Compliant Structures for Morphing Aircraft

M. I. Friswell*, D. Baker, J. E. Herencia, F. Mattioni and P. M. Weaver
Department of Aerospace Engineering, University of Bristol, Bristol BS8 1TR, UK
* Corresponding author: Queens Building, University Walk, Bristol BS8 1TR, UK
Tel: +44 117 928 8695, Fax: +44 117 927 2771, E-mail: m.i.friswell@bristol.ac.uk

ABSTRACT

Morphing aircraft are flight vehicles that change their shape to effect both a change in the mission of the aircraft and to perform flight control without the use of conventional control surfaces. The key to morphing aircraft is the full integration of the shape control into the wing structure, and this is most easily achieved using composite structures. The design of these vehicles must take full account of the aerodynamic loads and must carefully consider the power requirements for shape control to ensure an overall performance benefit. This paper overviews three possible methods to achieve the required structural compliance that are under investigation at Bristol. The first is the design of the internal structure to produce a compliant mechanism that achieves the required aerofoil deformation using a small number of actuators. The second is the use of stiffness tailoring, incorporating the performance objectives, together with material constraints such as buckling and manufacturing requirements. The final approach is the use of multi-stable structures to perform large shape changes. For these structures, no force is required to maintain their stable configurations. The general features of these approaches will be described and illustrated using simulated and experimental results.

Keywords: morphing aircraft, compliant structures, bistable structures, aeroelastic tailoring

1. INTRODUCTION

The design of conventional fixed wing aircraft is constrained by the conflicting requirements of multiple objectives. Mechanisms such as deployable flaps provide the current standard of adaptive aerofoil geometry, although this solution places limitations on manoeuvrability and efficiency, and produces a design that is non-optimal in many flight regimes. The development of new smart materials together with the always present need for better aircraft performance is increasingly prompting designers towards the concept of morphing aircraft [1]. These aircraft possess the ability to adapt and optimise their shape to achieve dissimilar, multi-objective mission roles efficiently and effectively. One motivation for such vehicles are birds that morph between cruise and attack missions by changing their wing configuration accordingly. Birds also use camber and twist for flight control.

The structural technologies available to achieve a shape changes in a morphing aircraft fall into two major categories, namely planform changes using rigid mechanisms, and compliance (for example wing twist or compliant mechanisms). Vibration control systems are usually based on directly applying a force to the structure, and are not considered further. Large scale morphing motions for configuration morphing (that is significant planform changes) include wing extension, wing folding and wing sweep. Significant aerodynamic performance gains are only really achievable through large overall changes in the aircraft geometry via wing sweep, area and/or span. The application of morphing to flight control usually involves small geometric wing changes such as the
use of deployable slats and flaps as well as wing warping techniques to enhance the control authority of the aircraft. At present, in both of these categories, such medium to large scale changes are obtained with complex and sophisticated mechanical devices significantly increasing the installation and maintenance costs as well as the structural weight of the airframe. It is clear therefore, that substantial gains in these areas could be made if alternative methods to enact these changes were found. Basic morphing motions for seamless flight control include wing twist, or wing chamber change.

This paper considers three different approaches to introducing compliance into a structure that may be used for a variety of applications. The first considers the design of the internal structure of an aerofoil by considering the topology of the internal members. Such a system could be used to provide seamless control surfaces. The second approach considers aeroelastic tailoring, where the lay-up of wing covers may be optimised to improve performance. The third approach considers bistable structures, where a composite structure with more than one stable state could be used to generate large displacements without the use of complex mechanisms.

2. COMPLIANT AEROFOIL DESIGN USING TOPOLOGY OPTIMISATION

A compliant mechanism is a single piece structure designed to transmit motion and force mechanically relying solely upon elastic deformation of their constituent elements. As such they may be subject to advantages including high displacement accuracy, zero backlash and wear and ease of manufacture without assembly [2]. The design of such mechanisms treads a balance between achieving adequate stiffness in order that external loads may be supported yet be simultaneously flexible enough that the required motion due to applied loads is realised.

The focus of this work is the design of a compliant system that is able to provide structural control and motion to the trailing edge of a morphing aerofoil. An initial skeletal frame type ground structure is selected whereupon the member cross-section dimensions and applied actuator deflection are controlled in order to provide a predetermined surface deflection.

2-1. Problem Formulation

The system under consideration comprises a compliant mechanism forming the trailing 40% chord region of a NACA 0024 aerofoil. Two ground structures are proposed for the purpose of the investigation. The first is a single piece structure subject to a horizontal actuated displacement, shown in Figure 1(a). A second system is formed by the mating of two separate structures, shown in Figure 1(b). For the purpose of the optimisation only a single piece of the structure (upper section) is modelled, the resultant lower section is assumed to be a mirror of the upper and is subject to an equivalent but opposite actuated displacement.

![Figure 1](image-url)  
**Figure 1.** Ground structure formations featuring restraints and applied actuator displacements.
The problem of achieving shape change is formulated as minimising the distance between the achieved deflection of the actuated trailing edge surface and a preconceived target surface. The precise location of the deflected structural surface nodes is only measured with respect to the required target curve; in this manner required nodal deflections are not explicitly given but formulated as the minimum distance between node and the objective surface.

The second objective is the minimisation of structural deflection due to applied air loading. The pressure distribution on the wing surface is calculated using PANAIR [3], a higher-order panel method. The resulting pressure coefficients at each panel location can then be transformed to an applied aerodynamic load vector. The multi-criteria objective function may then be formulated as a weighted sum of the two objectives.

2-2. Results

Figure 2(a) displays the resulting deformation of the single piece ground structure subsequent to the optimisation procedure, Figure 2(b) then compares the resulting surface profile with the target deflection profile. Observation of the resulting topology reveals degeneration of a number of members comprising the upper aerofoil surface to zero cross sectional area; such a structure would be unable to provide adequate support to a surface skin. In order to overcome this and maintain required deflection characteristics, the split type structure, shown in Figure 1(b), was conceived. Figure 3 shows upper section of the structure resulting from the optimization procedure. This structure provides satisfaction of the required surface displacement criteria whilst retaining those elements that form the upper surface of the aerofoil and in turn provide support to a surface skin.

2-3. Discussion

The objective of the design method was to create a structure that was able to provide a significant deflection of the trailing edge when subjected to the input displacement of a limited number of actuators whilst also ensuring a minimal deflection in response to an applied aerodynamic load. This is achieved by optimising a multi-criteria objective function comprised of a weighted sum of two displacement functions, the displacement error of the structure with respect to a target geometry and
the resultant displacement due to aerodynamic loading to the structure. Using these methods compliant structures forming the trailing 40% of a NACA 0024 aerofoil with chord length 430mm are shown to provide a vertical trailing edge deflection of approximately 20mm whilst also sustaining a simulated aerodynamic load.

3. AEROELASTIC TAILORING

Aeroelastic tailoring [4-6], in conjunction with structural optimisation, enables engineers to design structures more efficiently to meet structural or aircraft performance requirements. Yet the design of such morphing concepts requires that for aerodynamic-structural coupling is included within the design loop [7, 8]. In addition, morphing designs can take advantage of composite materials, which may be stiffness tailored. This latter feature of composites is ideal for aeroelastic tailoring applications.

3-1. Morphing Concept and Design Strategy

The proposed morphing concept consists of an aircraft wing which has covers made from unbalanced laminates. Bending loads in these wings induce a twisting moment due to the opposite shearing effect between the top and bottom skin. The design strategy includes: characterising composite materials by lamination parameters to account for their membrane and flexural anisotropy, employing structural optimisation to carry out material stiffness tailoring, and performing a coupled aerodynamics and structures analysis to determine the structure’s deformation.

An aeroelastic steady-state scheme is used to obtain the aerodynamic loads. Using the initial flight conditions and wing geometry, an aerodynamic and a structural mesh are generated. PANAIR [3] and MSC/NASTRAN are coupled, and used to obtain pressure loads and structure deformation, respectively. The scheme is iterative, and the geometric distance travelled by each specific node during each cycle, is evaluated. The process terminates when the geometric distance difference between iterations is less than a specified tolerance.

3-1. Structural Optimisation

A global structural optimisation as shown in Figure 4 is proposed. The optimisation is divided into two levels. At the first level, optimum lamination parameters and thicknesses of the wing covers are determined under structural and aerodynamic constraints.

**Objective function:** The objective function is the sum of the weight of each of the panels that comprises the wing.

**Design variables:** The design variables for each of the wing panels are: laminate thickness, membrane and bending lamination parameters.

**Structural constraints:** The following set of design constraints are considered: the feasible domain of the lamination parameters [9], failure strength at laminate level [10], local and global buckling for a combined loading using closed form solutions [10], and practical design rules [11,12].

**Aerodynamic constraints:** Lift and induced drag constraints are imposed during the optimisation. For example, following Reference [7], these aerodynamic constraints are to maintain at least 90% of the lift corresponding to a baseline configuration, and to reduce the induced drag of the baseline configuration by at least 25%.

**Sensitivities:** Sensitivities of the objective function and constraints are calculated by the forward finite difference approximation. Structural sensitivities are determined by chain rule differentiation [13].
At the second level, the actual laminate stacking sequence is identified using a standard GA. **Fitness function:** The fitness function is expressed in terms of the square of the difference between the optimum and targeted lamination parameters [9]. Extra penalty terms are added to account for design rules such as the maximum number of plies of the same ply angle [12].

**Design variables – Genes:** The design variables are the total thickness and the 0, 90, 45, and −45, degrees ply angles that constitute the laminate stacking sequences for the wing panels. These variables are modelled as chromosomes in genes within the GA. The corresponding encoded chromosomes to ply angles are: 1, 2, 3, 4, 5, 6 and 7 for ± 45, 90, 2, 0, 45, -45, 90, and 0 degrees, respectively.

### 4. MULTI-STABLE COMPOSITES

To minimize the structural weight and complexity of morphing aircraft, composite materials provide a promising solution. Here attention is focused on multi-stable composites, which comprise unsymmetric laminates that exhibit out-of-plane displacements at room temperature even when cured flat. These displacements are caused by the residual stress fields induced during the cool down process of the laminate from the highest curing temperature (~170°C) to room temperature (~20°C). The thermal stresses are mainly generated by the mismatch of coefficients of thermal expansion of the constituent layers. The unsymmetric stacking sequence allows the stresses to generate bending and twisting moments within the laminate, resulting in out-of-plane displacements. Material displacements are usually difficult to predict accurately and therefore unsymmetric stacking sequences are generally avoided during manufacturing. However, if the thermal behaviour is thoroughly understood, these effects could provide an economic alternative for the manufacturing of complex parts (see Figure 5) or even with multistable configurations (see Figure 6).
If properly tailored, unsymmetric laminates possess more than a single stable equilibrium configuration; presenting the great advantage for the designer of multiple configurations without the need of a mechanism. It is then possible to snap from one configuration to another by mean of an actuation system. The actuator is only required to provide energy during the snap-through process and not to maintain a configuration since it is stable.

It is possible to predict the equilibrium shapes of unsymmetric laminates by modelling the cool-down process. The numerical simulation involves large displacements and abrupt change in the stiffness of the structures, and therefore non-linear solution algorithms are generally required. Such simulations are an essential tool for the prediction of equilibrium configurations, loads and the general behaviour of these structures. Figure 7 shows the load-displacement diagram obtained for the rectangular plate shown in Figure 8, it highlights the non-linear elastic response that a bi-stable structure possesses.

Various type of stacking sequences and geometry have been tested, and a few examples that demonstrate how it is possible to tailor the final shape, are shown in Figure 8 to Figure 10. This technology is likely to find many applications in morphing structures. Figure 11 shows an experimental set-up for a blended winglet configuration that is currently under investigation.

![Variable curvature shell](image5.png)  
**Figure 5.** Variable curvature shell

![Bi-stable plate](image6.png)  
**Figure 6.** Bi-stable plate

![Load-displacement diagram](image7.png)  
**Figure 7.** Stabilised load-displacement diagram versus reaction forces
CONCLUSIONS

This paper has highlighted a number of approaches to change the shape of a wing. Although considerable effort has already been expended to investigate a variety of morphing concepts, much more work is required to produce robust and viable morphing aircraft. Current designs are well optimised at one design point or flight regime, and the benefit of morphing occurs when the aircraft has to operate away from this design point for significant periods. Inevitably the standard design approach has to compromise the performance, however morphing still needs to demonstrate an overall performance benefit that outweighs the increased complexity and weight, for example through reduced life cycle costs or significant performance enhancement.

There are many challenges in the design of morphing aircraft [14]: the integrity of compliant structures needs to be ensured, the system should be designed so the required actuation force is realisable, the skin has to be designed to give a smooth aerodynamic surface yet support the aerodynamic loads, the design process should be extended to encompass multiple flight regimes,
engines need to be designed for efficient low and high speed operation, and control systems will have to cope with highly coupled control effectors. While many questions remain unanswered regarding the utility of morphing aircraft, enough evidence of improved performance and new abilities have been presented to warrant further consideration of the prospects of morphing, both for multiple flight regimes and for flight control.

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