Multidisciplinary Design Optimisation of a Morphing Wingtip

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Abstract

Over the last few years, better knowledge of aerodynamics and structures and the permanent need to improve the performance and efficiency of aircraft has led to the generalised adoption of wingtip devices. The requirements faced by wingtip devices throughout the various flight conditions are, however, different. A static wingtip device (as is the case with existing designs) must be a compromise of these various conflicting requirements, resulting in less than optimal effectiveness in each flight condition. A morphing device, on the other hand, can adapt to the optimum configuration for each flight condition, leading to improved effectiveness. The concept now being studied consists in a moving wingtip device, able to rotate about two different axes: vertical axis (toe angle) and aircraft's longitudinal axes (cant angle). These can be controlled independently by servo-actuators. The wingtip behaviour is inherently multidisciplinary (with coupled structural and aerodynamic effects), requiring multidisciplinary design optimisation (MDO) in order to determine the ideal wingtip configuration for each case: for each flight condition, an MDO procedure is carried out in order to determine the optimum wingtip geometry (design variables) such that a performance metric (such as the lift, drag or lift-to-drag ratio, depending on the flight condition) is maximised or minimised (objective), subject to certain constraints, such as the mechanical stress or displacement (state variables). The multidisciplinary analysis procedure uses a multifield solver based on ANSYS (for the structural field) and CFX (for the computational fluid dynamics). A purpose-built fully parametric routine generates the geometry and mesh and applies the boundary conditions and loads, launches the solvers and performs all the required post-processing (retrieving the quantities of interest and computing the desired variables). This allows an entirely automated multidisciplinary analysis where the optimiser controls all the parameters. It also allows for greater flexibility in the choice of the optimiser logic (since the optimisation algorithm is separated from the analysis procedure and can either be one of ANSYS' built-in methods or another method implemented in any programming language). Preliminary results are presented along with the resulting geometries. The feasibility of such a morphing wingtip is discussed. The performance metrics of the morphing wingtip are compared to those of a fixed wingtip to quantify the gain associated with the use of the morphing concept. The next step will be a cost-benefit analysis of the morphing wingtip device taking into account this gain and the incurred penalties (e.g. weight; complexity; actuation energy) in order to assess the interest of the proposed concept.

Keywords: MDO; fluid-structure interaction; aircraft; morphing; winglet

1. Introduction

Although the potential benefits of wingtip devices have been known since the early 20th century, it wasn't until recently that designs whose benefit (in terms of induced drag reduction) offset the penalties (extra cost and weight).

Furthermore, these devices are static and as such their configuration is the result of a compromise between the different (and sometimes conflicting) requirements of the various flight stages/missions. Moreover, the winglet designs must comply with geometric constraints imposed by airport terminals and maintenance facilities. Morphing devices can overcome these limitations by permitting winglets to adopt the optimum configuration for each scenario.

Wings generate lift by changing the airflow so that the air pressure beneath the wing is higher than the air pressure above the wing. This pressure differential causes the air in the high pressure region (beneath the wing) to flow to the low pressure region (above the wing) whenever it can, as is the case at the wingtip. This vortex of air flowing from beneath the wing to above it diminishes the wing's efficiency and poses a hazard to other aircraft in the vicinity. An approach to mitigate this problem consists in introducing a physical barrier to the flow of air from beneath the wing to above it. Many designs of such barriers have been presented and are collectively known as wingtip devices. Figure 1 shows the wingtip device on an Airbus A320 family aircraft. All these designs come at a cost, both in terms of price and weight (which consequently entails an efficiency penalty) and it wasn't until recently that progress in terms of materials and structural engineering mitigated this penalty to the
point where the benefits of winglets outweigh their disadvantages. Büscher et al [1] have shown that the penalty associated with the extra weight (caused by both the wingtip device itself and the stronger structure necessitated by the increase in wing root bending moment) must be taken into account when designing wingtip devices, since a wingtip device designed from a purely aerodynamic approach (e.g. so as to obtain the greatest reduction in induced drag) may not be the optimum design if the increase in drag due to the higher weight is taken into account.

Figure 1: Wingtip device

Different flight conditions have different (and often conflicting) aerodynamic and structural requirements. A fixed design has static characteristics (shape; wetted area; location) that result in a sub-optimal solution for flight conditions in which a different trade-off between the increase in profile drag and the reduction in induced drag would be desired or when different centre of gravity and moment of inertia would be key to manoeuvrability. Hence, the potential benefits of winglets are never fully realised by a fixed design. Morphing winglets can overcome this problem by adapting to each flight condition's requirements and hence improve the aircraft's performance (speed; manoeuvrability; runway requirements; climb performance; range; endurance; fuel consumption) and/or extend its flight envelope. In the future, it may be possible to design morphing winglets for specific tasks, such as mitigating an aircraft's wake turbulence (which would allow closer spacing of aircraft during landing and take-off, thus improving runway's throughput), improving the wing's dynamic characteristics (flutter behaviour) or even controlling shock wave formation and/or propagation. Furthermore, morphing winglets change the wing's aerodynamic forces and moments as well as its centre of gravity. This can be used to augment or altogether replace traditional control surfaces [2].

2. Morphing Wingtip Mechanism

Conventional wingtips are attached to the fuselage at a fixed orientation. If this connection is replaced by one or more articulations commanded by servo-actuators, the wingtip can now change its orientation throughout the flight in order to maximise efficiency at each flight condition. Compared to the multistable wingtip previously proposed [3], this system has the disadvantage of requiring permanent actuation (and hence energy consumption) but has important advantages:
- The only size constraint is that of the actuators themselves (and if necessary these can be moved away from the articulation, although this increases the complexity of the mechanism)
- Using conventional construction techniques and having total freedom in material selection enables the creation of wingtips with virtually any shape
- Allows a much greater degree of morphing - an articulated wingtip can adapt to endless configurations

Figure 2 illustrates the toe and cant angles that characterise the wingtip orientation and whose morphing potential will be studied. In particular, the toe angle shows great promise for morphing, since it is only optimum for one flight condition. This is because the toe angle controls the overall loading on the winglet as well as its effect on the load distribution of the whole wing and, simultaneously, the angle of attack of the winglet is a function of the wing's lift coefficient, which depends on the flight condition. For this reason, the toe angle in a fixed wingtip is a compromise that attempts to maximise the wing's performance over the entire flight envelope [4].
The wing is rectangular with 1m chord and 3m half-span, and the NACA 0015 aerofoil. The wingtip has the same aerofoil and chord and a variable width. The choice of the aerofoil favoured a simple, well-known design for which exhaustive data exists, so that the computational model could be adequately validated and the effects of the wingtip isolated. At the same time, the thickness had to allow the installation of a servo-actuator. The symmetrical, 15% relative thickness NACA 0015 is one of the most thoroughly studied aerofoils and meets the geometric constraints imposed by the need to actuate the wingtip.

3. Multidisciplinary Analysis of a Morphing Wingtip
A multidisciplinary analysis requires the combined solution of different fields. For the morphing wingtip problem, ANSYS solves the structural equations while CFX solves the fluid dynamics equations. Both solvers exchange information in order to obtain a single solution that satisfies the equations of the two fields. ANSYS and CFX are designed to interact in a seamless manner and this information exchange procedure requires no user...
interaction. Figure 3 describes the data exchange between the two solvers.

However, the interface along which the two solvers communicate (i.e. the wing surface, which is the area that divides the structural and the fluid problem domains) must be previously defined by the user, along with the geometry and boundary conditions of the design. Similarly, after the solution, the results must be treated in order to obtain the quantities of interest. If this multidisciplinary analysis is to be included in an optimisation procedure (where many analyses must be carried out), it is necessary to automate all the pre- and post-processing tasks that require user input. Figure 4 summarises the steps involved in this automated multidisciplinary analysis procedure [6].

First, the geometry and mesh are created based on the design variable values defined by the optimiser. The mesh is exported to CFX and the boundary and fluid conditions (temperature, pressure and density, which depend on the flight condition) applied. The structural and computational fluid dynamics solvers run simultaneously (with the structural solver supplying the displacement to the fluids solver which in turn supplied the loads to the structural solver) and iteratively until the solution satisfies the structural and fluid equations. Once this solution is obtained, the results from both solvers are read and treated (e.g. a coordinate transformation is applied to the aerodynamic loads obtained by CFX in order to obtain the lift and drag) and the quantities of interest (objective function; state variables) are calculated. These values are then passed to the optimiser so that the next design can be defined.

### 4. Morphing Wingtip Optimisation

The computational model presented in the previous chapter allows the analysis of different configurations of the morphing wingtip. An optimisation procedure can use these analyses to determine the optimum configuration for each flight condition.

For the case of the morphing wingtip, the optimisation problem consists in finding the wingtip geometry (described by the toe angle, cant angle and wingtip length) that maximises or minimises a performance metric (lift; lift-to-drag; drag) for each flight condition, while respecting some imposed conditions (such as maximum stress or displacement).

At the time of writing, the optimisation is in the early stages of implementation. In order to demonstrate the method, an example with 3 sample flight conditions was created in order to obtain preliminary results. The flight conditions are indicated in table 1.

<table>
<thead>
<tr>
<th>Flight condition</th>
<th>Altitude</th>
<th>Velocity</th>
<th>Angle of attack</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>sea-level</td>
<td>15 m/s</td>
<td>11º</td>
</tr>
<tr>
<td>2</td>
<td>sea-level</td>
<td>47 m/s</td>
<td>11º</td>
</tr>
<tr>
<td>3</td>
<td>11000 m</td>
<td>47 m/s</td>
<td>6º</td>
</tr>
</tbody>
</table>

Table 1: Sample flight conditions
The design variables and the admissible interval for each are summarised in Table 2.

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Minimum value</th>
<th>Maximum value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toe angle</td>
<td>-5°</td>
<td>5°</td>
</tr>
<tr>
<td>Cant angle</td>
<td>0°</td>
<td>180°</td>
</tr>
<tr>
<td>Wingtip length</td>
<td>0.2 m</td>
<td>0.8 m</td>
</tr>
</tbody>
</table>

The objective of this sample optimisation was the maximisation of the lift-to-drag ratio in each flight condition. At this stage, the ANSYS built-in first order optimisation method was used for simplicity. At later stages, an optimisation algorithm more suited to the multidisciplinary analysis of the morphing wingtip will be implemented. Table 3 presents the results of the sample optimisation.
Table 3: Sample optimisation results

<table>
<thead>
<tr>
<th></th>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toe angle [º]</td>
<td>0.94</td>
<td>0.56</td>
<td>1.22</td>
</tr>
<tr>
<td>Cant angle [º]</td>
<td>68.75</td>
<td>111.25</td>
<td>42.49</td>
</tr>
<tr>
<td>Wingtip length [m]</td>
<td>0.59</td>
<td>0.66</td>
<td>0.54</td>
</tr>
<tr>
<td>Lift-to-drag ratio</td>
<td>6.40</td>
<td>6.52</td>
<td>6.58</td>
</tr>
</tbody>
</table>

It is fundamental to compare the performance of the morphing wingtip to that of a fixed wingtip. To this end, a separate optimisation was carried out, in order to obtain a wingtip configuration that leads to the best overall performance (i.e. to the highest average lift-to-drag ratio, considering all flight conditions). This optimisation resulted in a wingtip with a toe-angle of 0.91º; a cant angle of 68.75º; and a length of 0.58m. The lift-to-drag ratio of a wing with this optimum fixed wingtip in each flight condition is shown in Table 4.

Table 4: Sample results for an optimum fixed wingtip

<table>
<thead>
<tr>
<th></th>
<th>Condition 1</th>
<th>Condition 2</th>
<th>Condition 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift-to-drag ratio</td>
<td>6.38</td>
<td>6.49</td>
<td>6.57</td>
</tr>
</tbody>
</table>

Comparison of the results in Tables 3 and 4, shows that the morphing concept leads to higher lift-to-drag in each flight condition than would be possible with a fixed wingtip but the gains are minute. This confirms the importance of implementing a more advanced optimisation algorithm. The lift-to-drag ratio values are also lower than expected, suggesting that a more advanced mesher may be required to ensure adequate finite element meshes for all geometries. The meshing algorithm must thus lead to accurate but also quick solutions (solution time is an important consideration in optimisation, where many evaluations will be carried out) and be robust (since it must handle a vast array of geometries).

Furthermore, this preliminary optimisation focused on improving the lift-to-drag ratio over a range of different flight conditions. In reality, however, the lift-to-drag ratio is not the adequate performance metric for all flight conditions. Table 5 lists different requirements and the objective function for each.

Table 5: Performance metric for different goals

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Objective function</th>
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</thead>
<tbody>
<tr>
<td>Endurance (propeller aircraft)</td>
<td>Maximise $C_L^{1/2}/C_D$</td>
</tr>
<tr>
<td>Endurance (jet aircraft)</td>
<td>Maximise $L/D$</td>
</tr>
<tr>
<td>Range (propeller aircraft)</td>
<td>Maximise $L/D$</td>
</tr>
<tr>
<td>Range (jet aircraft)</td>
<td>Maximise $C_L^{1/2}/C_D$</td>
</tr>
<tr>
<td>Gliding angle</td>
<td>Maximise $L/D$</td>
</tr>
<tr>
<td>Rate of climb</td>
<td>Maximise $L/D$</td>
</tr>
<tr>
<td>Stall speed</td>
<td>Maximise $C_L$</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>Minimise $C_{D,0}$ and/or $K$</td>
</tr>
<tr>
<td>Turn radius</td>
<td>Minimise $C_{D,0}$ and/or $K$</td>
</tr>
</tbody>
</table>

The variety of objectives greatly increases the potential of morphing: it is not just a matter of adapting the wing to different environments (velocity; air density; angle of attack) but rather a problem of changing the wing in order to focus on the relevant quantity for each requirement. It is therefore expected that a morphing wingtip based on the concept presented in this article will significantly outperform a fixed design in the various requirements encountered by an aircraft.
5. Discussion
Wingtips have significant potential for morphing. A morphing wingtip concept was proposed and the results available at this preliminary stage suggest that the proposed design is able to adapt to the different requirements of the various flight conditions and improve the wing's efficiency in each scenario. This performance improvement can translate to extended capabilities and/or to operating cost and environmental footprint reduction. In order to realise these potential gains, a more advanced mesh generation and optimisation algorithm are presently under development. The meshing algorithm, in particular, is crucial to the success of the design and optimisation of a competitive morphing wingtip. Naturally, the analysis and optimisation of the morphing wingtip will consider a greater variety of flight conditions and performance metrics (as the efficiency of an aircraft is not always proportional to the lift-to-drag ratio).

Acknowledgements
This work was possible thanks to the funding provided to the project SMORPH by the Portuguese FCT – Fundação para a Ciência e Tecnologia and the funded project POCTI-EME-61587-2004. Additional funding was provided by RTO-NATO Support Program under the framework of the collaborative project PRT-002 between Instituto Superior Tecnico, Portuguese Air Force Academy in Portugal and the University of Victoria, in Canada. The first author gratefully acknowledges the financial support of FCT – Fundação para a Ciência e a Tecnologia through Grant SFRH/BD/39296/2007.

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