SMART STRUCTURES FOR HELICOPTERS

by
S. Hanagud*, G.L.N. Babu', C.C. Won and M.B. Obal**
Georgia Institute of Technology
Atlanta, Georgia, 30332-0150 USA

Abstract

In this paper, applications of smart or adaptive structure concepts to helicopter structures are discussed. Definitions of smart, adaptive or intelligent structures and their application to vibration suppression, health monitoring of structures and possible performance improvement are discussed. Available sensors, actuators and their application to a specific problem of health monitoring, a specific problem of vibration control by use of the concept of adaptive structure are presented.

Introduction

During the past few years, research workers in the areas of structural mechanics, materials and controls are attempting to define, analyze, develop, test and produce smart structures (1-12). Other adjectives such as intelligent and adaptive have been used to describe these structures. In one of the early definitions (1,2) smart structures are defined as those structures that contain their own sensors made of intelligent materials, signal detection circuits, identifiers, controllers, the necessary computational capabilities and actuators made of intelligent materials. The current definition of an intelligent structure is to be able to design a structure that will behave like a human being. For example, a cut on the finger of a human being is felt immediately and its location is immediately known. Depending on the serious nature of the cut, an appropriate action is taken to either ignore the cut or seek appropriate cures. On the other hand, many cracks developed in a helicopter airframe can be detected, only to a certain level of probability, during certain field or depot inspections. An example of the possible intelligent system is an airframe structural system that can use smart sensors to health monitor the system to detect cracks or other flaws and depending on their sizes, location and critical crack sizes, where applicable, and make decisions concerning actions such completion of the mission, repair or other options.

* Professor

' Graduate Student

** Dr. Obal's contributions were made when he was a graduate student at Georgia Tech. He is currently with U.S. Air Force.

Another example of a smart structure which can be more precisely described as an adaptive structure and fits one of the early definition of the smart structure is that of a composite beam type of structure with embedded or bonded piezoceramic or other types of smart of intelligent sensors, piezoceramic or other types of smart actuators, and embedded units that can be used to filter the detected signal, condition this signal by operations such as phase shift and amplification before feeding back to the actuators. This type of smart structure was primarily used to control or suppress vibrations in the parent beam structure. Intelligence, smartness or an adaptive capability is provided by the use of either suitable materials or algorithms. The intelligence of the material is programmed through the choice of material composition, processing, incorporation of appropriate microstructure or selected methods of conditioning. The intelligence is introduced into algorithms by using artificial intelligence techniques or the concepts of neural networks. Through these concepts, reasoning, decision making, learning and searching are introduced into the algorithm.

The example discussed in the previous paragraphs represents an application of the concept of smart structures to control of flexible bodies including vibration suppression. More precisely, we can define this as an adaptive structure. Other applications of the concept of smart adaptive or intelligent structures include (a) health monitoring including flaw detection and control of flaw growth, and (b) improvement of different aspects of the helicopter performance by the use of adaptive actuators for operations such as shape control.

As can be seen from these discussions, an analysis and design of adaptive or smart structure to meet certain specified design objectives, needs the selection of appropriate materials for use as sensors and actuators, an understanding of the modelling process of a given structure with these smart sensors and smart actuators, computational capabilities and hardware to implement control or other algorithms to achieve the desired objectives of vibrations suppression, flaw detection and control, or the desired performance improvement.

Smart Sensors and Smart Actuators

The field of smart structures is a multi-disciplinary field. Among the different fields involved, there is a considerable amount of research and developmental activity in the area of smart sensors. For example, biophysicists are studying the mechanisms involved in a human sensor so that these mechanisms incorporated in a smart sensor that can be used in a structural system. However, at present, a structural engineer has to use sensors that are available. Some of the smart sensors and actuators that are being used in a smart or adaptive structural development include piezoceramic devices, PVDF films, shape memory alloys, electro-rheological fluids, fiber optic devices, and electrostrictive devices.

Piezoceramic and Electrostrictive Devices

Piezoelectricity was first discovered by the Curie brothers. (13) This work led them to look at the electrification of crystals upon the application of pressure. The converse piezoelectric effect, which is the change in crystal dimensions upon the application of an electric field was first theoretically predicted by Lippman and in the same year verified by the Curies. (13) Later investigators established the relationship between piezoelectricity and the crystalline structure of various materials.

The first practical application of the piezoelectric effect was for the development of acoustic waves in fluids. Quartz crystalline material was initially used until the development of the ferroelectric class of materials. (13) The term ferroelectric is used to describe a material which does not have a center of symmetry or electric diapole moment above a certain temperature called the Curie temperature. (14)

The single most important factor of the ferroelectric's over other piezoelectric materials is that they have a higher electromechanical coupling. Electromechanical coupling is defined as the amount of deformation achieved per field strength applied to the piezoelectric material.

Ferroelectric materials contain both organic and inorganic compounds. The piezoceramic ferroelectric materials are used in this investigation for structural control applications. The constitutive relationships for piezoceramic material have been discussed by a number of investigators over the years and compiled by the IEEE and the Electronic Industries and American Standards Association into standards. (15, 16) One of the most serious disadvantages of piezoceramic ferroelectric type materials with reference to this application is the sensitivity of their piezoelectric properties to changes in temperature. Berlincort (17) has discussed the relationship of the performance of selected piezoceramics with temperature and other environmental factors. Doping of piezoceramics with lead and other elements helps to stabilize these parameters over a wider temperature range. The lead zirconate titanate (PZT) type piezoceramics have proven to be the most promising compounds for stable piezoelectric properties and mechanical behavior over a temperature range that includes -22 to 150 degrees C.

The electrostrictive or magnetostrictive effects in some materials can perform the same function as the converse piezoelectric effect. Electrostriction is related to a material change of shape upon the application of a large electric field. Usually the change in shape is very small and until recently was considered as a second order effect. W.P. Mason (18) has studied the electrostrictive effect in nonpolarized ferroelectric type ceramic of materials. According to Mason the electrostrictive effect is quite large when compared to the corresponding converse piezoelectric effect of the same polarized material. One of the advantages of electrostrictive actuators is that they do not exhibit hysteresis effect common to piezoceramic type materials (19). This feature may make electrostrictive ceramics to be more suitable as driving devices for vibration control.

Some of the applications of piezoceramics can be classified as quasistatic applications, dynamic applications with resonating piezoceramics and non resonating dynamic applications (14). Most of the work involving quasistatic applications is in the area of adaptive optics (20-27). Dynamic applications with resonating piezoceramics have been primarily used in creating acoustic surface and bulk waves (28-33). Non resonating dynamic application are mostly in the area of transducers and only recently, non resonating dynamic applications have been in the area of active control of flexible structures.

Electronic Damping

One of the earliest known uses of piezoceramics to active control of structures is attributed to olsen (34). In this work he proposed an electronic vibration reducer consisting of a piezoelectric driver and sensor attached to a structure with a suitable feedback amplifier.

Another early example of this type of control is by Mckechnie (35) who has used piezoceramic sensors in a specially built accelerometer to drive a forcing piezoceramic to reduce the resonant response of an accelerometer. This experimental results indicate a reduction in the predicted peak response by thirty percent.

The first application to the active control of a structure is due to Forward (36) who has investigated the vibration control of a mirror subjected to acoustical excitation of its resonances. One piezoelectric transducer has been used to sense the vibrations and its output has been conditioned by a negative feedback amplifier to drive another spatially separated transducer. The vibration response of a single mode of the optical structure was reduced significantly.

Forward and Lui (37) have also demonstrated additional applications of "electronic damping" to control resonances in gimbal torquer control loops where they reduced the peak response of a gimbal torquer loop at various modal frequencies corresponding to gimbal mechanical resonances. This was accomplished by using small piezoelectric strain transducers to provide signals into a summing junction in the torquer control loops. Forward and Swigert (38) have applied an "electronic damping" system to reduce orthogonal bending modes in a cylindrical satellite antenna mast. The application of piezoceramic sensors and actuators to reduce the amplitude of response of two problem modes in a large composite optical bench has been reported in reference (39). One piezoelectric ceramic strain transducer has been used as a sensor, and ten others were wired in parallel as a combined driver in a velocity feedback loop. In a recent work, Crawley (40), has presented a mechanics coupling type of model for a piezoceramic bonded to a small cantilever beam. The model predicts the first mode dynamic response of a beam when driven by the piezoceramic transducers.

An examination of the response literature in the field of active control of systems with piezoceramic sensors and actuators has revealed the following. A consistent analytical model does not exist for an active structure with piezoceramic or piezoelectric sensors and actuators that occupy selected subdomain of the structure. The problem of identification of the dynamic characteristics of an active structure from measurements of time histories of appropriate input and output has not been explored. In particular, a significant problem of practical importance is the identification of dynamic characteristics of an active structure with non collocated sensors and actuators. Procedures for the identification of system parameters such as electromechanical coupling does not exist. The problem of optimal control (2) of structures with piezoceramic sensors and actuators has not been thoroughly examined. Only the problem of "instantly optimal" control of a structure with a single PVDF actuator and a conventional accelerometer sensor has been explored (1).

PVDF Films

Polyvinyldene fluoride (PVDF) films can be described as flexible and light weight polymeric materials with piezoelectric properties. The piezoelectric properties of PVDF films was reported by Kawai in 1969. PVDF films are available in large sheets and can be integrated into structure by bonding or embedding. Thin films can be stacked to optimize the sensing capabilities. Also, these sensors have the potential of providing strains of an order of magnitude larger than the piezoceramic devices. However, these large strains are achieved by applying a much larger electric field.

Shape Memory Alloys

The shape memory phenomenon occurs in some alloys of nickel-titanium family. The shape memory phenomenon is attributed to a matensitic phase transformation. For example, a shape memory wire can be stretched by an amount of 4 to 5% of its original length by using a force of approximately 10,000 psi at a temperature below the characteristic transformation temperature of the particular shape memory alloy (1). When this wire is heated through the transformation temperature the wire shortens by the same amount of 4 to 5%. If the wire were bonded to a structure the change in the length of the wire with memory can be used to either change the shape of the structure or act as an actuator and transmit energy to the structure. The transformation temperature of the nickel-titanium alloys an designed to very over a range of temperatures. At present the range is from cryogenic temperatures to a value slightly larger than 100 degrees centigrade. A commercial alloy, known as Flexinol, has transformation temperature in the range of 80 to 100 degrees centigrade.

Electro-Rheological Fluids

The term electro-rheological fluid is used for a class of suspensions of selected micro-sized hydrophilic particles in a selected hydrophobic carrier liquid. When an electric field of the order of 2kv/mm is imposed on these fluids, the random distribution of the suspended particles change and the particles align themselves in a regular chain - like columns. If these electro-theological fluids are incorporated in a structure (for example a beam like structure) and an electric field is applied to the ER fluid, the resulting columnar structure has the effect of adding additional damping and stiffness to the structure (7).

Flaw Detection and Control

At present, inspection of flaws or cracks in a helicopter structure is accomplished during scheduled field or depot inspections. With a smart structure, one would like to accomplish the detection of flaws automatically by using smart sensors that are embedded or bonded to the structure at various critical locations. Then, the long range objective will be to (a) assess the residual strength of the structure and the remaining life of the structure in making decisions concerning the present mission, future missions, and repair options, and (c) implement any available control procedures to retard crack growth. In this section only options for flaw detection by using smart sensors are discussed.

In general, flaw detection means detection of cracks, major structural damage including battle damage, and corrosion effects. Some of the mechanisms responsible for these damages are fatigue, stress corrosion, corrosion, impact and maneuvers exceeding the design envelope. As applied to composites, the subject of flaw detection reduces the detection of delaminations, fiber breakage, and matrix cracking. At Georgia Tech, we have been studying the theoretical foundation and experiments for qualitative and quantitative detection of delaminations in graphite - epoxy composites by using embedded or bonded piezoceramic actuators and piezoceramic sensors (smart sensors and smart actuators). Some of the results of our investigations are presented in references (42 - 44). A brief summary of these works is presented here.

For example, in critical locations of an air frame structure, where delaminations are likely to occur, we would like to have piezoceramic devices bonded or embedded in a predetermined arrangement. One of the properties of piezoceramic devices is that each of the piezoceramic device can be used as either a sensor or an actuator. In order to explain the theory and practical methods of detecting these flaws a delamination in a beam like structure, as shown in figure (1) is considered.

A dynamic finite element model with appropriate boundary and interface condition of the beam with delaminations and an eigen analysis shows that there are certain natural frequencies and modes associated with delaminations in addition to the usual natural frequencies associated with the beam without these delaminations. In a specific cantilever beam that we studied, there was a delamination mode between the fourth and the fifth mode. For a specific cantilever beam a comparison of the calculated natural frequencies with without a specific size of delamination is presented in table No. 1. It is noted that in addition to a new mode associated with the delamination, other natural frequencies also change when a delamination is present. As the size of the delamination decreases, effects on other natural frequencies decrease and the magnitude of the delamination natural frequency increases.

In order to experimentally detect these changes of the dynamic characteristics, it is necessary to measure dynamic responses for specific loading conditions imposed on the structure by piezoceramic or other types of smart actuators. The dynamic response of a beam with a delamination is nonlinear because the two segments of delamination can impact each other during a dynamic excitation and provide the effect of elastic or inelastic stops restricting the amplitude of oscillations. The nonlinear dynamic response has been calculated for a cantilever beam with a twenty percent delamination (40-44). The response has been later measured experimentally by using a piezoceramic sensor. First, the results of the calculation of the dynamic response are summarized.

A graphite-epoxy fixed beam of length 0.1 m is considered. The beam is made of 60 plies arranged in a 0/90/0 lay-up. The effective thickness the beam is 0.006m. It is assumed that a delamination of a length 0.02m exists at a depth of 12 layers from the top and is centrally located along the length of the beam. A dynamic finite element model has been formulated by considering both the transverse and axial displacements. In a delaminated beam it is necessary to consider axial displacements in addition to transverse displacements to assure the compatibility of the deformed beam. Details of the modelling and solution procedures are discussed in reference (41) by Nagesh, Babu and Hanagud. Various times at which the two segments of the delamination start to impact with each other, duration of the impact, velocities, accelerations and stresses during these impacts, times at which the two segments again separate have been determined by comparing the displacements of appropriate nodes, impulse - momentum balance of appropriate elements, and an energy balance.

It is assumed that a unit impulse is applied at the node 2 (figure 1). An output detected by piezoceramic sensors located at elements 4-5, 6-7, 14-15, are calculated. As discussed by Hanagud, Obal and Calise (2), a piezoceramic sensor with a detection circuit measures a signal that is proportional to the difference of the time rates of changes of slopes of transverse displacements of the end points of the sensor. For example, a piezoceramic sensor located between nodes 6 and 7 can detect an electric voltage (2).

$$v(t) = Ks\ (w,x_7 - w,x_6)$$

In figure 1, the calculated signals are shown at locations 7-8, for a perfect beam and for a beam with 0.02m delamination. The difference between the responses at location 7-8 on top of the delamination can be easily seen in this figure. In order to obtain an estimate of the magnitude of the delamination, a frequency response function from the time domain response are calculated at nodes 4 and 7. The frequency response functions are shown in figures 2 and 3. Additional frequency and nonlinear effects can be seen in these figures.

By using the results of the theory, tests have been conducted by Hanagud, Negash Babu and Won on a cantilever beam to demonstrate the feasibility of detecting delamination in composite beams (42). Tests were conducted on three composite beam specimens prepared by using T300/f934 graphite-epoxy tapes. Each beam had 12 layers with a stacking sequence of 0/90/0. All beams had dimensions of 18.8mm x 1.8mm x 254mm. One of the three beams was a control beam and two other beams had delaminations of lengths 63.5mm located symmetrically at the center of the beam. The piezoceramic sensors are located as shown in the figure 4. Results of the tests and a comparison with the analysis is shown in the figure 5 and table no. 2. The magnitude of the additional frequency detected indicates the size of the delamination.

Vibration Control

In many helicopter designs, aeroelastic effects may limit the operational flight envelope, add weight penalty, reduce the fatigue life, and cause crew and passenger fatigue. In particular, we would like to address the problem of the oscillatory loading transmitted to the fuselage. The oscillatory loading increases with the forward speed. In addition to many different approaches like the use of different tip geometries, hingeless and bearingless rotor construction, optimization of roto blade, hub and airframe structural dynamic characteristics, and use of vibration absorbers, several active control schemes have been examined. The concept of adaptive structures can play a significant role in the area of active control.

Higher harmonic control (HHC) and the individual blade control constitute two of the approaches that have examined in detail. In addition to the collective and cyclic pitch changes, higher harmonic pitch changes through the swash plate (44 - 53). While the collective and cyclic inputs are used to control the primary parameters, such as life, thrust and trim, the higher harmonic inputs can be used to reduce or cancel the oscillatory loading transmitted to the fuselage under steady flight conditions. In the individual blade control (IBC), the individual blade root pitch is changed. By using such control inputs at the blade root, IBM procedures have been developed to augment hingeless rotor stability, to suppress ground resonance and to improve in plane stability of articulated rotors. A recent review of the IBM can be seen in reference (54). Ham (55) and his coworkers have discussed a modal decomposition approach, McKillip (56 - 59)has developed an optimum full state feedback procedure, and Wasikovsky, Calise and Schrage have developed an optimum output feedback procedure.

The problem considered here is to use an adaptive structure concept to reduce vibrations at selected locations of the airframe. At different locations of the airframe, the observed vibrations result from (a) the oscillatory loads transmitted by rotor systems to the airframe, (b) the elastic stiffness of the airframe structure, (c) the mass distribution and (d) damping characteristics. The approach is (a) to use smart actuators to reduce or cancel the oscillatory loads transmitted to the airframe and (b) introduce additional damping and change stiffness at critical airframe structural locations by means of smart actuators. We would like to approach both these problems from a point of view of optimum control.

The details of the analysis will be discussed in another paper. Only a simple problem that considers the introduction of additional damping is discussed in this paper. Specifically the problem considered is that of an active control of a vibrating elastic beam by using piezoceramic sensors and actuators and an output feedback. Results are presented for a case where optimum gains have been obtained by minimizing a quadratic performance index.

An example of a cantilever beam has been considered to illustrate the developed procedure for optimal vibration control of structures by the use of piezoceramic sensors, actuators and rate feedbacks with appropriate gains. The cantilever beam is of length 22.86 cm and cross sectional dimensions 1.65 cm x 0.44 cm. The beam is made of an aluminum alloy. Two piezoceramic transducers made of lead zirconate titanate (g1195) of sizes 1.91 cm x 1.91 cm x 0.02154 cm and 3.9;6 cm x 0.02154 cm have been selected for use as collocated sensors and actuators as shown in Figure 1. In this study. sensor and actuator pairs have been assumed to be at given locations. Optimization of the sensor/actuator placement has not been considered. A finite element model with ten degrees of freedom has been initially formulated of the open loop beam without feedback. In the current state of the art, the desired finite element model does not contain the values of the damping matrices. An assumed linear viscous damping matrix has been determined from tests conducted on the beam and a structural dynamic system identification procedure. The first ten eigenvalues, ten eigenvectors and an a priori model are required in the use of the selected identification procedure which is based on the equation error approach. The derived finite element model has been used as an a priori model. laboratory tests have been conducted and the required eigendata have been obtained using a GENRAD computer aided data acquisition system and SDRC modal plus software. The identified model resulting from the identification algorithm yields the experimentally obtained eigendata and asymmetric damping matrix. This damping matrix has been noted as the baseline matrix in the proper to distinguish it from the augmented damping matrix due to an active control input vector to the piezoceramic actuators.

Three different types of weight have been selected. The diagonal elements of the weighing matrix are inversely proportional to the square of the eigenvalues, inversely proportional to the eigenvalves and an identity matrix. Optimal gains have been obtained (2) for cases in which off diagonal terms have been penalized and cases where off diagonal terms have not been penalized. The latter case corresponds to the case where each sensor output fed back to both actuators with appropriate gains.

Figure 2 is the time history of an open loop sensor output at x = 16.60 cm. Figure 2 is the corresponding closed loop time history of sensory output when off diagonal terms have been penalized. Figures 4 and 5 are closed loop time histories for sensor output and tip velocity for systems with cross feedback, where it is not necessary to penalize the off diagonal terms.

Conclusions

In this paper, only a very brief sketch of the possible applications of the concept of smart or adaptive to helicopters are discussed. There are many other applications possible including the possibility of improving the performance of the helicopter. At Georgia Tech, we have studied some of these problems are we are actively studying some. A carefully conducted research and development program offers a significant amount of benefit to the rotor craft technology. During the past few years, there is a significant amount of attention given to this subject. Such an attention and eagerness towards immediate commercialization may hamper the progress in this field.

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Table No. 1

Frequencies With and Without Delamination (Analysis)

Mode No.	Frequencies (Hz) Without Delamination	Frequencies (Hz) With Delamination
1	32	27.62
2	200.25	143.80
3	561.57	471.88
4	1100.66	944.45
5	1819.47	1424
6	2718.00	1632

Table No. 2

Comparison of Frequencies From Experiment and

Theory For Delamination Beams

Mode No.	Analysis Frequencies (Hz)	Expt Freqnencies (Hz)
1	27.62	24
2	143.8	174
3	471.88	456
4	944.45	972
5	1424	1356
6*	1632.92*	1760*

*Delamination Modes

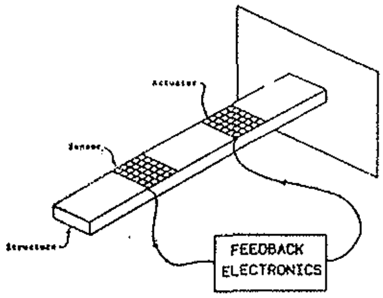

FIGURE 6. ACTIVE CONTROL OF STRUCTURES WITH PIEZOELECTRIC ACTUATORS AND SENSORS

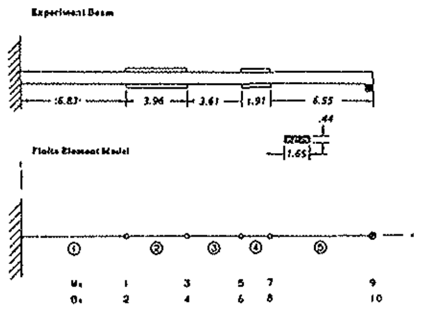

FIGURE 7. TEST BEAM'S COLLOCATED SENSOR AND ACTUATOR LOCATIONS.

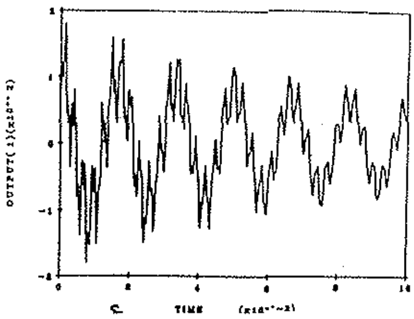

FIGURE 8. TIME HISTORY OF SENSOR #1 OUTPUT, NO CONTROL

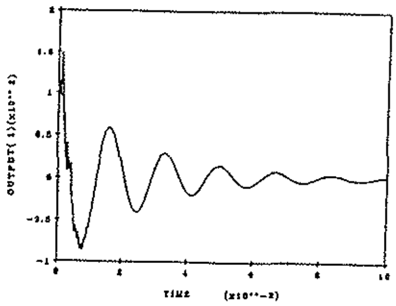

FIGURE 9. CLOSED LOOP TIME HISTORY OF SENSOR#1 OUTPUT FOR GENERAL GAIN MATRIX WITH CROSS FEEDBACK.

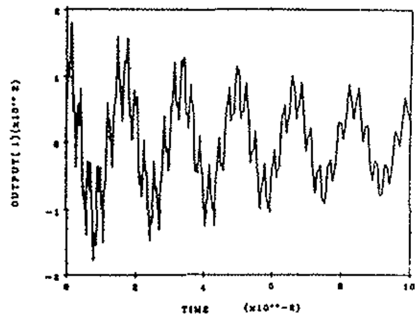

FIGURE 10. TIME HISTORY OF SENSOR #1 OUTPUT FOR PENALIZED ODT GAIN MATRIX

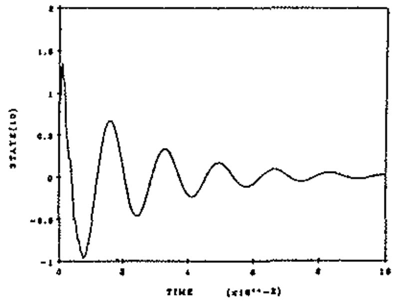

FIGURE 11. CLOSED LOOP TIME HISTORY OF TIP VELOCITY FOR GAIN MATRIX WITH CROSS FEED-BACK