Applied Mathematics, Modeling and Computer Simulation
C.-H. Chen et al. (Eds.)

doi:10.3233/ATDE230987

Analysis of the Influence of Blade Tip Geometry on the Aeroelastic Response of Rotors

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Abstract. Using the theory of moderately deformed beams and considering the nonlinear displacement coordination relationship at the blade tip, a differential equation of rotor aeroelasticity with different blade tip shapes was established. The aeroelastic responses of rotor blades with forward convex and backward swept, backward swept and backward reversed angles were systematically analyzed. The results showed that forward swept and backward swept were beneficial for rotor vibration reduction, while downward reversed caused significant fluctuations in response, and the amplitude changes of the blade tip were different at different reverse angles, this may have adverse effects on the vertical vibration response of the aircraft body. When using a lower angle to achieve noise reduction and improve rotor aerodynamic performance, the dynamic impact caused by the complexity of flow field motion should be considered to avoid excessive vibration.

Keywords. Geometric shape; aeroelasticity; dynamics; vibration loads.

1. Introduction

The three-dimensional shape changes in the blade tip region have shown excellent characteristics in improving rotor aerodynamic performance and noise reduction. However, changes in the geometric shape of the blade tip cause the center of gravity of the blade to shift, which to some extent enhances the coupling of blade pulling bending, swinging twisting, or swinging twisting direction motion [1-4].

Although some advanced geometric blade tips have been applied in practical models, theoretical analysis and experimental research in this field are still ongoing. Celi [5,6] fully considered the coupled motion between blade flapping, shimmy, and torsion, established the displacement coordination relationship between the blade tip element and the straight blade element, discretized the blade dynamics equation. Kim [7] of the University of Maryland introduced the nonlinear transformation relationship between the blade and the blade tip element, and used the three-dimensional Finite difference method combining the Transonic small disturbance theory with the finite element blade dynamics analysis to analyze the influence of tip swept back, down turning, etc. Ganguli [8,9] used the geometric shape of the blade tip, the characteristic parameters of the unit

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profile, and the composite layer angle as design variables to analyze the impact of various optimization schemes on the vibration load of isolated rotors. Professor Yang Weidong [10] established an aeroelastic dynamic analysis model for a swept blade tip rotor and studied the aeroelastic response characteristics of the swept blade tip. The numerical calculation results showed that the swept blade tip had a significant impact on the torsional response of the blade and a relatively small impact on the swing. The Yang Weidong research group [11,12] studied the effects of active variable backswept and active variable downdraft on rotor dynamics, and proposed an active control mechanism to achieve changes in the backswept angle and downdraft angle of helicopter rotor blades. Lin Jie [13] conducted research on intelligent rotor vibration reduction optimization based on active changes in airfoil shape, utilizing active changes in airfoil aerodynamic shape to achieve rotor vibration load suppression.

In this paper, based on the moderately deformed beam theory, combined with the ONERA model and the unsteady aerodynamic analysis model of rotor with complex three-dimensional shape formed by dynamic inflow, a set of rotor aeroelastic differential equations applicable to various blade tip configurations are established through the Hamilton's principle. Using the time finite element method, a study was conducted on the influence of forward swept backward, backward swept backward, and forward swept backward strip backward combination on the aeroelastic response of rotors, providing a theoretical basis for the vibration load assessment and dynamic design of complex three-dimensional rotor hub.

2. Complex Three-Dimensional Rotor Aeroelastic Model

Based on the Hamiltonian Variational principle, a rotor/fuselage coupling dynamic model with different tip shapes is established by using a 15 degree of freedom nonlinear moderately deformed beam element. The rotor aeroelastic dynamic model with complex three-dimensional shape can be described as:

$$\delta\Pi = \int_{\psi_1}^{\psi_2} [\sum_{i=n}^{N} \left(\delta U_i - \delta T_i - \delta W_i\right)] d\psi = 0 \tag{1}$$

The above equations U, T, and W respectively represent virtual deformation energy, virtual kinetic energy, and aerodynamic virtual work, written as matrix expressions:

$$\delta U_i - \delta T_i - \delta W_i = \delta q_i^T \left(\boldsymbol{M}_i \ddot{q} + \boldsymbol{C}_i \dot{q} + \boldsymbol{K}_i q - \boldsymbol{F}_i\right) \tag{2}$$

Wherein, $\boldsymbol{M}_i$ $\boldsymbol{C}_i$ and $\boldsymbol{K}_i$ are the mass, damping and Stiffness matrix matrices of the ith element in turn, which are linear matrices and $\boldsymbol{F}_i$ corresponding load vectors, including linear and nonlinear parts. The structer is shown in the figure 1.

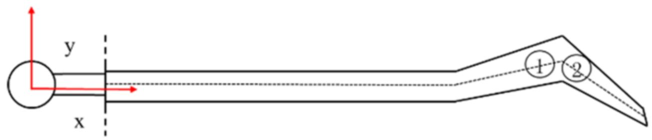

Figure 1. structure diagram.

3. Calculation Results

In this paper, using BO-105 homogeneous blades, the starting points of forward sweep, backward sweep, and downward reflection were set at 0.8R, 0.9R, and 0.93R, respectively.

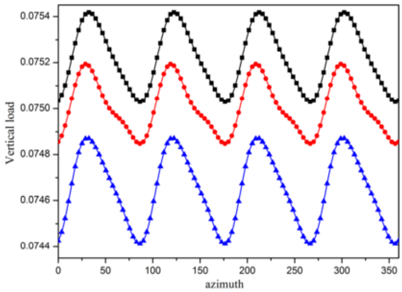

Figure 2. Effect of forward sweep on vertical load.

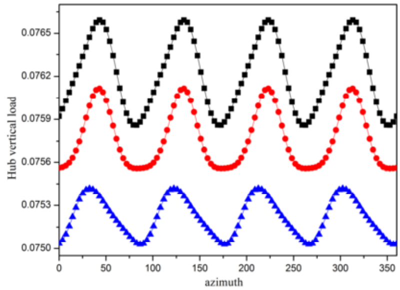

Figure 3. Effect of swept back on vertical load.

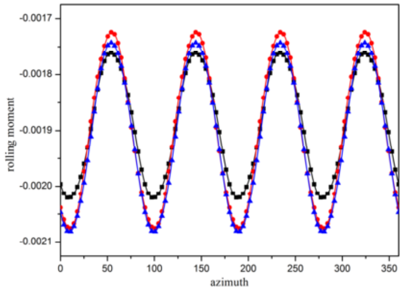

Figure 4. Effect of forward sweep on rolling moment.

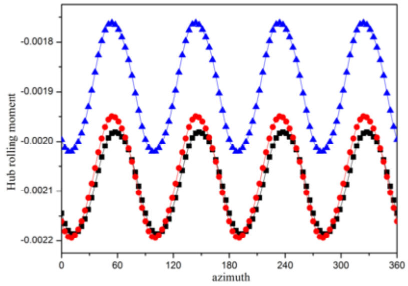

Figure 5. Effect of swept back on rolling moment.

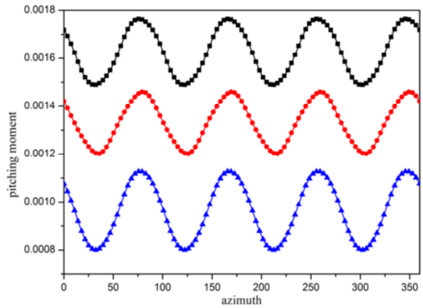

Figure 6. Effect of forward sweep on pitching moment.

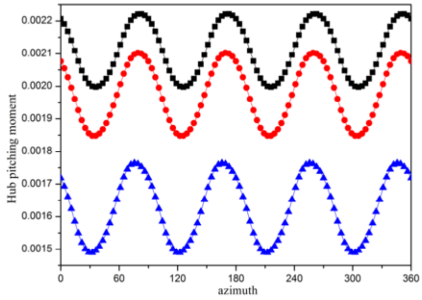

Figure 7. Effect of swept back on pitching moment.

In figures 2, 4 and 6, black, red, and blue respectively represent a forward sweep of 10°, 20°, and 30°. From figures 2, 4 and 6, it can be seen that for the rotor with a forward and backward swept tip, an increase in the forward swept angle reduces the vertical load and pitching moment of the rotor hub. Among them, the vertical vibration load of the hub decreases weakly, only from 0.754 to 0.744, and does not affect the amplitude and variation of the vertical vibration load. However, the pitching moment decreases significantly, reaching 35.8%, and the peak pitching moment increases from 0.00157 to 0.00178. When the vertical vibration load of the hub reaches its peak, The pitch torque of the propeller hub is reduced to the minimum value, but it does not affect the variation pattern and alternating amplitude of the vertical load and pitch torque of the propeller hub, and has minimal impact on the rolling torque of the propeller hub.

In figures 3, 5 and 7, black, red, and blue respectively represent a sweep back of 10°, 20°, and 30°, from figures 3, 5 and 7, it can be seen that for a rotor with a forward and backward swept blade tip, an increase in sweep angle reduces the vertical load, rolling moment, and pitch moment of the rotor hub, significantly reducing the amplitude of the vertical vibration load of the hub and changing the variation pattern of the vertical vibration load. For the rolling torque of the propeller hub, it does not affect its load amplitude within 20 degrees of backswept. When the backswept reaches 30 degrees, the rolling torque of the propeller hub decreases significantly. For the pitching torque of the propeller hub, it does not affect its amplitude when the backswept angle is small. When the backswept angle is large, the pitching torque amplitude decreases significantly. This may be due to the backswept causing changes in the center of gravity and aerodynamic center of the propeller tip, and the decrease in Mach number resulting in lift loss, this in turn leads to a decrease in the vertical load and pitch torque of the propeller hub, which is beneficial for helicopter flight to some extent from the perspective of vibration reduction.

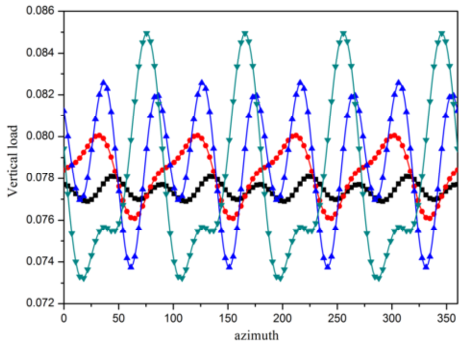

Figure 8. The influence of the down reflection angle on the vertical load

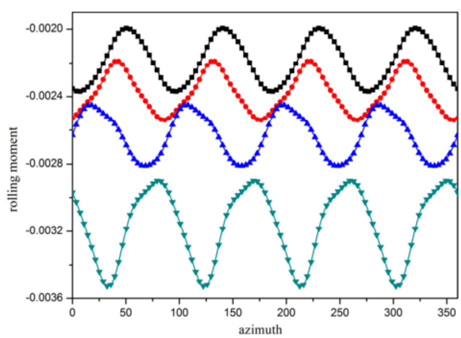

Figure 9. The influence of reverse angle on rolling moment

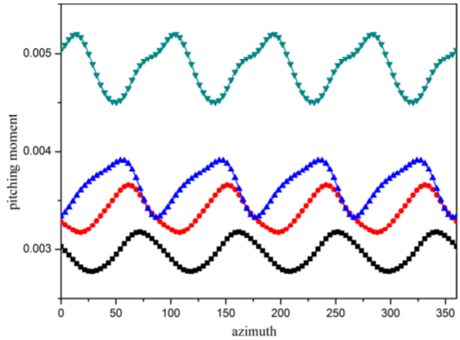

Figure 10. The influence of the down reaction angle on the pitching moment

In figures 8–10, black, red, blue, and green respectively represent a downward rotation of the blade tip at 10°, 15°, 20° and 30 °. Due to the strong centrifugal force field and more complex aerodynamic environment of the downstream reverse rotor tip, compared to the forward and backward swept two-dimensional plane configuration of the blade tip, the load variation of the downstream reverse rotor hub is more intense. From the figure 8–10, it can be seen that as the downward angle of the propeller tip increases, the alternating amplitude of the vertical vibration load of the propeller hub increases, especially when the downward angle is large, the alternating amplitude of the vertical vibration load changes too much, jumping from 0.001 to 0.01. Moreover, the amplitude change rules of the propeller tip are different at different downward angles, which may have adverse effects on the vertical vibration response of the engine body. Overall, the use of a lower angle should not only achieve noise reduction and improve rotor aerodynamic performance, but also take into account the dynamic issues caused by the complexity of flow field motion to avoid excessive vibration.

4. Conclusions

In this paper, the moderately deformed beam theory is used to establish the rotor aeroelastic dynamic model with different tip shapes based on the Hamilton's principle. The time finite element method and the force integration method are used to analyze the effects of forward swept backward, backward swept backward, etc. on the rotor aeroelastic response. The conclusions are as follows:

(1) The influence of swept back on the blade tip lagging response is relatively greater than that of flapping response, and it reduces the load on the rotor hub, with the pitch torque decreasing the most, but it basically does not affect its load variation amplitude and variation pattern.

(2) The introduction of the down angle increases the amplitude of the hub load variation, especially when the roll torque and pitch torque increase significantly at large down angles. Overall, when using the down angle to achieve noise reduction and improve the aerodynamic performance of the rotor, the dynamic problems caused by the complexity of flow field motion should be taken into account to avoid excessive vibration.

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