DESIGN, MANUFACTURING AND TESTING OF A SMALL-SCALE COMPOSITE MORPHING WING

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Abstract This paper presents the optimization methodology used in the design of a composite morphing wing. A small wind tunnel prototype was designed at École de Technologie Supérieure (ETS) to validate the optimization process that will further be applied on a larger scale wing for the CRIAQ (Consortium for Research and Innovation in Aerospace in Quebec) MDO-505 «Morphing Architecture and Related Technologies for Wing Efficiency Improvement» project. The optimization proposes a three steps approach in order to optimize the global shape response of an active morphing wing. The first step is a free-size optimization to roughly evaluate ply orientation and overall thickness on an element based level. Results are then interpreted to perform as a second step a composite size optimization subject to structural and manufacturing constraints. Lastly, the best stacking sequence is optimized with respect to all predefined constraints. A prototype was manufactured and the experimental morphed shapes are compared to the finite element shapes.

1 General Introduction

In the last decades, the aeronautical sector has seen important growth worldwide, growth that also occurs in a period of time were carbon emissions and oil price are of high concerns. The need of developing new technologies to adress these issues is then of main interest. Morphing airframes are part of those new technologies that focus on carbon emission reduction. A morphing airframe, or in this specific case a morphing wing, is a wing that can reconfigure its shape while in flight [1]. According to IATA (International Air Transport Association), the morphing technologies predictions on fuel burn reduction are from 5 to 10% and they should be available on airplanes after 2020 [2]. The morphing wing are then of main interest for their promising benefits.

Morphing wings are classified in three different types: planform alteration, out-of-plane transformation and airfoil profile adjustment. The challenge in developing an efficient morphing wing is to design a skin made of a continuous layer that smoothly match a specific aerodynamic shape. Most researches focus on high strain materials or compliant structures to achieve high deformation but with less consideration on structural integrity under in-flight loading [1,3,4].

The work presented in this paper is the continuity of a previous morphing wing project (CRIAQ 7.1). The concept was developped and tested in a wind tunnel where the laminarity of the airfoil was controlled by morphing an active composite extrados with small actuator displacements. This morphing concept has proved to be relevant [5]. However, few structural consideration were taken into account at the moment. The morphing skin was allowed to slightly move at the rear end while deformed, giving an open wingbox section unable to sustain real in-flight loads. Moreover, the morphing skin was not intended to perfectly match the aerodynamic shapes. Those issues will be adresssed in the CRIAQ MDO-505 project, where the morphing skin will be made of typical materials used for aeronautic structures and will have to sustain in-flight loads.

In this paper, an optimization methodology was developped for a composite morphing skin. In section 2, the context and the main objectives will be presented. The finite element model and the design loading cases will be presented in section 3, while the optimization process and the finite element
results will be presented in section 4. The experimental setup and results will be presented in section 5, where the manufacturing and the testing of the morphing wing prototype are presented.

2 Project’s context
2.1 Morphing wing concept

The morphing wing concept is made of two distinctives parts: a lower surface that serves as a rigid structure and sustains all reaction forces and a upper surface consisting of a flexible skin. The composite flexible skin is totally fixed at both end and comprised between 10%c and 70%c. It is morphed by means of two actuators located at 30%c and 50%c respectively. Aerodynamic changes occur over the morphing upper surface, where the transition point move towards the trailing edge and therefore increase the laminarity of the airfoil. Figure 1 shows a schematic representation of the morphing concept.

![Fig.1: Sketch of the morphing concept](image)

2.2 Aerodynamic optimization

The aerodynamic objective of this project was to increase laminarity of a rectangular wing by morphing the upper surface. The predicted morphed shapes were obtained by an in-house aerodynamic optimizer using a genetic algorithm coupled with the 2D-aerodynamic software XFOIL 6.96 [6]. The objective of the aerodynamic optimizer is set to reduce the drag and extend laminarity of the airfoil by moving two control points. The morphing shapes of the upper surface were generated using mathematical representation (B-Splines) of the flexible skin passing through four control points (see Figure 1); two fixed points at both end of the flexible skin (1 & 4) and two moving points represented by the actuator stokes (2 & 3). The best shape corresponds to the spline increasing the laminarity and reducing the drag the most with the combined displacements of the actuator points.

2.3 Project Objectives

As mentionned in the introduction, the aim of the previous CRIAQ 7.1 project was to control the laminarity of a morphing wing and validate it during wind tunnel testing. It was validated that the laminar flow can be extended by controlling an active composite upper surface on a wing[7-8]. However, the structural feasibility was not taken into account at the moment.

The main objective of the work presented in this paper is to develop an optimization methodology allowing a morphing skin to be fixed at both ends. In a typical wing structural design, the skins are fixed on spars and ribs and carry important loads. It is then a key objective to design a morphing skin that is totally fixed and keep his structural integrity. It was also part of the objectives to validate the morphing ability of the skin and to prove it matches at best the desired aerodynamic shape.

3 Structural design

The morphing wing prototype is a small scale wind tunnel model. It is 609 mm long (spanwise) and 244 mm wide (chordwise). Those dimensions were limited by the maximum height of the wind tunnel chamber and were chosen to respect the dimensioning rules for bidimensional flow analysis with a maximum chord length allowable of 40% of the span length [9].

The prototype was made in two distinct parts: a rigid lower surface and a morphing upper surface. The prototype was totally composite-made and was assembled in one piece avoiding discontinuities on the upper surface. Both upper and lower surfaces were made of glass/epoxy. Since the lower surface is rigid and sustains all reaction forces, it was stiffened using a bonding paste. Two rods were also used in the inner stiffened volume as reinforcement to add greater stability and rigidity.

Due to the restrictive dimensions of the small wing prototype, actuators could not be inserted directly inside the wing. The skin displacement was assured by the rotation of two eccentric shafts coupled to rotative actuators. Figure 2 shows the global concept of the morphing wing system.
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3.1 Finite Element Model

The structural and functional optimization methodology proposed is a finite element (FE) based optimization. The previously discussed morphing wing design was modeled and is represented on Figure 3. The finite element model was made and meshed using the finite element software Altair Hypermesh [10]. It is composed of three main regions: the composite flexible skin (red), the composite rigid skin (blue) and the inner structure composed of bonding paste used to fill the rigid part of the wing (green). Only the flexible skin is considered a design space in the structural optimization process. Table 1 summarizes the three regions of the finite element model with the ply stacking information for both the flexible and rigid skins.

<table>
<thead>
<tr>
<th>Parts</th>
<th>Names</th>
<th>Regions</th>
<th>Ply Stacking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>Morphing Skin</td>
<td>Design</td>
<td>[±45/0/90]desvar</td>
</tr>
<tr>
<td>Blue</td>
<td>Rigid Skin</td>
<td>Non-Design</td>
<td>[0/90]_2s</td>
</tr>
<tr>
<td>Green</td>
<td>Bonding Paste</td>
<td>Stiffener</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The morphing skin and the rigid skin were made of glass-epoxy composite. The fibers used were JB Martin’s UD TG-9U fibers infused with epoxy at a fiber volume fraction of 50%. Only the morphing skin was part of the optimization process and plies of ±45°, 0° and 90° were used. The thickness and number of each necessary ply were set as design variables in both free-size and size optimization. The thickness for each ply of the material used was 0.25mm at a fiber volume fraction of 50%. The rigid lower skin was part of the non-design space and the thickness was set to t=2 mm. The total laminate was composed of 8 plies. It was made of a stacking composed of chordwise 0° ply (x-axis) and spanwise 90° ply (y-axis) repeated two times and symmetric ([0/90]_2s). An epoxy based bonding paste was also used to stiffened the lower structure. The properties of both materials used are presented in table 2.

Table 2: Properties of materials

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>$E_1$ [GPa]</td>
<td>48</td>
<td>4</td>
</tr>
<tr>
<td>$E_2$ [GPa]</td>
<td>13</td>
<td>-</td>
</tr>
<tr>
<td>$G_{12}$ [GPa]</td>
<td>4.75</td>
<td>1.2</td>
</tr>
<tr>
<td>$S_1^T$ [MPa]</td>
<td>848</td>
<td>62</td>
</tr>
<tr>
<td>$S_2^T$ [MPa]</td>
<td>62</td>
<td>-</td>
</tr>
<tr>
<td>$S_1^C$ [MPa]</td>
<td>579</td>
<td>100</td>
</tr>
<tr>
<td>$S_2^C$ [MPa]</td>
<td>239</td>
<td>-</td>
</tr>
<tr>
<td>$S_{12}$ [MPa]</td>
<td>76</td>
<td>13.35</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.26</td>
<td>0.31</td>
</tr>
</tbody>
</table>

3.2 Aerodynamic cases

For each aerodynamic load cases, the morphing skin is subjected to specific displacements. The displacements of both actuators, located at 30%c and 50%c respectively, are used to match the desired morphed shape. Each optimized airfoil shape presented in Table 3 is obtained for two actuators (Act 1 & Act 2) displacement values and for a pair of Mach number (Ma) and angle of attack (α). The wing model is to be tested at Mach numbers of 0.08 and 0.1, and angles of attack from -2° to 3° with an increment of 1°.
The finite element Altair Optistruct solver was used to optimize the behavior of the morphing skin [10]. The three step method is used, as implemented in Optistruct [12-13]: free-size optimization, size optimization and ply stacking optimization. Firstly, a free-size optimization was required to roughly evaluate the overall thickness distribution. The total element thickness distribution was freely optimized to match the aerodynamic shape given by the aerodynamic optimization. That process determines the composite patch size (or section) and gives information about the plies at each different patch location (orientation, thickness, patch shape). Ply patches were generated as results and were interpreted to later divide the skin in different sections with specific composite parameters (nb of plies, thickness and orientation). The second step is a sizing optimization procedure that determines the thickness of the composite layers of all sections as function of manufacturing and structural constraints. The last step is used to find the best stacking sequence determined as function of the same constraints used in the sizing optimization.

### 4.1 Free-Size Optimization

Prior to the free-size optimisation, a load case had to be selected for the optimization. The loading case retained for the optimization combined the maximum displacements of actuators, corresponding to a Mach number $Ma=0.1$ and an angle of attack $\alpha=3^\circ$ (see Table 3). The actuator displacements were maximum for this case and were applied on the model as enforced displacements at their respective actuation line. A rigid element RBE2 was also created at the root of the wing to set the boundary condition. The rigid element RBE2 (green lines) and the actuators displacements (yellow triangles) are shown on figure 4. Based on a preliminary analysis, the influence of the aerodynamic pressure compared to the loads from the actuators was proved to be negligible. As a consequence, the aerodynamic pressure was not applied as a load on the FE model to minimize the CPU calculation time.

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$Ma=0.08$</th>
<th>$Ma=0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Act1</td>
<td>Act2</td>
</tr>
<tr>
<td>-2</td>
<td>0.16</td>
<td>0.08</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>0</td>
<td>0.5</td>
<td>1.03</td>
</tr>
<tr>
<td>1</td>
<td>1.08</td>
<td>0.99</td>
</tr>
<tr>
<td>2</td>
<td>1.48</td>
<td>1.41</td>
</tr>
<tr>
<td>3</td>
<td>1.53</td>
<td>2.44</td>
</tr>
</tbody>
</table>

![Image](Imposed displacements.png)  
**Fig.4: FE model with boundary conditions**

The main purpose of the free-size optimization was to determine the ideal distribution of the composite layers in order to match the desired morphed shape of the upper skin.

As described in equation (1), the objective function was set to minimize the total mass, $m_{total}$, of the morphing skin. The constrained displacements $\delta_j$ of specific nodes $j$ on the upper skin were set as a response in the optimization process. The displacements of about 2400 nodes on the flexible skin (design space) were constrained to their respective upper, $d^U_j$, and lower, $d^L_j$, allowable values to match the desired aerodynamic morphed shape.

The design variables $t_k$ used in this optimization refers to the thickness of each ply $i$ found in all shell elements $k$. The summation of all the design variables $t_i$ must stay within the lower limit, $T_k^L=0.5mm$, and upper limit, $T_k^U=2.5mm$, of the total laminate thickness for each element k. The initial value of each design variable used was set to 0.5mm.

As mentioned earlier, the free-size is an element based optimization that vary freely the thickness of each element between a minimum and a maximum value. The laminate thickness is optimized in order to respect the constrained displacement of the upper skin to best match the desired aerodynamic morphed shape.
To keep the design realistic, the laminate was set as a smeared symmetric superply composed of plies orientated at 0°, 90° and ±45°. Thus, by using the smearing option, the stacking sequence of the plies is approximated by an evenly shuffled laminate. A symmetric plane was also used at half span of the wing to dimish the calculation time and later ease the interpretation of the results.

Manufacturing constraints were also necessary to obtain representative results. Firstly, the design variables were discretized to the minimum thickness of a single manufacturable ply (t=0.25mm). Also, the total thickness of the laminate lower limit was set to 0.5mm and the upper limit to 2.5mm. Finally, to avoid any bend or twist coupling effect, the ±45° plies were balanced and the laminate was set to be symmetric.

The optimization formulation can be stated mathematically as:

\[
\begin{align*}
\min & \quad m_{\text{TOTAL}} \\
\text{subject to:} & \\
& \quad d_j^L \leq d_j \leq d_j^U, \quad j=1,...,n_j \\
& \quad t_i^L \leq t_i \leq t_i^U, \quad i=1,...,NP, \quad k=1,...,NE \\
& \quad T_k^L \leq \sum_{i=1}^{NP} t_i \leq T_k^U, \quad k=1,...,NE
\end{align*}
\] (1)

where the variable \(n_j\), \(NP\) and \(NE\) represent respectively the total number of nodes, plies and elements.

### 4.1.1 Free-size optimization results

The free-size optimization and ply orientation results show the minimum thickness distribution of the skin needed to match the aerodynamic shape. The laminate thickness obtained varies between 0.75 mm to 1.75 mm. Figure 5 shows the thickness distribution. The leading edge of the skin is thicker while its trailing edge tends to reach the minimum thickness value. The local maximum is located on both ends of the leading edge section, possibly due to edge effects.

Figure 6 shows the ply thickness distribution with respect to the different ply orientations. The 0° plies (a) are located near the edges and can be attributed to the local stiffening of the structure to counteract the edge effects. The 90° plies (b) are mostly located in the middle while the ±45° plies (c) have proved to be dominant and are presented in at least 3 distinctive thickness.

The results shown in Figure 6 were used to divide the skin in different sections to setup the size optimization. The 0° and 90° plies were removed from some of the sections in the size optimization. Otherwise, as shown in Figure 6, they are mostly unnecessary and reduce to a thickness of zero for more than half of the skin area.

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**Fig.5:** Total thickness of the morphing skin after free-size optimization (mm)

**Fig.6:** Ply orientation distribution

<table>
<thead>
<tr>
<th>a)</th>
<th>b)</th>
<th>c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>t ≥ 0.25mm</td>
<td>t ≥ 0.25mm</td>
<td>t ≥ 0.5mm</td>
</tr>
<tr>
<td>t ≥ 1.0mm</td>
<td>t ≥ 1.5mm</td>
<td></td>
</tr>
</tbody>
</table>
4.2 Size Optimization

From the results of the free-size optimization, the skin was divided in four different sections as shown in Figure 7. Those section were determined from their respective thickness distribution. From figure 6 (c), the skin was divided in two major parts: the front part composed of sections 1, 2 and 3 altogether, and the rear part composed of section 4.

Each section required specific ply orientations according to the ply thickness results of the free-size optimization. From those results, the first three sections were setup to only contained ±45° and 0° plies as a superposition of results shown in Figure 6, except for section 2 that also contained 90° plies. Section 4 contained ±45° and 90° plies only.

The size optimization used the same objective and design variables as the previous free-sizing optimization routine. The objective function was set to reduce the total mass of the skin as function of the constraints on the nodal displacements of the skin. The design variables were in this case the thickness of the plies required in each individual section of the skin.

The same manufacturing constraint were used which are ±45° balanced plies, Min/Max thickness of the total laminate (between 0.5mm and 2.5mm) and a discrete minimum value of 0.25mm for the thickness of each ply. The Tsai-Wu failure index was also used as a constraint and had to remain under the value of 1 for all elements.

The mathematical formulation for the sizing optimization is:

\[
\begin{align*}
\text{min } & m_{\text{TOTAL}} \\
\text{subject to: } & \\
& d_j^L \leq \delta_j \leq d_j^U, \quad j=1,\ldots,n_j \\
& FL \leq 1.0, \quad e=1,\ldots,NE \\
& t_i^L \leq t_i \leq t_i^U, \quad i=1,\ldots,NP \\
& 0.5mm \leq \sum_{i=1}^{NP} t_i \leq 2.5mm
\end{align*}
\]

where \( m_{\text{TOTAL}} \) is the total mass of the morphing skin, \( \delta_j \) the constrained displacement of every nodes \( j \), \( FL \) is the failure index (Tsai-Wu) for every element \( e \) and \( t_i \) is the design variable for the thickness of each plies \( i \). Again, the variable \( n_j, NP \) and \( NE \) represent respectively the total number of nodes, plies and elements.

4.2.1 Size optimization results

The results of the sizing optimization gave thicknesses of zero for the 0° and 90° plies. The 90° plies are reduced to a thickness of zero to respect the Tsai-Wu constraint, while the 0° plies add too much stiffness in the first three sections and are reduced to a thickness of zero to best match the aerodynamic shape.

Only the ±45° plies were required after the sizing optimization. The thickness for the three first sections is 1.5 mm (6 plies) while the fourth section has a thickness of 1 mm (4 plies). Tables 4 summarize the size results for each zone.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Nb plies(±45°)</th>
<th>t (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>1.5</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

4.3 Finite Element Analysis

To validate the retained design, a complete numerical model was made and tested for all load cases presented in Table 3. The corresponding structural deformation were compared to the aerodynamic spline required to validate the efficiency of the design.

The deformed shapes from the FE model analysis were compared to the aerodynamic ideal morphed...
airfoil. Figure 8 shows example of two cases at $\alpha=0^\circ$ for two different Mach numbers (Ma=0.08 and Ma=0.1).

![Figure 8: FE Model results comparison to aerodynamic morphed airfoil(mm)](image)

a) Ma=0.08, $\alpha=0$

b) Ma=0.1, $\alpha=0$

Fig. 8: FE Model results comparison to aerodynamic morphed airfoil (mm)

All cases show results that are similar to those presented in Figure 8. The relative error on displacement for all comparisons was always under 3% and never exceeded the absolute value of 0.1 mm. The results show that the finite element model properly match the desired aerodynamic morphed airfoil (splines).

5 Experimental Validation

A wing model was manufactured and tested to validate the FE model. The process used to manufacture the composite skins was vacuum bag infusion. Aluminum molds were first machined and polished prior to infusion. Once the skins were infused, they were trimmed and drilled to insert small pressure sensor that will later be used for the wind tunnel testing. The two skins were then bonded together at room temperature. The wing was then assembled with all other mechanical parts (base, axis, rod, motors, etc.)

Following manufacturing, the wing deformation was tested to measure the morphed shape and compare it to the numerical results. A Coordinate Measuring Machine (2) was used to measure morphed shapes. Three chordwise scans of the upper surface were done per case at a measuring interval of 2 mm, giving approximately 150 points per scan. The wing (3) was placed and bolted on the aluminum mold (see Figure 9) to make sure it remains stable for the duration of the test. Every aerodynamic cases from Table 3 were tested. The displacement of the actuator were assured by the rotative actuators (1) and operated by a control program previously developed.

![Figure 9: CMM test setup](image)

Once all the morphed shape were scanned, the generated profiles were compared to the FE results. Some comparisons are shown on Figure 10. The experimental results were all close to the numerical value. Nonetheless, slight experimental errors were noticed in the actuator displacement. They were for some cases slightly different from the expected displacement value. As shown in Figure 10 c), the displacement of the second actuator (located at 121 mm) was 0.5 mm under the desired value. That slight displacement error had a strong impact on the precision of the adjacent measured points. That case has the highest error values, which prove that such small experimental errors, even of the order of 0.1 mm, can lead to non-negligible mismatch between the desired morphed surface and the actual surface obtained.

The mean absolute and relative error between the two morphed shapes (experimental and FE model) are shown and summarized in Table 5. The results shown are for the cases presented in Table 3. All mean absolute error are comprised between 0.13 mm and 0.28 mm and the mean relative error never exceeds 2%. Such small error values were judged
Fig. 10: FE model morphed shape compared to experimental results
a) Ma=0.1, $\alpha=0^\circ$ b) Ma=0.1, $\alpha=2^\circ$ c) Ma=0.08, $\alpha=-2^\circ$ d) Ma=0.08, $\alpha=0^\circ$
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Table 5: Morphed shape error comparison

<table>
<thead>
<tr>
<th></th>
<th>Ma-0.08</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>α</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>Mean Absolute Error (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ma=0.08</td>
<td>-1</td>
<td>0.34</td>
<td>0.13</td>
<td>0.22</td>
<td>0.28</td>
<td>0.28</td>
<td>0.14</td>
<td>0.15</td>
<td>0.19</td>
</tr>
<tr>
<td>Ma=0.1</td>
<td>0</td>
<td>1.67</td>
<td>0.68</td>
<td>0.97</td>
<td>1.34</td>
<td>1.16</td>
<td>0.72</td>
<td>0.74</td>
<td>0.75</td>
</tr>
</tbody>
</table>

satisfactory to globally improve the laminar flow over a morphing upper surface. The results confirmed the optimized skin was able to adequately match the desired aerodynamic shapes.

6 Conclusion

The main objective of the project was to develop an optimization methodology to design a morphing skin able to sustain flight loads. The optimization methodology presented has shown it is possible to optimize a morphing skin to match a specific shape while being totally fixed upstream and downstream. The 3 steps sizing optimization has proved it is possible to optimize the skin by dividing it in sections with different properties that allow better flexibility or rigidity as needed.

The wing was then manufactured and tested to validate the optimization process. The results showed the errors between the morphed shapes and the target aerodynamic shapes were low and that the shapes obtained were sufficient to obtain good aerodynamic improvement.

As future work, a similar methodology will be applied for the project CRIAQ MDO-505. As mentioned, the morphing skin should be able to withstand in-flight loads of a real aircraft wing. The later optimization will integrate more constraints such stress or buckling due to in-flight loading. Other consideration will be made to respect geometrical constraints, angle minus loaded (AML) allowables and actuation forces constraints.

References


