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Shape memory alloy-based mechanism for aeronautical application: Theory, optimization and experiment

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ABSTRACT

Efforts to create efficient and lighter aeronautical structures are defining morphing systems especially those associated with smart materials. In this regard, three simple mechanisms using shape memory alloy (SMA) wires are investigated to generate torque that could be used for flap actuation. The devices consist of an SMA wire biased by a linear spring in the following configurations: concurrent, collinear, and in parallel attached to a pulley. The design of such mechanisms are modeled, optimized, and experimentally verified. The model for the flap consists of two rigid bodies, one fixed and the other rotating, with a single actuator connected to each body. Aerodynamic loading and heat transfer analysis are also considered. The model utilizes the thermomechanical properties for an SMA wire experimentally characterized via improved inverse problem techniques. A multiobjective genetic optimization is implemented to find designs for the three configurations that minimize power consumption and maximize flap deflection magnitude. Overall, as design complexity (i.e., number of degrees of freedom) increases, the power to achieve a certain flap deflection decreases. The maximum deflection for all three mechanisms is sufficient for typical aircraft operations. Finally, numerical results were verified via an experimental apparatus, where similar performance to the model was achieved.

1. Introduction

Aircraft wings are designed to have high performance during cruise, the flight condition that represents the majority of flight time. For other conditions, mechanisms are implemented to modify wing geometry and aerodynamic properties. High-lift devices, such as flaps and slats, are implemented to increment lift during various flight conditions [1]. As an essential aircraft component, flap actuators are compact, have a high fatigue life, and are able to exert high forces. To exceed the limitations of modern actuators built out of traditional materials, the use of smart materials is receiving increased attention. It is the authors' belief that the technical readiness level (TRL) for some of these smart materials is high enough to develop new and realistic aerospace applications. A possible application for flap technology is to substitute pneumatic mechanisms for compact shape memory alloy (SMA) actuators.

Shape memory alloys undergo solid-to-solid phase transformations induced by an appropriate temperature and/or stress [2]. Compared to other actuators, SMA actuators have high actuation stress, high actuation strain, and high energy density [3]. SMA actuator configurations utilizing shape memory effect are classified as either *bias* or *antagonistic* in regards to how the restoring force is applied to the system. A bias configuration consists of one SMA actuator acting against one bias spring. It is characterized as having larger stroke, fast actuation during heating, but slow reset during cooling. An antagonistic configuration consists of a pair of SMA actuators arranged antagonistically. When one actuator is heated, the other remains at room temperature and acts as a stiff spring until it is also heated restoring the initial configuration.

The main challenges for the implementation of SMAs is low energy efficiency and functional fatigue [2], i.e. the loss of actuation stroke over a number of cycles. Accordingly, SMA actuators are suited for applications with low frequency and high force requirements such as flaps. However, the actuators must be designed to reduce energy consumption as demonstrated by Bellini et al. [4] for automotive tumble flaps. Another relevant factor is that the design of high displacement SMA-based mechanisms is not trivial. Although some researchers have obtained significant rigid body displacements utilizing mechanisms with SMA wires [5–7], other researchers have found SMA wires quite limiting [8–10] and even resorted to SMA springs which provide larger stroke in ex-

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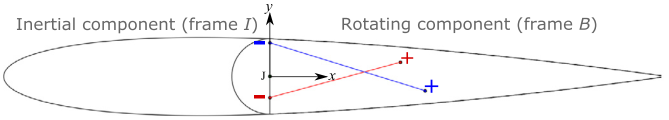

Fig. 1. Design A: schematic of concurrent design (SMA wire in red and elastic spring in blue). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

change of lower actuation forces [11,12]. Therefore, a complete study of the most common configurations of an SMA wire-based mechanism is beneficial to demonstrate the capabilities not only for aerospace applications, but for any application implementing this mechanism [13].

Previous work from the authors introduced the notion of skin-based camber morphing utilizing SMA actuators for an aircraft wing [14]. Despite the advantages of this technology, manufacturing and switching barriers are an issue. Instead, herein the authors focus on developing a simple SMA-based mechanism that is easy to manufacture and minimizes switching costs. Inspired by prototypes found in the literature for bias configuration [4,5], a bias mechanism consisting of an elastic bias spring and an SMA wire is utilized as driving mechanism for a single-actuated flap. The flap itself acts as a lever for magnifying the displacement of the SMA component which is modeled via the constitutive model by Lagoudas et al. [15], and utilizing properties of the SMA wire obtained following a modified procedure elaborated by Lagoudas et al. [2]. To minimize the effects of a small stroke and energy consumption, a multi-objective optimization is undertaken maximizing adiabatic efficiency and flap deflection. The framework implemented can be used to explore several actuation configurations. As such a total of three mechanism designs are considered and compared. One of the mechanisms is experimentally verified.

This work is organized in the following fashion: the mathematical model for the rigid body system is developed in section 2, the experimental characterization of the SMA wires is described in section 3, the numerical/experimental results for the flap system are depicted in section 4, and a summary of the findings is provided in section 5.

2. Mathematical modeling

Morphing structures are becoming important due to adaptive behavior that confers to several applications such as aeronautical systems. As a proof of concept, this paper focuses on the design of a two-dimensional plain flap prototype. For actuation, the mechanism consisting of an elastic bias spring and an initially martensitic SMA wire. The following approximations are considered: the model is quasi-static since actuation is slow; the flap components are rigid bodies since deformations and resultant fluid-structure interaction of flap components are negligible; the flap mechanism is simplified to two parts, one fixed and the other free to rotate, connected at joint point J; and each actuator (i.e., SMA wire or linear spring) has one end, point $-$, fixed on the inertial component, while the other end, point $+$, is connected to the rotating component as depicted in Fig. 1. Multiple SMA actuator mechanisms are possible [9,16], but here only three of the most used designs are explored. In decreasing order of complexity, the designs are:

- *Design A – Concurrent*: Inspired by the work by Abreu [9] the design in Fig. 1 is proposed. The end positions of the linear and SMA actuators are independent, and the actuators are concurrent (i.e., each $-$ end can be positioned anywhere on the inertial component and each $+$ end is positioned anywhere on the rotating component). Each actuator is placed on a different parallel plane to the airfoil; hence, the actuators do not intersect each other. Because this design has the most degrees of freedom, eight design variables, a greater design domain is explored.
- *Design B – Collinear*: In this application an SMA actuator is positioned inside of a compression linear spring and both actuators are concentric as depicted in Fig. 2. The two $-$ end points of both actuators are at the same location. The same is true for the $+$ end points. The final design is compact and has only four design variables.
- *Design C – Pulley*: a pulley design is also considered since experimental results by Song et al. [16] showed that it can effectively be used to actuate a flap. The pulley is annexed to the rotating component concentric to point J. When the pulley rotates θ degrees, the flap also deflect θ degrees. Each actuator has the $-$ end point annexed to the inertial component and the $+$ end point attached to a steel wire that connects both actuators. To avoid entanglement of the passive actuator and to thermally isolate the nitinol wire, only the steel wire is in contact with the pulley (see Fig. 3).

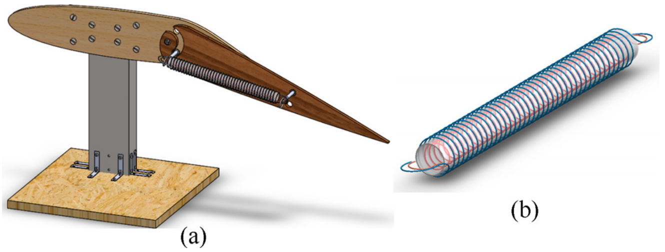
(a) (b)

Fig. 2. Design B: collinear actuator design: (a) flap model utilizing collinear actuators; and (b) the actuator itself.

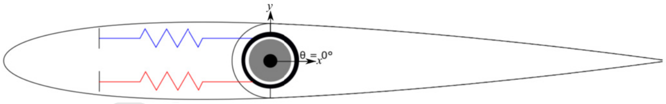

Fig. 3. Design C: actuators connected via a pulley.

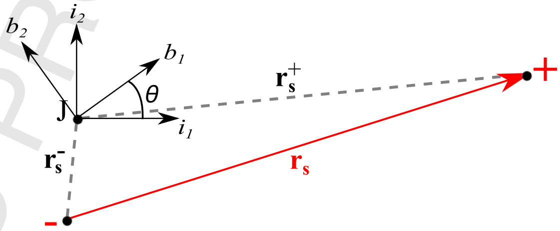

Fig. 4. SMA wire: actuator schematics.

The mathematical modeling for all designs is the same since every concept has two actuators connecting the two rigid bodies, and the deflection angle is torque-driven. In the following sections, the kinematics (section 2.1), governing equation (section 2.2), SMA constitutive model (section 2.3), and thermal performance modeling (section 2.4) are elaborated.

2.1. Kinematics

The spring and the SMA wire have the same geometric and kinematic properties as implied in Fig. 4; hence, the equations derived for this section are valid for both components. If $\mathbf{r}$ is the position vector for an actuator, it can be further decomposed into position vectors $\mathbf{r}^-$ and $\mathbf{r}^+$ (cf. Fig. 4). Since the distance between two points on the same rigid-body is constant, the position vectors $\mathbf{r}^-$ and $\mathbf{r}^+$ are constant in the inertial frame I and body frame

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