DEVELOPMENT AND TESTING OF AN ADAPTIVE ROTOR SYSTEM BASED ON SOLID ACTUATION AND NON-CONTACT SIGNAL TRANSMISSION TECHNOLOGY

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Abstract

In this paper, an adaptive rotor system based on solid actuation and non-contact signal transmission technology is investigated. The solid actuation system consists of an electro-strictive stack actuator, and a mechanism to amplify the displacement of the actuator. A theoretical model is used to predict the frequency response of the stack actuator. A non-contact signal transmission device is designed to transfer the multiple testing and controlling signals between the fuselage and the rotating rotors, so as to minimize the maintenance work. In close loop experiments, an adaptive algorithm is adopted to suppress the vibratory load of the blades by ground effect in hovering test. A special sensor is designed to provide reference signal to ensure the stability of the algorithm. Experimental results show that the vibration can be suppressed effectively.

1 Introduction

Helicopter is a complex dynamic system, its rotor blades operate in a highly complex aerodynamic environment where different cross-sections of blade undergo different adverse aerodynamic phenomena, like dynamic stall, reverse flow, compressibility, radial flow and blade-vortex interaction. In addition, the highly flexible rotor blades undergo structural deformations, such as coupled flap bending, lag bending, torsion and axial modes. The cyclic variation of inertia and aerodynamic loads in flight is the main source of vibration in helicopters. The vibratory hub loads are transmitted to the fuselage and cause discomfort to the crew, accelerate equipment deterioration, fatigue damage to the fuselage, thereby increasing the cost of maintenance.

There has long been a desire to reduce helicopter vibration and improve its performance. The control schemes adopted so far to reduce vibration in helicopters can be classified as either passive or active control technologies. The passive technologies include optimization of rotor hub and blades, hub or blade mounted passive vibration absorbers, and anti-resonant vibration isolators. One of the major disadvantages of passive vibration control systems is that they are designed to provide maximum vibration reduction at a specific frequency. Therefore, the performance is degraded with changes in the operating conditions of the rotor.

In recent years, increasing attention has been devoted to active control technologies to benefit helicopter vibration. Active control technologies include Higher Harmonic Control (HHC) [1], Individual Blade Control (IBC) [2], Active Flap Control (AFC) [3] and Active Control of Structural Response (ACSR) [4]. The disadvantage of conventional HHC and IBC is the complexity of control system to oscillate the entire blade at higher harmonic pitch motion at its root. Implementation of these schemes through actuators in the primary flight control system involves difficulties in satisfying stringent airworthiness requirements. To overcome these difficulties, a new concept of active flap control has emerged. In this scheme, instead of oscillating the entire blade, a trailing edge control flap is activated in higher harmonic pitch motion to reduce the vibratory hub loads.

Comparing with the HHC and IBC, The AFC is promising in reducing energy consumption [3], however, the amplitude of pitch angle for AFC is of the order of 8 degree, which is much higher than that for HHC and IBC. Currently many experimental studies are being taken to develop a smart structure actuated flap to achieve a maximum angular deflection of 6 to 8 degrees.

In this paper, an adaptive rotor system based on solid actuation and non-contact signal transmission system is presented. Research includes four parts. In the first part, a theoretical model of the solid actuator is derived and verified by experiments. Since there is a need to transfer multiple channels of signal reliably between the fuselage and the rotors, a non-contact signal transmission system is designed using the principle of magneto-electric coupling in the second part. The third part is an adaptive controller, in which a new method to extract reference signal is introduced. At the end part, a close loop experiment is made to activate the flap so as to minimize the vibratory load of the rotor system.

2 Mechanical model of stack actuators

The actuator used in adaptive rotors is a solid actuator based on functional materials, which can produce driving displacement under controlled electric field. Due to the high velocity of the rotating blades, it is essential to control the flap angle quickly and accurately in order to adjust the aerodynamic load effectively. Therefore, a mechanical model of the stack actuators under the external field (electric and force field) has to be built to study its output characteristics.

The electro-strictive material is a kind of ferroelectric ceramics whose strain has a second order effect to potential displacement. It can be applied to the design of stack actuators to produce high displacement output. But the complexity of strain characteristics of electro-strictive materials and the influence of external force and electric field have brought difficulties to the stack actuator design. Considering the structural features of stack actuators, this paper attempts to derive the mechanical model of stack actuators and analyze the problems in actuator design from the constitutive equation, equation of motion and mechanical equivalent theories.

2.1 Structural analysis of stack actuators

To increase displacement output, stack actuators use electro-strictive layer, electrode layer and adhesive layer to form a multi-level serial structure (Fig. 1). Without taking into account boundary effect and current leak, displacement occurs to stack actuators under electric field in the direction of thickness (polarization).

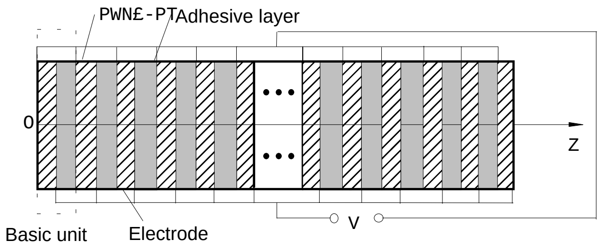

Fig.1 structure of stack actuators

Since the electrode coating is so thin in thickness that it can be neglected in analysis. Every unit is composed of two parts - electro-strictive layer and adhesive layer. The whole actuator is a serial system made up of large amount of identical units.

2.2 Mechanical model of the electro-strictive layer

The electro-strictive material is ferro-electric crystal with non-linear mechanical and electrical coupling relationship, and there exists linear piezoelectric effect term and second order of electro-strictive term in the constitutive equation. Its mechanical and electrical coupling relationship can be expressed as [5]

$$S_3 = s^E{}_{3i} T_i + (g_{mi} + Q_{mr3} D_r) D_m \qquad (1)$$

where s_{ij}^{E}, g and Q is the open loop flexible coefficient, piezoelectric voltage constant and electo-strictive coefficient of the ferroelectric material, respectively.

Only when the potential displacement is very small can the electro-strictive effect of ferroelectric materials be neglected. However, as the driving electric field of stack actuators is relatively high, this non-linear term can not be neglected. For the electro-strictive material, the working temperature is slightly higher than curie point; there is no piezoelectric effect while the electro-strictive effect is strong, so the effect of the second term must be taken into consideration.

Under the controlled voltage V in the polarization direction, each electro-strictive layer only bears a one-way load F in the thickness direction. According to Newton's second law, we get the equation of motion in the thickness direction as

$$\rho \frac{\partial^2 u_3}{\partial t^2} = \frac{1}{s_{33}^{E}} \frac{\partial^2 u_3}{\partial z^2} \tag{2}$$

Suppose the controlled voltage V changes according to sine rule and neglect boundary effect, we get the stable displacement response of the electro-strictive layer:

$$u_3 = \frac{\delta \sin \frac{\omega z}{v_3^E}}{\sin \frac{\omega l}{v_3^E}} e^{j\omega t}, \quad v_3^E = \left(\frac{1}{\rho s_{33}^E}\right)^{1/2} \tag{3}$$

Considering the axial force F is evenly distributed along the cross-section, and ignoring the hysteresis effect between the potential displacement and the controlled field in the ferroelectric layer, the displacement of the ferroelectric layer can be expressed as

$$\delta = \frac{F + g_{33}\varepsilon_{33}\frac{V_3}{l s_{33}^E} + \frac{\varepsilon_{33}^2 Q_{333} A V_3{}^2}{l^2 s_{33}^E}}{K_F} = \frac{F + F(V)}{K_F} \tag{4}$$

where

$$K_e = \frac{v_3^E \sin \frac{\omega l}{v_3^E}}{\omega \cos \frac{\omega l}{v_3^E}}, \quad K_F = \frac{A}{K_e s_{33}^E},$$

$$F(V) = g_{33}\varepsilon_{33}\frac{V_3}{l s_{33}^E} + \frac{\varepsilon_{33}^2 Q_{333} A V_3{}^2}{l^2 s_{33}^E} \tag{5}$$

According to equation (4) and (5), the electro-strictive layer is equivalent to the parallel system of a spring with dynamic stiffness K_F and a force source F(V). The spring stiffness depends on the density of the ferroelectric material, flexible coefficient, cross-section area and working frequency, while the force source is determined by controlled voltage, piezoelectric and electro-strictive coefficient of ferroelectric materials, elastic modulus, dielectric coefficient and structural size. One point to be noticed is that the dielectric coefficient of ferroelectric materials is a non-linear function of external force and electric field which increases as the density of controlled electric field rises and decreases as frequency rises. Hence we may conclude that the output force and displacement of electrostrictive layers in the actuators are in non-linear relationship to driving frequency, and are also closely related to external load.

2.3 Mechanical model of the stack actuators

Not considering the damping of the adhesive layer, it can be regarded as a mass-spring system, where M is the concentrated mass of the adhesive layer, and the K_m is the spring stiffness

$$K_m = \frac{EA}{t} \tag{6}$$

where E, A and t is the elastic modulus, cross-section area and the thickness of the adhesive layer.

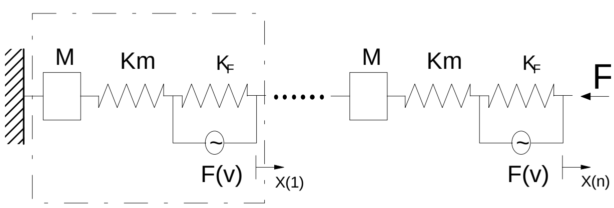

Fig.2 Mechanical model of the stack actuator

So that stack actuator can be treated as a mechanically serial and electrically parallel structure, as shown in Fig.2.

3 The design of a non-contact signal transmission system

In order to control the flap on the rotating blade, it is essential to transmit both measuring and controlling signals between the rotating blades and the fuselage in an adaptive rotor system. Present adaptive blade test is usually based on direct contact transmission device - slip ring system. Most of the slip ring systems are designed to transmit low voltage signals, and are sensitive to vibration and shock. Specially designed slip ring for high voltage signal transmission is expensive, not reliable enough because of friction and electric corrosion, and has to be replaced after a short time of work.

In our research, a novel non-contact system for signal transmission is introduced. It is based on magneto-electric coupling principle [6]. Signal modulation and frequency division multiplexing is used to transmit multiple channels of signal simultaneously. Since no directly contact electrode is needed, the reliability of the system can be guaranteed and the maintenance work can be reduced.

The following is a schematic diagram of the non-contact signal transmission system, where vibration of the rotor blades are measured by piezoelectric sensors and then modulated by a high frequency carrier signal, then it is transmitted through the magneto-electric coupling coil. Afterwards, it is demodulated to the original signal. On the other hand, the controlling signal is transmitted from the fuselage to the rotor blade in the same way.

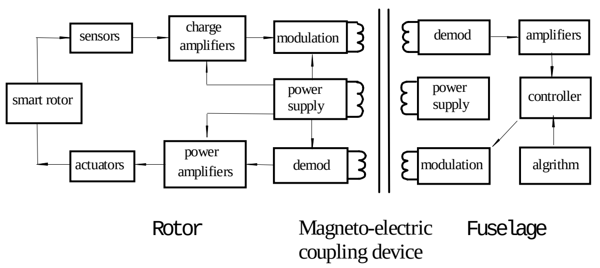

Fig.3 Schematic diagram of non-contact signal transmission system

There are many modulation methods, such as amplitude modulation (AM), frequency modulation (FM) and pulse coded modulation (PCM). In this system, AM method is used to transmit the controlling signals because it is characterized by high response frequency, and can ensure the stability of the close loop system. FM is adopted to modulate the measuring signals since it is more accurate. In the same time, Frequency Division Multiplexing (FDM) method is employed to transmit multiple signals in one physical channel, so that the structure of the transmission system can greatly simplified.

4 Strategy of vibration control

As we know, the deflect position of the active flap control surface on the rotating blades should be adjusted in higher harmonic pitch motion to reduce the vibratory hub loads. Here an adaptive filtering feed forward strategy is introduced for real time vibration cancellation [7].

The idea of adaptive filtering control is to design such a filter that its output signal is used to drive the flap control surface, generating unsteady aerodynamic load to counteract the vibratory load in the hub. Fig.4 illustrates the typical structure of an adaptive filter, where *d* is the desirable output, *y* is the output of the filter, *x* is the reference signal, *e* is the error between *d* and *y*. The weights of the filter is regulated by adaptive algorithm according to the error. There are many methods to compute the weight such as LMS, RLS, FTF etc. The LMS is adopted in our research.

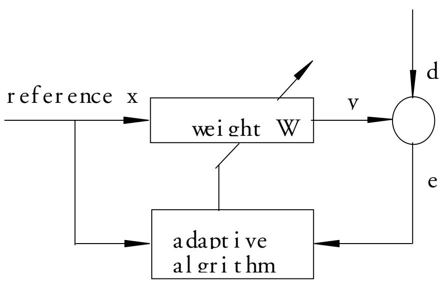

Fig.4 Structure of adaptive filter

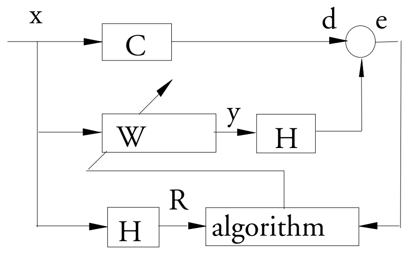

Fig.5 An adaptive filtered feed forward controller

Consider a system as shown in Fig 5, to be actively controlled using a control actuator, an error sensor, and a sensor to provide an input sequence. The control signal y(n) is given by

$$y(n)=\sum_{i=0}^{I-1} w_i(n)x(n-i) \qquad (7)$$

where w is the filter coefficient sequence for Ith order LMS control filter, x(n-i) is the input sequence and n is the discrete time index. If the transfer function from the actuator to the error sensor is modeled as a time-varying FIR filter, with coefficients $h_j(n)$, the error signal can be written as

$$e(n)=d(n)+\sum_{i=0}^{I-1} w_i \sum_{j=0}^{J-1} h_j(n)x(n-j-i) \qquad (8)$$

The term $\sum_{j=0}^{J-1} h_j(n)x(n-j-i)$ is a filtered version of the input signal and will be denoted by $r(n-i)$. So that the equation can be rewritten as

$$e(n)=d(n)+r^T(n)W \qquad (9)$$

where

$$r^T(n)=[r(n),r(n-1),\cdots,r(n-I+1)] \qquad (10)$$

$$W^T=[w_1 \quad w_2 \quad \cdots \quad w_{I-1}] \qquad (11)$$

The LMS based algorithm is designed to minimize the mean-square error performance criteria given by

$$J=E\left[e(k)^2\right]\rightarrow Min \qquad (12)$$

The error performance surface is a bowl shaped surface with a minimum. The resulting update equation for the LMS control filter is given by

$$W(n+1)=W(n)-\mu e(n)r(n) \qquad (13)$$

where μ is convergence factor, it influences the stability and the convergence speed of the system. The system will be stable if

$$0<\mu<\frac{1}{\sum_{i=0}^{I-1} E[X^2(k-i)]} \qquad (14)$$

Above equations comprise the Filtered-X LMS algorithm, where the transfer function sequence H should be identified in real time.

Another problem with the adaptive algorithm is to get the reference sequence X(n) which should be in close correlation with external exciting load. Because the exciting force with helicopters is the $N\Omega$ frequency component, a synchronous transformer is designed and installed coaxial with the rotator, which can provide the desired reference signal, and be sampled directly. The feasibility of this device is verified in close loop experiments.

5 Close loop experiments

5.1 Active flap control surface

Based on the analysis from part 2, a solid stack actuator is designed. It is used to drive an active flap control surface, as shown in Fig 6. Performance testing is made before close loop experiments. Results are shown in Fig.7 and 8.

Material: PMN-PT, Cross-section: $9\times 9mm$, Thickness of each layer: 0.3mm, Thickness of the adhesive layer: 0.1mm, Length of the actuator: 135mm, Lag: $tg\delta=6.4\%$, Block force: 800N. Maximum displacement: 90 μm.

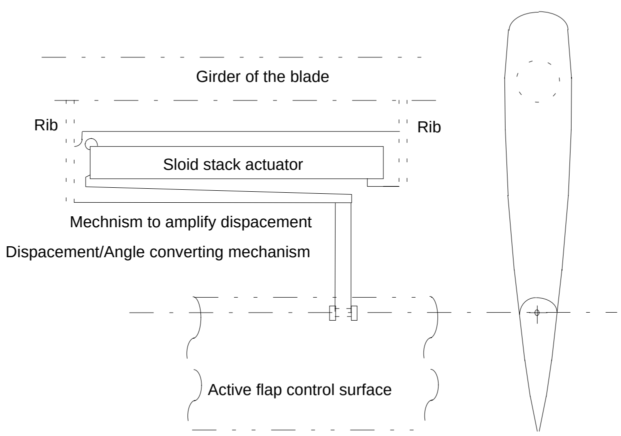

Fig. 6 Structure of the active flap

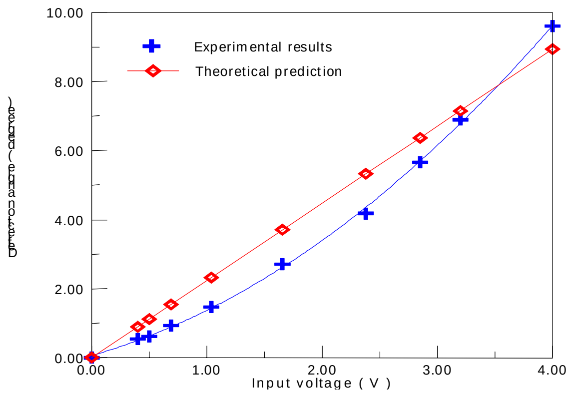

Fig. 7 Deflection of the AFC in static test

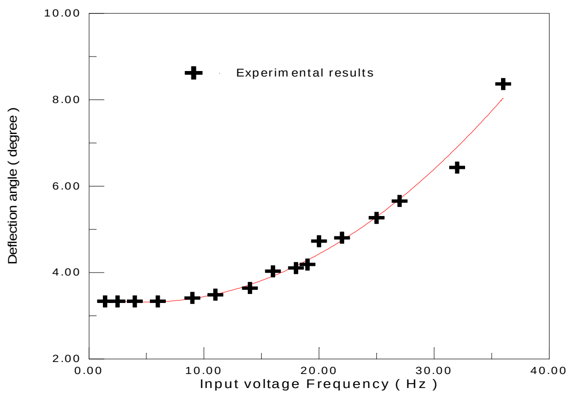

Fig. 8 Frequency response of the AFC model

It can be seen from Fig 7 that the maximum angle of the AFC model can up to 9.8 degrees in static experiment, and the non-linear effect is serious because the functional layer is actually made of electro-strictive material, which is in second order of non-linearity in its constitutive equation. However, the frequency response of the AFC is as low as 10 Hz, which should be improved in future design. The reason for this is that the dynamic characterization of the mechanism to drive the flap is not considered in design, which decrease the first order of natural frequency dramatically. It should also be noted that there is a contradiction between larger displacement and frequency response in the design of solid stack actuators, because increasing the number of piezoelectric layer can improve driving displacement, while reduce its natural frequency in the same time. In order to satisfy the two stringent requirements, optimization method should be used in design by choosing proper size of the functional layer and the adhesive layer, and matching their physical parameters.

5.2 Close loop experiments

On the basis of the FLMS algorithm, a testing rig is setup up using the principle of non-contact signal transmission technology. To simulate the periodical vibration of the blades in hovering state, a plane board is placed between the rotor and the fuselage. When rotated, the blades will vibrate because of periodical aerodynamic load from ground effect.

The digital adaptive algorithm is written in C++ programming language. The experiment is divided into two steps: 1) Set the length of filter as I=60, and different convergence factor is evaluated; 2) Set the convergence factor as constant, and different length of the filter is evaluated. A typical result is shown Fig9.

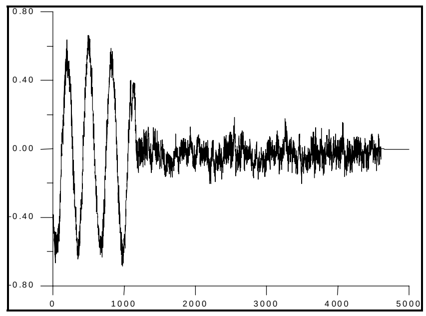

Fig.9 A typical Result of vibration control (I=60 μ=0.0005,R=200rev/Min)

6 Summary

In this paper, An adaptive rotor system is developed based on a solid actuator and a non-contact signal transmission system, which is aimed at reducing the vibration of rotating blades of helicopters. The following aspects have been studied in research, and conclusions can be drawn from theoretical analysis and experiments.

According to the requirement of AFC, a mechanical model is built to instruct the design of the solid state stack actuator, which has taken both the functional material layer and the adhesive layer into account. It is found from the model that there is a contradiction requirement between the displacement and frequency response of the solid state actuator. It should be optimized to satisfy both the two indexes in design. Besides, The dynamic performance of the mechanism to drive the AFC surface is also an important factor to be considered in the system.

A non-contact signal transmission system is designed to improve the reliability of signal transmission process, which is based on magneto-electric coupling principle. It can transmit several channels of signal at the same time and the feasiblity has been verified in experiments.

In close loop experiments, a FLMS algorithm is adopted, and a coaxial installed synchronous transformer is used to provide the reference signal, which is in close correlation with external exciting load. The results show that the vibratory load of the blade have been reduced evidently. The experiments verified the feasibility of the adaptive rotor system.

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