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Extendable chord for improved helicopter rotor performance

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A B S T R A C T

Extendable blade sections are investigated as a method for reducing rotor power and improving helicopter performance. A validated helicopter power prediction method, based on an elastic beam model is utilized. The static extendable chord can deliver a rather small power reduction in hover, and significant power savings at high speed flight, however, the cruise power is increased. In hover, the active chord is best deployed in the middle part of the blade, and just inboard of the tip at high speed flight. The increase in chord length can lead to power savings at high speed flight but the benefits decrease in other speeds. The 1/rev dynamically extendable chord can lead to an overall power reduction over the speed range of a helicopter. The best deployment location is at the blade tip, which is different from the statically extendable chord. It is best extended out in the retreating side, and retracted back in the advancing. The power reduction by the 1/rev dynamically extendable chord increases with the increase in the length of the chord extension and take-off weight of the helicopter. Generally, a lower harmonic extendable chord can save more power than one actuated at higher harmonics. The dynamic chord can reduce more power than the corresponding static chord.

1. Introduction

Rectangular rotor blades are convenient for manufacturing, but not optimal for aerodynamic performance, so rotor blade plan-form optimization is an effective method to reduce rotor power in hover and forward flight, and improve helicopter performance. In 1940s, blade taper was investigated to improve hover performance, and a taper ratio of 3 to 1 could increase the rotor thrust by approximately 2 to 3 percent [1]. Effort has also been put to optimize the blade plan-form, but most helicopter rotors still adopt rectangular blades. The use of composites makes practical to fabricate non-rectangular rotor blades, especially with advanced blade tips. Passive rotor blade shape design has seen great progress leading to improvements of helicopter rotor performance [2–4], and the aerodynamic parameters could be optimized to balance the requirement and obtain more performance improvement [5–8]. To further improve rotor performance is, however, a challenging topic.

Léon et al. examined quasi-statically extendable chord sections to improve helicopter performance near the envelope boundaries [9]. The analyses based on the UH-60 helicopter showed an expansion of the flight envelope. Khoshlahjeh and Gandhi investigated extendable chord rotors for flight envelope expansion and performance improvement [10]. The analyses were based on the quasi-steady trailing-edge plate and showed significant power reduction at high gross weight and altitude, and performance improvement at maximum speed, gross weight and altitude. The trailing-edge plate reduced the angle of attack in the retreating side, and shifted the lift inboard. This offloading of the blade tips reduced the drag and torque, and the rotor power was consequently reduced. Among active blade controls, the extendable blade chord has shown significant potential in reducing rotor power, especially at high speed flight [11]. The 1/rev dynamic blade chord reduces the blade chord length in the advancing side to alleviate compressibility effects, and increases it in the retreating side to lower the angle of attack of the blade and delay stall. This way, the rotor profile drag can be reduced and rotor power can be saved. Past research concentrated on the effect of the static or 1/rev extendable chord on the performance improvement of helicopters, especially near the flight envelope boundary. Nevertheless, the question whether static or dynamic chord extension is better for rotor performance should be addressed. The same is true for the identification of the optimal location of the extendable chord and the best harmonic excitation.

This work focuses on the potential of static and dynamic chords in reducing helicopter rotor power. The dynamic chord is not lim-

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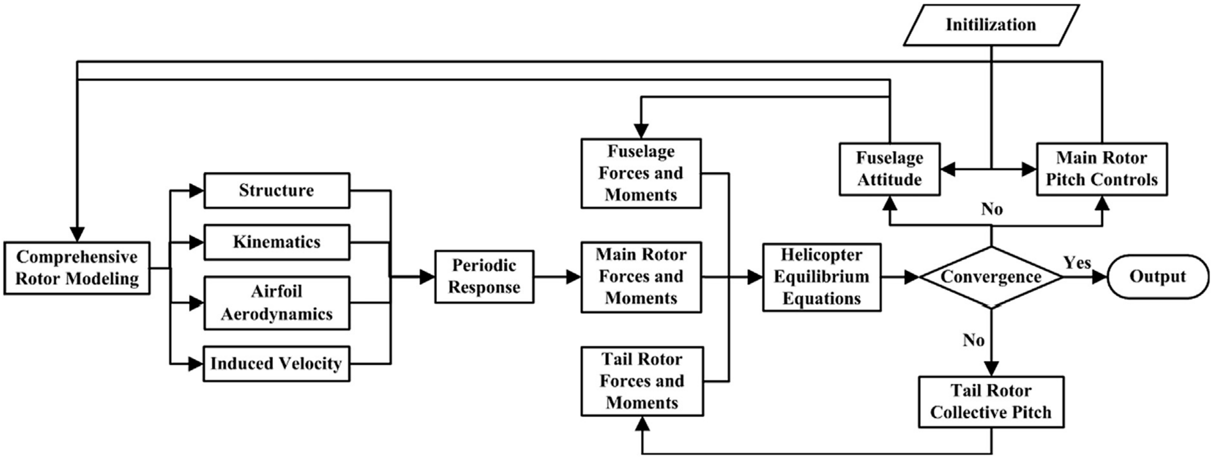

Fig. 1. Flowchart of performance prediction.

ited to 1/rev, and higher harmonics are also investigated. Parametric analyses are conducted to enhance the potential of chord extension in the flight performance improvement of helicopters.

2. Modeling and validation

2.1. Performance prediction method

A helicopter model is utilized, which includes a rotor model, a tail rotor model, a fuselage model and a propulsive trim method. The rotor model is based on an elastic beam model with moderate deflections, which can capture the geometric nonlinearity of advanced helicopter blades. The blade rotations about the blade hinges and rotor shaft are introduced as generalized coordinates. Look-up aerofoil aerodynamics is used. The induced velocity over the rotor disk is captured by the Pitt-Peters inflow model [12]. The equations of motion of the system are derived based on the generalized force formulation. The Newmark integration method is utilized to calculate the steady response of the rotor in the time domain [13]. The hub forces and moments of the main rotor are derived from the resultant root forces and moments of the blades. The fuselage is treated as a rigid body with aerodynamic forces and moments. The thrust and power of the tail rotor are determined by momentum theory with the uniform inflow model.

Given the initial values of the pitch controls and the fuselage attitude angles, the steady response of the rotor can be obtained at a prescribed forward speed, flight altitude and take-off weight. The hub forces and moments of the main rotor are balanced by the forces and moments acting on the fuselage and tail rotor. These component forces and moments constitute the equilibrium equations of the helicopter, which are solved to update the pitch controls and attitude angles. After some iterative computation of the periodic response of the rotor and solutions of the equilibrium equations, the trimmed pitch controls and attitude angles can be obtained. Then the main rotor power and related information of the helicopter can be derived. The flowchart is shown in Fig. 1. This modeling methodology has been used to analyze the transient aeroelastic responses of shipboard rotors and the helicopter performance improvement by variable rotor speed and variable blade twist [14,15].

2.2. Validation

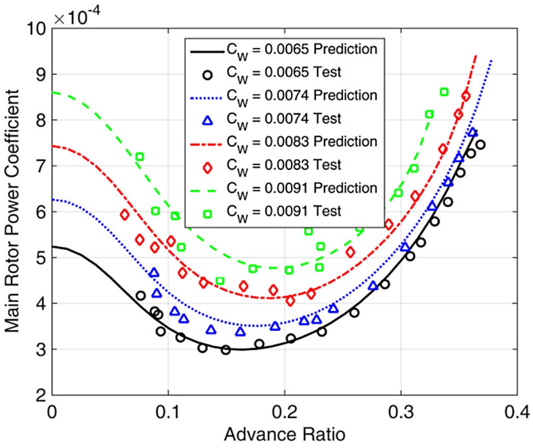

Fig. 2. Comparison of the prediction with the flight data.

The flight data of the UH-60A helicopter is utilized to validate the methodology used in this work [16]. The parameters of the main rotor and tail rotor are provided in Ref. [17]. The distributions of the airfoil and blade pre-twist of the main rotor are given in Ref. [18]. For performance analysis, a model of the aerodynamic fuselage drag can provide acceptable predictions [16]. The fuselage drag equation utilized in the present work is

$$\frac{D}{q}\left(\text{ft}^2\right) = 35.83 + 0.016 \times \left(1.66\alpha_s^2\right) \tag{1}$$

where, D is the fuselage drag, q is the dynamic pressure, and α_s is the aircraft pitch angle. In this work, the geometric parameters of the baseline helicopter are the same as the UH-60A helicopter. To reduce the effect of the flexibility of the blade structure on the rotor performance, a hingeless rotor blade with uniform blade properties is utilized. The fundamental flap, lag and torsional frequency ratios of the baseline rotor at full rotor speed are taken as 1.14, 1.40 and 6.50, respectively. The comparisons of the prediction of rotor power with the flight test data for the take-off weight coefficients 0.0065, 0.0074, 0.0083 and 0.0091, are shown in Fig. 2. It is obvious that the predictions by the present method are generally in good agreement with the flight test data for these take-off weights, which verifies the use of the present method in analyzing helicopter performance.

2.3. Airfoil aerodynamics

An extendable chord can change the chord length and modify the aerodynamic characteristics of the airfoil. Given a suitable deployment angle ($\delta = 2^\circ$) of the extendable chord [10], as shown in Fig. 3, there is virtually no change in the aerodynamic lift coefficient. Since this work focuses on the effect of the static and