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Optimal design of a variable-twist proprotor incorporating shape memory alloy hybrid composites

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ABSTRACT

The tiltrotor blades, or proprotor, act as a rotor in the helicopter mode and a propeller in the airplane mode. The helicopter mode generally requires relatively a low built-in twist angle, whereas in the airplane mode, a high built-in twist is desired. Meeting these rather conflicting requirements make the tiltrotor design a challenging task. This paper explores an optimal design of a variable-twist proprotor that changes the built-in twist in an adaptive manner by using the shape memory alloy hybrid composite (SMAHC). The optimum design problem attempts to find the cross-section internal layout that maximizes the twist actuation of the variable-twist proprotor while satisfying a series of design constraints. An optimum design framework is constructed in the current work by combining various analysis and design tools, such as an active composite cross-sectional analysis, a nonlinear flexible multibody dynamics analysis, a 3-D strain analysis, and a gradient-based optimizer. The MATLAB is used to integrate and synthesize the individual tools. A static tip twist is chosen as an objective function that should be maximized for the best performance. The optimum results exhibit that the twist actuation of the variable-twist proprotor can be maximized while satisfying all the prescribed design constraints.

1. Introduction

The tiltrotor aircraft is a highly attractive and versatile vehicle since it has the capability of vertical take-off/landing and high-speed flight. The vehicle consists of three operation modes: helicopter mode, transition mode and airplane mode. Also called a proprotor, the tiltrotor blade can function as a blade in the helicopter mode and as a propeller in the airplane mode. Because of the dual function role, the proprotor experiences two different aerodynamic environments. In the helicopter mode, it has a relatively small inflow, high blade loading and high rotor speed, whereas in the airplane mode, it has a high inflow, small blade loading and relatively low rotor speed. The difference in the inflows and rotor speeds between the two operation modes necessitates that the proprotor requires a low built-in twist for the helicopter mode but a high built-in twist for the airplane mode in order for a good performance characteristic. Because of the conflicting requirements, the built-in twist often determined from a compromise between the two built-in twist angles adequate for the helicopter and airplane modes, respectively. Naturally, this conventional design method is unable to guarantee the best performance in either operation mode.

Several researchers have studied the variable-twist proprotor concept to overcome this problem. The most successful approach was to take advantage of the anisotropic nature of fiber-reinforced composite materials. When a composite blade is elastically tailored in an appropriate manner, the extension and torsion behaviors may be coupled. In this method, the change of centrifugal actions due to different rotor speeds between the two operation modes is used to vary the built-in twist distribution [1–3]. However, since this approach is based on a passive way, it is difficult to achieve necessary built-in twist angles appropriate under different flight conditions. The shape memory alloy (SMA) was introduced in the variable-twist proprotor design to overcome this drawback [4]. Since the SMA can produce a large strain with a low actuation frequency, it is suitable for the structural shape control rather than vibration and noise controls. Recently, an adaptive shape control using the SMA has been a focus of research. Prahlad and Chopra [4] demonstrated that the twist performance of an SMA actuator could be increased using a torque tube configuration.

The first serious work on the design and performance analysis of the variable-twist proprotor using SMA was conducted by the present authors [5]. An SMA hybrid composite (SMAHC), which consists of SMA wires and composite matrix, was introduced as an actuator for a built-in twist control. As is depicted in Fig. 1, the SMA wires are uniformly embedded with the composite laminae in the fiber direction (1-direction). The SMAHC is employed in the variable-twist proprotor design because of its potential advantages. First, the

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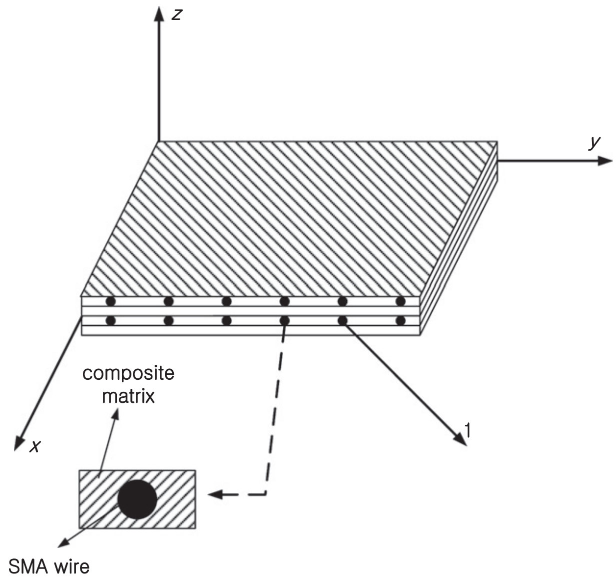

Fig. 1. Shape memory alloy hybrid composites (SMAHC).

design method for a variable-twist proprotor using the SMAHC is similar to that of a conventional composite proprotor, since the SMAHC ply can be regarded as a composite prepreg. Second, the SMAHC is used to endure the loads as well as to control the built-in twist distribution. In other words, the SMAHC plies can play roles as a primary structure. Third, through the SMAHC actuation by applying the temperature change, the proprotor performance could be improved in an adaptive manner. This is because the twist actuation can be controlled adaptively by adjusting the applied temperature to the SMAHC. It is noted that the authors' previous work [5] has a limitation since it used a manual iterative process to design the cross-section, thus the desired maximum twist actuation was not achieved. The maximization of a twist performance is truly desired for more efficient variable-twist control.

There have been numerous studies on optimal designs for composite proprotors [2,3], helicopter blades [6–8] and active twist rotor incorporating anisotropic piezoelectric composite actuators [9,10]. However, no prior work could be found on the optimal design of the variable-twist proprotor using the SMA. The present study demonstrates the optimal design of the variable-twist proprotor for maximizing the twist actuation using the SMAHC. The model proprotor is designed based on the composite proprotor of the KARI (Korea Aerospace Research Institute) SUAV (Smart Unmanned Aerial Vehicle, [11]), which is illustrated in Fig. 2. The thermomechanical behavior of SMA wires in the SMAHC is predicted using the Brinson model [12], and the effective material properties of the SMAHC prepreg are obtained by applying the rule of mixture. A design optimization framework is constructed and composed of several analysis and design tools: active composite cross-sectional analysis, nonlinear flexible multibody dynamics analysis, 3-D strain analysis, and gradient-based optimizer.

2. Technical approach

2.1. Thermomechanical behavior of SMA wire

The Brinson model [12] is used to simulate the thermomechanical behavior of the SMA wire. This model basically uses the rate constitutive equation as the one developed by Tanaka [13] and Liang–Rogers [14]. However, the martensite volume fraction, ξ, in the Brinson model is divided into two parts: the stress-induced martensite volume fraction, ξ_S and the temperature-induced martensite volume fraction, ξ_T, and $\xi = \xi_S + \xi_T$. The constitutive equation is then expressed as

$$\sigma - \sigma_0 = E(\xi)(\varepsilon - \varepsilon_0) + \Omega(\xi)(\xi_S - \xi_{S_0}) + \Theta(\xi)(T - T_0) \quad (1)$$

where the subscript 0 indicates the initial state. The detailed expressions of ξ_S and ξ_T in the phase transformations can be found in Ref. [12]. In addition, E, Ω and Θ are Young's modulus, the thermoelastic coefficient, and the phase transformation coefficient, respectively, and they are represented as

$$\begin{aligned} &E(\xi) = E_A + \xi(E_M - E_A), \quad \Omega(\xi) = -\varepsilon_L E(\xi) \\ &\Theta(\xi) = \Theta_A + \xi(\Theta_M - \Theta_A), \quad \Theta(\xi) = \alpha(\xi)E(\xi) \end{aligned} \quad (2)$$

where ξ_L is the maximum residual strain and α is the thermal expansion coefficient. Furthermore, the subscripts A and M denote the austenite phase and the martensite phase, respectively.

2.2. Effective material properties of an SMAHC prepreg

For the SMAHC, the SMA wires are embedded into the composite matrix along with the fibers. The effective material properties of the SMAHC can be obtained using the rule of mixture [15] as follows:

$$\begin{aligned} &E_1 = E_{1m}V_m + E_sV_s \quad E_2 = \frac{E_{2m}E_s}{(E_{2m}V_s + E_sV_m)} \\ &G_{12} = \frac{G_{12m}G_s}{(G_{12m}V_s + G_sV_m)} \\ &\upsilon_{12} = \upsilon_{12m}V_m + \upsilon_sV_s \\ &\rho = \rho_mV_m + \rho_sV_s \end{aligned} \quad (3)$$

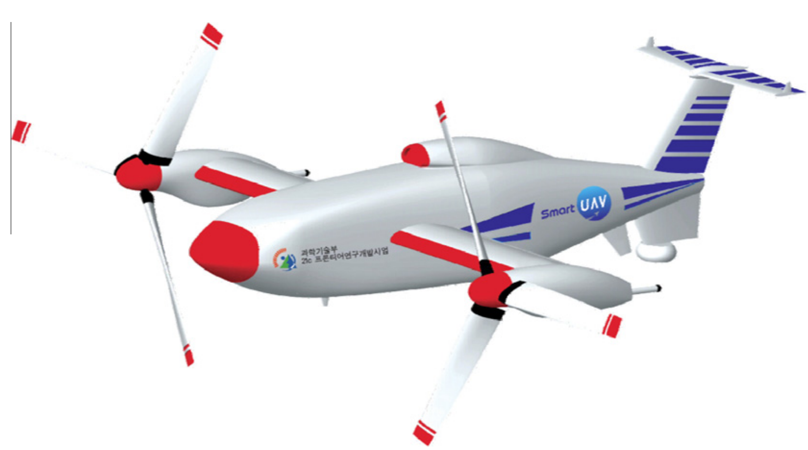

Fig. 2. KARI SUAV tiltrotor.