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Experimental study of a bio-inspired robotic morphing wing mechanism actuated by shape memory alloy wires

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ABSTRACT

In this work, a two degree-of-freedom (DOF) mechanism is designed and fabricated that is appropriate for morphing wing applications. The mechanism is developed in such a way that it can undergo different two degrees of freedom so that the wing can have more efficient maneuvers. Among the smart materials Shape Memory Alloy (SMA) actuators are capable of providing more efficient mechanisms in comparison with the conventional actuators due to their large force to stroke ratio, smaller size with high capabilities in limited spaces, and lower weight. As SMA wires have nonlinear hysteresis behavior, their modeling should be implemented in a meticulous way. In this research, after proposing a two DOF morphing wing, a modification is done on a well-known model of SMA, and then the mechanism is modeled. The numerical results of the model simulation are verified against the experimental results using a test setup to validate the proposed model prediction. The proposed mechanism is fabricated in order to verify the model with experimental data. The comparison between theoretical and experimental results shows that the experimental results have good agreement with the theoretical results.

1. Introduction

The term "morphing" comes from the field of biomimetics. Biomimetic researchers try to observe and replicate concepts of nature, and their ultimate goal is to make use of nature's tendency to reach optimal functionality in new designs. In the field of aeronautics, the term morphing is linked to shape adaptation and is commonly used when talking about morphing wings. Birds change the shape of their wings at different flight conditions and this enables them to improve the performance of their flights. Researchers are also trying to achieve a wing which can morph like birds' wing, and numerous designs and concepts have been presented so far [1]. Current interests in the morphing structures have been boosted by advances in smart technologies such as materials, sensors, and actuators [2]. Smart materials have received significant attention in recent years to be used as actuators. Shape memory alloy (SMA) miniature actuators are the most common smart materials used in morphing wings because of their high power to mass ratio, frictionless actuation, silence, and the simplicity of their mechanisms [3]. SMA wire has great advantages as a morphing actuator and this is due to its shape memory effect and simple actuation mechanism. Although numerous analytical and phenomenological models have been developed for SMAs over the last decades, it is difficult to choose proper models for different applications. In what follows, the literature review for morphing mechanisms is presented.

1.1. Morphing wing classification

There are many types of wing morphing mechanisms. In [4], the morphing designs are classified into three categories based on the mechanism which causes the wing to change its shape and size: (a) rotating the selected segments or the whole wing, (b) telescopic and (c) inflating the selected components or the whole wing.

In another context, as illustrated in Fig. 1, some basic modes of wing deformations are presented. Basic in-plane wing shape deformations are chord, sweep and span adaptations while taper ratio modifications are a superposition of the abovementioned modes. Airfoil thickness, camber, twist distribution and gull are typical out-of-plane wing shape deformations.

There are relatively few single degree of freedom concepts capable of approximating a general shape while many designs and concepts have been proposed for shape or curve approximation using multi degrees of freedom. Both conventional and compliant mechanisms have been developed for active camber control (shape control) using a single degree of freedom on either the leading or the trailing edge. In this case, the shape morphing was limited to a single airfoil section.

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This paper is organized as follows. In Section 2, a literature review on morphing wing mechanisms is presented. Section 3 presents design of the proposed morphing wing mechanism and the fabricated prototype is explained in detail. The modeling of the SMA wire is discussed in Section 4 and the derived equations are employed for dynamic modeling of the mechanism. Finally, in Section 5 some experiments are presented to validate the modeling and performance of the proposed morphing wing mechanism.

2. Morphing wing mechanisms

Wiggins et al. in [6] developed a single-degree-of-freedom morphing mechanism to provide a means for the wing to continuously morph from a planar to a nonplanar configuration. After describing the aerodynamic analysis of the wing in order to predict the aerodynamic loads, the structural analysis of the mechanism was investigated. The mechanism was similar to a scissor linkage, and the motion was translated from one wing segment to the next since the mechanism used a repeating quaternary–binary link configuration. It was claimed that the mechanism was fabricated in such a way that with one input to the first segment of the chain, the other wing segments can move into their desired positions.

In order to change the wing section smoothly, Kang et al. [7] proposed a new flap morphing mechanism using a smart actuator. The mechanism did not require a change in the length of the skin. To operate the mechanism, they used shape memory alloy (SMA) wires as actuator. Resistive heating method was used to activate the SMA wire actuator. Furthermore, the allowable electrical current range was experimentally investigated. A wing section that has a Clark Y airfoil was fabricated with SMA wire actuator and the actuation test was performed to prove the feasibility of the morphing mechanism. Also, the aerodynamic characteristics of the morphing wing were analyzed by using the commercial programs [7].

In [8], Barbarino et al. presented a morphing wing mechanism to control the airfoil camber at the wing trailing edge by producing a smooth morphed flap, substituting a traditional split flap on a full scale wing. A 2D study was developed to design a compliant rib. The idea was to combine the benefits of Variable Geometry Trusses (VGTs) with some “active” rods made of SMAs, to numerically design an internal truss structure able to both withstand external aerodynamic loads and be capable of changing its shape.

In an important research, University of Florida has studied the effect of a biologically inspired variable gull-wing morphing [9]. This kind of small aerial vehicle can change its shape in a variety of configurations. In other words, the angle between the inboard and outboard wing sections was changed during the flight by the use of a simple actuator [9]. In another work, Galantai et al. presented a new concept for shape morphing which was based on planform alteration [10]. It is stated that the goal of this morphing concept is to reduce drag at high speeds by decreasing the wing surface area. A deformable structure was formed of adaptive spars and ribs. To provide a two-way actuation with limited energy usage, the adaptive spars made use of the Antagonistic Flexural Cell (AFC) concept.

Another suggested mechanism to achieve shape morphing was developed by Ramrakhyani et al. at Penn State University [11]. They claimed that the structure can undergo large complex morphing states by the use of an octahedral unit cell truss structure. Moments were transmitted by compliant joints. Eight rigid links were connected through tensioned cables, and each unit cell of the structure consisted of these eight links. By the use of cylindrical length of SMA, the compliant joints were created. The SMA was used as a passive element in its pseudoelastic mode. Numerous morphing shapes can be achieved by modifying the dimensions of trusses for required deflections and through the specific actuation or release of the tensing cables. Although no details were provided, it was declared that a morphing wing for a representative section of a 300 lb aerial vehicle wing has been developed.

Truss structures actuated by SMA are a good choice for obtaining other various complex curves. Elzey et al. [12] developed a biologically-inspired vertebrate structure. By the use of several SMA wires and the differential actuation of them, the structure can undergo complex morphing shapes. The vertebrate structure consisted of a series of hollow cores which provided stiffness to the structure and were attached through hinge pins. Adjacent vertebrates were connected to each other along the top and bottom through a series of SMA wires that provided actuation for the structure [12].

In spite of the fact that all of the mentioned mechanisms can improve the performance of flight, they are all one degree of freedom mechanisms, and one morphing mode can be covered by using them. In this study, the proposed mechanism is a two degree-of-freedom mechanism, and two different modes of morphing can be achieved, i.e. sweep and gull. The mechanism is designed in a way that it can sweep by the actuation of one of the SMA wires, while the gulled shape can also be achieved by the actuation of the other SMA wire. The independency of these directions of rotation is an important factor that should be considered. In other words, the efficiency of the wing may be reduced when a swept wing has a gull rotation or vice versa. Moreover,

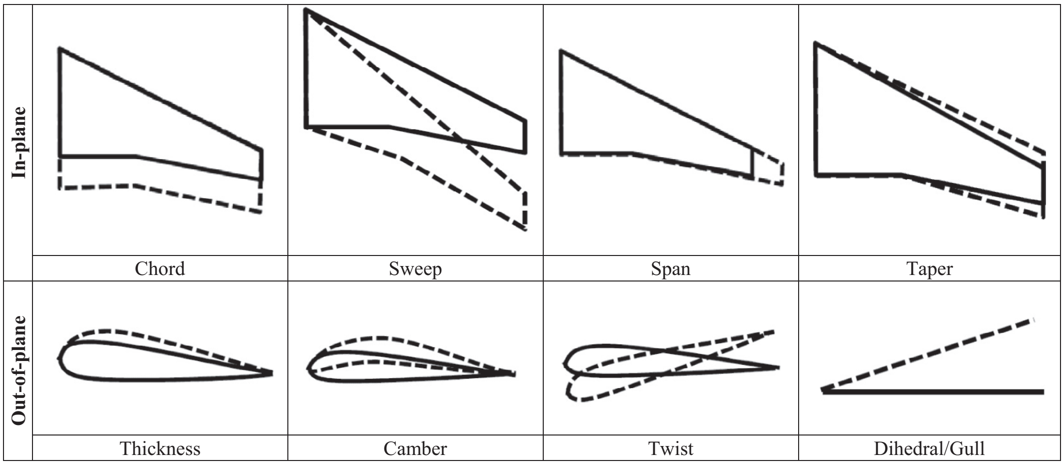

Fig. 1. Basic modes of wing deformations [1,5].