Aerospace Science and Technology 45 (2015) 228–241

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Zero Poisson's ratio flexible skin for potential two-dimensional wing morphing

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ARTICLE INFO

Article history:
Received 5 March 2015
Received in revised form 20 May 2015
Accepted 20 May 2015
Available online 27 May 2015

Keywords:
Two-dimensional morphing
Flexible skin
Hyperelastic
Antagonistic
SMA

ABSTRACT

This study presents and examines the concept of flexible skins for two-dimensional morphing applications composed of a zero-Poisson cellular core and a hyperelastic face sheet. The overall properties of the flexible skins are mainly determined by the cell structure types and parameters. The in-plane mechanical properties of three different zero-Poisson cell structures were investigated with analytical, numerical and experimental methods to determine the most suitable cell structure for two-dimensional morphing. The geometric and material nonlinearity effects on the in-plane mechanical properties of the cell structures were also discussed. The material constants of a silicone rubber as flexible face sheet were then experimentally determined and its hyperelastic behaviors were simulated to find a better boundary condition in which uniform strain and larger global strain could be obtained. 98.6% global strain for span morphing and 9.2° angle change for sweep morphing were achieved in the simulation tests of integrated skin, which validates the two-dimensional morphing capacity of the passive sandwiched skin proposed in this article. For the actuation requirement of the passive skin, a shape memory alloy (SMA) based antagonistic actuator for span morphing was developed and tested. With 11.5% global strain finally achieved, the results, to certain extent, validates the feasibility of SMA actuator application to wing span morphing.

1. Introduction

Aircraft morphing, especially wing morphing, can significantly improve system performance over an aircraft's nominal operational envelope, allow a single aircraft to perform multiple missions effectively and efficiently, and even expand its operating envelope [1]. Much effort has been devoted to the subject of morphing aircraft and several major morphing aircraft development and demonstration programs have been carried out since the 1980s [24]: the Mission Adaptive Wing Program the Active Aeroelastic Wing Program, the Smart Wing Program, and most recently, the Morphing Aircraft Structures Program.

Throughout all of these programs the flexible skin problem has been found to be a challenging one, and many of the requirements, concepts, and technologies are presented in comprehensive review article by Thill et al. [32]. Morphing aircraft wings require skins with unique properties, the most important of which are: low in-plane axial stiffness, high strain capability and high out-of-plane stiffness [12]. The type of flexible skin required depends on the specific application. For airfoil camber type applications, strain requirements are relatively modest (on the order of 2–3%) and the flexible skins are in an area where the aerodynamic loading is relatively low. However, for large area morphing applications, such as large changes in wing span, chord or sweep, the design goals require that such flexible skins undergo large in-plane strain (on the order of 50–100%) with low actuation effort (a requirement of high strain capability with low in-plane stiffness and so low actuation forces), while simultaneously carrying significant out-of-plane aerodynamic loads (a requirement of high out-of-plane stiffness) [35].

Extensive work is ongoing on developing flexible skins to achieve these design goals. Kikuta [17] experimentally tested a few thermoplastic polyurethanes, co-polyester elastomer, shape memory polymer (SMP) or woven materials that are commercially available to investigate the materials' viability as morphing skins and identified some of them to be promising candidates. Perkins et al. [28] gave an overview of research carried out at a company called Cornerstone Research Group which tried to use SMPs for flexible skin in wing chord morphing applications. Keihl et al. [16] did shear tests on various SMPs and believe that SMPs are an attractive and promising solution for morphing skins since the multiple sta-

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http://dx.doi.org/10.1016/j.ast.2015.05.011
1270-9638/

Nomenclature

SMA	shape memory alloy
SMP	shape memory polymer
l	length of the cell inclined wall
α	cell aspect ratio
β	wall thickness ratio
b	cell depth
θ	cell angle
δ_x	total displacement of inclined wall in x-direction
$\delta_{bending}$	horizontal displacement of inclined wall due to bending
δ_{axial}	horizontal displacement of inclined wall due to axial deflection
F	stretching force on cellular structure
E	elastic modulus of raw material
I	moment of inertia of inclined wall
A	area of inclined wall cross section
σ_x	equivalent normal stress on cell
ε_x	equivalent normal strain of cell
E_x	effective transverse modulus of cell
δy	vertical deflection of cell
γ	equivalent shear strain of cell
τ	equivalent shear stress of cell
E_{shear}	effective shear modulus of cell
ν	raw material Poisson's ratio
PLA	polyactic acid
Al	aluminum
FEA	finite element analysis
U	strain energy per unit of reference volume
C_{10}, C_{01}	temperature-dependent material parameters of rubber
$\bar{I}_1$, $\bar{I}_2$	the first and second deviatoric strain invariants
$\bar{\lambda}_i$	the deviatoric stretches $(i = 1, 2, 3)$
J	the total volume ratio
λ_i	the principal stretches $(i = 1, 2, 3)$
μ_i, κ_i	temperature-dependent material parameters of rubber $(i = 1, 2, \ldots, N)$
FGM	functionally graded material

ble abilities of SMPs allow them to easily change shape and once cooled to resist appreciable loads. There have been attempts to utilize the capabilities of SMP skins e.g. Lockheed Martin's Z-wing morphing concept [9]. However, electrical heating of the SMP skin to reach transition temperature proved difficult to implement in the wind tunnel test as well as brittleness and thermal fatigue problems of the material. Another approach proposed by [36] and Thill et al. [31] considered corrugated composites covered with flexible face-sheet to create a smooth aerodynamic surface as a flexible skin for one-dimensional morphing applications. This concept was then further developed and evaluated by wind tunnel tests of chord morphing wing [33,37]. Murray et al. [20] examined the use of flexible matrix composite skins for one-dimensional wing-morphing applications. By aligning the matrix-dominated direction of a skin with the morphing direction, morphing can be achieved at a relatively low actuation cost, while by aligning the firer-dominated direction normal to morphing direction can increase the capacity of the skin to carry out-of-plane pressure loads.

In the future, a novel composite material might also be used in the morphing skin structure. This class of engineered materials was design as functionally graded material (FGMs) [34]. FGMs are heterogeneous materials in which the material properties are varied continuously form point to point. This continuously varying composition eliminates interface problems, and thus, the stress distributions are smooth. In order to describe the mechanical properties of FGMs, many mechanical models have been developed including beam [5,27] and plate [4,3,6]. However, these research works are only theoretical study and no experiment or application has been carried out.

One of the more promising concepts suggested was to use sandwiched skins with cellular honeycomb core and thin, low-modulus, high-strain-capable face-sheets [23–25,8]. The flexible face-sheet provides a smooth aerodynamic surface, but the cellular honeycomb provides the ability to carry aerodynamic pressure loads with low in-plane axial stiffness and high-strain capability. The topology optimization was also used to determine the best topologies of cellular cores for one-dimensional morphing purpose [26,10]. The sandwiched skin concept was experimentally testified by Bubert et al. [8] with a prototype morphing skin which demonstrated 100% uniaxial extension. However, the above mentioned research works mainly focus on the one-dimensional morphing capabilities of these sandwiched skins, especially on span and chord morphing abilities, while the sweep morphing capacities of the flexible skins or cellular cores have not been investigated. Sweep plus span morphing leads to a two-dimensional morphing skin, as shown in Fig. 1, which would be studied in this paper.

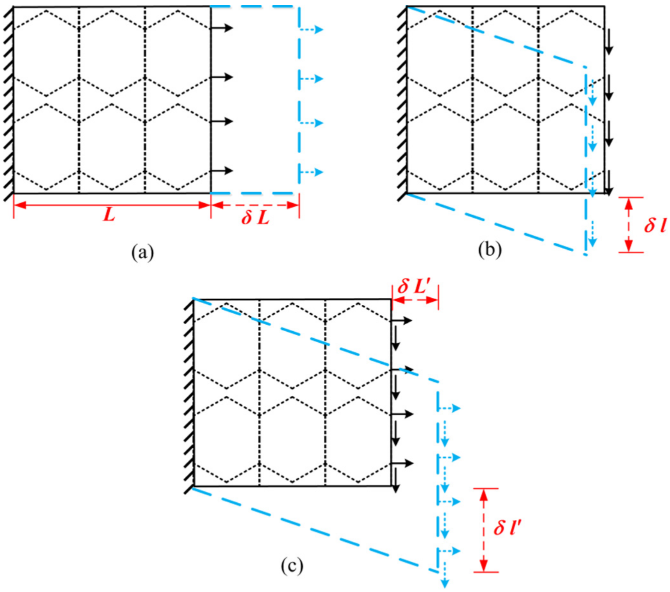

Fig. 1. Flexible skin morphing configurations: (a) span morphing; (b) sweep morphing; (c) coupling morphing.

Since sandwiched skin is a passive structure, proper actuators are needed to actuate it. Recently, the use of shape memory alloys (SMAs) as actuators has gained a wide interest in the field of morphing aircraft. SMAs are a unique class of metallic materials with the ability to recover their original shape at certain characteristic temperatures (shape memory effect) [15]. If a pre-stretched and mechanically constrained SMA wire with a large residual strain (several percent) is heated, then a recovering force is generated at the constraints, which could be used to actuate morphing structures (one-way shape memory effect) [30]. However, according to a comprehensive review of the morphing aircraft literature [1] and a review on shape memory alloys with applications to morphing aircraft [2], by far, SMAs have been mainly used for twist and cam-