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Multi-physics design and optimization of flexible matrix composite driveshafts

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ABSTRACT

Flexible matrix composites (FMCs) consist of low modulus elastomers such as polyurethanes which are reinforced with high-stiffness continuous fibers such as carbon. This fiber–resin system is more compliant compared to typical rigid matrix composites and hence allows for higher design flexibility. Continuous, single-piece FMC driveshafts can be used for helicopter applications. In the present investigation, an optimization tool using a genetic algorithm approach is developed to determine the best combination of stacking sequence, number of plies and number of in-span bearings for a minimum-weight, spinning, misaligned FMC helicopter driveshaft. In order to gain more insight into designing driveshafts, various loading scenarios are analyzed and the effect of misalignment of the shaft is investigated. This is the first time that a self-heating analysis of a driveshaft with frequency- and temperature-dependent material properties is incorporated within a design optimization model.

The analysis assures that the material does not overheat and that allowables are not exceeded. The challenge is that the analysis needs to address several physical processes such as self-heating in the presence of material damping, conduction and surface convection, ply-level stresses and strains, buckling and dynamic stability. Quasi-static and dynamic temperature- and frequency-dependent material properties for a carbon-polyurethane composite are embedded within the model. For two different helicopter drivelines, weight savings of about 20% are shown to be possible by replacing existing multi-segmented metallic drivelines with FMC drivelines.

1. Introduction

Drivelines are crucial mechanical components in a rotary-wing aircraft. Depending on the aircraft design, the driveline may connect the main and tail rotors or two main rotors. Current helicopter drivelines consist of multi-segmented, stiff, metallic or composite shafts as shown in Fig. 1a. Flexible couplings and in-span bearings are utilized to join the segments and support the driveline between the ends and to accommodate misalignment due to manufacturing tolerances and aerodynamic loads on the airframe. This approach presents a rather heavy and maintenance-intensive design.

In order to develop and improved driveline utilizing emerging materials, a one-piece shaft with a minimal number of in-span bearings and no flexible couplings is envisioned 1b. A flexuraly compliant yet torsionally stiff shaft is required in order to accommodate misalignment while transmitting power. A major challenge in designing a one-piece driveshaft is heat generation within the cyclically flexing shaft. Generally speaking, rigid matrix composites are flexuraly very stiff, leading to a high running temperature under misaligned conditions. Flexible matrix composites (FMCs) have shown promise for this application based on past research [1–4]. FMCs consist of low modulus elastomers, such as polyurethane, which are reinforced with high-stiffness continuous fibers, for instance carbon. Therefore, FMCs exhibit a high strength and stiffness in the fiber direction and at the same time they allow large strains transverse to the fibers and in shear. Hence, FMC composites can be several orders of magnitude more compliant compared to typical RMCs in certain directions and therefore allow for greater design flexibility.

There are two main philosophies with respect to shaft operating speed. Driveshafts can be operated either in a subcritical or supercritical range—meaning that the operating speed is below or above the first natural frequency of the spinning driveline. An advantage of the supercritical design is that the same amount of power can be transmitted with a lower torque, which allows for a lighter driveshaft design. However, in order to avoid potentially unstable whirling, external damping needs to be applied along the length of the driveline, which adds additional complexity and weight to the system [5]. In the following work, only subcritical drivelines, as they are deployed in Blackhawk (UH-60) and Chinook (CH-47) helicopters, are considered. As a result, the operating speed of the driveshaft needs to stay below its first natural frequency at all times.

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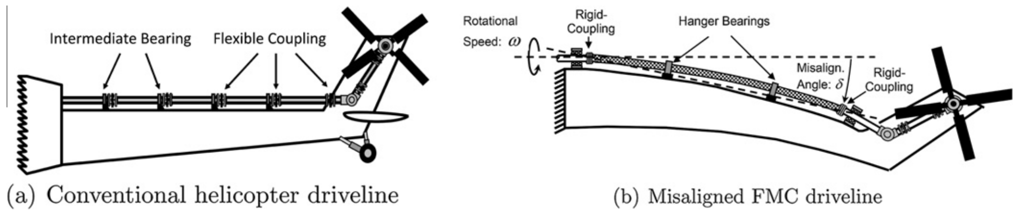

Fig. 1. Conventional and proposed FMC helicopter drivelines.

This project aims to optimize helicopter driveshafts with respect to weight using FMCs. The analysis includes multiple design criteria such as buckling, critical whirling frequency, temperature, stress, and strain. Also, in order to minimize maintenance requirements of the driveline, a minimum number of bearings and no flexible couplings are to be used in the span between the ends. Quasi-static and dynamic material properties are used in various parts of the analysis.

2. Theory and calculation

2.1. Overview

The multi-physics structural model used to design a laminated, orthotropic driveshaft, referred to as the *structural model* in this work, incorporates the following properties and design criteria: lamina-level quasi-static and dynamic temperature- and frequency-dependent material properties for a trial FMC composite based on experiments (Section 2.2), self-heating under cyclic loading (Section 2.3), stress and strain calculations (Section 2.4), critical whirl speed (Section 2.5), and torsional buckling (Section 2.6). Analytical solutions are employed, enabling a low computation time, which is of highest importance for optimization. The structural model is run sequentially. First, the driveshaft temperature ϑ_S is determined by executing the self-heating model for a spinning misaligned driveshaft with a particular cyclic flexural strain amplitude. Material properties at the shaft temperature ϑ_S and frequency f_{op} are calculated. These properties are used within the stress and strain calculation, buckling and critical speed calculations.

Inputs to the structural model are geometry (laminate stacking sequence,[1] ply thickness, outer radius, length of shaft between in-span bearings, number of bearings, ambient temperature), material properties (elastic constants, material density, material allowables), and applied loads (torque, strain due to misalignment). Outputs of the structural model are shaft temperature, lamina-level stresses and strains, critical buckling torque $T_{b,crit}$, and critical whirling speed, f_{crit}.

2.2. Material properties

Filament-wound composite shafts or tubes are economically manufactured with helically oriented reinforcement fibers. Instead of obtaining separate layers of $+\theta$ and $-\theta$ fiber orientations, each layer contains interwoven, undulated [$\pm\theta$] fibers. This leads to different mechanical behaviors in helically-wound and unidirectional-layered tubes. Much research has been carried out to model the effects of fiber undulations on material properties [6–11]. However, none of these models are generally effective for multi-angle FMC tubes under combined loadings. For this reason, discrete $+\theta$ and $-\theta$ layers are utilized in the current investigation to model a helically-wound shaft.

Equivalent unidirectional ply-level quasi-static elastic and strength properties were obtained from tension, compression, and torsional experiments carried out at room-temperature (23 °C) on a series of helically-wound tubes having fibers at various angles [4]. The carbon fiber used to manufacture the tubes is HexTow® AS4D-12k [12]. The polyurethane matrix is obtained by mixing liquid polyether pre-polymer Adiprene® LF750D and a pre-polymer Caytur® 31DA curative, both from Chemtura Corporation [13] in a mass ratio of 100:50.3. The tubes were wound with a fiber volume fraction of 58%. This carbon fiber reinforced polyurethane composite is referred to as AS4D/LF750D. Dynamic mechanical analysis (DMA) tests were carried out from 23 to 100 °C on unidirectionally reinforced AS4D/LF750D specimens. One set of flat specimens was loaded in tension perpendicular to the fibers to determine the temperature- and frequency-dependent transverse storage and loss moduli. A second set of unidirectional, longitudinally-reinforced tubes were tested with torsional DMA to determine the shear storage and loss moduli versus temperature and frequency. The remainder of the elastic properties and all strength properties were fixed according to values measured quasi-statically at room-temperature. The effects of temperature and loading rate on strength may be important, but are neglected due to insufficient data. Full details of the experiments are available in [4].

A linear viscoelastic material behavior is assumed. Lamina are assumed to be transversely isotropic in the 2–3 plane. Due to the DMA testing conditions, the material model is limited to a maximum temperature of around 100 °C. Laminate properties are predicted from lamina properties by applying a fractional derivative model as described by Shan and Bakis [3]. Appendix A lists the viscoelastic properties used in the structural model.

2.3. Self-heating model for a spinning, misaligned driveshaft

2.3.1. Assumptions

- All strain energy loss (dissipated energy) which is caused by internal damping is converted into heat. At the ply level, energy loss occurs only due to normal strains in all three principal material directions and shear strain only in the 1–2 plane in accordance with the findings reported in [3].
- There is no coupling between the temperature and elastic fields except for the aforementioned temperature dependence of dynamic properties in the transverse and shear directions.
- The shaft is modeled as a thick, laminated, orthotropic, viscoelastic material with 3-dimensional stresses and strains that vary ply by ply.
- The shaft is subjected to cyclic pure bending loads—i.e., where flexural strain does not vary along the length of the shaft.
- Torque is assumed to be constant and to have no influence on heating.
- The effects of tangential through-thickness shear stress, $\tau_{r\theta}$, is neglected in the heat-generation calculation for simplicity.
- A one-dimensional heat transfer problem in the radial direction is assumed. Heat transfer along length is neglected.

[1] The stacking sequence in the structural model starts from the inner radius of the shaft which implies that the numbering of the layers starts at the inner radius r_i.