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Aerodynamic optimisation of a camber morphing aerofoil

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ABSTRACT

An aircraft that has been carefully optimised for a single flight condition will tend to perform poorly at other flight conditions. For aircraft such as long-haul airliners, this is not necessarily a problem, since the cruise condition so heavily dominates a typical mission. However, other aircraft such as UAVs, may be expected to perform well at a wide range of flight conditions. Morphing systems may be a solution to this problem, as they allow the aircraft to adapt its shape to produce optimum performance at each flight condition. Optimisation of morphing aerofoils is typically performed separately to the morphing mechanism design. In this work, an optimisation strategy is developed to account for a known possible morphing system within the aerodynamic optimisation process itself. This allows for the limitations of the system to be considered from the start of the design process. The Fishbone Active Camber (FishBAC) camber morphing system is chosen as the example mechanism, and it is shown that the FishBAC can achieve large improvements in performance over non-morphing aerofoils when multiple flight conditions are considered. Additionally, its performance is compared to an aerofoil whose shape can change arbitrarily (as if a perfect morphing mechanism can be designed), and it is shown that the FishBAC performs nearly as well, despite being a relatively simple mechanism.

1. Introduction

In a broad sense, the camber of an aerofoil describes its asymmetry, and is typically used to control its zero-lift angle of attack. Adding camber, for example, will tend to increase the amount of lift produced at a given angle of attack of the aerofoil, although this is of course limited by stall and separation. There may be changes in the lift to drag ratio also, though with such a broad definition of camber, it is difficult to state in a general way what this effect will be.

Almost all modern aircraft use discrete control surfaces, such as flaps, ailerons, or sometimes slats, to adjust the camber of the wing. Trailing edge devices are typically hinged surfaces occupying the rearmost 20–30% of the chord which rotate to change their angle, sometimes also translating in the chord-wise direction to increase chord as well as camber. The camber change, however, is almost always discrete in that after actuation of the control surface, there is no longer a smooth transition of camber in the chord-wise direction. This causes a similarly sudden change in the pressure distribution over the corner created at the hinge line, and is associated with a drag penalty and the possibility of separation.

While this drag penalty may be deemed acceptable either because the control surface is only used occasionally (such as flaps on an airliner being used only at takeoff or landing), or because there is no suitable alternative, the penalty on surfaces that are in a continuously deflected shape can become significant over a long flight. An example of this would be an elevator or rudder device that is used to trim the vehicle, and is thus being employed for extended periods of time.

Camber-morphing aerofoils aim to achieve their camber change in a smooth way, to potentially reduce this drag penalty. This could be useful in normal aircraft applications, such as the above mentioned example of a trim-tab or tailplane control surface, but if the problem scope is extended to include rotorcraft, wind turbines, or any number of other applications where aerofoils are required to operate in a wide range of flight conditions, the potential advantages of a camber morphing aerofoil become more apparent. It is at these varied flight conditions that morphing aircraft may be able to provide a significant advantage over traditional aircraft. If the optimum aerodynamic shape is considerably different at the different flight conditions, then it makes sense to have an aircraft whose shape can change on the fly to react to changes in flight conditions, such that it always flies at optimum aerodynamic efficiency.

The concept of camber morphing aerofoils is not a new one, and has been extensively studied by engineers over the last hundred or so years; an early example is the 1920 design by Parker [1].

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Research activity in this area is even more intense now than it has been in the past, with the general trend being towards compliance rather than mechanism-driven camber changes. Ref. [2] provides a comprehensive review of past and current camber morphing concepts.

In traditional aircraft design, aerodynamic and structural design are handled by different groups of engineers, and the design is iterated until an optimum is converged upon. However, morphing aircraft design requires tighter integration of the aerodynamic and structural design to ensure that the aerodynamic design produced can be achieved by the morphing systems and structures available. This is a problem that does not appear to be commonly addressed. There are a large number of papers where an aerodynamic analysis is first performed at the different flight conditions, and then a morphing mechanism is produced that can deform the structure to match those desired shapes. Refs. [3–7] are examples of such a design philosophy: the morphing is achieved through compliant mechanisms that can approximately match the target shapes. However, the accuracy to which the external shape can be matched clearly depends upon the complexity and number of degrees of freedom of the system. A very simple mechanism may only match the target shapes very approximately, whilst a more complex system will match the shapes more accurately, but come at the cost of increased weight (which may very rapidly offset the reduction in drag due to a higher lift-coefficient requirement) and complexity. For example, Gamboa et al. [8] used a complex actuation system that can alter the thickness distribution around the chord line in flight, whilst also being able to change the chord length. Despite this, the authors showed that when the flexible skins were considered in an FSI problem, the shapes obtained were still only approximately those obtained from the aerodynamic optimisation.

In this work, rather than performing an aerodynamic optimisation and then designing a morphing system to obtain the required shape-change, the morphing system is explicitly accounted for within the optimiser. This means that the final design that the optimiser produces will be directly related to the morphing system in question, effectively turning the problem from multiple single-objective aerodynamic optimisations into a single multi-objective optimisation. The camber morphing system used as an example in this paper is the Fishbone Active Camber (FishBAC) system.

The FishBAC system [9–12] is a biologically inspired compliant structure, comprised of a thin bending spine with stringers branching from it. A pretensioned elastomeric matrix composite skin surface provides the aerodynamic shape. The skin tension is used to increase the out-of-plane stiffness, whilst the reinforcement is used to produce a near-zero Poisson's ratio in the spanwise direction. Unlike many other camber morphing designs, the FishBAC deformations are achieved purely through compliance of the structure, rather than mechanisms. A non-backdriveable antagonistic tendon system is used to drive the deformations.

This work concerns only 2D (aerofoil) optimisation, but the shape-change and optimisation frameworks could be trivially extended to 3D with a suitable aerodynamic analysis tool.

2. Shape-change framework with radial basis functions

The optimisation tool needs to be able to change the shape of the aerofoil in two ways: firstly, it must be able to directly modify its external shape (regardless of camber morph) to obtain an optimum thickness distribution along the chordline; secondly, it must be able to add the effect of the FishBAC system.

Typically in aerofoil optimisation, the aerofoil is parametrised in some fashion. A common approach is to use a series of splines with control points [8], or to express the aerofoil as a baseline shape plus a summation of shape functions [13]. Spline-based methods approximate the shape of the aerofoil, and the accuracy of the approximation is dependent upon the number of control points used. Higher degrees of accuracy then imply more degrees of freedom for the optimisation to operate on, which in turn will require longer computational time to reach a converged optimum. These commonly used methods may also not be compatible with an additional camber change, such as the one imposed by FishBAC. However, Gamboa et al. [8] had good success using splines to model both an external shape, and a camber morph.

Radial basis function methods [14] are favoured by some authors [15–18], especially for FSI simulations where they provide not only a framework to deform the aerodynamic and structural meshes, but a way to interpolate the forces and moments between them, as the two meshes will likely not be coincident. Additionally, they extend trivially to three-dimensional problems. A similar approach is used in this work. Using the RBF method, the aerofoil does not need to be parametrised, and is instead expressed as a cloud of points of arbitrary order and spatial resolution. This point cloud is referred to as the aerodynamic surface. A second series of points is used to control the shape of the aerodynamic surface, generally referred to in this work as shape-control points. Again, the order and spatial resolution of these points is arbitrary. Choosing a large number of these shape-control points increases the number of degrees of freedom in the optimisation, giving the opportunity to have more complex shape changes at the cost of increased computational effort. Finally, a third point cloud is used to represent the camber line of the aerofoil, and thus the effect of the morphing actuation system.

These three point clouds are coupled together via matrices, and changes in any one point cloud are interpolated onto the others through these matrices. One of the advantages of the RBF method is that whilst the initial calculation of the coupling matrices requires some significant computational effort, once established, the matrices remain constant. If a point cloud changes, then its effect upon the other two point clouds can be calculated by a simple matrix multiplication of the change in the cloud by the relevant coupling matrix. Therefore, once the coupling matrices have been established, all shape changes can be computed with very little computational cost. The optimisation framework is discussed in more detail in Section 3, but in general terms, the optimiser does not act on the aerodynamic surface cloud directly, but rather modifies the shape-control cloud, which then affects the aerodynamic cloud directly via its coupling matrix. Camber changes occur through the camber cloud, which causes a change in the shape-change cloud, which then in turn changes the external shape to reflect the change in camber.

There are a large number of basis functions to choose from. A radial basis function operates on the radius between points, and returns a scalar value. The returned value will vary between 1.0 when the distance is 0, and 0 when the distance is equal to the support radius. This support radius is chosen by the user, and roughly speaking represents the radius of influence of one point on the other points. A support radius of just larger than the aerofoil chord length is used in this paper, as this allows all points to affect all others. The Wendland C2 function (shown in Eq. (1)) is selected as the RBF, as it has been used by previous authors with good success [17].

$$\phi(r) = \begin{cases} (1-r)^4(4r+1) & : 0 < r \le 1 \\ 0 & : 1 < r \end{cases} \tag{1}$$

Rendall and Allen [17] give a thorough description of the RBF method for FSI problems, and so only a brief summary will be provided here. They commented on the use of polynomial terms in addition to the basis functions to exactly recover rotations and translations. For their work, they used the polynomial terms to