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Low energy actuation technique of bistable composites for aircraft morphing

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ABSTRACT

Morphing structures for lightweight and energy-efficient aircraft mobile surfaces have been investigated for several years. This paper presents a novel lightweight, passive and low-energy morphing surface concept based on the “lever effect” of a bistable composite plate that can be integrated in aircraft moving surfaces. By using appropriate boundary conditions, it is demonstrated that the magnitude of the activation force on the bistable composite can be tailored to match the differential pressure on the aircraft’s airfoil. As a consequence, the bistable laminate can be used as a passive morphing surface. Both numerical simulations and experimental testing are used to prove this concept on a NACA 2412 airfoil structure. The results show that, by choosing proper configuration of constraints, lay-up and aspect ratio of the bistable composite, it is possible to tailor and activate the snap-through mechanism in a passive manner. The proposed concept would save significant weight when compared to an active morphing concept.

1. Introduction

The ability to adapt the aerodynamic shape of an aircraft to the environment in which it operates represents a key factor in the development of a new generation of air vehicles and it has been the focus of several researches initiatives during the last past decades [1]. This conformal change (morphing ability) can enhance the aircraft capabilities in terms of manoeuvrability, fuel efficiency, and ability to perform dissimilar tasks in an optimal manner. The current standard approach to modify the geometry of an aeronautical structure is to use conventional mechanisms such as hinged flaps on airfoils that can place limitations on the performance and lower the efficiency [2]. In the early years of aircraft design, rigid-body mechanisms were not the standard approach. Wright brothers [3] used structural flexibility, such as the wing-warping solution to control the roll and yaw of their vehicle, because a rigid body solution would have been significantly heavier.

However, as aircrafts became more and more advanced, these flexible solutions were not efficient since stronger structural parts were required in order to lift the fuselage off the ground. As a consequence, movable flaps, ailerons and slats made of stiffer materials such as aluminium and steel, were introduced into the wing structure with the disadvantage of a weight increase and a lower overall efficiency generated by the drag increase.

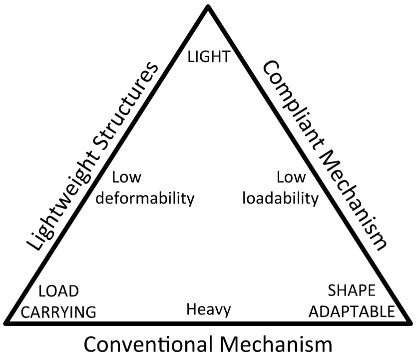

Fig. 1. The structural requirements for lightweight shape adaptation.

Hence, it is clear that in order to overcome the drawbacks of traditional moving parts, a shape adaptive structure should satisfy the following three requirements, i.e. compliance, load carrying capability and low mass. These requirements can be represented by the triangle for lightweight shape adaptation shown in Fig. 1. The interaction between these important design variables can be considered as a balance of energy between the work done on the

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Nomenclature

A, B, X	non-dimensional parameters	
C_p	pressure coefficient	
C_L	lift coefficient	
c	airfoil chord	m
F	bistable activation force	N
h	altitude	m
$\mathcal{L}$	lift	N
L	activation force position	m
l	beam length	m
M	bending moment	Nm
p	air pressure	Pa
R	hole radius	mm
$\mathcal{S}$	wing surface	m^2
S	septum position	m
S_h	hole surface	cm^2
$ST1/2$	stable state 1/2	
T	air temperature	K
U_z	z displacement	mm
V	air speed	m/s
x	abscissa along airfoil chord	m

Greek symbols

$\varepsilon_{x/y}$	deformation in x/y direction	mm/mm
ρ	air density	kg/m^3

Subscript and superscript

∞	free stream
$*$	standard configuration
L	lever configuration
std	ICAO standard

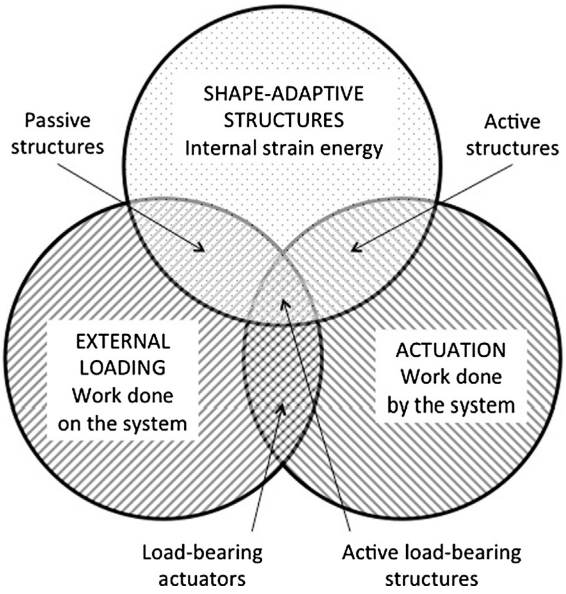

Fig. 2. The interaction between an adaptive structure, its external loading and actuation for a generic morphing system.

system (external loading), the work done by the system (actuation) and the internal strain energy of the adaptive structure.

Aircraft moving surfaces can be activated in an active or passive manner. Clearly a passive surface, while satisfying all the structural and performance requirements, would be preferable due to lack of an actuation system, costs and potentially weight saving. As it is possible to see from Fig. 2, by matching the internal strain energy of a shape-adaptive surface with the loads applied to the structure (work done on the system), it is possible to develop a system which can be defined as *passive*. Such a system will be able to respond autonomously by activating the morphing mechanism when an external force, e.g. deformable aircraft surfaces [4] or airfoil pressure, overcomes a specific threshold (which is defined by the constraints and the structural characteristics of the specific part) without the use of actuators or other mechanical devices.

In recent years, multistable composites have been investigated as aircraft morphing structures: such kind of materials are capable of varying their shape when a force is applied in an appropriate location and represent an interesting candidate for the development of passive morphing structures (Sofla et al. [5], Fortini et al. [6]). Multistable materials exhibit multiple statically stable shapes, which can be designed to show different directional stiffness as described by many authors (e.g. Barbarino et al. [7] and Arrieta et al. [8,9]). Changes between states occur due to externally forced deflections triggering a phenomenon known as *snap-through mechanism* which may involve large deflections of the laminate depending on the designed shapes and boundary conditions (Feng et al. [10], Ghosh et al. [11]). In addition, considering the high level of customisability which is intrinsic of all composite systems, the mechanical properties can be easily tuned to match the external loading distributions with the force required to activate the snap-through mechanism (Nicassio et al. [12]). As a result, the energy provided by the external load can be effectively used to trigger a change to a different shape configuration, making these materials suitable components for shape morphing.

Daynes et al. [13] considered the composite bistable airfoil as a coupled structure–mechanism system. The actuator system and the aerodynamic loads were also coupled to the structure. The analysis performed in this work was divided into two steps: an aeroelastic analysis which couples the adaptive structure with variable aerodynamic loads and an analytical model formulated to simulate the interaction between the structural and aerodynamic stiffnesses. Inviscid calculations of the aerodynamic pressure distributions around the airfoil were then carried out in order to assess the load carrying capability of the structure. The airfoil flap could remain in one of two stable geometries and both states were able to withstand the aerodynamic loading without any additional holding forces or locking mechanisms. However, in order to activate the transition between the two stable geometries, an external actuator was required. Based on the results obtained in their previous work, the same authors presented in [14] the design and wind tunnel test results of a full-scale helicopter rotor blade section with an electromechanically actuated bistable trailing edge flap. In the first stable state the flap followed the profile of the standard rotor blade section, while in its second stable state it deflected the trailing edge downwards. The flap system was designed to change between these two positions when the helicopter moved between hover and forward flight conditions. The bistability of the flap system allowed the rotor blade to keep the shape without the application of continuous loads, however it still required an electromechanical actuator to activate the snap-through mechanism between the two stable states. In this context, Bilgen et al. [15] investigated the reversible dynamic snap-through mechanism of a bistable composite plate with a clamped edge actuated by a surface mounted piezoelectric material. Following a numerical and experimental approach they concluded that by using micro fibre composite (MFC) transducers it was possible to actuate a bistable plate system able to carry out a wide range of aerodynamic loads.