EXTENSION-TWIST-COUPLED STAR-BEAM COMPOSITE ROTOR BLADE TIP CONCEPT

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1 Introduction

The rotor blade tip region is characterized by the highest dynamic pressure and consequently provides potential for the generation of highest airloads. Additionally, blade tip sections are characterized by large moment arm of with respect to the blade root. Consequently, rotor blade tip sections have the highest potential for the generation of active and/or passive rotor control airloads (forces and moments) aimed at both vibration level and aeroacoustic noise reduction as well as – more ambitiously – primary flight controls.

A primary means of airload control is via cross sectional pitch control. While in fixed wing aircraft mechanism-based solutions are possible, in rotor applications the use of on-blade mechanisms is discouraged by the very high level of centrifugal loading in the blade tip region (on the order of hundreds of g) causing friction/sticktion, precise balancing requirements, reliability concerns, complexity and cost, and potentially catastrophic consequences of mechanism failures.

Composite materials represent the preferred material option for modern rotor blade design, particularly in the field of rotorcraft and wind energy, due to superior specific mechanical properties (stiffness, strength, fatigue resistance) as well as due to their ability to allow coupled mechanical behavior (bend-twist, extension-twist, etc.) via tailoring.

An additional form of tailoring can generate compliant mechanisms – structures with specific desirable distributions of compliance that, under specific loading modes, exhibit deformation modes characterized by displacement fields approaching those of specific mechanisms.

2 Background

In prior research [1-7] we have proposed and investigated star-beams [1-4] and modified-star-beams [5], Fig. 1, tailored composite structures combining high axial and bending stiffness with high torsional compliance. In this case tailoring leverages both the composite layup and the cross-sectional geometry. We have shown that they represent outstanding solutions for tension-torsion bar applications, including the case of extension-twist coupling, for which the star-beam preserves the high level of coupling achievable in composite strips.

We have proposed and investigated the use of star-beam and modified-star-beam tension-torsion bars as pitch-controllable compliant mechanisms for on-blade rotor control applications, including blade flap hinge and blade tip hinge configurations, Fig. 2. We have also investigated the use of coiled bender piezoelectric actuators for such configurations.

3 Extension-Twist Coupled Compliant-Mechanism Integral Blade Tip Concept

In the present work we are investigating the extension of our prior work [6-7], the compliant mechanism integral blade tip configuration shown in a generic sketch form in Fig. 3. More specifically, we are focused on an implementation of the concept ensuring that a smooth outer blade surface (the lifting surface) is generated for the undeformed configuration and preserved throughout the desired deformation range while allowing for longitudinal relative displacement (sliding) along the blade joints, thereby allowing the necessary out-of-plane warping of the cross section that is typical of open cross sections and an essential requirement for torsional compliance. This is accomplished by bridging the airfoil surface gaps in Fig. 3 with flexible elastomeric (rubber type) strips (Fig. 4). In the present work we are focused on passive control of pitch applications via extension-twist coupling as a result of changes in axial (spanwise) force, typically obtained as a result of blade centrifugal force change with rotor speed.

For this initial investigation the response of the elastomeric material is assumed linearly elastic, and the modulus of the material is assumed a parameter, with values a fraction of the transverse stiffness of the composite material. An ABAQUS-based finite element approach is employed to characterize the blade tip mechanical response.

4 Blade Tip Structural Model

The bridging of the small gaps of the cross section in Fig. 3 with elastomeric strips, Fig. 4, results in a fundamental change from an open to a closed cross section, which is typically characterized by much higher torsional stiffness and much lower levels of extension-twist coupling. However, due to the assumed much lower modulus of the elastomeric material (of between one and three orders of magnitude lower compared to the transverse modulus of the composite material), considered a parameter, it is expected that the resulting torsional stiffness and level of extension-twist coupling will effectively bridge the gap between the corresponding values of the fully composite limit cases (open cross section and closed cross section, respectively).

Given the focus of this initial work on investigating the effect of variation of elastomeric stiffness, it is assumed that the entire cross section is of uniform thickness (including the elastomeric strips) and lay-up (excluding the elastomeric strips), a constraint that should be relaxed for realistic blade tip sections.

We have assumed a NACA 0012 airfoil cross section, and have modeled a constant chord uniform section with a slenderness (chord/span) ratio of 20. The chord length of the model is 1m. Six webs and the chord form the support structure for the outer surface skin strips (Fig. 4). The relative location of the six webs is at 0.21, 0.35, 0.52, 0.70, 0.80, and 0.89 of the chord, measured from the leading edge. The chordwise size of the gaps bridged with elastomeric strips is 0.01 of the chord. An extension-twist coupled eight ply $[\theta_4 / -\theta_4]$ antisymmetric lay-up was assumed throughout. The assumed thicknesses are shown in Table I.

We assumed a Hexcel IM7/8551-7 graphite-epoxy composite material system with the characteristics shown in Table II.

The elastomeric material is assumed to have a Poisson's ratio of 0.5 and an elastic modulus of 0.1 (Case 1), 0.01 (Case 2), and 0.001 (Case 3) of the E_{22} value in Table II, respectively.

The model was discretized using S4R reduced integration shell elements. The model size was on the order of 90k elements. Figure 5 shows the level of mesh refinement at one end of the discretized structure, with built-in boundary conditions imposed.

In order to reduce the influence of end effects, the axial stiffness (EA), torsional stiffness (GJ), and level of extension-twist coupling (K) were numerically determined using the relative displacement and rotation under applied axial force and/or torque of the cross sections located at 40% and 60% of the span, respectively.

5 Results and Discussion

The variation of axial stiffness, torsional stiffness, and coupling with ply angle, θ, are shown in Figs. 6-8, respectively.

As expected, Fig. 6 shows that the axial stiffness of the cross section is not significantly influenced by the presence and the stiffness of the elastomeric strips, given their small cross sectional area.

It is interesting to note from Fig. 7, however, that the torsional stiffness shows a significant variation with elastomeric stiffness (Case 1 vs. Case 2. vs. Case 3), while at the same time the level of extension-twist coupling (Fig. 8) shows only a small variation.

Based upon the results of this initial investigation it therefore appears that the use of elastomeric strips to bridge the gaps between the composite strips of a cross section such as the one in Fig. 3 provides an avenue to increase the level of torsional stiffness without any significant sacrifice in axial stiffness or level of extension twist coupling. The stiffness of the elastomeric strip is an effective parameter governing this response.

6 Conclusions

This initial finite element investigation confirmed the authors' expectation that the use of elastomeric strips to bridge the gaps between the strips of an extension-twist coupled generalized star-beam airfoil cross section provides an effective means to increase the torsional stiffness of the cross section without sacrificing the level of extension-twist coupling.

Based upon these initial results a more in-depth investigation is warranted to determine the full potential of the concept, in particular for more realistic cross sectional configurations representative of rotorcraft and of wind turbine applications. An investigation of other extension-twist coupled lay-ups, in particular those that satisfy a hygro-thermal stability constraint while maximizing the level of extension-twist coupling is of both academic and practical interest.

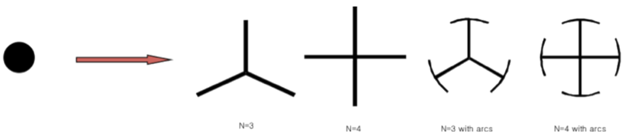

Fig. 1. Star-beam and modified-star-beam cross sectional configurations.

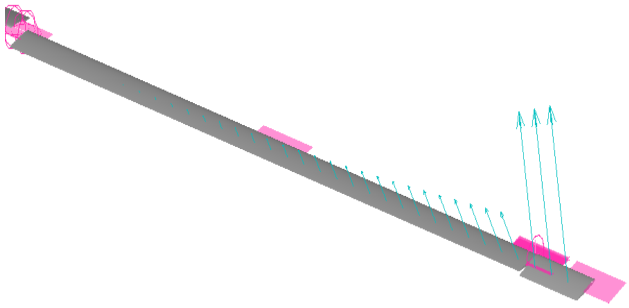

Fig. 2. Star-beam compliant mechanism supported rotor blade tip – aeromechanical analysis.

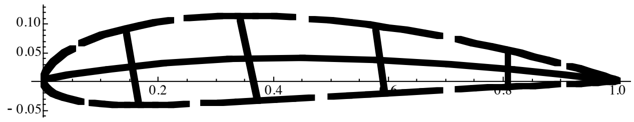

Fig. 3. Generalized modified star-beam airfoil section.

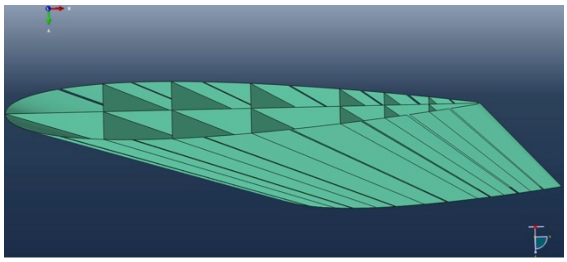

Fig. 4. Elastomeric strip bridged generalized modified star-beam airfoil section.

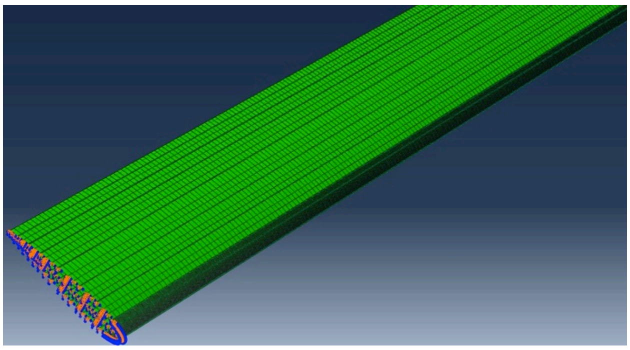

Fig. 5. Built-in end of the S4R discretized model.

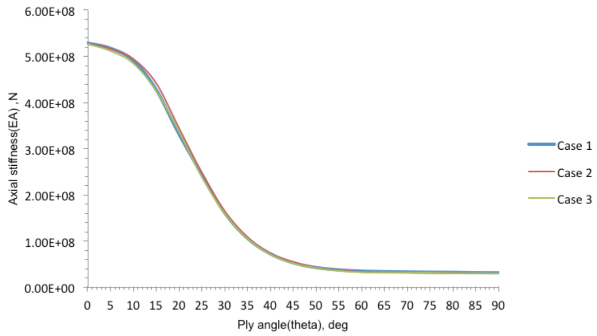

Fig. 6. Variation of axial stiffness (EA) with ply angle, θ.

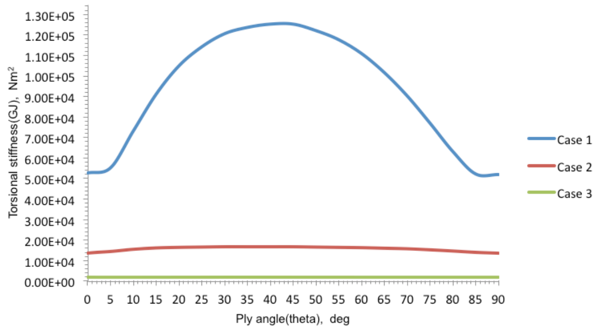

Fig. 7. Variation of torsional stiffness (GJ) with ply angle, θ.

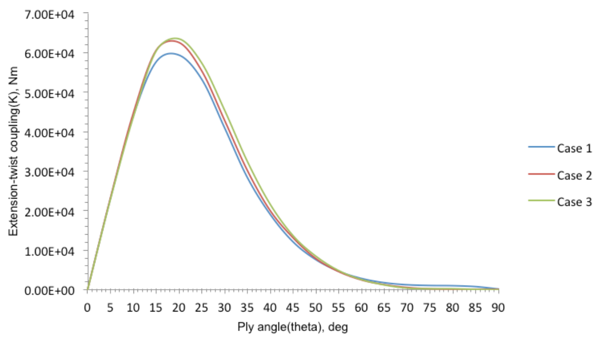

Fig. 8. Variation of extension-twist coupling (K) with ply angle, θ.

Table I. Assumed thicknesses

Component	Thickness
Ply thickness	138.75 µm
Laminate thickness	1110 µm
Elastomer thickness	1110 µm

Table II. IM7/8551-7 material properties

Property	Value
E_{11}	146.14 GPa
E_{22}	8.472 GPa
$G_{12} = G_{13}$	3.879 GPa
G_{23}	3.3 GPa
$\nu_{12} = \nu_{13}$	0.341
ν_{23}	0.5

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