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A Preliminary Design on the Second Generation Integral Twist-Actuated Blade

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Summary

This paper presents the preliminary design effort of a brand new integral twist-actuated blade incorporating single crystal piezoelectric fiber composites. Although the previous integral twist-actuated blade was able to reduce the vibration and acoustic noise of rotorcrafts significantly, a quite high input-voltage was unavoidably required. Therefore, in this paper, it is suggested to develop a new active blade using single crystal piezoelectric composites to reduce the vibration and acoustic noise of helicopters more efficiently. For the preliminary design of a new blade, the characteristics of the sectional properties and the twist actuation frequency responses in hover are investigated in terms of the active region magnitude.

Introduction

The high level of vibration in helicopters is a serious problem in terms of the component fatigue life, their ride quality and the maintenance cost. It results from the highly complex unsteady aerodynamic environment that surrounds the rotor system, particularly during forward flight. In order to solve these problems, the active rotor controls using piezoelectric materials have been investigated. Under these concepts, there have been two typical approaches investigated. One is the Active Trailing edge Flap (ATF) blade, and the other the Active Twist Rotor (ATR) blade [1]. The ATR blade utilizes piezoelectric fiber composite actuators such as either Active Fiber Composites (AFC) or Macro Fiber Composites (MFC) that are embedded directly within the composite blade structure. Direct twisting deformation of the blade structure is then obtained through activation of the actuators. The ATR blade with the AFC's was designed, manufactured, and tested successfully as part of the NASA/Army/MIT ATR program [2]. Although the ATR blade could reduce significantly the vibration and acoustic noise of the rotorcrafts, a quite high input-voltage ($4,000\,V_{pp}$) was unavoidably required.

The single crystal piezoelectric materials [3] can produce strain levels more than 1% and exhibit five times larger than that of the conventional piezoceramic materials in terms of strain energy density. In addition, they have the high coupling constants. Although it is difficult to manufacture the single crystal piezoelectric materials in large quantities and complex geometries, it is apparent to take advantage of the improved actuation performance of the piezoelectric fiber composites (single crystal MFC [4]).

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In this paper, it is suggested to develop a new ATR blade incorporating the single crystal MFC, i.e., the Advanced Active Twist Rotor (AATR) blade. It is anticipated that the AATR blade can reduce the vibration and acoustic noise of the rotorcraft more efficiently, although much lower input-voltage and active region length are used when compare with the previous ATR blade. Specifically, for the preliminary design of the AATR blade, the characteristics of the sectional properties and the twist actuation frequency response in hover are examined.

Modeling of AATR blade

In order to design and analyze the blade structure, its analysis is separated into two-step approaches, i.e., 2-dimensional cross-section analysis and 1-dimensional beam analysis. In this paper, the 2-dimensional cross-section analysis is conducted through the variational asymptotic method [2]. The cross-section is modeled as a two-cell composite beam as seen in Figure 1.

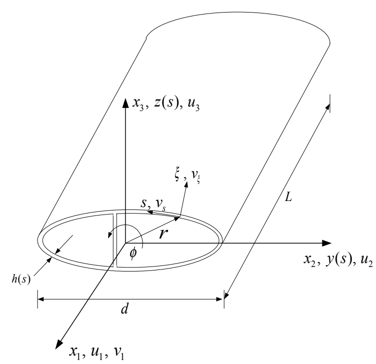

Figure 1: Two-cell, thin-walled beam

The variational asymptotic method provides the closed-form expressions of displacement, strain, stress and beam stiffness coefficients. Because the detailed formulation can be found in [2], this paper focuses only on the main results of the formulations. With an assumed linear piezoelectric constitutive relation and starting from shell strain energy, the slender thin-walled shell is modeled as a beam through an iterative process.

After the second order approximation, the constitutive equation of the thin-walled composite beam including piezoelectric actuation terms can be obtained as

$$\left\{\begin{array}{c} F_1 \\ M_1 \\ M_2 \\ M_3 \end{array}\right\} = \left[\begin{array}{cccc} K_{11} & K_{12} & K_{13} & K_{14} \\ K_{12} & K_{22} & K_{23} & K_{24} \\ K_{13} & K_{23} & K_{33} & K_{34} \\ K_{14} & K_{24} & K_{34} & K_{44} \end{array}\right] \left\{\begin{array}{c} \gamma_1 \\ \kappa_1 \\ \kappa_2 \\ \kappa_3 \end{array}\right\} - \left\{\begin{array}{c} F_1^{(a)} \\ M_1^{(a)} \\ M_2^{(a)} \\ M_3^{(a)} \end{array}\right\} \tag{1}$$

where $\mathbf{K}$ is the stiffness matrix, γ_1 is the axial strain, κ_1 is the elastic twist, and

κ_2, κ_3 are two bending curvatures. Furthermore, $F_1^{(a)}$, $M_1^{(a)}$, $M_2^{(a)}$ and $M_3^{(a)}$ are the generalized actuation force, moments, respectively.

For the 1-dimensional beam analysis, the AATR blade is modeled as a composite beam undergoing axial-deformation, flapwise-bending, chordwise-bending and elastic twist [5]. In order to derive a governing equation, Hamilton's principle and finite element method are adopted. Furthermore, an ordering scheme [5] is used to simplify the resulting equation of motion. For the aerodynamic loads in hover, both a simple aerodynamic model [6] and the combined blade element and momentum theory [7] are used.

The finite element equation for the rotor blade is based on Hamilton's principle, which can be written as

$$\delta\Pi = \int_{t_1}^{t_2} (\delta U - \delta T - \delta W)\, dt = 0 \tag{2}$$

where δU, δT and δW are the variations of the strain energy, kinetic energy and external work, respectively. Since the detailed derivation for the equation of motion of the composite rotor blades is described in [5], this paper shows the final equation as

$$\mathbf{M}\ddot{\mathbf{d}} + \mathbf{C}\dot{\mathbf{d}} + \mathbf{K}d = \mathbf{F} \tag{3}$$

where **M**, **C**, **K**, **d**and **F** are the mass, damping, stiffness matrices, nodal displacement vector and force vector, respectively. In this paper, the beam elements with 15 degrees of freedom [5] are used.

Results and discussions

The AATR blade is designed based on the NASA/Army/MIT ATR prototype blade. The blade length R is 1.397 m, the linear pretwist angle is 10°, the rotor rotational speed is 687.5 RPM, and Lock number is 9.0. The material properties of the passive and active materials are given in references [2] and [4], respectively.

Figure 1 shows the cross-section of the AATR blade for the preliminary design study. The points P_1 and P_2 denote the starting and ending points of the active region, respectively. In this paper, the starting point P_1 is fixed at the starting point of the blade spar. However, the ending point P_2 may be varied in order to examine the effect of the active region length on the sectional properties and aeroelastic characteristics in hover.

The sectional properties obtained in terms of the active region length are shown in Figure 2. As the active region length is increased, the flapwise-bending stiffness is decreased dramatically; however both the torsional and chordwise-bending stiffness are observed to be almost insensitive.

The dynamic frequency response of the AATR blade under the aerodynamic

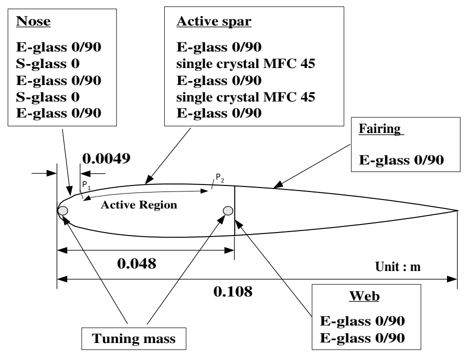

Figure 2: The cross-sectional design of the AATR blade (NACA0012 airfoil)

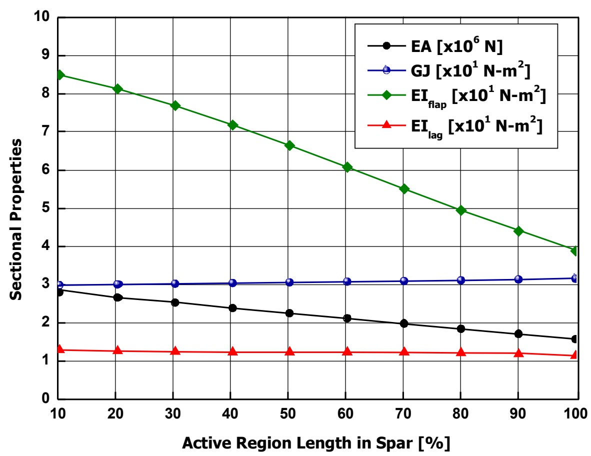

Figure 3: Sectional properties in terms of the active region length

load in hover is shown in Figure 3 in terms of the active region length. At 5/rev excitation frequency, which locates lower than the first torsional resonant frequency, the AATR blade can achieve the tip twist actuation amplitude of 4° with 75% lower input-voltage and 20% smaller active region compared to those of the ATR prototype blade. Therefore, as compared with the ATR prototype blade using AFCs, it is anticipated that the AATR blade will have more capability to eliminate the rotorcraft vibration.

Conclusion

This paper presents the preliminary design effort of a new ATR blade incorporating single crystal piezoelectric fiber composite actuators. The present result shows that a new ATR blade has the capability to reduce the vibration and acoustic noise of rotorcrafts more efficiently, even with much lower input-voltage and active region length are used when compared with the previous ATR blade.

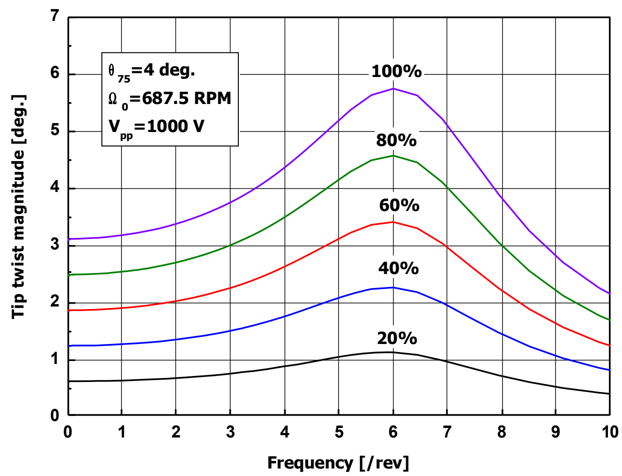

Figure 4: Frequency responses in hover in terms of the active region length

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