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Review

Stiffness tailoring using prestress in adaptive composite structures

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ABSTRACT

Adaptive aerostructures offer the potential of increasing both aerodynamic and structural efficiency compared to conventional aerospace technologies. However, there is frequently an awkward trade-off between designing for large deformations whilst being able to withstand external loads. Multistable laminates which derive their multistability via thermal expansion mismatches are of interest for adaptive structures due to their ability to demonstrate relatively high stiffness in multiple stable states whilst being able to undergo large deformations with reduced stiffness. In addition, actuators only need to work during transition between stable shapes. However, many practical problems have arisen with the application of these laminates when designing adaptive structures. Such problems include hygrothermal variability, a limited design space with regards to achievable shape change, and insufficient stiffness for many applications. Prestressing technologies offer solutions to all of these problems. This paper summarises recent developments concerning the various means by which prestress can be used for stiffness tailoring in adaptive structures. Example prestressed structures are given including camber and twist change morphing airfoils. The use of prestress for stiffness tailoring in the design of novel passive vibration isolators and adaptive air intakes is also discussed.

Contents

1. Introduction

The background to this research is the challenge of designing and realising adaptive structures. Such research offers the potential to create structures which have the advantages of being lighter and simpler than conventional mechanisms as well as enabling geometric changes which would not traditionally be simple to achieve. However, there is an inherent and difficult design trade-off in adaptive structures, such as morphing aerodynamic control surfaces, between the need for low stiffness to enable large deformations with acceptable actuation requirements and material strain limits while still being sufficiently stiff to withstand external loading in a controlled manner [1,2].

The conventional approach to stiffness tailoring in thin-walled composite structures is via selection of the individual ply material properties, fibre orientation and laminate stacking sequence. This large design space can result in beneficial stiffness anisotropy and coupling behaviour [3,4] or tailored buckling characteristics [5,6]. A development of this technology is functionally graded

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materials where the material properties continuously vary though the thickness unlike a conventional laminate consisting of discrete plies [7,8]. Variable angle tow composites, on the other hand, offer an enhanced design space beyond conventional composite laminates by enabling fibre tow paths to be steered continuously within a given ply [9,10].

A promising solution to the conflicting stiffness requirements in adaptive structures is multistability. Multistable structures have multiple states of equilibrium where transition between states can be caused by the application of an external force or moment resulting in the structure buckling or 'snapping through' into a different local energy minimum. Multistable structures can be designed to have high stiffness in their stable 'rest' states while the transition between stable states is often characterised by lower stiffness. The simplest example of a multistable system is the case of bistability where two stable states exist. Schematic representations of mechanical systems which can demonstrate bistability are shown in Fig. 1a and b. In these mechanical systems bistability can be achieved by adding negative stiffness, via prestress, to the system which is of sufficient magnitude to overcome the positive stiffness of the monostable structure and cause a bifurcation via buckling. Between the cases of monostability and bistability a case of reduced, or even zero-stiffness, can also be realised for modest deflections where the positive stiffness of the structure is in equilibrium with the added negative stiffness from residual stresses [11,12]. Exact load paths followed depend on the particular geometry and stiffness characteristics of a system but typically, as a first approximation, they can be described using a cubic polynomial, Fig. 1c.

The earliest research into multistable structures used thermal expansion mismatches upon cool down from curing temperature in unsymmetrically laminated composites [13–15]. However, the practical implementation of such laminates into adaptive structure designs has proved problematic due to their low stiffness [16], their limited design space with regards to achievable shape change [17], and their inherent hygrothermal variability [18]. A proposed solution to the limitations of using thermal expansions is to design adaptive structures which derive their multistability using prestressing technologies.

This paper summarises the various research efforts made into prestressing technologies with the aim of establishing a unified taxonomy. The paper concludes with an outline of recent research by the listed authors into the design of a passive torsional vibration isolator and a morphing wing design which exhibits zero torsional stiffness about its aerodynamic centre.

2. Stiffness tailoring using prestress

As with all buckling phenomena, multistable structures have at least one dimension which is substantially smaller than its other dimensions (i.e., two dimensional thin plates and shells) or two dimensions are much smaller (i.e., one dimensional slender columns). All of these structures derive their multistability through a combination of their geometry, internal stress states, and material properties. Stable states are formed when there is a balance between membrane and flexural effects. It is well known that for thin structures it is easier to deform through bending than it is through stretching (or compressing). Upon snap-through internal stress resultants are redistributed and equilibriate in the adjacent stable state. Stable states are conventionally sought by minimising the energy of the system with respect to potential mode shapes and their magnitudes. The elastic energy density of a general anisotropic plate in terms of the strain, curvature, and the material properties is given by [19]:

$$u = \frac{1}{2}(A_{ij}\varepsilon_i\varepsilon_j + 2B_{ij}\varepsilon_i\kappa_j + D_{ij}\kappa_i\kappa_j) \quad (1)$$

where the A_{ij} coefficients represent extensional stiffness, the D_{ij} coefficients represent bending stiffness and the B_{ij} terms embody the possible coupling between stretching and bending owing to material anisotropy. In (1) the first and third terms are the stretching and bending energy densities respectively while the second term describes the energy associated with the coupling between bending and stretching. The strain energy varies when there is a change in either the strain tensor ε or the mid-plane curvature tensor κ. Strain energy can therefore be tailored by either the modification of mid-plane strains (in-plane prestressing) or the modification of bending strains (out-of-plane prestressing). A taxonomy for multistability using prestress is presented in the following two sections based on this observation, Fig. 2.

3. In-plane prestressing

3.1. Structures with in-plane prestress

Possibly the most ubiquitous example of a bistable prestressed structure is the single piece metal hair clip which becomes bistable during manufacture when its two extremities are pinned together, locking the structure into a heightened state of elastic strain energy. This causes the hair clip to buckle resulting in two stable geometries consisting of equal and opposite out-of-plane curvatures. Similar concepts have been patented [20] as means of creating multistable tabs for helicopter rotor blades where initially flat, stress free, isotropic plates are pinned in heightened states of strain energy to form bistable structures. Bistable concepts which work on the principle of buckling as a result of in-plane loads have also been proposed as a means of augmenting the performance of piezoelectric actuators [21] and also as basis for extendable chord bistable morphing airfoils [22].

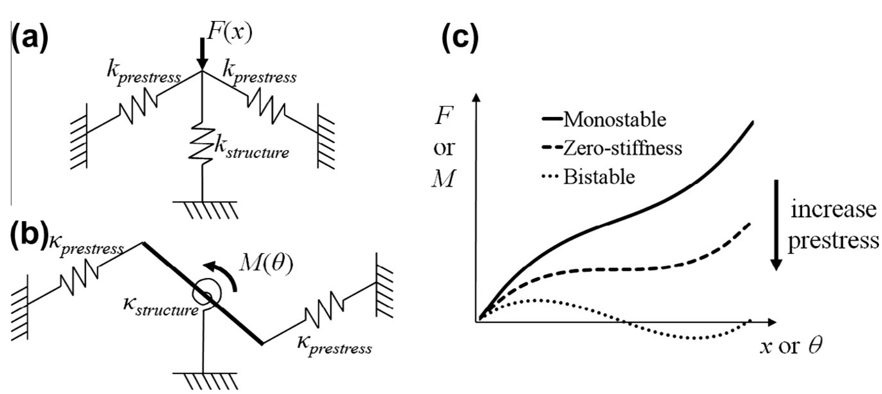

Fig. 1. Schematic representations of prestressed mechanisms subject to (a) axial load and (b) torsion. Inset graph (c) demonstrates that tailoring the magnitude of prestress can lead to either monostable, zero-stiffness or bistable mechanisms.