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Performance improvement of small-scale rotors by passive blade twist control

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A passive twist control is proposed as an adaptive way to maximize the overall efficiency of the small-scale rotor blade for multifunctional aircrafts. Incorporated into a database of airfoil characteristics, Blade Element Momentum Theory is implemented to obtain the blade optimum twist rates for hover and forward flight. In order to realize the required torsion of blade between hover and forward flight, glass/epoxy laminate blade is proposed based on Centrifugal Force Induced Twist concept. Tip mass is used to improve the nose-down torsion and the stabilization of rotating flexible blade. The laminate blades are tested in hover and forward flight modes, with deformations measured by Laser Displacement Sensor. Two Laser Displacement Sensors are driven by the tracking systems to scan the rotating blade from root to tip. The distance from blade surface to a reference plane can be recorded section by section. Then, a polynomial surface fitting is applied to reconstruct the shape of rotating blade, including the analysis of measurement precision based on the Kline–McClintock method. The results from deformation testings show that nose-down torsion is generated in each flight mode. The data from a Fluid Structure Interaction model agrees well with experimental results at an acceptable level in terms of the trend predictions.

1. Introduction

Multifunctional aircrafts can fly in hover like a helicopter and forward flight like an airplane. Designing a rotor to operate efficiently in hover and forward flight presents a challenge since the inflow velocity and thrust requirement for each flight condition are quite distinct. In hover, the inflow velocity is small and the rotor must provide high thrust to support the aircraft weight. By contrast, in forward flight, the inflow velocity is relatively large and the low thrust must only overcome the drag. The large difference in inflow velocity and the thrust requirement for each flight condition suggests varied blade shapes, such as chord and twist.

The blade twist of XV-15 rotor aircraft was obtained through linear interpolation of twist between ideal rotor and propeller by a compromise analysis (McVeigh and Rosenstein, 1983). Although this trade-off solution provided an acceptable performance on XV-15, the stiff rotor with certain twist cannot maximize the overall efficiency. In the early 1980s, the study of passive blade twist control was started to improve the performance of rotor. The extension–twist coupling blade was applied on XV-15 rotor in two designs (Bauchau et al., 1983). This approach provided torsion for the improvement of rotor

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efficiency. The investigation was conducted to observe if the required twist deformation of full-scale extension–twist coupling rotor blades can be achieved within material design limit loads (Nixon, 1987). The results showed that the design is sufficient to satisfy the torsion requirements at design limit loads. A passive blade twist control method was proposed for the rotor on XV-15 (Nixon, 1988). If the optimum linear twists for hover and forward flight, instead of the compromise linear twist can be achieved, the rotor efficiency can be improved evidently. The study demonstrated successfully the feasibility of the passive blade control on conventional rotor aircraft. The feasibility of passive twist control for composite rotor blades was studied further using additional experiments (Lake et al., 1994). Since a typical tiltrotor blade would require much higher twist rate changes, the authors finally suggested the addition of tip masses to reach high twist rates for practical applications. The unique aeroelastic tailoring concepts of composite materials were discussed for aeroelastic stability and aerodynamic performance of rotor aircrafts (Nixon et al., 2000), e.g. bending–twist coupling and extension–twist coupling. The small-scale rotors on Micro Air Vehicles (MAVs) also suffer the problem caused by different blade twist rates between hover and forward flight (Shkarayev et al., 2008). Due to the small size of rotors on MAVs, the complex tailored cross section of blade for passive twist control based on conventional tiltrotor aircraft is not available any more. A small-scale flexible and stowable rotor was applied on a micro helicopter (Sicard, 2011). However, the blade was proposed to reduce impact damage and access confined spaces instead of to increase the aerodynamic efficiency of rotor in terms of torsion generation. Therefore, in current study, a laminate blade is introduced as applied to small-scale rotor.

A key issue to study flexible blade is to measure the deformation of rotating blade. Optical measurement techniques have been developing for some years in aerodynamics, materials and structure, such as Holographic Interferometry (HI), Electronic Speckle Pattern Interferometry (ESPI), Projection Moiré Interferometry (PMI) and Digital Image Correlation (DIC) (Rajpal, 2009; Schmidt and Tyson, 2003). There are limited investigations of optical measurement techniques for rotor blade deformation. The PMI technique was presented to obtain quantitative deformation profiles conditionally sampled as a function of rotor azimuth (Fleming and Gorton, 1998). Experimental results showed blade bending, twist, and unsteady motion. This initial proof-of-concept test was demonstrated the capability of PMI to acquire accurate, full field data of blade deformation. PMI was then used in wind tunnel tests to obtain azimuthally dependent blade bending and twist for a 4-bladed Active Twist Rotor (ATR) (Fleming et al., 2002). The measurement helps to understand the overall behavior of the ATR system and the physical mechanisms causing the reduction in rotor loads and noise. Blade deflection measurements using stereo photogrammetry were performed for a UH-60A 4-bladed rotor system (Olson et al., 2010). The ability to photogrammetrically measure blade deflection during wind tunnel testing was successfully demonstrated. The deformation of small-scale rotating blade was measured using DIC system (Lawson and Sirohi, 2011). A commercial DIC software was used to obtain bending and twist on three different types of rotors with varying flexibility. As discussed above, PMI was found to have low sensitivity for in-plane deformation and moderate for out-of-plane deformation. By contrast, DIC has a relatively high sensitivity that can reach 1/30 000 of the test field. However, it needs a pre-processing which is to apply a stochastic speckle pattern to the surface by spraying it with a high-contrast and non-reflective paint. The painting in pre-processing will probably affect the stiffness of small-scale blades.

In this study, Blade Element Momentum Theory (BEMT) model was implemented to obtain the optimum twist rates of blade in hover and forward flight. A concept of Centrifugal Force Induced Twist (CFIT) was proposed using glass/epoxy and tip mass to generate stable torsion of rotating blade. A Laser Displacement Sensor (LDS) rig and corresponding post-processing method were developed to measure the deformation of rotating blade. The experimental results were compared with Fluid Structure Interaction (FSI) model in terms of bending and torsion deformations.

2. Optimum blade twist rates in each flight mode

Incorporated into a database of airfoil characteristics, a model based on Blade Element Momentum Theory is implemented to obtain the optimum blade twist rates for hover and forward flight. The BEMT is a method that combines the Blade Element Theory (BET) and Blade Momentum Theory (BMT) in order to estimate the inflow distribution (Leishman, 2006; Adkins, 1990). In the classical approach of rotor analysis, lift polar is a linear function. To solve the BEMT equations, the blade should be numerically discretized into a series of small elements. In rotor mode, solution of induced flow ratio λ can be solved by Eq. (1) through a few iterations:

$$4F\lambda^2 r dr = \frac{1}{2}\sigma C_l r^2 dr, \tag{1}$$

where λ is the inflow ratio, F is the Prandtl's tip-loss factor, r is the non-dimensional radius, dr is the non-dimensional length of each element, C_l is the local lift coefficient and σ is the local solidity ratio. The BEMT model used for propeller mode includes the swirl induced velocity. The analysis procedure requires an iterative solution for the inflow angle at each radial position. The inflow angle ϕ is defined by

$$\tan\,\phi = \frac{V_c(1+a)}{\Omega r_l(1-a')}, \tag{2}$$

where V_c is the inflow velocity, a and a' are the interference factors respectively in the axial and swirl directions, Ω is the rotational speed and r_l is the local radius.