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SENSORS FOR A SMART ROTOR BLADE SYSTEM

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ABSTRACT

A smart rotor blade system that uses shape memory alloy actuators and strain gage sensors on the rotating blades is proposed. The actuator is an active component used to achieve a camber change in a NACA 0012 airfoil. The camber changes are used to provide a collective control for a two bladed model helicopter. This means the collective control is moved to the individual blades. A data transmission mechanism that transfers measured data from the rotating blades to the fixed system where the controller is located is proposed. A two actuator control system with consideration of time delay has been designed using μ synthesis - a robust control technique.

1. INTRODUCTION

Most of the current day helicopters[1,2] use very complex mechanical systems to achieve the required lift using a stationary swash plate, a rotating swash plate, pitch links to connect the rotating swash plate to the helicopter blade and numerous bearings to allow the rotor head to spin freely and the rotor blade to pivot about it's feathering axis. Alternatively, collective control can be moved to individual blades and generate the required lift by camber changes of the rotor blades. Changing the camber of an airfoil by bending some part of the airfoil downward at a hinge point is a very simple and effective method for providing the lift. The objective of this research is to use the concepts of smart structures to replace the conventional collective control that is currently used. The camber change is achieved by deflecting the trailing edge of the airfoil with a shape memory alloy actuator. Potential improvement to performance by implementation of the individual blade control to alter the cross section shape and blade twist, the potential improvements to reliability through reduction in the number of moving parts and maintainability through a reduction in the mechanical complexity of the actuation system are some of the motivations for the current work.

We selected a two blades baseline helicopter of length 35 in, width 8 in and weight of 108 oz and incorporated many modifications. Internal combustion power plant is replaced by an electric power plant. Airframe of the helicopter is modified to integrate the electric motor into the airframe. An electronic speed controller is located in the downwash of the main rotor to regulate the motor speed. A heat sink is added with fins to remove the heat from the speed controller. Thermal problems of the motor are reduced by adding a cooling fan to the bottom output shaft of the motor. A NACA 0012 standard motor blade with 2.5 in chord is originally used in the base line helicopter. Smart structures concepts are introduced in the modifications of the blades. Conventional swash plate system is replaced using shape memory alloy actuated system. The standard blade is modified by cutting a control surface into the blade. The control surface is located 4 inches from the tip of the blade. The spanwise length of the control surface is 8 inches and the chordwise length is 40 percent of the airfoil chord or 1 inch. A plastic hinge is glued to the top surface of both the control surface and the blade to attach the two pieces. Shape memory alloy (SMA) wire is introduced into the control surface. Design configuration of the control surface and the shape memory alloy actuation element is shown in Figure 1. Based on this figure, when the SMA wire is heated, it will contract pulling the free end point "A" of the actuator lever arm forward. As the free end of the actuator lever arm moves forward, the portion between the points "b" and "C" will rotate clockwise and the embedded end point "D" of the control surface lever arm will move downward.

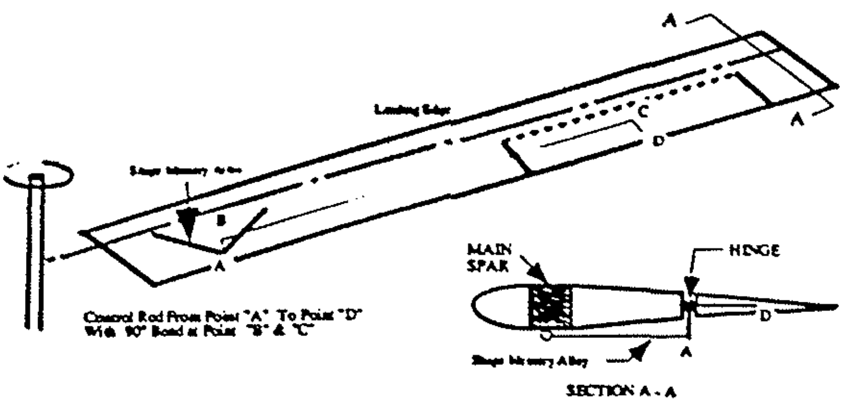

Figure 1: Adaptive Airfoil with Shape Memory alloy

These modifications are made after a series of wind tunnel, ground and flight tests. During these tests, many problems are identified and corrected [3-8]. One of the problem that still exists include the generation of same amount of lift in hover or vertical flight by all the rotor blades. As each blade in the rotor system is unique due to the method of modification and the actuator construction, both the blades may not produce exactly same amount of lift. This uneven generation of lift result in an instability in the rotor system that uses individual blade concept. This problem can be solved by designing a feedback controller such that motion of one blade will follow the motion of the other blade. This requires measurements of data on each of the blade and then transmission of this data from the rotating blade to the fixed airframe where a controller can be installed to control the uneven lift generation. In this paper, we addressed these important issues of data transmission from rotating systems to the fixed system and the design of a feedback controller to reduce the uneven generation of lift using a robust control technique - μ synthesis. Time delays involved in data transmission are modeled as uncertainty.

2. DATA TRANSMISSION

In a multi blade rotor system, it is imperative that all the blades produce same amount of lift for a helicopter in hover or vertical flight. This issue becomes significant particularly when the individual blade control is used as each blade in the rotor system will be unique due to the method of blade modification and actuator construction. These differences will be manifested in terms of uncertainty in the blade and control surface mass and stiffness properties and the actuator power requirements and cooling rates. Uneven camber changes of individual blades result in an uneven amount of lift for each of the rotor blades and result in complications during the flight of the helicopter. By incorporating sensors, it is possible to measure the changes on each of the rotor blades and by using actuators and a feedback controller, it is possible to reduce the uneven camber changes of the blades. The development of sensors for a smart collective system require the measurement of the structural response of the rotor blades. These sensors are extremely important to ensure the lift being generated by each of the rotor blades is the same. and if the actual control surface deflection is the same as the commanded control surface deflection. Advancements in large scale integration of circuits on a single chip presents the opportunity to perform most sensor signal processing in the rotating system, in the rotor blade itself. In blade processing eliminates the need to pass raw signals into the fixed system, a potential source of error. Data that need to be transferred from the rotating system to the fixed system, or visa-versa, may be handled as digital data addresses sources of error normally encountered in rotating system to fixed system data transfer. A proposed smart rotor sensing and data handling scheme for rotor blade response and the associated issues are shown in Figure 2.

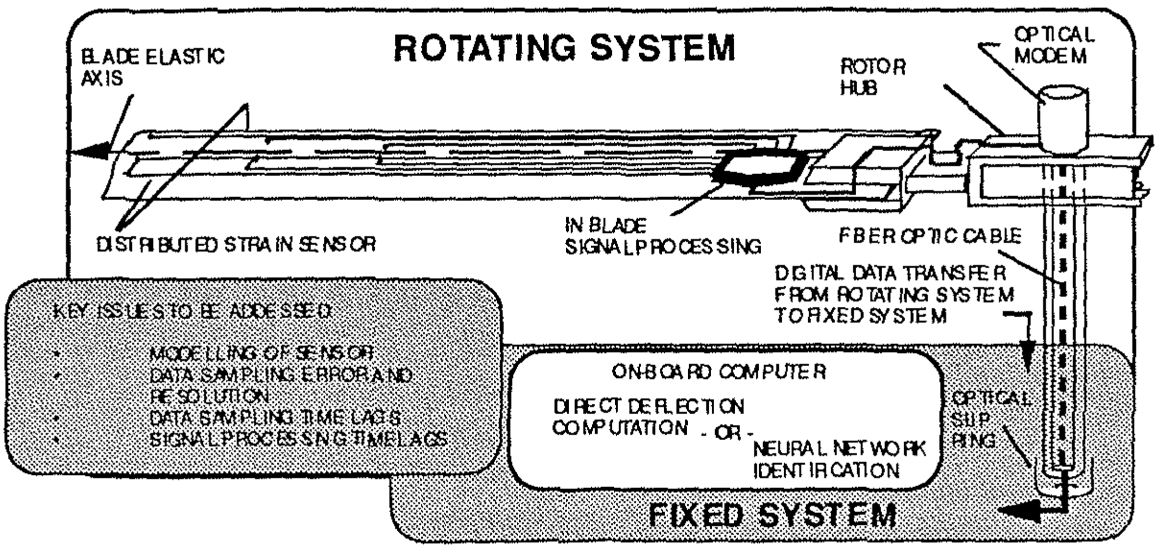

Figure 2: A proposed data Handling system

Embedded Electronic Controller

A Motorola HC11 8-bit microcontroller is used to collect and transmit data. The chip has an internal A/D converter that can be used to collect information from strain gauges mounted on each of the rotating blades. The main electronic circuit consists of an HC11 chip, 8K bytes of external ram, signal conditioning circuitry, a wireless infrared transmitter, and a power system and is packaged between two aluminum plates. This electronic package is centered about and fixed to the rotating hub of the helicopter. Data collected from the rotating blades can be digitally transmitted to a fixed airframe system using a wireless infrared transmitter and receiver or through a fiber optic cable and optical slip ring as shown in Figure 2. In our first stage experiments, we developed an electronic controller and transmitted the data using a wireless infrared transmitter and receiver.

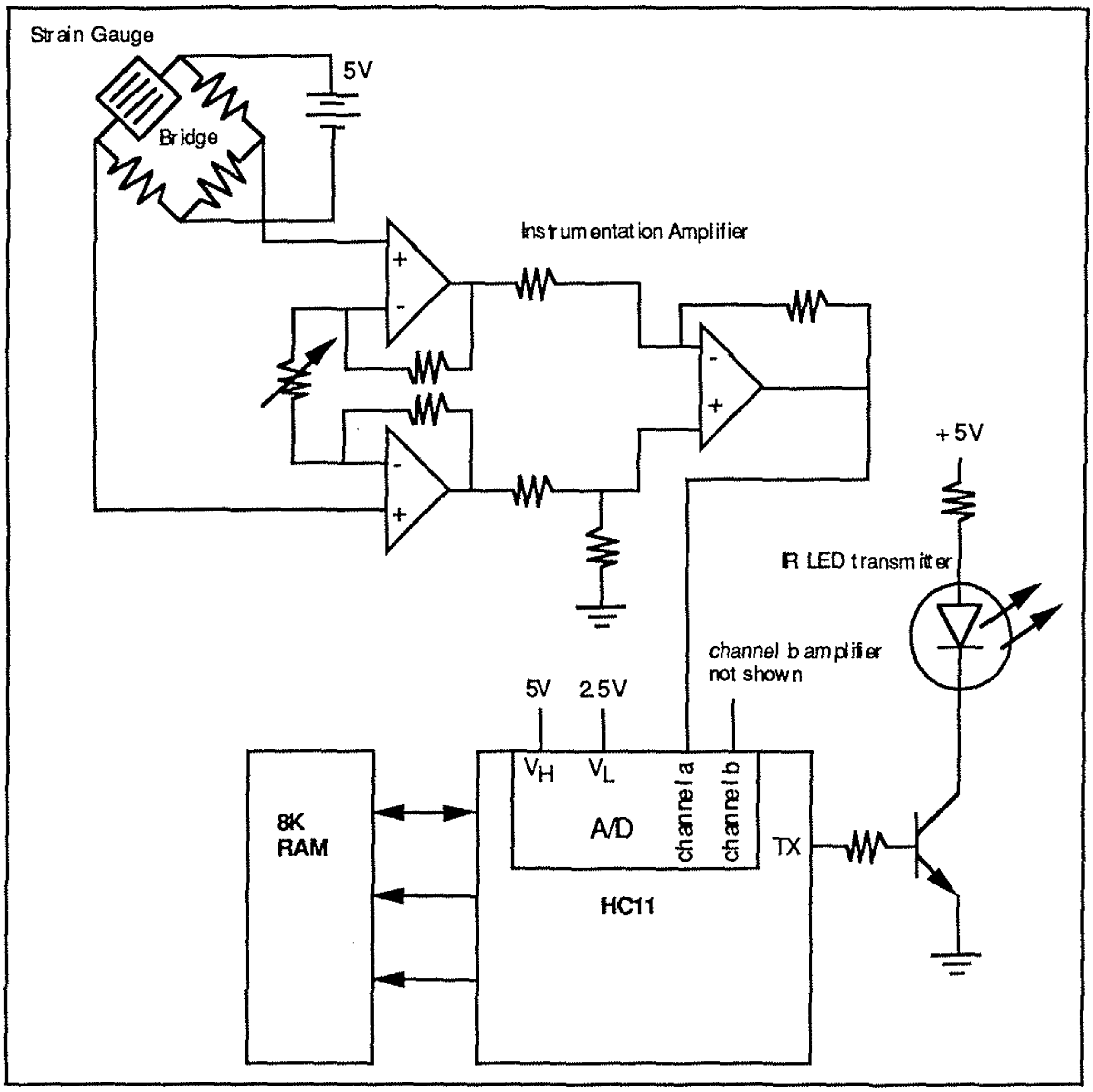

Figure 3: Embedded Electronic Controller Circuit

Data Collection

Electronic circuit used in the embedded controller is shown in Figure 3. The strain gauge that is mounted on the rotating blade is connected to a Wheatstone Bridge whose 2 outputs are inturn connected to the differential inputs of an instrumentation amplifier. The gain of the amplifier can be set using a potentiometer in order to set the amplified output voltage to be within the voltage range of the Analog to digital (A/D) converter.

The high and low voltage values of the A/D converter are set by the voltage levels on the V_H and V_L pins respectively. In the system developed, V_H is 5 volts and V_L is 2.5 volts for an A/D voltage range of 5V - 2.5V = 2.5V. This is the minimum voltage range needed to ensure a conversion accuracy of + or - 1 bit in the least significant bit of the A/D value according to the factory specifications. Since the A/D converter is an 8 bit converter, the smallest change in voltage that can be detected is (5V - 2.5V) / 2^8 which is equal to 9.77 mV + or - 38.3 µV.

Data Sampling and Time Lags

The A/D converter in the HC11 is a multiplexed 8-channel, 8 bit successive approximation converter with a built in sample and hold circuit. Each A/D conversion takes 16 µs per channel. As this is a multiplexed A/D converter, only one channel can carry out a conversion at a time. This means that there is at least a 16µs time difference between samples taken on different channels.

Preliminary static tests are conducted on the developed data acquisition system. In the static test, code was written for the microcontroller to read in 2 A/D values from 2 strain gauges. These values were then stored in an external 8K byte ram chip. The maximum rate that the strain gauges can be continually sampled is determined by the amount of time it takes to complete an A/D conversion and the time it takes for the processor to transfer the values to the external ram chip. The A/D converter read inputs in groups of 4 channels for a total time of 4 x 16µs = 64µs. The program instructions used to transfer the A/D readings into ram took a total time of 43µs. This resulted in a total time lag of 64µs + 43µs = 107µs between samples taken in groups of 4 as illustrated in Figure 4.

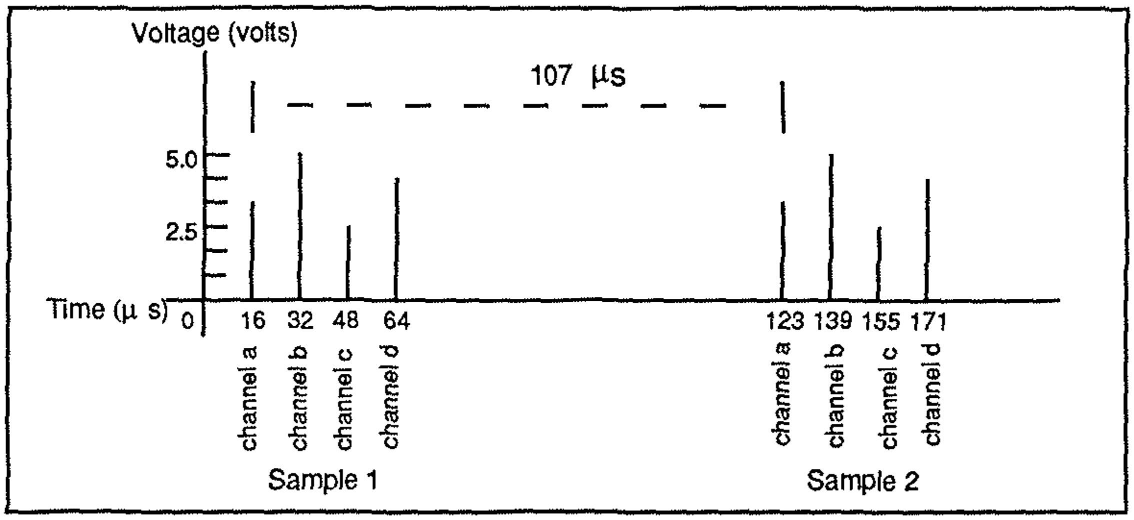

Figure 4: Time Lag Between A/D Samples

Data Transmission

The external ram chip acts as a data buffer to store values read by the A/D converter. At the maximum sampling rate of 107µs between samples, it takes 0.877 seconds to completely fill the data buffer. The information in the data buffer can then be used by the local processor or it can be downloaded serially through an infrared link to a more powerful fixed processor.

The static system tested transmitted data at a rate of 9600 bits per second (bps) to a personal computer. At this rate, it would take approximately 8.53 seconds to completely empty the buffer. However, if a faster switching infrared transmitter and receiver were used, it should be possible to download data at a maximum rate of 1,000,000 bps. At this value, the contents of the buffer would be completely download in approximately 0.082 seconds.

Currently, tests are underway to mount this developed data acquisition system on the base helicopter selected. Also, the current system is transferring data from the rotating system to the fixed system (sensor information to the controller). A similar data transfer system is under development to transfer the data from the fixed system to the rotating system (from the controller to the actuator). In the next section, details of a controller design that uses the sensor data and corrects for the uneven lift generation of the rotating surfaces.

3. CONTROLLER DESIGN

In the earlier section, we discussed the issues related to the data collection and data transmission of a two bladed rotor system. In this section, we developed a methodology to robustly design a controller that reduces the differences of the camber changes in a two bladed rotor system.

Assuming the blades and the control surfaces to be rigid, the equations of motion for each of the individual blades can be written as

$$\begin{aligned}
I_1 \ddot{\theta}_1 + \gamma_1 \dot{\theta}_1 + \beta_1 \theta_1 &= M_1(t) + M_{s1}(t) + z_1(t) \\
I_2 \ddot{\theta}_2 + \gamma_2 \dot{\theta}_2 + \beta_2 \theta_2 &= M_2(t) + M_{s2}(t) + z_2(t) \\
y_1 &= c_1 \theta_1 \\
y_2 &= c_2 \theta_2 \\
M_s &= \begin{Bmatrix} M_{s1} \\ M_{s2} \end{Bmatrix} = H \begin{Bmatrix} y_1 \\ y_2 \end{Bmatrix}
\end{aligned} \qquad (1)$$

Here I_i are the moments of Inertia of the control surfaces, γ_i are the damping coefficients of control surfaces, β_i are the stiffness coefficients of control surface, M_i are the moments at control surface hinge from external airloads, z_i are the moments at control surface hinge from gust disturbance, Ms_i are the moments about control surface hinge due to control force, y_i are the strain gage sensor measurements on blades and H is the control to be designed. The suffix "i" denote the control surface number and a linear viscous damping is assumed.

For the successful flight conditions, it is necessary that each of the control surfaces should follow a certain trajectory, the trajectory being defined by the variable θ, the flap rotation in radians. Depending on the differences of the blade modification and actuator construction, trajectory for each blade can be specified. In the present paper, without lose of generality, it is assumed that the control surfaces of both blades follow the same trajectory which can be described mathematically as follows:

$$\begin{aligned}
\theta_r &= \frac{100\pi t}{6} - \frac{\sin 200\pi t}{24} && 0 \le t \le 0.01\text{sec} \\
\theta_r &= \frac{\pi}{6} && t > 0.01\text{sec}
\end{aligned} \qquad (2)$$

The desired trajectory is shown in Figure 5. Here θ_r denote the desired trajectory. If Ms1 and Ms2 are the control forces to achieve this trajectory in the presence of gust disturbances z_1 and z_2, this control force can be assumed to be of two components. First components of the control force is needed to overcome the applied airloads and system stiffness and inertia. If no gust disturbances exist, this control force is sufficient to obtain the desired trajectory. Determination of this control force is relatively simple task as one can obtain exact amount of force required by substituting the value of θ_r in equation (1), after setting the gust disturbances to be equal to zero.

Assuming the moments of inertia of both the surfaces to be equal to 0.067 in-lb/sec/sec, damping coefficients to be equal to 0.01, moments due to external loads to be equal to 1173.33 in-lbs, stiffness for the first control surface to be 10.21 lb/in and the stiffness of the second surface to be 9.61 lb/in, the amount of control force required to overcome the external applied load can be obtained as

$$\begin{aligned}
M_{s1a} &= 1101.68\sin(200\pi t) - 0.2617\cos(200\pi t) + 534.59 - 1172.81 && 0 \le t \le 0.01\text{sec} \\
M_{s1a} &= 1167.95 && t > 0.01\text{sec} \\
M_{s2a} &= 1101.71\sin(200\pi t) - 0.2617\cos(200\pi t) + 503.18 - 1172.81 && 0 \le t \le 0.01\text{sec} \\
M_{s2a} &= 1168.26 && t > 0.01\text{sec}
\end{aligned} \quad (3)$$

But gust disturbances z_1, z_2 influence the trajectory for both blades. To overcome the effect of the disturbances, a closed loop optimal control based on H_∞ control theory is designed. To design the closed loop controller, two new variables e_1 and e_2 are introduced such that

$$\begin{aligned}
\theta_1 &= \theta r + e_1 \\
\theta_2 &= \theta r + e_2
\end{aligned} \quad (4)$$

Substituting equation (4) into equation(1), we obtain the equations required for designing the closed loop controller as

$$\begin{aligned}
I_1 \ddot{e}_1 + \gamma_1 \dot{e}_1 + \beta_1 e_1 &= M_{1b}(t) + z_1(t) \\
I_2 \ddot{e}_2 + \gamma_2 \dot{e}_2 + \beta_2 e_2 &= M_{2b}(t) + z_2(t) \\
\bar{y}_1 &= c_1 e_1 \\
\bar{y}_2 &= c_2 e_2
\end{aligned} \quad (5)$$

Now to reduce the effect of disturbance on the performance of the rotor system, the transfer functions between the disturbances z1 and y1 and disturbances z2 and (y1 - y2) need to be minimized based on a chosen optimal criteria. Mathematically, the controller can be written in a state space form as

$$\begin{aligned}
\dot{g} &= \mathbf{A} g + \mathbf{B} y \\
Ms_b &= \mathbf{C} g
\end{aligned} \quad (6)$$

Here g is the state of the controller, y is the input to the controller and Msb is the desired control force that minimizes the required transfer functions. To achieve the desired objectives different control design methods can be used. In this paper, a robust controller based on m synthesis is designed to provide robustness to handle the various uncertainties[10]. Uncertainty that is considered is the time delay in the data transmission.

Uncertainty Modeling - Effect of Time Delay

Shape memory alloy uses temperature as the actuation mechanism to obtain the desired actuation forces. Effect of time delay is very important for any controller that deal with shape memory actuators. Also, it is important to consider the time delays involved in the data transmission. If these time delays are not properly accounted, the resulting system may become unstable because of the effect of the time delay. Here, we discuss the methodology to accommodate the time delay using robust control concepts. If P denotes the system equations (1) then the system equations with a time delay can be expressed as

$$\tilde{P} = P e^{-sd} \qquad (7)$$

where d denote the time delay. The same plant with time delay can be written approximately as

$$\tilde{P} = [\,1 + \Delta W_2\,]\,P \qquad (8)$$

where W2 is a first order transfer function that encloses the expression [e^{-sd} - 1] completely. This representation is called multiplicative uncertainty. If the time delay varies from 0 to 0.1 sec, a first order transfer function of $\frac{0.21\,S}{0.1S+1}$ is chosen for W_2. Bode plots for W_2 and [e^{-sd} - 1] are shown in Figure 6. Taking this W_2 as the uncertainty weight, a μ controller is designed [10]. The controller thus designed can be written in state space form as

$$A = \begin{bmatrix} 0 & 1 \\ -1.49E+12 & -0.01 \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 \\ 2.73E+10 & -2.73E+10 \end{bmatrix} \qquad (9)$$

$$C = \begin{bmatrix} -5.47E+4 & 0 \\ -5.47E+4 & 0 \end{bmatrix}$$

The effectiveness of the designed controller is validated by assuming a gust displacement of 100 sin(2000t) in -lbs on each blade. Trajectories of the blade 1 and 2 are shown without the controller in Figure 7 and Figure 8. The difference of these two trajectories is shown in Figure 9. The trajectories associated with the control surfaces in blade 1 and blade 2 with the controller active are shown in Figures 10 and 11. The difference between the trajectories of the control surfaces in blade 1 and blade 2 is illustrated in Figure 12. From these plots it can been seen that the controller design is effective in reducing the error between the desired trajectory and the trajectory of the control surface in blade 1. The designed controller is also effective in reducing the error between the trajectory of the control surface in blade 2 and the trajectory of the control surface in blade 1.

4. CONCLUSIONS

In this paper, a new data transmission system from the rotating blades to the fixed airframe is proposed and developed. Preliminary static tests are completed to test the developed data transmission system. Currently, tests are underway to mount on the base helicopter selected. A similar data transfer system is under development to transfer the data from the fixed system to the rotating system (from the controller to the actuator). The signal received by the sensors on each of the rotor blades is used to develop a closed loop μ controller for reducing reduce the uneven lifts of a two bladed rotor system.

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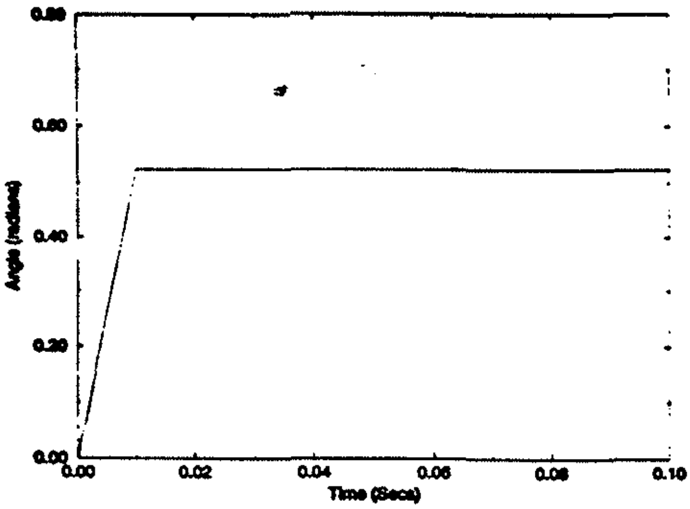

Figure 5: Desired Trajectory

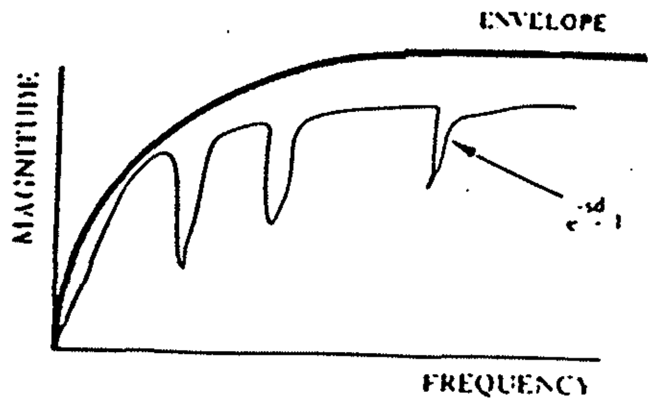

Figure 6: Weight W2 for the Time Delay

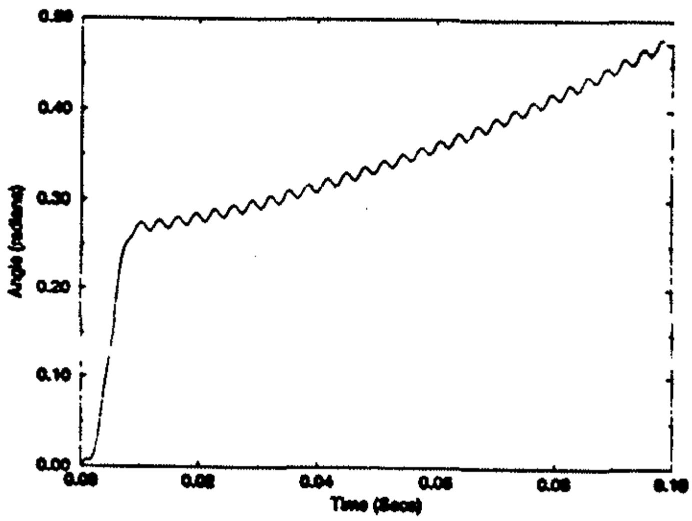

Figure 7: Trajectory of blade 1 without controller

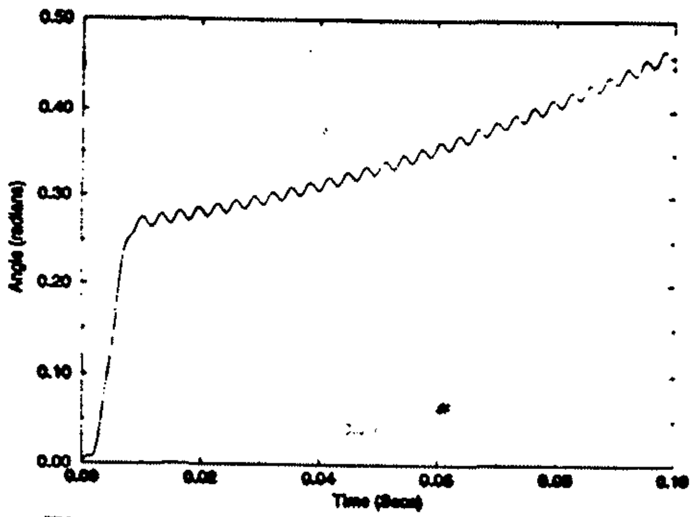

Figure 8: Trajectory of blade 2 without controller

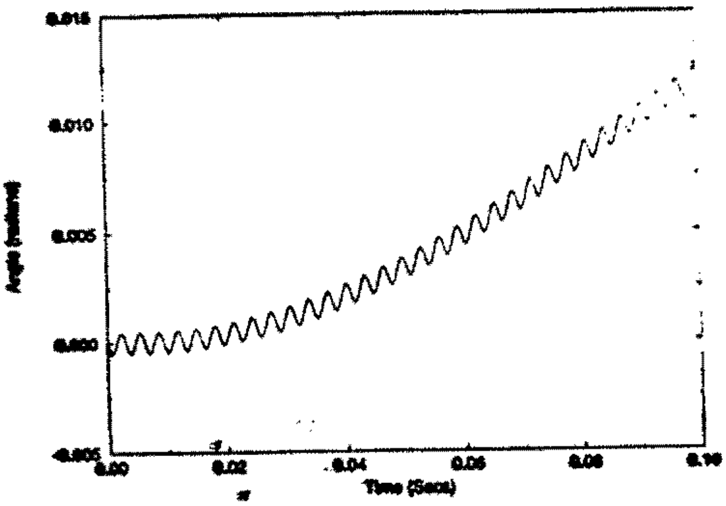

Figure 9: Difference of trajectories without controller

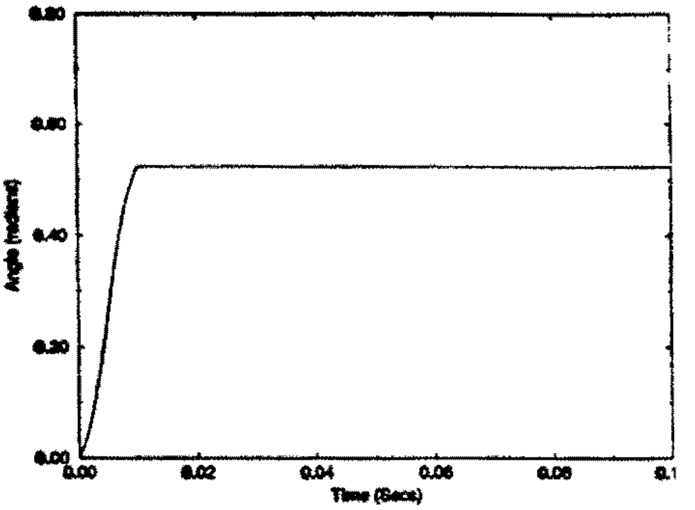

Figure 10: Trajectory of blade 1 with control

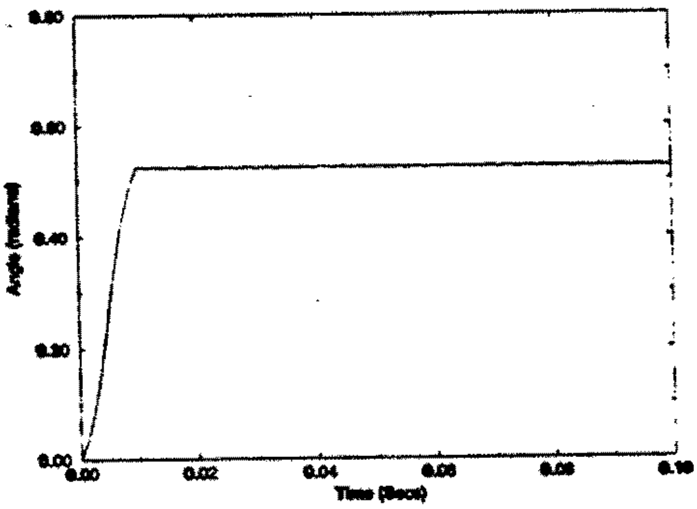

Figure 11: Trajectory of blade 2 with controller

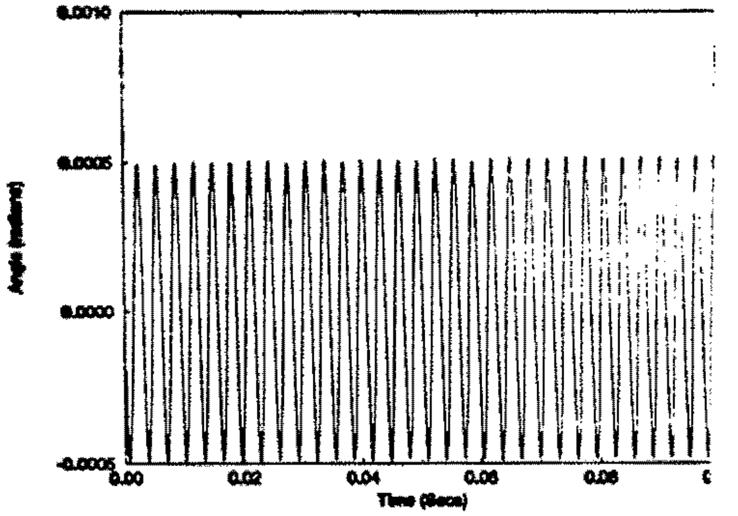

Figure 12: Difference of trajectories with contr