. A comprehensive analysis was developed with accurate modeling of the rotor dynamics, inflow field and aerodynamics. The code was validated with wind tunnel test data and unsteady Navier-Stokes simulations.

Vibrations can be reduced by means of higher harmonic blade twist variation with $N_b\Omega$, $(N_b-1)\Omega$, $(N_b+1)\Omega$ frequencies where N_b is the number of blades and Ω is the rotor rotational frequency. The BVI noise emissions are best reduced by means of a blade twist variation with 2P inputs. Also, the rotor efficiency and blade track can be optimized by adjusting the steady part of the blade twist. The tension-torsion coupling method discussed in detail in [46] was used and realized using a helical winding in the blade skin. Laboratory experiments showed that a twist of at least I degree was realizable at the blade tip for a Mach scaled rotor with piezoelectric actuators. The actuator mass was 12 percent of the blade mass and was driven with an electric field of approximately 200V. The BO105 helicopter was equipped with an IBC system and noise was measured at the ground level and on the landing gear. Results showed that BVI noise can be reduced by up to 6dB using 2P forcing [48-50]. However, these studies with IBC did not use smart material actuators.

In another study, Ghiringelli et. al [51] developed an analytical procedure for modeling of an active twist helicopter rotor using active fiber composites. The rotor blade was twisted using induced- strain actuators distributed into the structure of the blade. Active fiber components made of piezoelectric fibers actuated by inter digitated electrodes (IDE) was used. Fiberglass was used for the outer skin and also placed between the piezoelectric plies. Unidirectional graphite epoxy (T900) was used for the inner part of the spar. The elastic, inertial and piezoelectric properties of the blade section were determined by a dedicated semi analytical formulation. A 4-bladed, articulated rotor was studied in hover and forward flight. The model was an analytical benchmark full-scale rotor based on Ref.[52] and is representative of a large class of medium weight helicopter rotors. Frequencies of the simulations were matched with the experimental frequencies. The aeroelastic anafysis was conducted using a multibody formulation. The multibody dynamics approach accounts for the possibility of large rotations, nonlinear aeroelastic behavior or non-uniform rotation speeds. The rotor blades were modeled as finite volume beam elements [53] subject to large displacements and rotations. Strip theory with dynamic stall, radial flow and Mach number correction factor was used along with dynamic inflow modeling [45]. This approach allows a detailed analysis of the kinematics and dynamics of rotorcraft avoiding any undue approximation in the kinematics of the system, and with the same order of refinement of a finite element model in the description of flexibility with reasonable and acceptable computational cost. However, the aerodynamic model used in this study was not as sophisticated as the structural one. An induced tip twist of 2 degrees in the range of $0\text{-}5\Omega$ is achieved. Open loop results showed good possibility for vibration reduction.

The above studies show improved modeling capabilities for the smart composite structure to predict the behavior of active twist rotor blades. The analytical methods provide a way to conduct parametric studies on actuator placement and on the design of the rotor cross section for obtaining maximum twist actuation. The analyses also allow the development of control algorithms. The studies also show the use of monoliths [41-42] placed at 45 degrees on the top and bottom of the box-beam, AFC's [43-45, 51] and stack actuators [46-47]. However, it should be noted that the active twist rotor requires a complete redesign of the rotor system, with corresponding complications due to the need to resolve stability, stress analysis, certification and other issues. According to Kube and Kloppel [47], active twist using smart materials is a research concept and it will be some time before it is feasible for practical implementation.

Blade Vortex Interaction Noise Reduction

Some studies have addressed BVI noise using IBC concept [48-50]. However, the only study addressing BVI noise using smart active twist rotor appears to be that by Chen et. al [55] and the work discussed earlier in [38]. A linearized unsteady aerodynamics model was derived from aeroacoustics predictions and validated with CFD analysis. Three control points were selected on the blade at 65, 80 and 95 percent of the blade span. The unsteady loading was minimized at the given control points. Noise reductions of 2-4 dB were predicted for strong, close blade vortex interactions and 7-10 dB for weaker interactions. However, they found that complete unsteady loading suppression was not possible with current technology due to large stroke and high frequency actuation required. The authors [55] mention that the development of smart materials such as single crystal piezoceramics which have an order of magnitude of higher stroke capability than present day materials is likely to result in the capability to almost completely eliminate BVI noise. Furthermore, there is a need to develop actuator control strategies based on open or closed loop pressure feedback which need to be investigated for realistic implementation. Chen [55] also points out the problems of cost and manufacturing difficulties with active fiber composites and the limits of current day smart materials in terms of stroke.

Induced Shear Mechanisms

All the studies discussed until now used the direct strain coefficients d_{31} or d_{33} piezoelectric coefficients. To achieve twist, poling is done in the length direction and voltage is applied in the perpendicular direction. It is very similar to the concept of bending actuation, except for the poling direction, which results into producing a twist.

Smith [56] analytically evaluated an induced shear piezoelectric tube as an active blade twist actuator. This induced shear actuator had already been investigated for trailing edge flap models; an effort for developing an active twist rotor was being pursued in this study. A finite element model of the induced shear actuator and rotor blade was used to guide the design of the tube actuator for both small scale and full-scale rotor blade applications. The performance of the induced shear actuator was then compared to NASA/Army/MIT Active Twist Rotor.

One advantage of using shear strain in a piezoelectric actuator is that the piezoelectric coefficient for shear is higher in magnitude than that for bending or axial. In addition, in the design aspects, unlike the trailing edge flap and active tip blade applications, amplification mechanism is not required for active twist rotor. One end of the actuator tube is clamped to a rib in the rotor blade while the other end of the tube actuator is attached to the rotor blade tip. A pre-compressive load must be applied to the tube actuator to alleviate any tension loading due to centrifugal effects. Possible chord-wise locations of the active blade twist actuator include the leading edge of the blade and the 25 percent chord location in the D-spar cavity. The leading-edge placement was desirable because this will allow the replacement of the inactive leading-edge weights with active leading-edge weights. Placement at 25 percent chord was also desirable because it allows for the most range in the tube radius design and will not shift the blade center of mass location. The twist performance of both these actuators was analyzed and compared.

A torsion finite element model of the rotor blade and induced shear actuator was developed using Lagrange's equation to predict the blade twist angle distribution. Boundary conditions were such that the tube actuator twist is zero at the actuator clamping near the blade root. It was assumed that there was no blade twist at the root and blade twist and tube twist were equal at the tip. Both full-scale and small-scale applications were investigated. Location at 25 percent chord was found to be more suitable than the leading edge location as the actuator torque is a function of the tube radius to the fourth power, while the tube twist is related to the tube radius to the first power. Thus, the drop of torque is more significant than the increase in twist that results from shifting the actuator to the leading edge. A full scale active twist tube actuator was designed with a weight of 1.36 kg (5 percent rotor blade mass penalty) and a maximum tube radius of 0.89 cm when placed at 25 percent chord location. In case of a small-scale active twist rotor the weight of the tube actuator was 0.23 kg and a maximum tube radius of 0.635 cm. The tube was subjected to an electric field of 4 kV/cm.

The induced shear tube actuator runs across 33 percent of the blade span while the active fiber packs are embedded from 30 percent to 98 percent radius location. The shear tube actuator has the benefit of generating the blade twist at a lower applied voltage level when compared to AFC. The shear tube actuator has an advantage of being discrete, while the active fiber design requires to be embedded in the rotor blade airfoil skin. Moreover, a discrete actuator is more accessible for maintenance, inspection, and replacement than an actuator embedded in the airfoil skin. One drawback of the tube actuator is the larger (approximately 1.13 kg) added weight compared to AFC (approximately 0.127 kg). A key result of this study was that the finite element analysis indicated that a 121.92 cm long tube actuator generates a tip twist of $\pm 1.1^{o}$ in a full scale MD900 blade and a 45.72 cm long tube actuator generates a tip twist of $\pm 1.4^{o}$ for a small scale blade.

In a recent study, Thakkar and Ganguli [57] studied the dynamic behavior of rotating isotropic beams with surface bonded piezoceramic actuators both for bending and shear actuation. Hamilton's principle was used to derive the governing equations for a beam undergoing transverse bending, inplane bending, torsion and axial deformations. These equations were solved using finite element method in space and time domain. Results were obtained for bending and shear actuation in case of rotating beams with pretwist and with added periodic tip loads.

The main aim was to obtain twist in the beams and thereby in the helicopter rotor blades. Thus, a proof of concept type study was done on rotating beams for d_{15} based shear actuation before the investigation in the field of rotor blades. In the case of beams, 2.66 degrees of twist was obtained at non-rotating level and 0.35 degrees at 100 Hz. It was found that even at very high rotating speeds, bending deflection was reducing to zero but a considerable amount of twist was still obtained.

Further, in another study [58], an extension of thIs concept was carried out for investigating vibration reduction in helicopter rotor blades using shear based actuation mechanism. The model used for numerical analysis was a two-cell box section and had outer dimensions of 165.1 x 37.0 mm (Fig.10). Piezoceramic actuators were surface bonded on top and bottom of the host material. For this configuration smart and non-smart terms in the derivation are identified and their optimum use was shown. The objective was to create a torsional moment with the help of d_{15} based shear actuation mechanism on the rotor blade and ultimately generate new unsteady airloads which can reduce the original vibratory hub loads when properly phased. For numerical results a four-bladed soft-inplane hingeless rotor was selected. Numerical results were obtained in forward flight condition at an advance ratio of 0.3. A parametric study was done over the objective function for 3, 4 and 5/rev vibratory loads. The applied voltage was active and azimuthally varying. A maximum overall reduction of around 48 percent at a phase of 250 degrees was obtained (for a typical case) in the objective function, which was a measure of vibration reduction. *The 4/rev vibration was reduced by about 48 percent on applying a 4/rev cyclic load with a phase of 250 degrees.* A maximum reduction of 68 percent was obtained in pitching moment, among all other vibratory loads (Fig. 11).

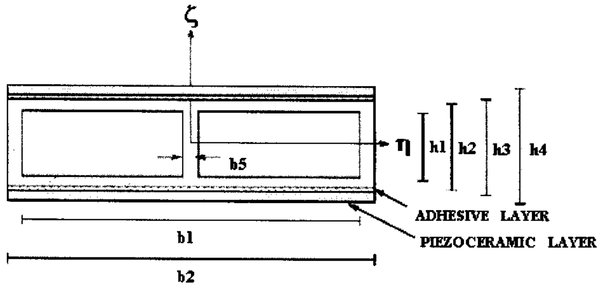

Fig. 10 Cross-section of a two-cell box beam

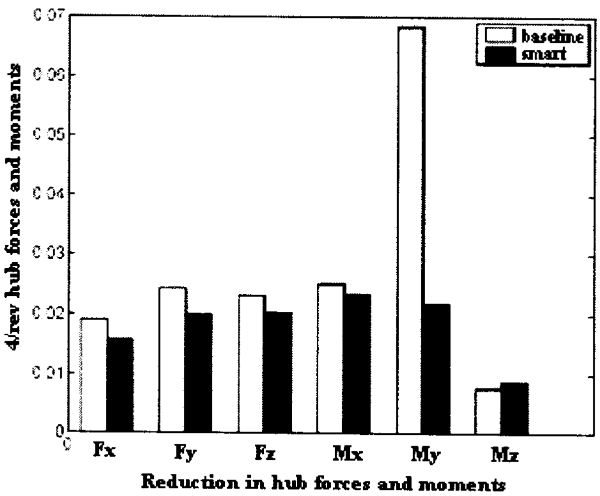

Fig. 11 Reduction in forces and moments at 4/rev at phase = 250°, normalised by rotor thrust

The studies [56-58] show the possible use of induced shear actuation for the active twist rotor. The piezoelectric coefficient d_{15} is larger than d_{31} and d_{33} and increases in a strongly nonlinear manner with increasing electric field leading to high induced strains. However, more research is needed in this area with a realistic airfoil section and experimental tests are needed to validate the concept.

Operational Issues

The main idea in the active twist rotor is to cause strain induced twist in a slender body such as the rotor blade by inducing shear strains in the beam sections that result in a global twisting of the structure. The most promising materials for such applications are piezoceramics which can be used either in embedded or surface mounted form. Embedded actuators have the advantage that they are not exposed to environmental degradation. However, it is difficult to monitor their condition in case of any problems. In contrast, surface mounted actuators are easy to install but can be damaged due to external effects. The active fiber composites have been widely used for active twist rotor design. While the piezo fiber composites are much less fragile than monoliths and are easier to embed in practical structures, they are also more difficult to manufacture and are also much more expensive than equivalent monoliths. Also, there are some issues for operational use of smart piezoceramics in aerospace structures that need to be addressed. First is the operational characteristic of piezoceramic materials in an actual helicopter setting that is subjected to considerable variation in loads, temperature, humidity and other environmental effects. In addition, damage mechanics, fracture and fatigue properties of piezoceramics need to be investigated, along with the damage phenomenon that may occur in such materials when they are bonded with or embedded with composite materials that are widely used in aerospace construction. Some studies in this area are given in [59-63].

Very little work has been .done on the structural integrity of smart materials and structures. However, a good knowledge of structural integrity is needed for peizoelectrics to be used in load bearing structures such as rotor blades, which are subjected to cyclic loads which can cause fatigue loading. Early studies looked at mechanical fatigue of inactive or passive piezoelectric materials or fatigue of structures with an embedded passive piezoelectric. Crawley and DeLuis [64] found that the ultimate strength of a graphite/epoxy laminate was reduced by 20 percent when a piezoceramic was embedded in the composite. These studies showed that the integrity of smart structures was affected by the insertion of sensors and actuators. Vizzini et. al [65] suggested an approach to reduce interlaminar stresses by distributing the discontinuity through the thickness.

The above studies involve inactive or inert embedded materials. Selected studies have looked at active embedded sensors and actuators for conditions where mechanical load and externally applied electric voltage are simultaneously applied, a condition known as electromechanical fatigue [66]. Such investigations are needed for helicopter rotors with active twist.

In presence of low electric fields and mechanical stresses, linear piezoelectric models can be used. Recent research suggests that the linear representation of piezoelectric strains with electric fields is not accurate at high electric fields [67-72]. Piezoelectric applications in helicopters involve severe loadings and complex geometries and the assumption of small signals may not be justified in many cases. This is especially true for the induced shear effects [70-71]. In general, greater actuation authority can be achieved by applying an electric field exceeding the limits of linear piezoelectric constitutive theories. Experimental results showing the nonlinear behavior of the piezoceramics have been obtained and need to be used in proper structural modeling. The nonlinear behavior of piezoceramics at higher voitages needs to be accounted for in modeling and control. The other nonlinear issue in piezoceramics is due to hysteresis [72-75]. Piezostack based actuators, for example, can undergo hysteresis which can cause problems in controller design if the hysteresis effects are not accounted for in the mathematical model. Hysteresis is a form of nonlinearity that is based on memory. There may be multiple possible outputs for a given input. Furthermore, the hysteresis present in the piezoelectric "d" constants is also present in the dielectric coefficients and therefore the capacitance. Unmodeled hysteresis can lead to inaccuracy in open loop control and can cause amplitude dependant phase shift and harmonic distortion that reduce the effect of feedback control. In summary, it is clear that nonlinear piezoelectric behavior shows hysteresis and rate effects, depends on the loading history and cannot be represented by simply adding some nonlinear terms to the constitutive models of linear piezoelectricity. Researchers have recently started addressing the issue of inclusion of the nonlinear electro-mechanical models into finite element codes and these types of models can be investigated for inclusion into aeroelastic analyses.

Another issue is the development of control algorithms that are suitable for implementation in a helicopter rotor, keeping in mind that helicopters operate in a highly noisy environment and the fidelity of helicopter models needs to be much improved. Most of the studies discussed in this paper use a open loop harmonic controller which is based on the premise that the BVI noise can be controlled by giving 2P actuation and the vibration can be controlled by giving 3P, 4P and 5P actuation to a 4-bladed rotor. The higher harmonic control methods use a linear transfer matrix that relates the higher harmonics of the control input to the harmonics of the vibratory hub loads. However, the performance of higher harmonic control methods deteriorates when nonlinearity is present or if the operating condition differs from those at which the sensitivity matrix was determined [76-78].

The HHC architectures do not use the fact that piezoceramics can be used as self-sensing actuators and therefore, strain rate feedback control strategies can be employed to obtain closed loop control systems which are more robust to disturbances. It is best to obtain the controller gains using a high fidelity simulation and an optimization procedure based on minimizing some metric such as vibration at the rotor hub or fuselage, or BVI noise. Furthermore, controllers devised using aeroelastic simulations should be fine tuned and gains recalculated using flight tests. Very few studies have looked at using feedback control in helicopters [79-80] or on the stability of closed loop controllers [81]. Since the helicopter system equations are periodic, Floquet theory for the stability analysis of periodic systems needs to be used [82].

A common aspect in the control design aspects discussed above is the need for a mathematical model. However, it is difficult to develop high fidelity models of helicopter dynamics because the physics of helicopter aerodynamics and aeroelasticity is not yet fully understood. There is a large uncertainty in the mathematical description of the helicopter plant and the exogenous inputs that affect its behavior. The H_∞ method of robust control provides a way to address this uncertainty.

Such techniques have been demonstrated for smart structures for disturbance rejection and robustness in the presence of variations in plant parameters [83]. Adaptive control is another approach in which the algorithm tunes its parameters based on online observation of the actual evolution of the system in response to control inputs. Adaptive methods are capable of correctly responding to changes in the dynamics of a system during its-lifetime resulting from damage or wear in the system or from changes in the environment. However, adaptive controllers need a highly structured characterization of uncertainty which can be difficult to obtain for a helicopter [69]. Neural networks have been studied to provide the additional structure which an adaptive controller needs to correctly compensate for poorly modeled systems. These applications have been recently demonstrated in smart structures [85-86] and helicopter dynamics problems [87].

Since the piezoelectrics draw power from the helicopter electrical system, models are needed for proper power prediction to help in design of the electrical system. The power consumption depends on the electrical characteristics of the PZT transducer, namely the capacitive and resistive behavior of the actuator, which in turn affects their power consumption characteristics [88-90]. A piezoelectric actuator can be treated as a capacitor with power losses. The actual energy dissipated in the capacitor is small. However, a large current is drawn from the power amplifier driving the capacitor leading to excessive heating. This requires bulky and inefficient circuitry which is problem in applications such as helicopters where compact smart systems with embedded electronics is desired and transfer of power from the fixed frame to the rotating frame puts serious restrictions on the slip ring unit. One approach suggested in [90] to reduce the current drawn from the amplifier is by using a tuned L-C oscillator circuit. For a typical helicopter application a physical inductor turns out to be very large. Therefore, a pseudo-inductor built using operational amplifiers has been proposed and shown to lead to a reduction in the current drawn from the amplifier.

Most commercially manufactured piezoceramic actuators are still low stroke and low force devices which limit the full potential of smart materials applications in aerospace. As mentioned in [1], an important goal for materials researchers is to increase displacement capability of smart material actuators by 300-500 percent. In addition, new smart materials such as single crystal piezoceramics and polymeric actuator materials have emerged that have a stroke of an order of magnitude larger than current piezoceramics [91-92]. These new materials are expected to greatly increase the applications of smart structures.

Concluding Remarks

The aim of the studies discussed above is to achieve higher harmonic twist in the entire blade so that new unsteady loads are generated which cancel existing loads and vibration reduction becomes achievable. From the above literature following major points can be noted:

1. Active twist is a feasible concept for helicopter vibration reduction and can be achieved by (a) Placing actuators at ±45º on top and bottom with proper spacing and dimensions (b) With smart active blade tips attached to the tip of the blade (c) Using active fiber composites (d) Using stack actuators and (e) Using induced shear actuators.

2. For a model rotor, vibration reduction has been reported up to 60-95 % with an active of twist 1º -1.5º. For a full-scale rotor (MD900), active twist of ±1.1º was obtainable.

3. A two-cell section is reported to be a realistic representation of a helicopter blade section. Using a single cell cross section can result in an inaccurate estimation of torsion stiffness, which plays a very important role in active twist control.

4. Magnitude of vibration reduction depends on the placement and number of actuators.

5. Open loop control results have been used in many studies and also for the experimental results. Closed loop control has been found to be feasible for vibration applications using model based approaehes. Recently, closed loop tests have also been conducted with good results. However, the close loop gains need to be fine tuned using experimental data.

6. The belief that reduction in torsion stiffness leads to increased twist actuation is not always true. Blade cross section can be designed such that the amount of twist obtained is maximized.

7. BVI noise reduction of as much as 6dB can be obtained using active twist as demonstrated through flight tests using 2P actuation. Other studies also show 5P actuation to be useful for BVI noise reduction. It appears difficult to simultaneously reduce BVI noise, low frequency noise and vibration.

8. Induced shear actuation is a useful concept for vibration reduction.

The above results show that several proof of concept type of studies has demonstrated the possibility of using smart materials for helicopter vibration reduction using active twist control. Efforts have been made to move from wind tunnel tests to flight tests. Selected studies have addressed the issues of improved modeling and analysis which can help in optimizing the blade configurations, actuator and sensor locations and design of control algorithms.

Finally, while one can be optimistic about the use of smart materials in aerospace applications, it is necessary to not get carried away by the hype, which surrounds any emergent technology. The key problems with active rotor control are cost, complexity, maintainability, safety and reliability. In addition, transferring power, either electrical or hydraulic, to the rotating system is difficult. In addition, many problems still remain in the successful *operational* use of smart structures. However, it is likely that with more research and development efforts of the engineering science community, smart structures. will reach the level of maturity that composite structures have today in aerospace applications and will lead to novel engineering designs.

References

1. Chopra, I., "Review of State of Art of Smart Structures and Integrated Systems", Journal of American Institute of Aeronautics and Astronautics, Vol.40, No.11, 2002, pp. 2145-2187.

2. Giurgiutiu, V., "Review of Smart Materials Actuation Solutions for Aeroelastic and Vibration Control", Journal of Intelligent Material Systems and Structures, Vol.11, No.11, 2000, pp. 525-544.

3. Loewy, R. G., "Recent Developments in Smart Structures with Aeronautical Applications", Smart Materials and Structures, Vol. 6, No.5, 1997, pp. 11-42.

4. Chopra, I., "Status of Application of Smart Structures Technology to Rotorcraft Systems", Journal of the American Helicopter Society, Vol. 45, No.4, 2000, pp. 228-252.

5. Irschik, H., "A Review on Static and Dynamic Shape Control of Structures by Piezoelectric Actuation", Engineering Structures, Vol. 24, No.1, 2002, pp. 5-11.

6. Valliappan, S. and Qi, K., "Review of Seismic Vibration Control Using Smart Materials", Structural Engineering and Mechanics, Vol. 11, No.6, 2000, pp. 617-636.

7. Trindade, A. M. and Benjeddou, A., "Hybrid Active-Passive Damping Treatments Using Viscoelastic and Piezoelectric Materials: Review and Assessment", Journal of Vibration Control, Vol. 8, No.6, 2002, pp. 699-745.

8. Kazanci, M., "A Review of Polymeric Smart Materials for bIomedical Applications", Materials Technology, Vol.18, No.2, 2003, pp. 87-93.

9. Damjanovic, D., "Ferroelectric, Dielectric and Piezo-Electric Properties of Ferroelectric Thin Films and Ceramics", Rep. Prog. Phys., Vol. 61, No.9, 1998, pp. 1267-1323.

10. Nguyen, K. and Chopra, I., "Application of Higher Harmonic Control to Rotors Operating at High Speed and Thrust", Journal of the American Helicopter Society, Vol. 35, No.3, 1990, pp.78- 89.

11. Johnson, W., "Self Tuning Regulators for Multicyclic Control of Helicopter Vibrations", NASA TP, 1996.

12. Davis, M. W., "Refinement and Evaluation of Helicopter Real-Time Self Adaptive Active Vibration Controller Algorithm", NASA Contractor Report 3821, 1984.

13. Molusis, J. A., Hammond, C. E. and Cline, J. M., "A Unified Approach to the Optimal Design of Adaptive and Gain Scheduled Controllers to Achieve Minimum Helicopter Rotor Vibration", Journal of the

American Helicopter Society, Vol. 28, No.2, 1983, pp. 9-18.

14. Hammond, C. E., "Wind Tunnel Results Showing Rotor Vibratory Loads Reduction Using Higher Harmonic Blade Pitch", Journal of the American Helicopter Society, Vol. 28, No. 1, 1983, pp. 10-15.

15. Wood, E. R., Powers, R. W., Cline, C. H. and Hammond C. E,."On Developing and Flight Testing a Higher Harmonic Control System", Journal of the American Helicopter Society, Vol. 30, No. 1, 1985, pp.3-20.

16. Shaw, J. and Albion, N., "Active Control of the Helicopter Rotor for Vibration Reduction", Journal of the American Helicopter Society, Vol. 26, No.3, 1981, pp. 32-39.

17. Shaw, J., Albion, N., Hanker, E. J. and Teal, R. S., "Higher Harmonic Control: Wind Tunnel Demonstration of Fully Effective Vibratory Hub Force Suppression", Journal of the American Helicopter Society, Vol. 34, No.1, 1989, pp. 14-25.

18. Richter, P., Eisbrecher, H. D. and Kloeppel, V., "Design and First Tests of Individual Blade Control Actuators", 16th European Rotorcraft Forum, Glasgow, UK, 1990.

19. Yu, Y. Y., Gmelin, B., Splettstoesser, W., Phillipe, J. J. and Prieur, T.F., "Brooks Reduction of Helicopter Blade-Vortex Interaction Noise by Active Rotor Control Technology", Progress in Aerospace Sciences, Vol. 33, Nos.9-10, 1997, pp. 647-687.

20. Muller, R. H. G., "The Influence of Winglets on Rotor Aerodynamics", Proceedings of the 12th European Rotorcraft Forum, Garmish-Parten Kirchen, Germany, 1986.

21. Desopper, A., Lafon, P. and Prieur, P. J., "Effect of Anhedral Sweptback Tip on the Performance of a Helicopter Rotor", Procedings of the 13th European Rotorcraft Forum, Arles, France, 1987.

22. Favier, D., Maresca, C., Berton, E. and Plantin de Hugues, P., "Investigation of Tip Shape Influence on the Flow Field Around Hovering Rotor Blades", Procedings of the 22nd AIAA Fluid Dynamics Conference, Honolulu, USA, 1991.

23. Broecklehurst, A. and Pike, A. C., "Reduction of BVI Noise Using a Vane Tip", American Helicopter Society Specialist Meeting, San Francisco, USA, 1994.

24. Chen, P. and Chopra, I., "Induced Strain Actuation of Composite Beams and Rotor Blades with Embedded Piezoceramic Elements", Smart Materials and Structures, Vol. 5, No.1, 1996, pp. 35- 48.

25. Chen, P. and Chopra, I., "Hover Testing of Smart rotor with Induced-Strain Actuation of Blade Twist", Journal of American Institute of Aeronautics and Astronautics, Vol. 35, No.1, 1997, pp. 6-16.

26. Chen, P. and Chopra, I., "Wind Tunnel Test of a Smart Rotor Model with Individual Blade Twist Control", Journal of Intelligent Material Systems and Structures, Vol. 8, No.5, 1997, pp. 414-423.

27. Derham, R. and Hagood, N., "Rotor Design Using Smart Materials to Actively Twist Blades", Presented at 52nd Annual Forum, American Helicopter Society, Washington DC, USA, 1996.

28. Bernhard, A. and Chopra, I., "Hover Testing of Active Rotor Blade-Tips Using a Piezo-Induced Bending-Torsion Coupled Beam", Journal of Intelligent Material Systems and Structures, Vol. 9, No.12, 1998, pp. 963-974.

29. Chandra, R. and Chopra, I., "Structural Modeling of Composite Beams with Induced Strain Actuations", Journal of American Institute of Aeronautics and Astronautics, Vol. 31, No.9, 1993, pp.1692-1701.

30. Vlasov, V., "Thin-Walled Elastic Beams", Wiley-Interscience, New York, 1961.

31. Bernhard, A. and Chopra, I., "Analysis of a Bending-Torsion Coupled Actuator for a sMart Rotor with Active Blade Tips", Smart Materials and Structures, Vol. 10, No.1, 1998, pp. 35-52.

32. Bernhard, A. and Chopra, I., "Hover Test of a Mach Scale Active-Twist Rotor Using Piezo-Induced Bending-Torsion Actuators", Journal of Aircraft, Vol. 39, No.4, 2002, pp. 678-688.

33. Rodgers, J. and Hagood, N., "Hover Testing of a 1/6th Mach-Scaled CH-47D Blade with Integrated

Twist Actuation", Presented at 9th International Conference on Adaptive Structures and Technology, Cambridge, MA, USA, 1998.

34. Rodgers, J. and Hagood, N., "Design, Manufacture, and Testing of an Integral Twist-Actuated Rotor Blade", Presented at 8th International Conference on Adaptive Structures and Technology, Wakayama, Japan, 1997.

35. Wilkie, W., Wilbur, M. and Mirick, P. et. al, "Aeroelastic Analysis of the NASA/Army/MIT Active Twist Rotor", Presented at 55th Annual Forum, American Helicopter Society, Montreal, Canada, 1999.

36. Johnson, W., "Rotorcraft Aerodynamics Models for a Comprehensive Analysis", Presented at the 54th Annual Forum, American Helicopter Society, Washington DC, USA, 1998.

37. Wilbur, M., P. Mirick., Yeager, W. E. A., Langston, C. W., Cesnik, C. E. S. and Shin, S., "Vibratory Loads Reduction Testing of the Nasa/Army/MIT Active Twist Rotor", Journal of the American Helicopter Society, Vol. 47, No.2, 2004, pp. 123-133.

38. Booth, E. R. and Wilbur, J. L. Jr., "Acoustic Aspects of Active-Twist Rotor Control", Journal of the American Helicopter Society, Vol. 49, No.1, 2004, pp. 3-10.

39. William, T., Yeager T. Jr., Wilbur, M. and Nixon M., "A Review of Recent Rotorcraft Investigations in the Langley Transonic Dynamics Tunnel", Presented at 44th AIAA/ASME/ASCE/AHS Structural Dynamics and Material Conference, Norfolk, Virginia, USA, 2002.

40. Shin, S., Cesnik, C. E. S. and Hall, S. R., "NASA/Army/MIT Active Twist Rotor Closed-Loop Control Test for Vibration Reduction", 29th European Rotorcraft Forum, Friedrichshafen, Germany, 16-18 September, 2003.

41. Chattopadhyay, A., Lin, Q. and Gu, H., "Vibration Reduction in Rotor Blades Using Active Composite Box Beam", Journal of American Institute of Aeronautics and Astronautics, Vol. 38, No.7, 2000, pp. 1125-1131.

42. Chattopadhyay, A., Lin, Q. and Gu, H., "Modeling of Smart Composite Box Beams with Nonlinear Induced Strain", Composite Part B: Engineering, Vol. 30, No.6, 1999, pp. 603-612.

43. Cesnik, C. E. S. and Shin, S., "On the Twist Performance of a Multiple-Cell Active Helicopter Blade", Smart Materials and Structures, Vol. 10, No.1, 2001, pp. 53-61.

44. Cesnik, C. E. S. and Shin, S., "On the Modeling of Integrally Actuated Helicopter Blades", Int. J. Solids Structures, Vol. 38, Nos.10-13, 2001, pp. 1765-1789.

45. Cesnik, C. E. S. and Shin, S., "Dynamic Response of Active Twist Rotor Blades", Smart Materials and Structures, Vol. 10, No.1, 2001, pp. 62-76.

46. Buter, A. and Breitbach, E., "Adaptive Blade Twist - Calculations and Experimental Results", Aerosp. Sci. Techno, Vol. 4, No.5, 2000, pp. 309-319.

47. Kube, R. and Kloppel, K., "On the Role of Prediction Tools for Adaptive Rotor System Developments", Smart Materials and Structures, Vol. 10, No.1, 2001, pp. 137-144.

48. Splettstoesser, W.R., Schultz, K.J., van der Wall, B., Buchholz, H., Gembler, W. and Niesl, G., "The Effect of Individual Blade Control on BVI Noise - Comparison of Flight Test and Simulation Results", Procedings of the 24th Europe Rotorcraft Forum, Marsielle, France, 1998.

49. Honert, H., van der Wall, B., Fritzsche, M. and Niesl, G., "Realtime BVI Noise Identification from Blade Pressure Data", Proceedings of the 24th Europe Rotorcraft Forum, Marsielle, France 1998.

50. Schimke, D., .Kube, R. and Arnold, U.T.P., "Individual Blade Root Control Demonstration Evaluation of Recent Flight Tests", Proceedings of the 54th Annual Forum of the American Helicopter Society, Washington D.C, USA, 1998.

51. Ghiringhelli, G.L., Masarati, P. and Mantegazza, P., "Analysis of an Actively Twisted Rotor by Multibody Global Modeling", Composite Structures, Vol. 52, No.1, 2001, pp. 113-122.

52. Wilkie, W.L., Park, K.C. and Belvin, W.K., "Helicopter Dynamic Stall Suppression Using Piezoelectric Active Fiber Composite Rotor Blades", AIAA/ASME/AHS Structures, Structural Dynamics and Materials Conference, Long Beach, USA, 1998.

53. Ghiringhelli, G.L., Masarati, P. and Mantegazza, P., "A Multi-body Implementation of Finite Volume Beams",AlAA Journal, Vol. 38, No.1, 2000, pp. 131-138.

54. Pitt, D. M. and Peters, D.A., "Theoretical Prediction of Dynamic Inflow Derivatives", Vertica 5, No.1, 1981, pp. 21-34.

55. Chen, P.C., Baeder, J.D., Evans, R.A.D. and Niemczuk, J., "Blade-Vortex Interaction Noise Reduction with Active Twist Smart Rotor Technology", Smart Materials and Structures, Vol.10, No.1, 2001, pp. 77-85.

56. Smith, E.C., "Induced-Shear Piezoelectric Actuators for Active Twist Rotor Blades", AIAA Paper No. 2002-1446-CP.

57. Thakkar, D. and Ganguli, R., "Dynamic Response of Rotating Beams with Piezoceramic Actuation", Journal of Sound and Vibration, Vol. 270, Nos.4-5, 2004, pp. 729-753.

58. Thakkar, D. and Ganguli, R., "Helicopter Vibration Reduction in Forward Flight with Induced Shear Based Piezoceramic Actuation", Smart Materials and Structures, Vol.30, No.13, 2004, pp. 599-608.

59. Zheng, M., Su, Y. J. and Zhou, G., "Damage Model for Flexural Strength Variation of Ferroelectric Materials Induced by Electric Field", Theoretical and Applied Fracture Mechanics, Vol. 32, No.2, 1999, pp. 137-145.

60. Freiman S. W., "Fracture Behavior of Electronic Ceramics", Journal of Ferroelectrics, Vol. 102, 1990, pp. 381-390.

61. Park, S. and Sun, C. T., "Fracture Criteria for Piezoelectric Ceramics", Journal of American Ceramic Society, Vol. 78, No.6, 1995, pp. 1475-1480.

62. Makino, H. and Kamiya, N., "Effects of dc Electric Field on Mechanical Properties of Piezoelectric Ceramics", Japanese Journal of Applied Physics, Vol. 33, No.9b, 1994, pp. 5323-5327.

63. Park, S.B. and Sun, C. T., "Effect of Electric Field on Fracture of Piezoelectric Ceramics", International Journal of Fracture, Vol. 70, No.3,1995, pp. 203-216.

64. Crawley, E. F. and de Luis, J., "Use of Piezoelectric Actuators as Elements of Intelligent Structures", AIAA Journal, Vol. 15, 1987, pp. 1373-1385.

65. Hansen, J.P. and Vizzini, A.J., "Fatigue Response of a Host Structure with Interlaced Embedded Devices", Journal of Intelligent Material Systems and Structures, Vol. 11, No.11, 2001, pp. 902-909.

66. Yocum, M., Abramovich, H., Grunwald, A. and Mall, S., "Fully Reversed Electromechanical Fatigue Behavior of Composite Laminate with Embedded Piezoelectric Actuator/Sensor", Smart Materials and Structures, Vol. 12, No.4, 2003, pp. 556-564.

67. Masys, A.J., Ren, W., Yang, G. and Mukerjee, B.K., "Piezoelectric Strain in Lead Zirconate Titanate Ceramics as a Function of Electric Field, Frequency and dc bias", Journal of Applied Physics, Vol. 94, No.2, 2003, pp. 1155-1162.

68. Tan, P. and Tong, L., "A One-Dimensional Model for Nonlinear Behavior of Piezoelectric Composite Materials", Composite Structures, Vol. 58, No.4, 2002, pp. 551-561.

69. von Wagner, U. and Hagedorn, P., "Piezo-beam Systems Subjected to Weak Electric Field: Experiments and Modeling of Non-linearities", Journal of Sound and Vibration, Vol. 256, No.5, 2002, pp. 861-872.

70. Mueller, V. and Zhang, Q.M., "Shear Response of Lead Zirconate Piezoceramics", Journal of Applied Physics, Vol. 83, No.7, 1998, pp. 3754-3761.

71. Glazounov, A.E., Zhang, Q.M. and Kim, C., "Torsional Actuator Based on Mechanically Amplified Shear Piezoelectric Response", Sensors and Actuators, Vol. 79, No.1, 2000, pp. 22-30.

72. Piquette, J.C., McLaughlin, E.A., Ren, W. and Mukherjee, B.K., "Generalization of a Model of Hysteresis for Dynamical Systems", Journal of Acoustical

Society of America, Vol. 111, No.6, 2002, pp. 2671-2674.

73. Hughes, H. and Wen, J.T., "Preisach Modeling of Piezoceramic and Shape Memory Alloy Hysteresis", Smart Materials and Structures, Vol. 6, No.3, 1997, pp. 287-300.

74. Hall, D.A., "Review of Nonlinearity in Piezoelectric ceramics", Journal of Material Science, Vol. 36, No.19, 2001, pp. 4575-4601.

75. Rodel, J. and Kreher, W.S., "Modeling Linear and Nonlinear Behavior of Polycrystalline Ferroelectric Ceramics", Journal of European Ceramics Society, Vol. 23, No.13, 2003, pp. 2297-2306.

76. Nguyen, K.P. and Schrage, D.P., "Fixed Gain Versus Adaptive Gain Higher Harmonic Control Simulation", Journal of the American Helicopter Society, Vol. 34, No.3, 1989, pp. 51-58.

77. Hall, S.R. and Wereley, N.M., "Performance of Higher Harmonic Control Algorithms for Helicopter Vibration Reduction", Journal of Guidance, Control and Dynamics, Vol. 16, No.4, 1993, pp. 793-797.

78. Zhou, X. and Chattopadhyay, A., "Hysteresis Behavior and Modeling of Piezoceramic Actuators", ASME Journal of Applied Mechanics, Vol. 68, No.2, 2001, pp. 270-277.

79. Lovera, M., Colaneri, P., Malpica, C. and Celi, R., "Closed Loop Aeromechanical Stability Analysis of the HHC and IBC, with Application to a Hingeless Helicopter Rotor", 29th European Rotorcraft Forum, Friedrichshafen, Germany, 2003.

80. Bittani, S. and Colaneri, P., Webster, J.G., "Periodic Control" in Encyclopedia of Electrical and Electronic Engineering, John Wiley and Sons, 1999.

81. Gupta, N.K. and Du Val, R., "A New Approach for Active Control of Rotorcraft Vibration", Journal of Guidance, Control and Dynamics, Vol. 5, No.2, 1982, pp. 143-150.

82. Du Val, R., Gregory, Jr., C.Z. and Gupta, N.K., "Design and Evaluation of a State Feedback Vibration Controller", Journal of the American Helicopter Society, Vol. 29, No.3, 1984, pp. 30-37.

83. Prakah-Asante, K.O. and Craig, K.C., "The Application of Multichannel Design Methods for Vibration Control of an Active Structure", Smart Materials and Structures, Vol. 3, No.3, 1994, pp. 329-343.

84. Ioannou, P. A. and Sun, J., "Robust Adaptive Control", Prentice Hall, New Jersey 1996.

85. Sanner, R.M. and Siotine, J.J.E., "Stable Adaptive Control of Robot Manipulators Using Neural Network", Neural Computation, Vol.7, No.4, 1995, pp. 753-790.

86. Damle, R., Rao, V. and Kern, F., "Multivariable Neural Network Based Controllers for Smart Structures", Journal of Intelligent Material Systems and Structures, Vol. 6, No.4, 1995, pp. 516- 528.

87. Spencer, M.G., Sanner, R.M. and Chopra, I., "Closed Loop Neuro-Controller Tests on Piezoactuated Smart Rotor Blades in Hover", AIAA Journal, Vol. 40, No.8, 2002, pp. 1596-1602.

88. Stein, S.C. and Rogers, C.A., "Power Consumption of Piezoelectric Actuators Driving a Simply Supported Beam Considering Fluid Coupling", Journal of the Acoustical Society of America, Vol. 96, No.3, 1994, pp. 1598- 1604.

89. Park, C.H., "On the Circuit Model of Piezoceramics", Journal of Intelligent Material Systems and Structures, Vol. 12, No.7, 2001, pp. 515-522.

90. Sirohi, J. and Chopra, I., "Actuator Power Reduction Using L-C Oscillator Circuits", Journal of Intelligent Material Systems and Structures, Vol. 12, No.12, 2001, pp. 867-877.

91. Pomirleanu, R. and Giurgiutiu, V., "Full-Stroke Static and Dynamic Analysis of High Power Piezoelectric Actuators", Journal of Intelligent Material Systems and Structures, Vol.13, No.5, 2002, pp. 275-289.

92. Yamashita, Y., Ho,sono, Y. and Harada, K., "Present and Future of Piezoelectric Single Crystals and the Importance of B-site Cations for High Piezoelectric Response", IEEE Transactions on Ultrasonics and Ferroelectrics, Vol. 49, No.2, 2002, pp. 184-192.