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Helicopter performance improvement by variable rotor speed and variable blade twist

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ABSTRACT

Variable rotor speed and variable blade twist are combined to reduce rotor power and improve helicopter performance. Two modeling methods are respectively utilized. One is based on an empirical aerodynamic model and the other is based on CFD (computational fluid dynamics). The flight data of the UH-60A helicopter is used to validate the methods. The predictions of the rotor power by the empirical method are in good agreement with the test data and the CFD method, which verifies the application of present methods in analyzing helicopter performance. The analyses indicate that significant rotor power reduction can be achieved by decreasing rotor speed. It is not appropriate to decrease the rotor speed too much in high forward flight. More power reduction can be attained by varying rotor speed than by variable blade twist. The individual variation of rotor speed or blade twist can reduce the rotor power by 17.8% or 10.4%, at a forward speed of 250 km/h and weight coefficient of 0.0065. A combination of rotor speed reduction and blade twist can save 20.9%. The maximum power reduction increases with forward speed and then decreases. The optimal performance improvement occurs at the medium to high forward speed. With increasing takeoff weight, the benefit in power saving decreases. Variable blade twist has the potential in reducing blade loads introduced by variable rotor speed.

1. Introduction

Helicopters are essentially low speed, low altitude, short range aircraft [1]. Improving helicopter efficiency, endurance, range, forward speed, and ceiling are therefore important topics in helicopter design. The objective of this paper is to investigate rotor power reduction and therefore increase the available engine power. Usually, the total power consumed by helicopters is primarily composed of main rotor induced power, main rotor profile power, tail rotor power and fuselage parasite power. Rotor morphing technologies provide possible effective solutions for reducing the main rotor induced and/or profile power [2]. Potential methods to be investigated include variable rotor speed, variable rotor diameter, active blade twist, trailing edge flaps and so on.

Among the potential rotor morphing technologies, the application of variable speed rotors in the V-22, X2 and A160 aircraft has demonstrated significant performance improvements, especially regarding long endurance, high speed and larger range. Decreasing rotor speed can effectively reduce rotor power at cruise in low altitude and light weight conditions, though the power reductions diminish with increasing altitude and/or gross weight, and in low speed flight [3]. This is due to the effective reduction of rotor profile power by decreasing rotor speed. In hover, and low forward flight, the rotor induced power dominates the total helicopter power. Varying rotor speed usually attains limited power savings. In fast forward flight, the angles of attack of blades have to be increased to generate enough thrust to trim the helicopter due to the reduction of rotor speed, which aggravates the stall area and decreases the power reduction ability. Some limited power reduction may be attained in high speed. However, varying rotor speed in flight may lead to dynamics issues [4,5]. With lower rotor speeds, and higher forward speeds, larger rotor advance ratios are attained, and this can introduce high blade loads and vibration problems. Wind tunnel test of a variable speed model rotor indicated the general increase of the root bending moments and higher harmonic pitch link loads with the reduction of rotor speed [6]. To retain the benefits in performance for variable speed rotors, and reduce or avoid excessive loads and vibration issues is a challenging task that is worthy of investigation.

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Active twist rotors change the blade twist distribution according to the flight state of the vehicles, and this can be utilized to improve helicopter performance. Increasing blade twist in hover and decreasing it in high forward flight is well recognized in helicopter rotor design. The wind tunnel tests confirmed that highly twisted rotors provided better hover performance, but higher forward flight blade loads and vibratory fixed frame hub loads [7]. The initial idea of active blade twist was utilized for rotor vibration reduction. In 1990s, Chen and Chopra conducted the hover and forward flight wind tunnel tests of smart model rotors with individual blade twist control using embedded piezoceramic materials [8,9]. These experimental results indicated that tip twist amplitudes on the order of 0.5 degrees were obtainable, which was less than the target value 1 to 2 degrees. However, they demonstrated that induced-strain actuation of blade twist was a feasible concept for rotor vibration control. The NASA/ARMY/MIT active twist rotor tested in the NASA Langley Transonic Dynamics Tunnel demonstrated rotor vibratory loads reduction in the fixed frame [10,11]. The active twist rotor of Sikorsky Aircraft also demonstrated 1% to 2% rotor power reduction in wind tunnel tests [12]. Cheng and Celi showed that the two-per-revolution input could be used to reduce rotor power [13]. Thakkar and Ganguli showed that shear induced piezoceramic actuation could be used for twisting the rotor blade which can reduce vibration, delay flow separation and alleviate dynamic stall [14,15]. The benefit studies of the active twist rotor using weak fluid–structure coupling clearly showed that the application of active twist control could reduce the rotor vibrations and power simultaneously [16]. The coupled computational fluid dynamics and computational structural dynamics analysis of the full-scale UH-60A Blackhawk helicopter rotor showed that the rotor lift to effective drag ratio increased by 7.3% and the corresponding power decreased by 3.3% by a 4-degree dynamic twist for the high forward flight (C8534) [17]. In this case, the pitch link loads increased by about 2%, and the other blade loads or rotor vibratory loads remained unchanged or decreased [18]. Experimental results in German Aerospace Center (DLR) suggested that the active twist blades incorporating MFCs (Macro Fiber Composite) were capable of generating sufficient twist deformation under full centrifugal loads at different higher harmonic excitations [19,20]. It is therefore possible that active twist rotors can be used for reducing vibratory loads and at the same time decreasing rotor power.

This work is focused on the application of variable rotor speed in conjunction with variable blade twist to obtain reductions in the required rotor power and the vibratory loads introduced by the decrease of rotor speed. The rotor can change its speed independently by varying the transmission ratio or the shaft speed of the engine without the variation of the blade twist. The rotor blades can change the twist according to the flight state but not with the azimuth. Two helicopter models to predict helicopter performance are utilized. One is based on an empirical aerodynamic model and the other is based on CFD (Computational Fluid Dynamics). To demonstrate the benefits in power reduction, a baseline rotor, aerodynamically approximating the UH-60A main rotor is used. The parametric analyses of different rotor speeds and blade twists are investigated to explore how much power reduction can be achieved. The optimal combined rotor speed and blade twist is analyzed to illustrate the selection of these variables for different flight states. The vibratory loads of variable speed rotors are also analyzed.

2. Modeling methods

2.1. Empirical model

To analyze helicopter performance, an empirical aerodynamic model is used. It includes a main rotor model, a fuselage model, a tail rotor model and a propulsive trim method. The rotor modeling follows [21,22]. A moderate deflection beam model is employed to describe the elastic deformations of the rotor blades. The rigid rotations associated with the blade hinges and the blade rotation about the rotor shaft are introduced as generalized coordinates [23]. Look-up aerofoil aerodynamics is used. The induced velocity over the rotor disk is captured by the Pitt-Peters inflow model [24]. Assembling the structural, kinetic, and aerodynamic terms yields the equations of motion based on the generalized force formulation. The implicit Newmark integration method is utilized to calculate the steady responses in the time domain. 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 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. Given the thrust and forward speed, the power of the tail rotor is determined by momentum theory in hover and forward flight.

Given initial three pitch controls (collective and cyclic pitches) and two rotor shaft attitude angles (longitudinal and lateral tilt shaft angles), the periodic response of the rotor 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 is derived from the rotor torque and fight state. These component forces and moments constitute the equilibrium equations of the helicopter, 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.

2.2. CFD model

CFD is nowadays used as the primary tool for analyzing the aerodynamics of helicopter rotors, propellers, or wind turbines. All CFD calculations shown here were performed using the Helicopter Multi-Block Method (HMB2) taking advantage of its ability to perform steady-state periodic or fully unsteady computations [25] using the RANS and URANS approach or even SAS [26] and DES [27]. For this work, fine multi-block grids were used with the sliding plane method [28]. The grids had approximately 12 million cells per blade for the isolated cases. It was assumed that the blades were rigid. For the cases presented in this paper, the Reynolds Averaged Navier–Stokes (RANS) method was used with the k–ω turbulence model.

HMB2 solves the Navier–Stokes equations in integral form using the arbitrary Lagrangian Eulerian formulation for time-dependent domains with moving boundaries:

$$\frac{d}{dt}\int_{V(t)} \vec{\omega} dV + \int_{\partial V(t)} \left(\vec{F}_i(\vec{\omega}) - \vec{F}_v(\vec{\omega})\right)\vec{n} dS = \vec{S}. \tag{1}$$

The above equations form a system of conservation laws for any time-dependent control volume $V(t)$ with boundary $\partial V(t)$ and outward unit normal $\vec{n}$. The vector of conserved variables is denoted by $\vec{\omega} = [\rho, \rho u, \rho v, \rho w, \rho E]^T$, where ρ is the density, u, v, w are the Cartesian velocity components and E is the total internal energy per unit mass. $\vec{F}_i$ and $\vec{F}_v$ are the inviscid and viscous fluxes, respectively. For hovering rotors, the grid is fixed, and a source term, $\vec{S} = \left[0, -\rho\vec{\omega} \times \vec{u}_h, 0\right]^T$, is added to compensate for the inertial effects of the rotation. $\vec{u}_h$ is the local velocity field in the rotor-fixed frame of reference.