Rotorcraft research in India: recent developments

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Abstract

Purpose - The published research in rotorcraft which has taken place in India during the last ten years is discussed in this paper. The helicopter research is divided into the following parts: (1) health monitoring (2) smart rotor (3) design optimization (4) control (5) helicopter rotor dynamics and (6) active control of structural response and (7) helicopter design and development. Aspects of health monitoring and smart rotor are discussed in detail. Further work needed and areas for international collaboration are pointed out.

Design/methodology/approach - The archival journal papers on helicopter engineering published from India are obtained from databases and are studied and discussed. The contribution of the basic research to the state-of-the-art in helicopter engineering science is brought out.

Findings - It is found that strong research capabilities have developed in rotor system health and usage monitoring, rotor blade design optimization, active control of structural response, composite rotor blades and smart rotor development. Furthermore, rotorcraft modeling and analysis aspects are highly developed with considerable manpower available and being generated in these areas.

Practical implications - Two helicopter projects leading to the "Advanced light helicopter" and "Light combat helicopter" have been completed by Hindustan Aeronautics Ltd. These helicopter programs have benefited from the basic research and also provide platforms for further basic research and deeper industry-academic collaborations. The development of well trained helicopter engineers is also attractive for international helicopter design and manufacturing companies. The basic research done needs to be further developed for practical and commercial applications.

Originality/value - This is the first comprehensive research on rotorcraft research in India, an important emerging market, manufacturing and sourcing destination for the industry.

Keywords - rotorcraft, helicopter, dynamics, modeling and simulation, smart rotor, health monitoring

Paper type - literature review

Introduction

Rotorcraft represent some of the most complex of flight vehicles, due to the strong aeroelastic interactions between highly flexible rotor blades and unsteady aerodynamic forces (Newman, 2005; Friedmann and Hodges, 2003; Newman, 2006). The challenge of designing a helicopter with low vibration levels, enhanced safety and low acoustic signature remains significant (Ozgumus and Kaya, 2007a; Ozgumus and Kaya, 2007b). Moreover, predictive capability of helicopter aeroelastic analysis lags behind that of fixed wing aircraft, leading to higher levels of experiments and testing. Helicopters therefore remain costly to manufacture and maintain compared to fixed wing aircraft. However, because of their unique ability to fly vertically and slowly, helicopters have niche applications in search and rescue operations, reconnaissance, civil transport and military.

Helicopters are useful for short distance travel in densely populated Asian countries, as has been already shown in Japan (Tsuchiya et al, 2007; Matsumoto et al, 2006), and is increasingly happening in India (Tatavarti et al 1996) and China (Yan et al, 2007a). However, the use of helicopters is limited due to high costs which could be alleviated by spreading the science and technology of rotary wing flight internationally. For example, automobile technology has spread worldwide and has resulted in lower costs with increased innovation. Interestingly, substantial rotorcraft activity has occurred in India in the last two decades such as the development of indigenous helicopters and increasing contribution to basic research as measured by journal publications. In addition to published research, helicopter design and development has also made significant progress. Pioneering work by Hindustan Aeronautics Limited (HAL) has resulted in development and manufacture of the advanced light helicopter "Dhruv" which is a sophisticated and modern helicopter in its class. Figure 1 shows a picture of the Dhruv helicopter which has a four bladed hingeless rotor and a bearingless tail rotor.

Figure 1 The “Dhruv” advanced light helicopter

Figure 2 Test flight of the light combat helicopter (LCH)

A unique feature of this helicopter is that it was designed to fly at very high altitudes in the Himalaya mountains. Other major initiatives in helicopters are also underway at HAL and the “Light Combat Helicopter” was test flown recently (Figure 2). This activity of HAL has resulted in the growth of an infrastructure in helicopter related components and suppliers along with the development of engineering designers.

This paper will cover the research activities on helicopters in India, with emphasis on the last 10 years. The helicopter research done is divided into the following parts: (1) health monitoring (2) smart rotor (3) design optimization (4) helicopter control and (5) helicopter rotor dynamics and (6) active control of structural response. The current paper is a revised version of the conference paper by Ganguli (2009) at the session on international research.

Helicopter Rotor Health monitoring

Helicopters suffer from flight safety problems because of unsteady time varying aerodynamic loading and rotating machinery. In fact, helicopters are prone to more frequent accidents compared to fixed wing aircraft and also have considerably higher maintenance costs. Therefore, health and usage monitoring of helicopters is an important research area (Wallace, 2004). Engineering health monitoring systems are often based on a mathematical model of the system, which is used to simulate the effect of damage on the system behavior (Reed, 2008; Trendafoilova et al, 2009; Ganguli et al, 1998). The development of a rotor helicopter health and usage monitoring systems (HUMS) requires a mathematical model of the damaged rotor system. Modern helicopter rotors are typically built using composite materials which have complex damage growth mechanisms. For example, composites first undergo matrix cracking under cyclic loading. The delamination/debonding stage of damage occurs after matrix cracks saturate. Finally, fiber breakage occurs and leads to the failure of the structure.

Pawar and Ganguli (2005a, 2005b) first studied the development of matrix cracks in composite rotor blades and their effect on blade elastic stiffness properties. A stiff-inplane rotor with a rectangular box and two-cell airfoil section with $[0/\pm45/90]_s$ family of laminates was considered. It was found that the stiffness decreased rapidly in the initial phases of matrix cracking and then becomes saturated. They found that matrix cracking had much more influence on the torsion stiffness relative to the bending stiffness of the blade. An important observation made by the authors was that matrix crack saturation can be used as a point after which the structure needs to be monitored more carefully. Thus, the damage indicator values at matrix crack saturation become thresholds for putting the helicopter blade on a watch list.

In a subsequent work, Pawar and Ganguli (2006) studied the evolution of damage in composite rotor blades in the form of matrix cracking, delamination and fiber breakage. The damage models were integrated into an aeroelastic analysis for composite rotor blades and the behavior of a damaged composite rotor blade in hover and forward flight was simulated by Pawar and Ganguli (2007a). It was assumed that one out of the four blades of a hingeless rotor was damaged. Both box-beam models and airfoil section blade models were used and soft-inplane and stiff-inplane rotor blades were addressed. Changes in measurements in tip response, blade root loads and strains between the undamaged blade and damaged blade were evaluated as prospective damage indicators. Damage indicators are measurable parameters which can be used as virtual sensors for tracking damage in a system. Often, changes in the measured parameters between the damaged and undamaged state are taken as damage indicators. It was found that considerable data reduction could be obtained by taking the changes in the peak-to-peak values of the blade response and loads as the damage indicator. Since matrix cracking is the first damage mechanism effecting composites, the use of matrix crack saturation for developing thresholds for damage detection systems was suggested. A less conservative approach is to develop thresholds based on the transition between the delamination and fiber breakage damage modes. Both these approaches were evaluated for developing thresholds on damage indicators.

Modeling of damage in helicopter rotors gives considerable physical insight into behavior which cannot be easily replicated by experiments. Flying helicopters with damaged rotor blades is difficult, if not impossible, due to airworthiness issues. However, practical use of these mathematical models requires that the change in measurable damage indicators such as blade response and loads be related to the presence, location and size of the damage. This is basically a pattern recognition problem where the damage needs to be identified from measured rotor system behavior. Unfortunately, the rotor environment is very noisy and the process of finding the damage from noisy measurements can be mathematically difficult. The health monitoring pattern recognition problem is complicated due to the presence of noise. It can be seen that the noise expands the space corresponding to a given fault which can make it more difficult to isolate the correct fault from measured noisy data. Pattern recognition algorithms are therefore often used for damage detection.

Noisy pattern recognition problems are often solved using estimation methods such as those based on Kalman filters. In recent years, soft computing approaches to solving health monitoring problems have become popular due to their robustness in the presence of uncertainty. Most soft computing applications to damage detection use neural networks. However, fuzzy logic systems can be better at solving damage detection problems as they convert numerical data into linguistic form and clearly state rules linking the damage location and size with the measured damage indicators. Algorithms based on fuzzy logic were developed by Ganguli (2002) to isolate the faults from noisy simulated data using an aeroelastic analysis of a damaged dissimilar rotor in forward flight. The results in Ganguli (2002) showed that fuzzy logic performs much better than a rule based expert system for damage detection from noisy response and vibratory hub loads data. However, the development of this fuzzy system required considerable effort in terms of selection of the fuzzy membership functions for the measured data sets and in the generation of the rules. In general, as the number of measurements in the diagnostic system become larger, the development of the fuzzy system becomes more difficult. This is a general problem plaguing health monitoring systems and is related to the 'curse of dimensionality'.

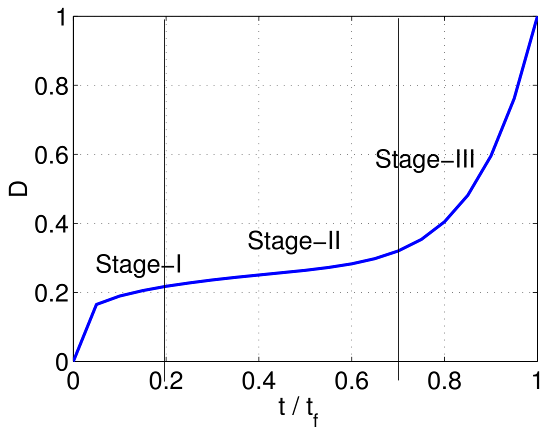
The process of rule generation in a fuzzy logic system becomes cumbersome as the number of measurements and faults in the system increase. This problem can be alleviated by using a genetic algorithm to develop an optimal fuzzy logic system. In this approach, the development of the diagnostic system is posed as an optimization problem of maximizing the success rate of the system under noisy data. Pawar and Ganguli (2007b) developed a genetic fuzzy system which automated the complex tasks involved in generating the fuzzy rules. This system was developed and tested for a composite rotor blade with seeded matrix cracks, delamination and fiber breakage damage. Both global and local damage detection was considered. For global damage detection, measurements such as changes in blade tip response, root loads and frequencies were used. For local damage detection, strain sensors placed along the blade were used. The simulated measurements were contaminated with noise and then used to both train and test the genetic fuzzy system. The damage detection system performed very well with noisy data and gave accurate estimates of the amount of matrix cracks, delamination and fiber breakage present in the structure.

Though it is good to know the level of physical damage in the structure, it is highly desirable that the remaining life of the structure be estimated. This process involves a nonlinear leap as connecting the damage mechanisms to life is very difficult. An approximate idea of remaining life in the structure can be found through the use of phenomenological models which exploit the fact that composite material damage growth occurs in three distinct phases, as shown in Figure 3. The functional relationship for damage growth shown in Figure 3 is given as,

$$D = q\left(\frac{t}{t_f}\right)^{m_1} + (1-q)\left(\frac{t}{t_f}\right)^{m_2} \qquad (1)$$

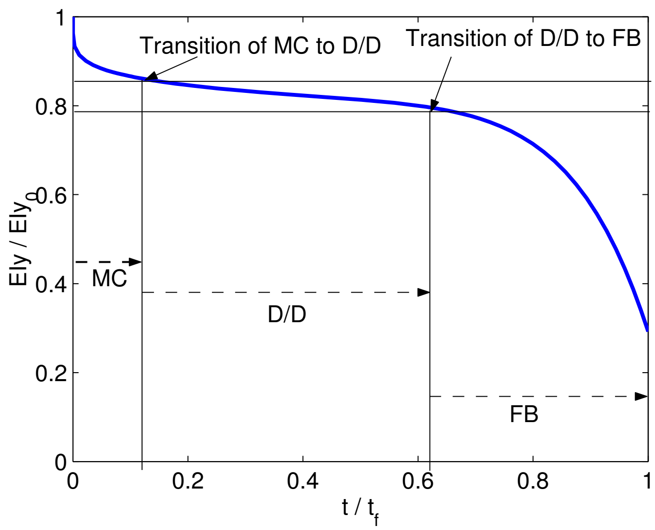
where $D = (E_0 - E)/(E_0 - E_f)$, E_0 is the initial stiffness at $t = 0$ and E_f is the stiffness at final failure time t_f, and E is the stiffness at any instant of time t. Though Eq. 1 was proposed by Mao and Mahadevan (2002) to model damage in composites, it can also be used to model the growth of damage indicators with time provided that the behavior is qualitatively similar.

Figure 3 Damage growth curve for composite materials (stage I is primarily matrix cracking, stage II is primarily debonding/delamination and stage III is primarily fiber breakage; D is the normalized stiffness reduction and t/t_f is the normalized life consumption with t_f being the time to fail)



The three damage growth phases in Figure 3 indicate the transition from matrix cracking to the delamination mode and from the delamination to the fiber breakage mode. It was found that the damage growth curves for elastic stiffnesses of composites were similar to the changes in the blade stiffnesses with damage growth. For example, Figure 4 shows the bending stiffness variation with damage growth and the transition between the different damage modes can be related to the remaining life of the blade.

Figure 4 Change in flap bending stiffness of helicopter rotor blade as the damage modes transition from matrix cracking (MC) to debonding/delamination (DD) and fiber breakage (FB) related to life of the structure (EIy / EIy_0 is the normalized flap bending stiffness of the blade with EIy_0 being the initial stiffness value and t / t_f is the normalized life consumption with t_f being the time to fail)



It can be observed that a similarity exists between Figures 3 and 4 and thus Eq. 1 can also be used to model the degradation in rotor blade stiffness due to composite material damage. The transition from matrix cracking to debonding/delamination occurs at about 15 percent of blade life and the transition from debonding/delamination to fiber breakage occurs at about 60 percent of blade life.

The damage detection system was linked to life prediction of the structure through the use of phenomenological models for degradation of composite materials by Pawar and Ganguli (2007c). The resulting damage detection system was able to predict the remaining life of the composite blade and the maintenance action needed. A schematic representation of the development and possible implementation of the genetic fuzzy system is shown in Figure 5 and 6, respectively.

A major problem in rotor health monitoring is the high level of noise present in signals of damage indicators (Ganguli et al, 1998). While pattern recognition methods based on fuzzy logic and neural networks are robust to the presence of a small amount of noise in data, even they can deteriorate when the noise levels become too large. The presence of non-Gaussian outliers in time series of damage indicators can have an especially negative effect on damage detection systems. Most diagnostics systems assume Gaussian noise and can show considerable performance degradation in the presence of non-Gaussian outliers.

Roy and Ganguli (2006) developed pre-filters for removing noise from data prior to health monitoring. In general, sharp trend shifts in measured signals are often an indication of faults and can be smoothed out by linear filters which are often used to smooth signals prior to health monitoring. In addition, linear filters are not good at removing non-Gaussian outliers which often occur in health signals of highly noisy systems such as helicopter rotors. Typical signals for gradual and abrupt faults were contaminated with outliers and neural network and weighted recursive median filters were developed for noise removal. An optimization approach based on genetic algorithm was used to optimize the filter weights which are integers for this class of filters.

This work was extended to more realistic signals in (Roy and Ganguli, 2005) where modal damage indicators were developed for a structure undergoing damage growth. The damage growth was modeled using a phenomenological approach for both metal and composite structures. Different filtering methods including those based on radial basis neural networks, wavelets and recursive median filters were proposed and compared with the damage indicator evolution signals. The signals included both random noise and non-Gaussian outliers. It was found that weighted recursive median filters are very useful for operational health monitoring and are also very easy to implement.

Most health monitoring work focuses on the main rotor but the tail rotor is also a source of many failures. Due the loss of yaw control, tail rotor failure can be catastrophic (Colombo and Giglio, 2007; Orourke 1994). Singh et al (2008) looked at the effect of mass and stiffness imbalance in the tail rotor system using an aeroelastic analysis. The effect of damage occurring in one, two and three blades was considered and the effect of damage growth on vibratory hub loads and blade responses was studied. Diagnostic tables which can be used for tail rotor health monitoring were compiled. The improvement in sensor technology has resulted in both ground based and online measurements of modal data becoming possible (Catbas et al, 2008; Yan et al, 2007b). Devices based on smart materials can be used to simultaneously actuate the structure and measure its response leading to online frequency measurement capability. In addition, helicopter rotor blades are designed to take large amounts of damage and the relative insensitivity of modal parameters to damage can be an advantage as it would prevent false alarms.

Both ground based (Ganguli, 2001; Suresh et al, 2004; Pawar et al, 2003; Pawar et al, 2005c) and online (Reddy et al, 2005) damage detection systems were developed for helicopter rotor blades and beam type structures similar to rotor blades. The effect of matrix crack detection for damage detection in tail boom type structures was studied using a circular hollow composite beam (Pawar et al, 2005c). These studies used finite elements to model the damaged rotor blade using either a reduction in elastic stiffness at the damage location (Ganguli, 2001; Reddy et al, 2003) or more elaborate fracture mechanics based crack models (Suresh et al, 2004). These research efforts (Ganguli, 2001; Suresh et al, 2004; Pawar et al, 2003; Pawar and Ganguli, 2005c; Reddy et al, 2003; Pawar et al, 2005) provide considerable insight into the development of robust damage detection systems from noisy data. For example, Pawar and Ganguli (2003) were the first to propose the development of the genetic fuzzy system for structural health monitoring. Suresh et al (2004) showed that the problem of finding the presence of damage could be decoupled from the problem of finding the size of damage using modular neural network architecture. This approach used principal component analysis and was found to be computationally efficient.

Pawar and Ganguli (2007d) have written a comprehensive review paper on helicopter rotor system health monitoring with suggestions for future work. This paper will help further research interest in this important area of flight safety and will be of use to new students and researchers in the field.

Figure 5 Schematic representation of development of the structural health monitoring system for the composite rotor blade

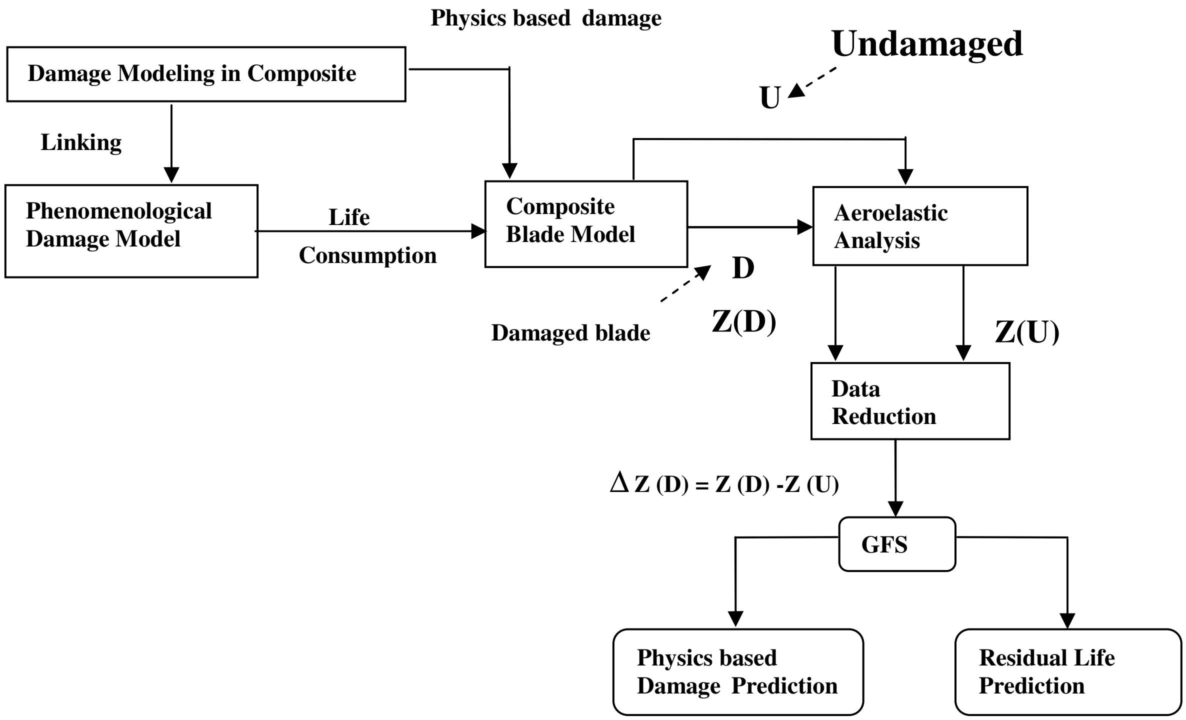
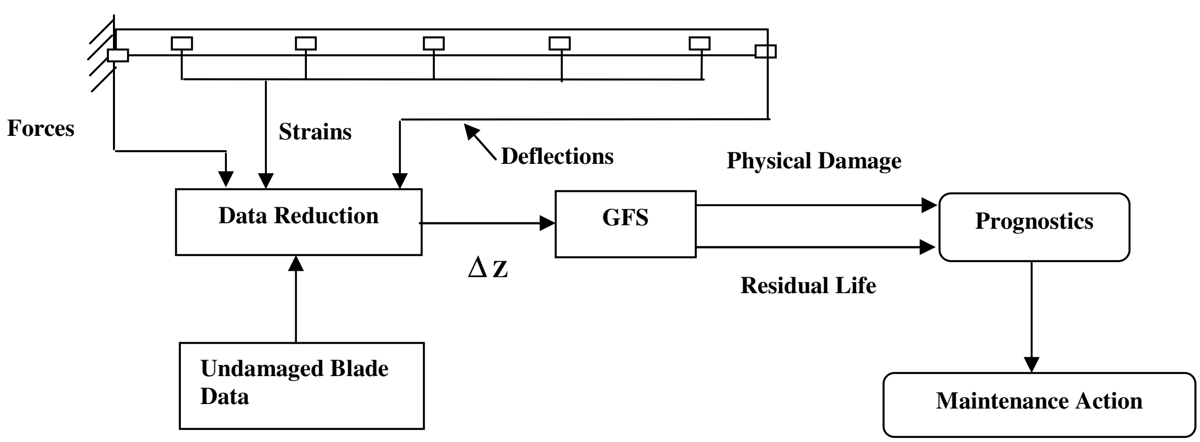


Figure 6 Schematic representation of implementation of the structural health monitoring system on a helicopter rotor blade

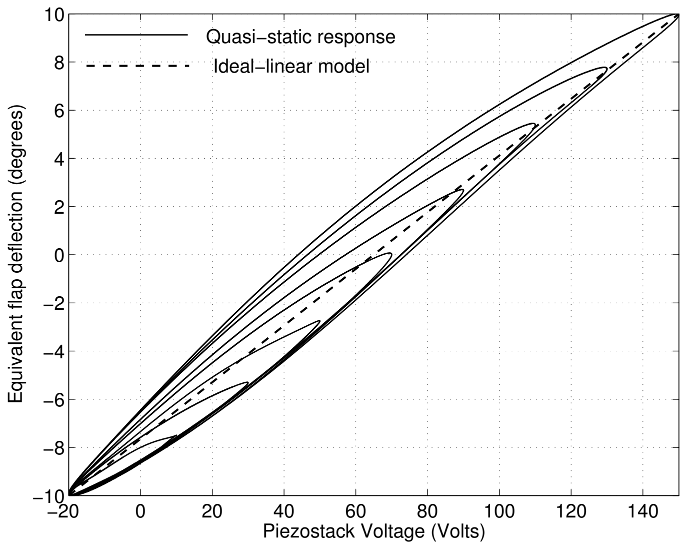


Smart Helicopter Rotor

Vibration is a key problem in helicopters. For an *N*-bladed helicopter rotor, the *N*/rev vibratory loads are transmitted to the fuselage as the main source of vibration. Therefore, reducing vibration at the main rotor is the most effective way for reducing helicopter vibration. Researchers have investigated both active and passive approaches to alleviate the vibration problem (Chen et al, 2009). The passive approaches involve the use of vibration absorbers and isolators or designing the rotor blade to have inherently low vibrations (Ganguli and Chopra, 1996). The popular active approach involves the use of individual blade control (IBC) where the blades are excited at higher harmonics of the rotor speed to cancel the existing unsteady loads which are the main cause of helicopter vibration. The advent of smart materials such as piezoceramics has lead to two active approaches becoming most popular. These are the trailing edge flaps (Roget and Chopra, 2008) and the active rotor twist approach (Barkano et al, 2008; Park and Kim, 2008). These two approaches are discussed next.

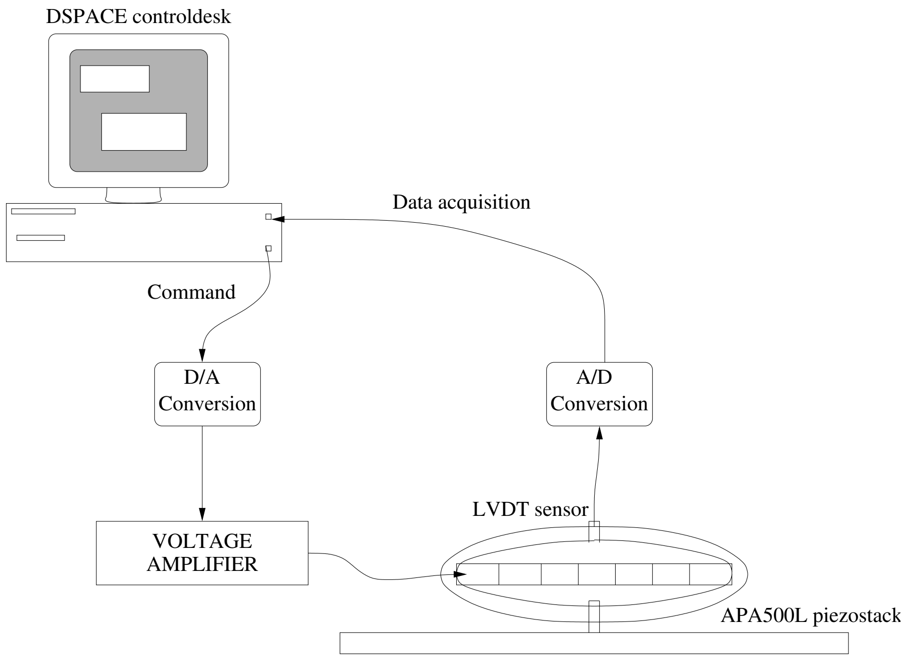
Trailing edge flaps placed near the blade tip are actuated at higher harmonics of the rotor speed to reduce the vibration at its source: the main rotor. For a 4-bladed rotor, actuation at 2, 3, 4 and 5/rev can reduce vibration and noise, and also improve performance. Viswamurthy and Ganguli (2006) investigated the use of piezostack actuators for moving the trailing edge flaps at higher harmonics of the main rotor speed. An aeroelastic analysis code was used to represent the helicopter rotor blade with trailing edge flaps. A compressible unsteady aerodynamic model is used to predict the incremental airloads due to trailing edge flap motion. The material and mechanics hysteresis in the piezoelectric actuator was modeled using the classical Preisach model. A harmonic controller was devised and the effect of static hysteresis on the controller was analyzed. The static hysteresis data was obtained from experimental data available in the published literature. Some typical voltage versus displacement curves illustrating piezoceramic hysteresis are shown in Figure 7. Here the idealized linear relationship between the flap deflection and the piezostack voltage represents the situation where there is no hysteresis. Numerical results from the aeroelastic analysis code showed that multicyclic control inputs gave 90 and 81 percent reduction in hub vibration at high speed flight (μ=0.3) for the ideal and real actuator, respectively. Here, the “real” actuator refers to one with hysteresis modeled. Numerical results showed that the presence of hysteresis nonlinearity leads to deterioration in controller performance and less vibration reduction in both high and low speed flight.

Figure 7 Static hysteresis effect on trailing edge flap deflection with varying voltage applied to the piezostack actuator



However, it was realized that the hysteresis effect in piezoelectric materials are a dynamic phenomenon. Experiments were conducted to study the APA500L actuators obtained from CEDRAT and the data was used to create dynamic hysteresis models (Viswamurthy et al, 2007a). The schematic and picture of the experimental setup are shown in Figure 8 and Figure 9, respectively. The hysteresis behavior for four different frequencies is shown in Figure 10. It can be seen that the effect of hysteresis is considerable and that the hysteresis is frequency dependant. These facts need to be considered when developing a controller for helicopter vibration using piezostack actuators.

Figure 8 Schematic diagram of experimental setup used for evaluating the hysteresis behavior of piezostack actuators used for helicopter vibration control



Aeroelastic simulations showed that hysteresis effects caused considerable change in the controller performance and a hysteresis compensation algorithm was proposed (Viswamurthy and Ganguli, 2007b). The hysteresis in the trailing edge flap actuator is due to both material property of piezostacks and mechanical linkage losses. A compensator based on complete actuator hysteresis gave up to a 90 percent reduction in hub vibration at cruise speed. Compensator based only on material nonlinearity of the piezostack does not yield the desired flap motion accurately, resulting in only 64 percent reduction in hub vibration. In comparison, the hub vibration reduced by 69 percent when actuator hysteresis was not compensated. The study concluded that it was important to completely compensate for both material and mechanics hysteresis in the actuator to extract good performance from the trailing edge flap vibration control system. Figure 11 shows the considerable difference between the optimal control inputs to the piezostack actuator predicted by simulations which ignore hysteresis (linear model) versus those which include dynamic hysteresis effects. These results are for a case where two flaps are placed along the blade and the advance ratio is 0.3.

Controller design is an important issue in the design and development of a smart rotor. Viswamurthy and Ganguli (2008a) compared global and local controllers for their computational efficiency and robustness to measurement and model uncertainties. They found that the global controller was adequate for helicopter vibration problems, and the local controller only offered an incremental advantage which came at high computational expense. If the typical single flap control algorithm is used for the two flap problem, only of the flaps is actuated at full authority and the other flap is underutilized. Viswamurthy and Ganguli (2008b) found that the global optimal controller could be adjusted to ensure that each flap worked to its full authority. Cases with one, two and three flaps were considered in this paper. The control effort for each flap was differentially weighted and each flap was limited to ± 2 degrees peak-to-peak deflection at full authority. For high speed forward flight, uniform and differential weighting methods resulted in 57 and 68 percent reduction in hub vibration reduction, respectively. For low speed forward flight, the aforementioned two methods results in 38 and 49 percent reduction in hub vibration. Therefore, differential weighting of multiple flaps gives an advantage in vibration reduction of about 10 percent without significant additional computational effort.

Figure 9 Picture of experimental facility used for evaluating the dynamic hysteresis behavior of the piezostack actuator

Figure 10 Dynamic hysteresis behavior of piezostack actuator performed at different frequencies (1, 10, 15 and 20 Hz)

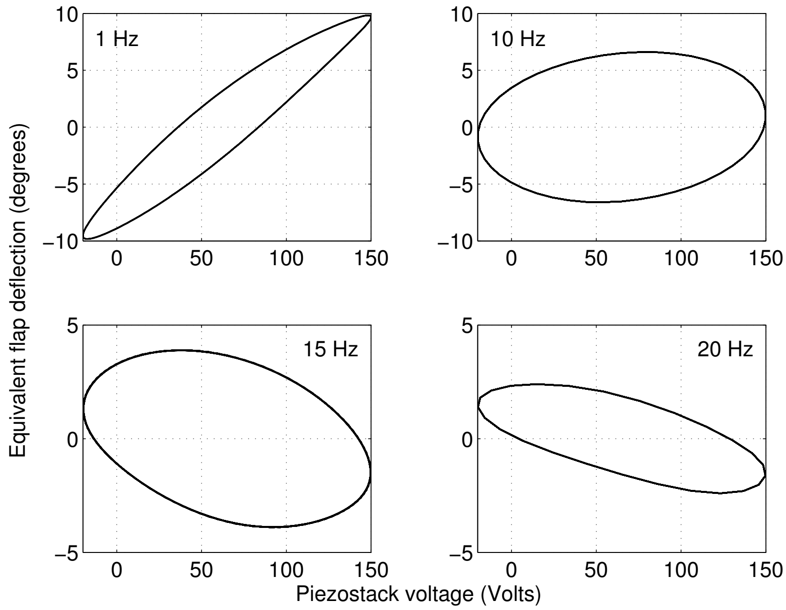
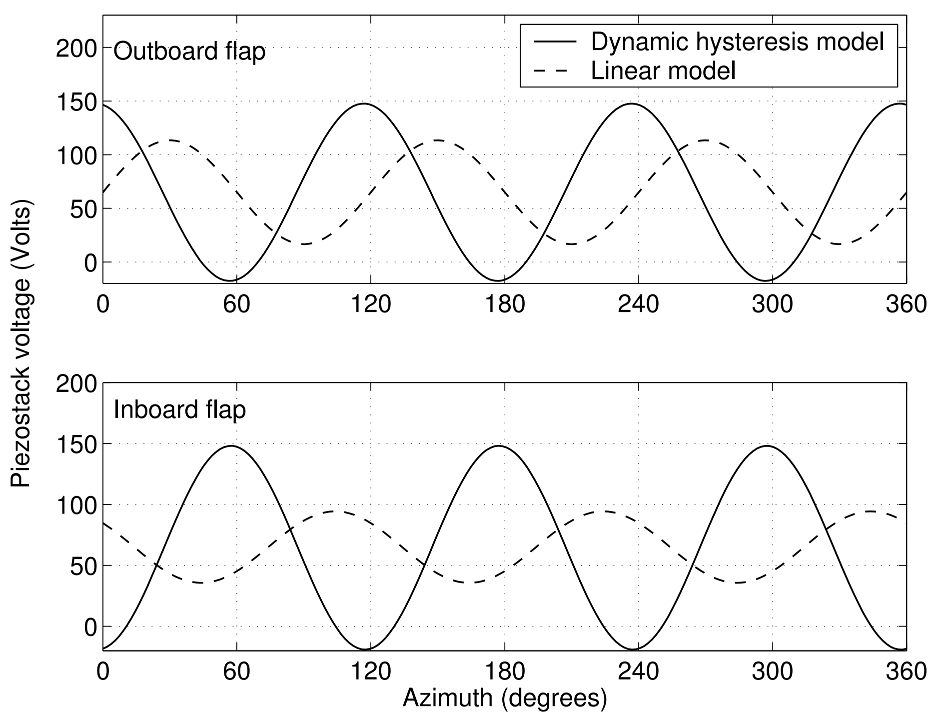


Figure 11 Effect of dynamic hysteresis on the optimal input voltage needed by the piezostack actuator moving the trailing edge flap (advance ratio μ=0.3)



Another important issue in vibration control of trailing edge flaps is the number of flaps which should be placed on the rotor blade and the location of these flaps. Viswamurthy and Ganguli (2004) investigated the use of one, two and four trailing edge flaps for helicopter vibration control. They found that two flaps give almost the same level of vibration reduction at the four flaps but has a lower level of complexity. Two flaps are therefore a good choice for the helicopter vibration reduction problem.

The optimal placement of two flaps along the rotor blade was studied and a multi-objective optimization problem was formulated which sought to minimize both hub vibration and flap power (Viswamurthy and Ganguli, 2007c; Viswamurthy and Ganguli, 2009). An aeroelastic analysis based on finite elements in space and time was used in conjunction with an optimal control algorithm to determine the actuator control input for vibration minimization. The vibration objective function comprised of the six 4/rev vibratory hub loads acting on the helicopter. The mean power needed by a trailing edge flap was obtained by integrating the product of its hinge moment and flap deflection rate over one rotor revolution. The flap power may change sign over some portions of the azimuth. As the actuator will generally not be able to transfer this power back to the flap actuation power supply, the negative power is neglected. A novel feature of this study was the use of metamodels of the objective functions for aiding the optimization process. Metamodels (models of models) are functional approximations of large computer programs and are sometimes called higher dimensional curve fits.

Numerical results showed that second order polynomial response surfaces based on the central composite design of the theory of design of experiments described both the vibration and flap power objectives adequately. Examples of the polynomial response surfaces are shown in Figures 12 and 13. Response surfaces are approximations of complex relationships between input and output variables and simplify the use of optimization tools for problems involving large codes. The numerical studies showed that both objectives were more sensitive to outboard flap location compared to inboard flap location. Optimization studies showed that the dual-flap configuration which gives the least vibration level is different from the one which gives minimum flap power (Figure 14). However, there is a trade-off design which gives a good level of reduction in both objectives.

Figure 12 Polynomial response surface for hub vibration objective function (F_v) with inboard and outboard flap locations as design variables (R is blade radius)

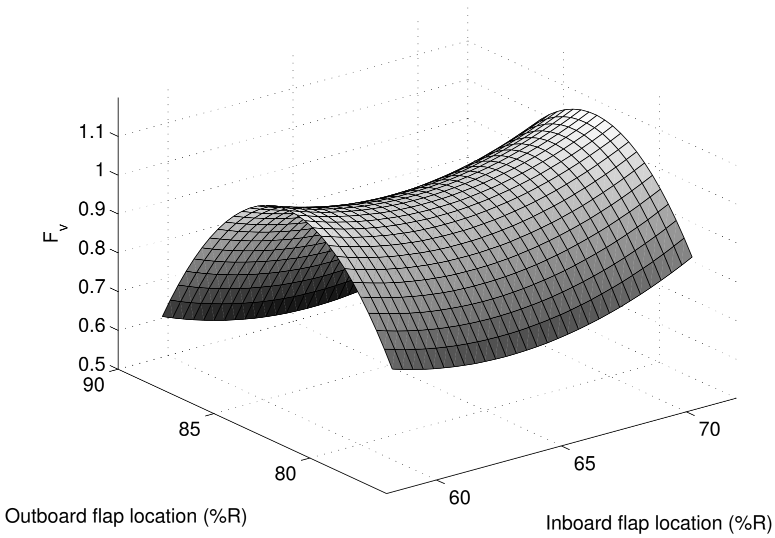


Figure 13 Polynomial response surface for flap power objective function (F_p) with inboard and outboard flap locations as design variables (R is blade radius)

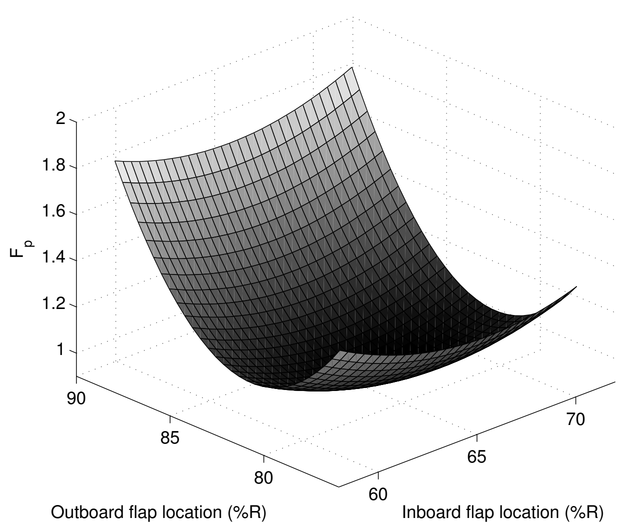
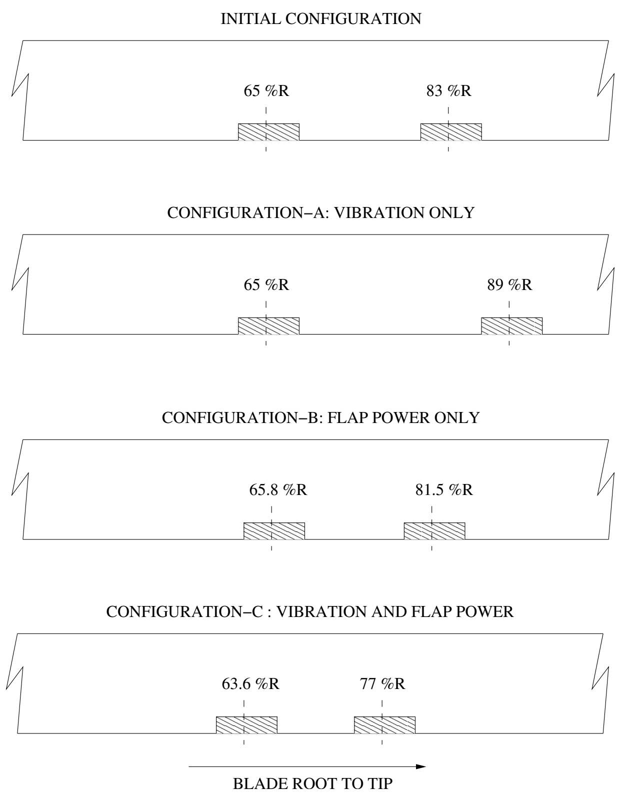


Figure 14 Optimal location of dual trailing edge flaps for initial, single objective and multi-objective optimization problems (advance ratio μ=0.3, *R* is blade radius)

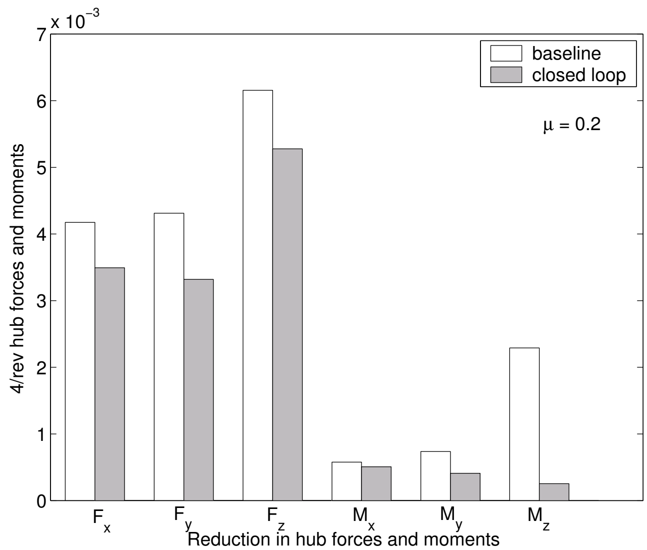


Besides trailing edge flaps, active twist is also a possible approach for vibration reduction in helicopters. However, this approach is classified as more long term in nature due to the need to design the rotor blade using integrated smart material actuators which would also require accounting for strength and other issues. Moreover, is more difficult to move the complete blade in a higher harmonic motion compared to moving one or two trailing edge flaps placed on the rotor blade.

Thakkar and Ganguli, (2004, 2006a, 2007) studied the possibility of using shear mode of the piezoelectric materials for twisting a rotor blade modeled as a rectangular section beam and a box-beam. They used the fact that the shear strain coefficient of piezoelectric materials is much higher than the direct strain coefficient and therefore can lead to higher actuation authority. The effect of high electric field was studied and it was found that the nonlinear relation of the strain coefficient with electric field could be used to further amplify the control authority of the actuators. A reduction in vibration levels in all the six 4/rev hub loads was obtained using a strain rate feedback controller, as shown in Figure 15.

Thakkar and Ganguli (2006b) also studied the use of new single crystal smart materials which have very high shear strain coefficients for twisting the blade. It was also found that actuation using single crystal piezoceramic materials could be used for dynamic stall suppression as the angle of attack across the rotor disk was actively reduced. For dynamic stall suppression, an objective function based on angle of attack variation around the rotor disk was proposed and the feedback controller gains were optimized to minimize this function. A review paper on the active twist rotor concept was written (Thakkar and Ganguli, 2005) to provide a good background to anyone planning to study this area. Pawar and Jung (2009) have recently extended the approach to dissimilar rotor blade.

Figure 15 Hub vibration reduction using active twist rotor with piezoceramic induced shear actuation (μ is advance ratio, hub loads are non-dimensional; F_x, F_y, F_z are longitudinal, lateral and vertical hub forces, M_x, M_y, M_z are rolling, pitching and yawing moments)



New technologies can lead to new problems, which again motivate research. The use of individual blade controls (IBC) such as through trailing edge flaps is being suggested for the swashplateless rotor concept. Since the swashplate is a heavy and complex mechanical system, its replacement is attractive for future generations of helicopters. Ganguli et al (2007a) investigated the problem of survivability of helicopters following the failure of the individual blade control system for a given blade. They found that it is often possible for the pilot to trim and fly the helicopter even in the case of individual primary control failure for a given blade. This can be done by suitably adjusting the trim controls of the other blades. However, large displacements and loads can result for some cases. The swashplateless rotor concept also requires that the longitudinal cyclic of the rotor remains low, especially in high speed forward flight. Otherwise, the actuation needed by the IBC system becomes too large. Ganguli et al (2007b) also investigated the optimal placement of helicopter center of gravity to help the swashplateless rotor concept. A parametric study based optimization approach was used to find the center of gravity location which drove the longitudinal and lateral cyclic to zero in a given flight condition. Both these works (Ganguli et al, 2007a; Ganguli et al 2007b) were a result of Indo-German research collaboration.

Another issue related to IBC was addressed by developing a finite element in time approach which was adaptive in nature. Accurate prediction of dynamic response is a key problem in helicopter (Shahmiri and Saghafi, 2007).The finite element in time is attractive for rotor dynamics problems due to its ability to use the periodic boundary condition to simplify the mathematical problem. A discontinuous finite element method in time can be used for adaptive solution of the periodic governing ordinary differential equations in forward flight (Gudla and Ganguli, 2006). The method was illustrated for the helicopter blade flapping equation in forward flight but is applicable to the broad class of periodic differential equations and can be used for problems in rotor dynamics.

Helicopter Rotor Design Optimization

A direct approach to reduce vibration in any structure is to design it by tailoring the mass and stiffness properties such that vibration levels are inherently low (Glaz et al, 2009; Ganguli and Chopra, 1995). For a helicopter, the main rotor is the key source of vibration. Therefore, the properties of the main rotor blade can be tailored for better vibration performance. Most modern rotor blades are made from composite materials and the design problem is complicated due to the integer nature of ply angle design variables (Bao et al, 2008; Bao et al, 2006). Further, the aeroelastic analysis codes used for rotorcraft modeling are very cumbersome and may be prone to numerical fragility i.e. there are points in the design space where the nonlinear analysis may not converge which can lead to problems with a direct application of optimization algorithms. These two problems were addressed by replacing the aeroelastic analysis code by response surface approximations (Ganguli, 2002; Ganguli, 2004; Murugan and Ganguli, 2005) and through the use of genetic algorithms for optimization (Murugan et al, 2007). Ganguli (2002) showed that the second order polynomial response surface provide a good approach of decoupling the aeroelastic analysis problem and the optimization problem in helicopter rotor optimization. The objective function involved the six 4/rev hub forces and moments. The blade flap, lag and torsion stiffness were taken as design variables and move limits were imposed on them.

Murugan and Ganguli (2005) used a two level approach to solve the helicopter rotor optimization problem. The upper level problem involved design of the rotor blade to minimize vibration and enhance aeroelastic stability. The design variables of the upper level problem were flap, lag and torsion stiffness. The lower level problem involved designing a box beam to match the stiffness calculated by the upper level problem. The lower level composite box-beam design problem had discrete ply angle design variables. The upper level problem was computationally expensive and was solved using sequential response surface approximations. The lower level problem was solved using genetic algorithms.

Murugan et al (2007) studied the use of real coded genetic algorithms for the box-beam design problem. It is well known that binary genetic algorithms can handle discrete or integer design variables. However, it is also possible to use real coded genetic algorithms with some innovative crossover and other operators to solve optimization problems with discrete design variables. These real coded approaches can be more efficient than the binary coded approaches and are becoming increasingly popular in design optimization. Murugan et al (2007) created a highly efficient approach for composite structure optimization relative to the binary genetic algorithm. Also, it was shown that composite couplings and elastic stiffness could be tailored by ply angle variations using an optimization approach. A box-beam design problem using strength constraints was also studied using particle swarm optimization (PSO) (Kathiravan and Ganguli, 2007). Since the composite design space is multi-modal, it was found that better optimal points can be found using the PSO approach than using gradient based methods.

Approaches based on Taguchi orthogonal arrays were studied for rotorcraft optimization by Bhadra and Ganguli (2006). The aim here was to develop very computationally efficient response surface approximations to the aeroelastic analysis. The results showed that in many cases, orthogonal arrays can yield adequate metamodels. Also, orthogonal arrays allow for a rapid sampling of the design space which can be used to find a good starting design for a gradient based method or to simply obtain an improved design in a very short time. Metamodeling methods for rotating beams are typically based on polynomial response surface approximations. It was found that approximate analytical expressions for rotating blade frequencies could be obtained using the genetic programming algorithm from finite element models (Singh et al, 2007). This work opens up a new approach to developing close-form metamodels for rotorcraft and other optimization problems.

Murugan and Ganguli (2008) also studied the effect of different inflow models on the helicopter rotor optimization problem. Inflow models have an important effect on helicopter response (Shahmiri and Saghafi, 2009). It was shown that free wake analysis is a must for the accurate prediction of vibration and the optimization results change considerably based on the inflow model used. Different objective functions for vibration reduction were studied by using the min-max approach in multi-objective optimization and it was found that a direct application of real coded genetic algorithm to the helicopter optimization problem was possible.

Helicopter Control

Patel and Datta (1999) showed that polynomial H-infinity control theory can be used to design a robust controller for a CH-47 helicopter. They were motivated by the fact that an unaugmented (open loop except for the pilot) helicopter shows unacceptable responses in hover. The key problem is that the responses to the collective, longitudinal and lateral cyclic, and pedals are highly coupled and unstable in the hover condition. The numerical results of the study were analyzed with singular value plots showing that H-infinity method gave superior results. Pandian and Sinha (1999) presented new periodic control approaches for the control of the napping motion of a helicopter rotor blade in forward flight. The mathematical model used here was a differential equation with periodic coefficients. Optimal control theory was used in conjunction with Floquet theory to design full-state and observer-state feedback controllers. Another approach known as the Liapunov-Floquet transformation to the periodic system model was also used. It was shown that both these methods resulted in periodic control gains being expressed as explicit functions of time which permit a real time control scheme to be implemented.

(Vijaykumar et al, 2006; Vijaykumar et al, 2008; Vijaykumar et al, 2009) have explored the development of a feedback error learning neural controller for an unstable research helicopter. Three different neural aided controllers were designed to satisfy the ADS-33 handling qualities specifications in pitch, roll and yaw axes. The proposed controller scheme was based on the feedback error learning strategy in which the outer loop neural controller enhances the inner loop conventional controller by compensating for unknown non-linearity and parameter uncertainties. The basic building block of the neural controller is a Nonlinear Auto Regressive Exogenous input (NARX) neural network. For each neural controller, the parameter update rule was derived using Lyapunov like synthesis. An offline finite time training was used to provide global asymptotic stability and on-line learning strategy was employed to handle parameter uncertainty and nonlinearity. The theoretical results were validated using simulation studies based on a nonlinear six degree of freedom helicopter undergoing an agile maneuver. Realistic gust and sensor noise were added to the system to study the disturbance rejection properties of the neural controllers. The work clearly showed that the neuro-controller meets the requirements of ADS-33 handling quality specifications.

Kumar et al (2008) proposed a new method for rotorcraft parameter estimation which does not require any mathematical models. The proposed method calculates the aerodynamic derivatives using radial basis function neural networks. The method was first tested on simulated data generated from a nonlinear simulation model. Ideal (noise free) and noisy data was used and state and measurement noise were added to the simulations. The radial basis function approach gave results in the same range as obtained from conventional parameter estimation techniques such as the maximum likelihood method. They developed algorithms with real flight test data for the BO105 helicopter obtained from DLR, German Aerospace

Center, Braunschweig. The results obtained were compared to the published literature on the BO105 rotor and found to be in good agreement.

Helicopter Dynamics

Rotating beams are key structural components of helicopter rotor blades, wind turbine blades, gas turbine blades, robotic arms etc. Approximate methods such as the finite element method are widely used in the modeling of rotating beams. There is a need to reduce the size of the rotating beam mathematical model; that is to solve for the frequencies and other dynamic parameters by using low degree of freedom systems. Accurate frequency predictions with smaller problem size can be obtained using innovative basis functions. Gunda and Ganguli (2008a) have explored the stiff-string basis function and Fourier-fem (Gunda et al 2007) for faster solution of the rotating beam eigenvalue problem. The stiff-string basis function occurs as a special case of the rotating beam equation when tension is constant. The assumption of constant tension may be a bad assumption for the entire rotating beam but can be a good approximation at the element level if the beam is divided into several finite elements. Numerical results in Gunda et al (2008a) showed that the stiff string functions perform better for the fundamental rotating frequency and at high rotation speeds.

In the Fourier-fem approach, Gunda et al (2007) combined polynomials with trigonometric shape functions and used these as basis functions for developing a single element which can be used to model the rotating beam. The advantage of this approach is that variations in the flexural stiffness and mass distribution can be easily accommodated and a low number of degrees of freedom are needed. In Gunda et al (2009), an effort was made to satisfy the static part of the governing differential equations for rotating beams. This lead to rational functions as basis functions which performed well for most cases but suffered from singularity problems in some situations. While the shape functions in this study performed well in numerical results, they violated some conditions of constant coefficients for basis functions. In general, it was found that attempts to improve the convergence of the first rotating beam mode resulted in poor performance for the higher modes. This happens because the first mode is more sensitive to the centrifugal stiffening effects and the higher modes on flexural effects.

In a recent work, Gunda et al (2009) combined the cubic polynomials and the stiff string basis functions to develop new hybrid basis functions for finite element analysis. The hybrid basis functions performed very well for both the fundamental mode and the higher modes and resulted in a considerable reduction in problem size in terms of degrees of freedom. (Vinod et al, 2006; Vinod et al, 2007) studied the wave propagation characteristics of rotating beams and devised an extremely efficient approach for finding the natural frequencies of such problems using spectral finite elements. The spectral finite element can find the frequencies of higher modes using a few elements while the conventional finite element method may needs hundreds of finite elements.

In a fundamental contribution to the dynamics of rotating beams, Ananth and Ganguli (2009) showed that there exist flexural stiffness functions for which the rotating beams yield the frequencies and mode shapes of a uniform non-rotating beam for a given mode. These functions can be used as test functions for any rotating beam code and was shown for both h-version and p-version finite element formulations. In another work, the flapping equations of a rigid helicopter blade were developed without making any small angle assumptions and using nonlinear aerodynamics (Majhi and Ganguli, 2008) and dynamic stall (Majhi and Ganguli, 2010). The limitation of using small angle assumptions in cases of high thrust and for climbing flight was brought out.

A significant contribution of research in recent years is in uncertainty quantification in rotorcraft aeroelasticity. It is known that all system modeling suffers from aleatory or random uncertainty and epistemic or model uncertainty (Rodzewicz, 2008). Almost all research in helicopter dynamics focuses on improving the structural and aerodynamic modeling. However, the random uncertainties cannot be reduced by improved modeling. (Murugan et al, 2008a; Murugan et al, 2008b) made a beginning in research in this area by studying the effect of uncertainty in composite material properties on the rotor blade frequencies, blade response, vibration and aeroelastic stability. Composite materials have a high level of scatter with a coefficient of variance ranging from 5-12 percent for the Young’s modulus, Poisson ratios and shear modulus. Monte Carlo Simulations were used for these numerical results (Dogan, 2007). Figures 16 and 17 show the dispersion in flap and torsion tip response around the rotor disk, respectively. It can be observed that there is considerable dispersion in the predictions from the baseline deterministic value. It was also found that the effect of uncertainty is considerable, particularly on vibration and stability. In fact, vibration predictions show a high level of sensitivity to uncertainty as they come from higher harmonics of the rotor response and blade loads, which are themselves very sensitive to uncertainty. The lack of good predictions of helicopter aeroelastic analysis with experimental data may not be only due to modeling deficiencies of an epistemic nature but could also come from uncertainty in the material, geometric, aerodynamic properties as well as in the boundary conditions. Monte Carlo simulations were found to be very computationally expensive for the helicopter aeroelastic analysis problem. Future work should address more efficient approaches such as the use of metamodels for the aeroelastic analysis and polynomial chaos expansions.

Pohit et al (2000) addressed the issue of limit cycle oscillations caused by elastomeric damper models in a bearingless helicopter rotor blade. The transient response of the blade was studied using two different models for elastomers. They found that even when both the elastomer models fit the data very well, the response of the blades was quite different. The authors concluded that care should be taken when selecting elastomer models.

Figure 3 Monte Carlo simulation of normalized blade tip flap response showing the dispersion caused by uncertainty in composite material properties (w is tip flap displacement, R is blade radius)

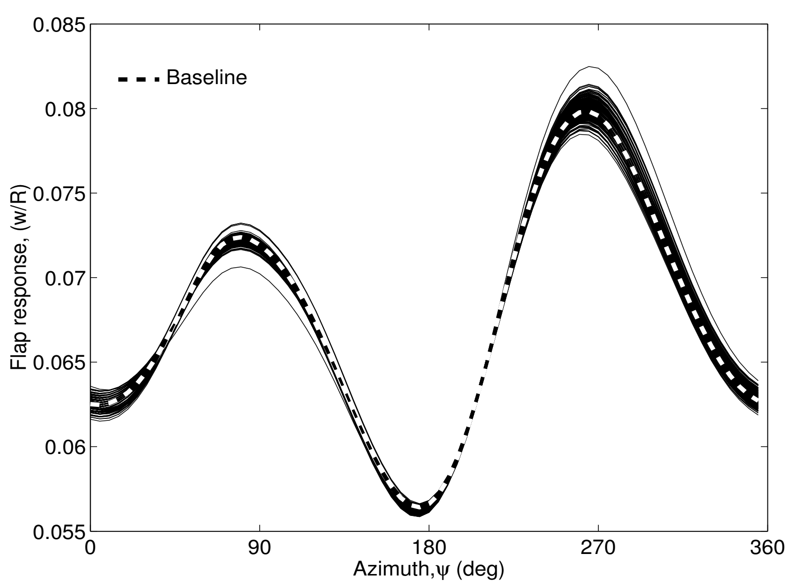
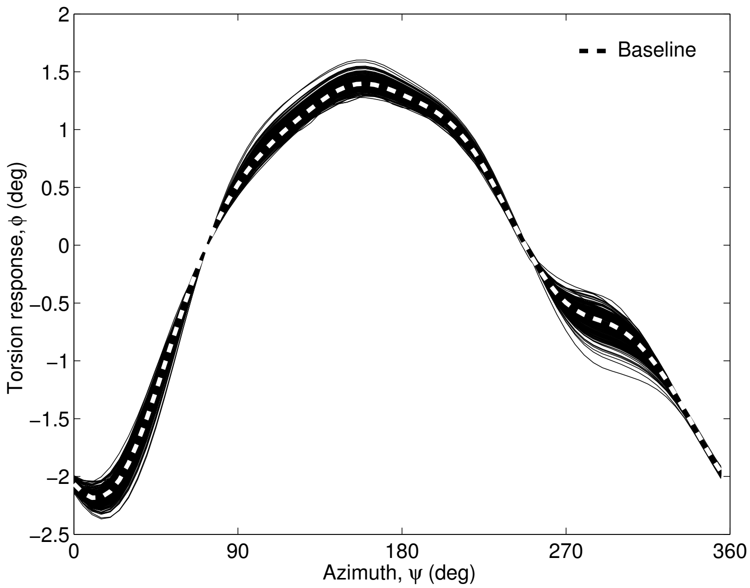


Figure 4 Monte Carlo simulation of blade tip torsion response showing the dispersion caused by uncertainty in composite material properties



Active Control of Structural Response

While the rotor is a key source of vibration, the effects of the transmitted vibratory loads on the fuselage are the means by which vibration is felt by the pilot and passengers. Therefore, attempts to predict and reduce vibration levels on the fuselage have been an area of research (Cribbs et al, 2000; Bauchau et al, 2004). Laxman and Venkatesan (2007) tried to understand the reasons behind the existence of a wide spectrum of frequencies in flight test data for fuselage vibration. They analyzed the effects of dynamic stall and aeroelastic couplings on the response of a 2D airfoil. The simple model was used to bring out the physical phenomenon of bounded chaotic motion. It was found that nonlinear aerodynamics such as dynamic stall effects and aeroelastic couplings are the root cause behind the bounded chaotic motion and may explain the presence of sub-harmonic frequencies in the fuselage vibration.

Mathews et al (2002) addressed the problem of vibration reduction in the helicopter fuselage using active control of structural response. The authors mention that while rotor based active control approaches aim to reduce the blade loads in the rotating frame; the active control of structural response (ACSR) is employed in the non-rotating frame to cancel the effects of vibratory hub loads on the fuselage. The ACSR concept uses the fact that the superposition of two independent responses of a linear system can be tailored to yield a zero total response. Typically, the rotor loads are transmitted to the fuselage through a gearbox support structure which can be modeled as a spring, damper and control force generator. In ACSR, the control force generator can be an electro-hydraulic actuator, an electromechanical actuator or a smart piezoelectric actuator. There are three key problems in the design of an ACSR system which the authors addressed in their paper: (1) selection of sensor locations for vibration measurement (2) selection of actuator location and (3) development of closed loop controller for vibration reduction. The authors considered a coupled gearbox-flexible fuselage system in this study and pointed out that the influence of sensor locations on vibration reduction is significant. A closed loop controller was developed to remove the external disturbance and reduced the vibration level both in the fuselage and the gearbox. They also showed that closed loop control reduces both fuselage and gearbox vibration, which is not the case in open loop control.

Venkatesan and Udayshankar (1999) addressed the helicopter vibration problem using the concept of active control of structural response. They derived the equations of motion for the dynamics of a coupled gearbox-fuselage model. Optimum sensor locations were obtained using a mathematical method based on the Fisher information matrix. This method seeks to eliminate sequentially the redundant sensors from an initial set of many candidate sensor locations. Such formal mathematical methods for sensor placements are needed for complicated 3D structures such as the helicopter fuselage. A control problem was formulated and solved to get the active control forces needed for vibration minimization in the helicopter fuselage using the measurements at the optimal sensor locations. It was found that vibration control using measurements from the optimal sensor locations provided greater reductions in the *g* levels compared to arbitrary placed or non-optimal sensors.

Conclusion

Helicopter research and development in India has made enormous strides in the past two decades. This paper has summarized the published research contributions. The key findings and accomplishments of basic research from India to the state-of-the-art in helicopter engineering can be summarized as follows:

1. Dynamic hysteresis nonlinearity caused by piezoelectrically actuated trailing edge flaps can considerably reduce the performance of harmonic optimal controllers used for helicopter vibration control.
2. Algorithms have been proposed which use all the flaps to full authority for the optimal control of helicopter vibration using multiple trailing edge flaps.
3. Optimal locations have been found along the rotor blade where placement of multiple trailing edge flaps can reduce both vibration and flap power.
4. Polynomial response surfaces and stochastic optimization methods offer an innovative combination for the robust design of low vibration composite rotor blades which are aeroelastically stable. The problem of numerical fragility in helicopter aeroelastic analysis can be avoided by using response surface metamodels.
5. Composite material uncertainty has a significant impact on helicopter aeroelastic response, vibratory loads and stability. These effects may be a cause of the poor comparison of aeroelastic analysis with flight test data and may also be indirectly linked to the high level of helicopter accidents which can occur due to minor changes in rotor properties among different manufactured blades.
6. Nonlinear aerodynamics such as dynamic stall effects and aeroelastic couplings can cause bounded chaotic motion and lead to sub-harmonic frequencies in fuselage vibration.
7. Closed loop control and optimal sensor location achieved using the Fisher information matrix method can significantly increase the vibration reduction obtained using active control of structural response.
8. A health monitoring system for composite helicopter rotors was proposed by addressing the damage mechanisms of matrix cracks, delamination and fiber breakage. This is the first health monitoring system to specifically address composite rotors.

9. Efficient finite element analyses for rotating beams were developed using new basis functions which seek to satisfy the governing differential equations of the problem.
10. Rotating beams which share an eigenpair with uniform non-rotating beams have been found.
11. A discontinuous time finite element for helicopter rotor dynamics problems has been developed. This algorithm is capable of adaptive refinement in the time domain for the accelerated solution of rotor response.
12. Neural controllers for helicopters have been developed to satisfy the ADS-33 criteria. System identification methods based on recurrent neural networks have been developed.
13. A model free rotorcraft parameter estimation method has been developed where control and stability derivatives are calculated using radial basis functions.

This paper has shown that there is a surge in basic research on helicopter engineering among the academic institutions. Most of the basic research has addressed problems in helicopter dynamics and control. There is a need to address helicopter aerodynamics and aeroacoustics in basic university research. Most of the research has focused on mathematical and computational modeling of physical phenomenon which take place in helicopters. There is a need to increase experimental work. Increased international collaboration with research centers at other universities in these areas will be useful. There is also a need to study and develop micro helicopters for use in agriculture and reconnaissance. For instance, a low cost helicopter for spraying fertilizers and pesticide in farms will be useful for increasing farm productivity. International helicopter companies should also consider India as a research, development and manufacturing base for the development of cost-effective helicopters. Considerable investments on simulators, pilot training and maintenance facilities are also seeded to spread helicopter usage in India and to increase the number of helicopter operators.

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