Aerospace Science and Technology 58 (2016) 445–452

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Helicopter flight performance improvement by dynamic blade twist

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ARTICLE INFO

Article history:
Received 28 June 2016
Received in revised form 21 August 2016
Accepted 13 September 2016
Available online 19 September 2016

Keywords:
Helicopter
Flight performance
Dynamic blade twist
Periodic harmonic twist

ABSTRACT

Dynamic blade twist is investigated as a method for reducing rotor power and improving helicopter performance. An analytical model able to predict helicopter rotor power is first presented, and the flight data of the UH-60A helicopter and the Helicopter Multi-Block Method (HMB2) are used for validation. The predictions of the rotor power are in good agreement with the flight test data and HMB2, which verifies the application of the present method in analyzing helicopter performance. In hover and low speed forward flight, the power reduction by the prescribed dynamic blade twist is substantially small. In high speed forward flight, the effect of dynamic blade twist becomes more pronounced. It is found that lower harmonic blade twist can achieve larger power savings than higher harmonic twist. The zero harmonic twist dominates the power reductions. The helicopter take-off weight was found to have a strong influence on the power reductions achieved by the prescribed dynamic blade twist.

1. Introduction

Negative blade twist can improve helicopter rotor efficiency in hover and forward flight [1,2]. It has been widely applied in rotor blade design to achieve better helicopter rotor performance [3–5] by optimizing the distribution of blade lift and reducing the rotor power. This effect is achieved by increasing the loading inboards along the blade. Blade twist can also delay blade stall at high forward speeds and mitigate compressibility effects at high tip speeds [1], since blade twist unloads the tips by reducing the tip angle of attack. Usually, passive pre-twist is used along the blade span, which cannot actively change around the azimuth. To accommodate the asymmetric aerodynamic environment of the blade at the retreating and advancing sides in forward flight, a change of the spanwise and azimuthal twist distributions is needed.

Currently, actively changing blade twist has not been applied in helicopter rotor design. This is partly due to difficulties with the required mechanism for the twist change and the manufacturing of this new breed of rotor blades. In recent years, piezoelectric materials have been used to actuate the blade twist [6,7], like active fiber composites (AFC) [8–10] and macro fiber composites (MFC) [11–13]. Smart materials and structures have demonstrated their potential in actuating blade twist and controlling rotor vibration loads, as well as, improving helicopter rotor performance. Yeo [14] investigated different active controls for rotor performance improvement. The 1/rev (per revolution) active blade twist had a small influence on the rotor performance, and the 2/rev harmonic control was found to improve the rotor lift-to-drag ratio. The benefit studies of an active twist rotor conducted by Zhang et al. [15] using a weak fluid–structure coupling method resulted in power reduction of about 14%. This value was probably overestimated, however, the numerical results showed clearly the performance improvement achieved by the active twist control. Body Jr. utilized a loosely coupled CFD/CSD (computational fluid dynamics/computational structural dynamics) method to analyze the aerodynamic and acoustic performance of an active twist rotor [16]. The 3/rev input reduced both mid-frequency noise and 4/rev hub vibrations with a penalty in the rotor lift-to-drag ratio. Kang et al. investigated different rotor morphing technologies for helicopter performance improvement [17]. The quasi-steady blade twist gave a 2% savings in the total rotor power in cruise. Jain et al. investigated three rotor morphing concepts for performance improvement [18], namely trailing-edge deflection, leading-edge deflection and active twist. The predictions by the CFD and CSD coupling for the UH-60A rotor showed that the active twist reduced the power in high speed flight (C8534) by 3.3% but no reduction was found for the high thrust flight (C9017). The examinations of on-blade active controls conducted by Jain et al. illustrated that the 2/rev input with the optimal amplitude of 4 degree of active twist could reduce the rotor power by 3.3% in high speed forward flight [19]. The previous analyses concentrate on rotor performance improvements by changing the blade static twist (pre-twist) without

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http://dx.doi.org/10.1016/j.ast.2016.09.013
1270-9638/

any dynamic twist or the dynamic twist based on prescribed static twist.

A blade twist can contain static, active and elastic components. One, two, or all three components may affect rotor performance. How to find the major factors dominating the performance improvement is a very challenging and worthy research area. Essentially, any a blade twist, which is a sum of the static, active and elastic twists, can be expressed as a sum of the components from 0/rev to $+\infty$/rev. If we can determine which harmonic twist dominates the performance improvement, active blade twist can be designed for optimized performance.

In this work, the blade twist is prescribed in the spanwise direction and around the azimuth, and investigated to determine which harmonic component (0/rev, 1/rev, $\cdots$, n/rev, $\cdots$) dominates the improvement in rotor performance. A helicopter rotor power prediction model is used, which includes a rigid blade model (suppress the effect of elastic twist), aerofoil table look-up method, the Pitt–Peters inflow model [20], a rigid fuselage model and a propulsive trim method [21]. The flight data of the UH-60A helicopter [22] is utilized to validate the model. The Helicopter Multi-Block Method (HMB2) [23–25] CFD method is also utilized to verify the analytical method. HMB2 has been validated for a range of rotorcraft applications and has demonstrated good accuracy and efficiency for very demanding flows. Examples of work with HMB2 can be found in references [23–25]. The zero harmonic twist combined with a periodic harmonic twist is analyzed to explore the potential of spanwise and azimuthal distribution of blade twist in saving rotor power and improving helicopter performance.

2. Modeling and validation

To determine the dominant harmonic components of blade twist for minimum rotor power, a parameter sweep for each flight state, at a prescribed forward flight speed is conducted. This process has to be repeated for several rotor power settings. If one computation requires a CPU of one minute, the sweep of the parameters can span dozens of days. Since the objective of this work is to explore the potential of the harmonic component of dynamic blade twist in reducing rotor power, an analytical model to predict the helicopter rotor power is utilized. This model can estimate the rotor power within less than a second using a standard personal computer.

The blade model is based on a rigid beam with a hinge offset and a hinge spring, which is used to match the fundamental flapwise blade frequency. Look-up table aerofoil aerodynamics is used to calculate the lift and drag coefficients of blade elements according to the local resultant air flow and angle of attack. The induced velocity over the rotor disk is predicted by the Pitt–Peters inflow model [20], which captures the first harmonic variation of induced velocity in azimuth. 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 specified aerodynamic forces and moments. For simplicity, the thrust of the tail rotor is determined by the main rotor torque divided by the distance from the hub center of the tail rotor to the main rotor shaft. The power and collective pitch of the tail rotor are determined by the thrust according to momentum theory.

Given three pitch controls (collective and two cyclics) and two rotor shaft attitude angles (longitudinal and lateral tilts), the periodic response of the rotor in steady forward flight can be obtained for a prescribed forward speed. The hub forces and moments of the main rotor are balanced by the forces and moments acting on the fuselage and tail rotor. The forces and moments on the fuselage are determined by the flight state and attitude angles. The thrust and power of the tail rotor are derived from the rotor toque and flight state. These component forces and moments constitute the equilibrium equations of the helicopter [21], which are solved to update the pitch controls and rotor attitude angles for the next iteration. After several iterations of the periodic rotor responses and solutions of the equilibrium equations, the converged or trimmed pitch controls and rotor attitude angles can be obtained. Then the main rotor power and related information of the helicopter can be derived.

Table 1
Main rotor parameters.

Main Rotor Radius	8.1778 m
Main Rotor Speed	27.0 rad/s
Blade Chord Length	0.5273 m
Blade Twist	Nonlinear
Blade Airfoil	SC1095/SC1094R8
Number of Blades	4
Flap Hinge Offset	0.381 m
Blade Mass per Unit Length	13.92 kg/m
Longitudinal Shaft Tilt	3°

Table 2
Tail rotor parameters.

Tail Rotor Radius	1.6764 m
Tail Rotor Blade Chord	0.2469 m
Tail Rotor Speed	124.62 rad/s
Tail Rotor Blade Twist	−18°
Blade Airfoil	NACA0012
Number of Blades	4

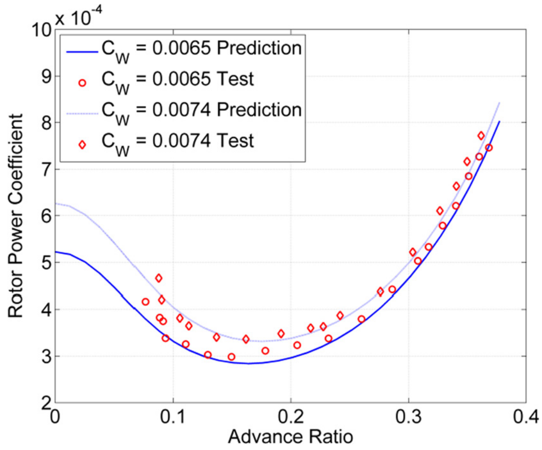

Fig. 1. Comparison of predictions with flight test data.

The flight data of the UH-60A helicopter [22] is utilized to validate the methodology used in this work. The parameters of the main rotor and tail rotor are listed in Table 1 and Table 2 [26]. The distributions of the airfoil and blade pre-twist of the main rotor are given in [27]. For the performance analysis, only the aerodynamic drag force is considered in the fuselage model. The fuselage drag equation utilized in the present analysis is [22]

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

where, D is the fuselage drag, q is the dynamic pressure, and α_s is the aircraft pitch angle. The distance from the hub center of tail rotor to the rotor shaft is 9.9263 m. The vertical distance from the mass center of the helicopter to the rotor hub is 1.77546 m. The comparisons of the prediction of the rotor power with the flight test data for the takeoff weight coefficients 0.0065 and 0.0074 are shown in Fig. 1. It is obvious that the predictions by the present method are generally in good agreements with the flight test data for these takeoff weights, which verifies the application of present method for the analysis of helicopter performance.