Morphing Concepts for UAVs

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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 or seams. Aircraft constructed with morphing technology promise the distinct advantages of being able to fly multiple types of missions, to perform radically new manoeuvres not possible with conventional control surfaces, to be more fuel efficient, and to provide a reduced radar signature. The key to morphing aircraft is the full integration of the shape control into the wing structure; a truly smart structure. 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 will overview possible morphing concepts and discuss their advantages and disadvantages. Several concepts will be discussed in detail based on the work performed at Bristol and Virginia Tech. Bristol is concentrating on methods using aeroelastic tailoring, bistable composites and truss structures. Virginia Tech is concentrating on methods such as variable wing extension and sweep and their implications for vehicle control.

BIOGRAPHY

Michael Friswell is the Sir George White Professor of Aerospace Engineering at the University of Bristol. His research interests are concerned with the dynamic analysis of structures and systems, both from a vibration and a control viewpoint. Recently his interests have expanded to include the design of morphing aircraft using composite structures, and is team leader of a 1.94M euro Marie-Curie Excellence Grant on this topic. He also holds a Royal Society-Wolfson Research Merit Award.

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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 UAV performance is increasingly prompting designers towards the concept of morphing aircraft. 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 uninhabited aircraft 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 Wright Brothers used wing warping as a seamless flight control in their first flying machine. Morphing wings for flight control bring new challenges to the design of control laws for flight. Because configuration changes move the aerodynamic centre, control of the aircraft during planform morphing requires attention. Hence both morphing mechanisms and control systems are overviewed.

One primary advantage of a morphing platform would be the increased cost effectiveness of aircraft through eliminating the need for multiple, expensive, mission specific aircraft. However, from current trends in this research area, it is clearly evident that the practical realization of a morphing structure is a particularly demanding goal with substantial effort still required. This is primarily due to the need of any proposed morphing airframe to possess conflicting abilities to be both structurally compliant to allow configuration changes but also be sufficiently rigid to limit aeroelastic divergence.

There are typically four applications of morphing:
- improve aircraft performance to expand its flight envelope;
- replace conventional control surfaces for flight control to improve performance and stealth;
- reduce drag to improve range; and
- reduce vibration or control flutter.

These different applications are all regarded as morphing, however each is very different in terms of the magnitude of the shape changes required and time constants necessary for these changes. Fortunately large changes for improved performance are only required at low frequency, and very fast changes for vibration control only need to be small amplitude. This does mean that there is never going to be a single solution for a morphing aircraft, and the technology employed will be vastly different depending on the application required. However all applications require that morphing achieves the objective of improved performance and/or functionality. Often this improvement will be at the expense of increased weight and complexity, and the performance improvement must account for this.

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 in this paper. For shape control, actuators are required to effect the shape change, and sensors are required to measure the actual deflection, although actuators and sensors are not considered further here.

Large scale morphing motions for configuration morphing (that is significant planform changes) include:
- wing extension
- wing folding
- 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
- wing chamber change
- asymmetric wing extension
Each of these in discussed in the following with both analytical and experimental examples given. Seigler (1) gave further details of previous morphing programmes.

**Planform Changes**

Large planform area changes may be obtained in two ways. The first is a folding wing arrangement suggested by Lockheed Martin and illustrated in Figure 1.

![Figure 1. The Lockheed Martin folding wing concept.](image1)

An alternative to wing folding is wing extension. Raytheon Corporation investigated wing extension for use in their Cruise missile and were able to greatly increase the range. Numerical simulations and experiments at Virginia Tech on wing extensions verified this with an RC model. The numerical simulations used analytical dynamics with shifting mass for dynamic modelling, and Vortex Lattice methods combined with Digital DATOCM for the aerodynamic modelling, to simulate a cruise missile with wing extension (1). The results showed a 28% increase in range over a conventional wing. An RC plane was fitted with an extended wing system and flown to illustrate the potential for an increase in range and to maintain stability while extending and retracting the wings. The aircraft is illustrated in Figure 2.

![Figure 2. A radio controlled model airplane flown to illustrate the practicalities of wing extension.](image2)

In addition to using wing extension for planform change, the extension may also be used asymmetrically for roll control. Again the Cruise missile system was used as a basis to simulate the dynamics, aerodynamics and control, to discover the possibilities for roll control. The control surfaces on a conventional cruise missile are all in the tail section and a comparison was made between bank-to-turn with wing extension versus bank-to-turn using the tail control surfaces. The exercise was further complicated because the missile is powered by ramjets limiting the slideslip angle. The wing extension turns out to have much more control authority for bank-to-turn compared to the tail once the angle of attack exceeds 3°. The roll moment is produced by the span differential.

Motivated by the success with these simulations, the concept of using anti symmetric wing extension to perform a roll manoeuvre was implemented on an RC plane. In this case, the plane in Figure 2 was modified by adding a second motor and gear set so that each wing could be extended separately. The asymmetric extension is pictured in Figure 3.
Wind Tunnel Model for Planform Changes

In order to investigate sweep, twist and camber changes, a wind tunnel model was designed to allow both aerodynamic and control studies to be performed. An obvious difficulty in designing morphing aircraft is that of modelling the aerodynamics. Full CFD takes too much computational resource and vortex lattice and panel methods cannot model all of the relevant phenomena. Hence, wind tunnel testing becomes necessary. Motivated by DARPA’s Morphing Aircraft program a wind tunnel model was constructed that would twist, extend, sweep and change body chamber. The created device is shown in Figures 4 and 5.

The wind tunnel model was sized to fit in the 6ft Virginia Tech Stability Tunnel and to satisfy the DARPA requirements of a 35% independent span change in each wing, a 40° independent sweep, a 12% chord change, a ±20° twist and a 32% change in planform area. This is accomplished by a series of pneumatic and electric actuators, and controlled remotely through a PC 104 board. Details can be found in Ref. (2).

An initial result verified by the wind tunnel model is the effect of morphing on lift and drag ratios. Plots of $C_L$ versus $C_D$ illustrate how low drag can be maintained over a large range of lift. This data is illustrated in Figure 6.

![Figure 3. RC flying model with anti symmetric wing extension.](image3)

![Figure 4. The wind tunnel morphing wing experimental plane in attack mode.](image4)

![Figure 5. The wind tunnel model in loiter configuration.](image5)

![Figure 6. $C_L$ versus $C_D$ as the plane morphs as measured in a wind tunnel.](image6)
Control Issues for Planform Changes

The main issues in controlling a morphing aircraft centre around stability. With radical changes in planform come dramatic changes in aerodynamic centre. The issue then becomes one of controlling the system to be stable while morphing (1). The second issue, is how to combine flight control with morphing control simultaneously. Currently, the limited experience with flying morphing vehicles has been based on separating the two in order to maintain stability. With the exception of using anti symmetric wing extension, separate control effectors have been used to change the shape, to those used to maintain stability. The more exciting performance possibilities result from combing flight control and morphing control simultaneously.

Flexible Structures using Aeroelastic Tailoring

For the purpose of minimising structural weight and complexity, composite materials provide a promising solution. In general, composite materials present high specific strength and stiffness ratios. This section concentrates on stiffness tailoring and the next section on bi- or multi-stable structures. Primary flight composite structures, such as wings or fuselages, are mainly designed using stiffened panels. Structures made of composite materials can be stiffness tailored, and this is a significant advantage over their metallic counterparts. Due to practical manufacture considerations, laminated fibre composite panels have been restricted to symmetric or mid-plane symmetric laminates with 0, 90, 45 and -45 fibre degree plies. However in the future this constraint may well be lifted (3).

The aim of aeroelastic tailoring is to provide intrinsic morphing by the use of elastic coupling (4). This morphing concept uses the extension/shear coupling within the composite to modify the wing twist under aerodynamic loads. The technique splits the optimisation problem into two levels (5). At the global level, the composite optimisation is performed where the skin and stiffeners are modelled using lamination parameters to account for their anisotropy. The panel is analysed using finite element software, and subjected to a combined loading under strength, instability and manufacture constraints. At the local level, the real skin and stiffener lay-ups are obtained, also considering manufacturing requirements. This approach introduces an accurate analysis at the global level, with a realistic computation time.

As an example, consider a rectangular wing with 302mm chord, 1.2m semi-span, a NACA 4412 profile and idealised elliptic aerodynamic loads. The angle of attack is 8° and the airspeed in 40m/s. For simplicity the wing is unstiffened and is split into five sections spanwise and different parameters for the composite structure are used for each region. Initially the top and bottom covers are an unbalance laminate with (+45°) plies, with a thickness varying from 1.5mm at the root to 1mm at the tip. The front and rear spars consist of a symmetric laminate with (+45°/-45°) plies and thickness 1mm. Figure 7 shows the deformation of the wing in this case. Figure 8 highlights that a laminate with (+45°) plies does produce the largest twist.

Multi-stable Composite Structures

In this section attention is focused on multi-stable composites. These comprise unsymmetric laminates which exhibit out-of-plane displacements at room temperature even if cured flat. These displacements are caused by the residual stress fields induced...
during the cool down process of the laminate between the highest curing temperature (~160°C) and room temperature (~20°C). The thermal stresses are mainly generated by the mismatch of coefficients of thermal expansion of the constituent layers; the unsymmetric stack sequence allows the stresses to generate bending and twisting moments within the laminate, resulting in the previously mentioned displacements. If the internal forces reach more than a single stable of equilibrium, there is a great advantage to the designer because a single structure can achieve two different geometric configurations. It is then possible to snap from one geometric configuration to another using actuators since both configurations are stable. Another benefit is that the actuator is only required to provide energy during the snap-through process and not to maintain a configuration.

The aim of the research at Bristol is to develop design guidelines using analytical tools and finite element analysis for tailoring the residual stress field and highlight possible applications to morphing aircraft. The initial work has validated the non-linear finite element models of simple plate structures (6). Figure 9 shows the stack sequence of a transversely reinforced plate and Figures 10 and 11 compare the experimental and predicted shapes for one of the stable solutions.

One concept being investigated is a variable sweep wing, which is a well known technology with significant aerodynamic advantages. The traditional technique consists of rigid pivoting wings. This design produces a concentration of the structural loads around the pivot and thus requires high strength materials and expensive manufacturing techniques. The use of an unsymmetrical laminated composite is being investigated as an alternative approach to realize a variable sweep wing (6). In particular a UAV application is considered. The aim is to realize a two spar wing with an unsymmetric laminate region close to the root. If the applied bending moment in a composite spar is greater than a critical value, the structure behaves like a hinge, as shown in Figure 12. In this way the stress due to the pivoting is spread over a much wider area and it is possible to tailor the critical moment for different applications. Methods to use this phenomena in variable sweep wings are currently being investigated.
Morphing Concepts for UAVs

Figure 12. The spar in a hinge-like configuration.

Truss Type Structures
The initial concept for a truss structure is the creation of an active, pin jointed, truss structure by the substitution of bar members with linear actuators. Such a system aims to provide an ideal solution to the problem of structural morphing by the removal of structural resistance to deformation. Of course the implementation of ideal pin joints is difficult, and would probably require flexible hinges which would lead to bending within the beams. Ultimately this could lead to general compliant mechanisms, where the detailed topology and geometry of the structure is modelled and optimised (7). However topology optimisation is a very difficult problem, and the pin jointed truss is used as a first trial along the compliant mechanism route.

The Kagome truss pattern has many useful properties for morphing structures. In the case of the three-dimensional manifestation two forms are possible, a Kagome plane with solid face sheet and two Kagome face sheets connected by a double tetragonal pattern core. Investigation of the application of Kagome structures for actuation (8) concluded that the single Kagome plate with solid face sheet may be deformed via truss actuation to form any long wavelength deformation however practical limits of actuation energy limit deformations to small Gaussian curvatures. In the case of the twin Kagome face structure it is suggested that no restriction is placed upon the Gaussian curvature of the desired form. By removing mid-plane symmetry from the structure it is possible to create a statically and kinematically determinate structure.

An aerofoil was created using a repeating network of the Kagome lattice structure, with upper and lower nodes displaced. Linear actuators replaced selected truss sections to allow active camber control (9). In order to replicate the effects of the actuation point forces are located at selected nodes with direction constrained to that of the selected member. Figure 13 shows the typical deformation of a truss structure, formed between 50% and 90% chord within a NACA 0012 aerofoil.

Figure 13. Typical deformation for the truss structure.

All the preceding analysis has assumed the presence of a prefect skin material; that is a material able to transfer aerodynamic forces to the structure whilst accommodating large shape changes. Such a skin is required for many morphing designs and is the subject of intense research. A segmented skin, similar to fish scales, allows membrane deformation of the skin whilst maintaining lateral stiffness and the transfer of aerodynamic loads (10). Or a spring-steel honeycomb mesh within a layer of silicon a flexible skin could be created (11).

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 UAVs. Current designs are well optimised at one design point or flight regime, and the benefit of morphing occurs when the UAV 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 UAVs (12): 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 UAVs, enough evidence of improved performance and new abilities have been presented to warrant further consideration of the prospects of morphing UAVs both for multiple flight regimes and for flight control.

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