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Aeroelastic stability of a flexible ribbon rotor blade

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ABSTRACT

This paper describes the static and dynamic aeroelastic behavior of a thin ribbon that is used as an extremely flexible helicopter rotor blade. The non-dimensional torsional stiffness of this rotor blade is three orders of magnitude lower than that of a conventional helicopter rotor blade. As a result, the rotor blade undergoes large torsional deformation and its static and dynamic behavior are dominated by centrifugal forces. An aeroelastic analysis is developed based on Euler–Bernoulli beam theory including large twist angles and unsteady aerodynamics including the effect of returning wake. The flow is assumed to be attached at all times, and only classical divergence and flutter stability are evaluated. The analysis is validated with deformation measurements of a 23 cm diameter rotor with ribbon blades. Divergence and flutter stability boundaries are identified, and the effects of rotational speed, rotor diameter, location of blade center of gravity and blade pitch are discussed. The analysis can be used as a design tool for flexible ribbon rotors in a variety of missions.

1. Introduction

Conventional helicopter rotor blades are typically long, slender structures constructed out of stiff materials such as metals or composites, with a closed-cell cross-section. This paper describes the aeroelastic behavior of an unconventional rotor blade comprised of a thin ribbon with a mass at the tip. The cross-section of the ribbon is a circular arc, and the ribbon is constructed out of a low shear modulus carbon fiber layup. This ribbon rotor blade has negligible structural stiffness. Its dynamic behavior is dominated by centrifugal and aerodynamic forces, and hence it is prone to aeroelastic instability.

In the 1960's, ribbon rotor blades were explored for heavy lift helicopters with large diameter rotors. These early flexible rotor blades consisted of a thin membrane (e.g. mylar, fabric or metal) supported by cables running spanwise and stabilized by a tip mass (Winston, 1968b, 1968a; Roeseler, 1966; Goldman, 1960; Linden, 1972). Simplified analyses of such blades indicated that stability boundaries were independent of rotational speed (Roeseler, 1966; Goldman, 1960) and limited experiments were performed to quantify their dynamic response. In addition, these analyses showed that divergence stability was assured when the elastic axis was ahead of the aerodynamic center, and flutter was prevented when the blade center of gravity was ahead of the elastic axis. These conclusions contrast with the classical criterion for aeroelastic stability of a conventional rigid rotor blade (Johnson, 2013), which only requires the blade to be mass balanced in such a way that the center of gravity is ahead of the aerodynamic center, and where the location of the elastic axis is of relatively minor importance.

Recently, Sicard and Sirohi (2014b) investigated extremely flexible, ribbon blades for a 46 cm diameter micro-helicopter rotor. These blades consisted of a thin flexible matrix composite ribbon, with a circular arc cross-section that served as the airfoil profile. A cylindrical tip body oriented chordwise at an index angle to the blade provided centrifugal stiffening and created a passive twist

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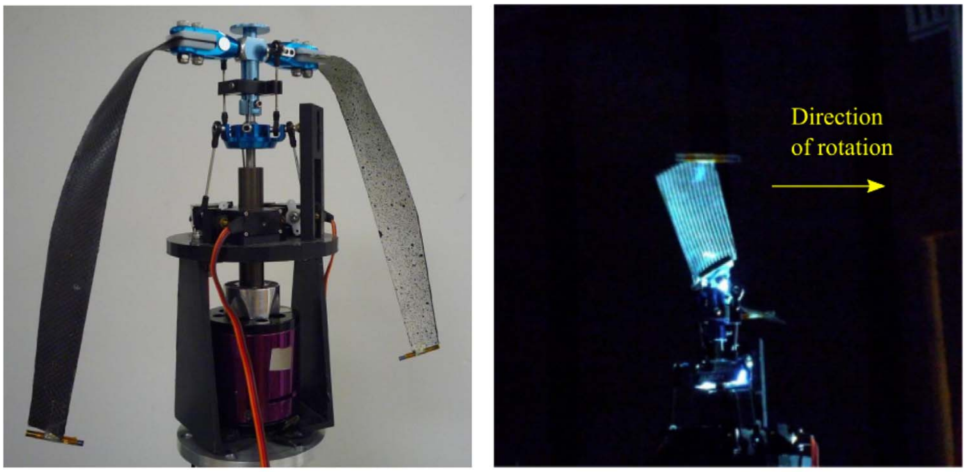
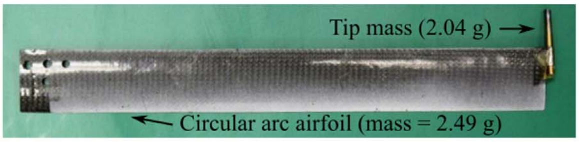


(a) Flexible ribbon rotor at rest. (b) Flexible ribbon rotor at 1500 RPM.



(c) Planform of ribbon rotor blade.

Fig. 1. Experiments on 46 cm diameter flexible ribbon rotor.

Table 1
Ribbon rotor parameters.

Airfoil		Circular arc
Rotor radius	R	22.86 cm
Ribbon blade length	L	17 cm
Chord	c	2.286 cm
Camber	C_a	7.5% of c
Thickness	t	1.39% of c
Total blade mass	M_B	4.53 g
Tip mass	M_m	2.04 g
Tip mass index angle	θ_{ind}	−22°
Rotational speed	Ω	1200 rpm
Tip Reynolds number	Re_c	46,160

Table 2
Ribbon rotor blade material properties and normalized stiffnesses.

Young's modulus	E	25 GPa
Shear modulus	G	1 MPa
Flap bending stiffness	$\frac{EI_\eta}{m_0\Omega^2R^4}$	9.65×10^{-2}
Lead-lag bending stiffness	$\frac{EI_\xi}{m_0\Omega^2R^4}$	2.54×10^{1}
Torsional stiffness	$\frac{GJ}{m_0\Omega^2R^4}$	1.00×10^{-3}

distribution. Fig. 1(a) shows a picture of the flexible ribbon rotor at rest with the rotor blades hanging under their own weight. A picture of the rotor spinning at 1200 rpm (Fig. 1(b)) taken under stroboscopic illumination shows the rotor blade stiffened by centrifugal force, and the blade planform is shown in Fig. 1(c). The parameters of this rotor are listed in Table 1 and the material properties of the ribbon are listed in Table 2. Note that the non-dimensional torsional stiffness of this ribbon rotor blade is three orders of magnitude lower than that of a conventional rotor blade.

Experiments in hover showed that these blades could generate the same thrust and efficiency as rigid rotor blades with the same planform. However, in contrast to previous analytical predictions, the stability boundaries of these rotor blades was found to depend on rotational speed and collective pitch (blade root pitch angle). Therefore, guided by these experiments, a more refined aeroelastic

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