Aerodynamic Performance of Corrugated Skins for Spanwise Wing Morphing

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Aircraft designed to fly a wide mission range will have their design compromised so that they can meet all mission requirements. There has been continued interest in morphing aircraft in recent years. These proposed morphing systems allow for aircraft to undergo large-scale planform shape changes, such that they adopt the optimum shape for the given mission phase. An aircraft that can change wingspan could operate with high aerodynamic efficiency at cruise, due to a large aspect ratio wing. Upon retraction of the wingspan, higher manoeuverability is gained. For a span-changing aircraft, the wing skins must also change geometry with the span change. One proposed type of skin to do this is a corrugated skin, which displays high anisotropy in stiffness, allowing it to take significant aerodynamic pressure loading, whilst being compliant in the spanwise direction to allow for wing morphing. The method of corrugation used produces sharp leading edges, and so different methods for rounding of the leading edge are examined to determine whether lost aerodynamic performance can be recovered. These are analysed first in 2D, and then the simulations are extended to 3D to determine the effects of corrugation wavelength in the spanwise direction, and the effect of corrugation depth. It is found that the leading edge profile can greatly impact performance, that corrugation wavelength has only a minimal effect on aerodynamic efficiency, and finally that corrugation depth can incur a significant performance penalty.

I. Introduction

A. Background

Aircraft designed for a wide range of missions may be required to balance conflicting requirements in order to fulfil all mission requirements. For example, a mission requiring long endurance at low speed might drive the wing design towards a high aspect ratio planform. Such a planform will reduce induced drag for a given amount of lift. A different mission requiring high manoeuverability could drive the wing design towards a low aspect-ratio planform, at the cost of aerodynamic efficiency. If the aircraft designed for these missions does not make use of morphing systems, its final design will be a compromise between these conflicting requirements, yielding an aircraft that performs adequately, but not spectacularly, for both missions. However, if the aircraft could be designed using morphing systems to allow the aspect ratio to change during flight, it could transition between the two missions smoothly, and obtain optimum performance for both [1].

Morphing systems come at a cost in both weight and complexity. Additionally, some form of compliance of the structure is required to allow the morphing to take place. In the case described above, a change in aspect ratio can be achieved by a variable wingspan wing. To achieve this, not only must the wing internal structure change shape and size, but the wing skins must also be compliant with that change. One option, first attempted by Ivan Makhonine [2] in 1931, used telescopic skins that retracted into each other to obtain the morphed shape. The disadvantage of this method lies in the discrete change in wing chord between the two sections. Additionally, this method is limited to wings without taper in the outboard section. A second option is to use a telescopic or articulated structure [3] covered by some form of morphing skin to

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provide a smooth aerodynamic surface. Most research on morphing skins can be broadly classified under three major areas [4]: compliant structures, shape memory polymers, and anisotropic elastomeric skins. Thill et al. [5] performed a comprehensive review of morphing skins and considered various novel materials and technologies. Compliant structures such as corrugated laminates are promising morphing skins mainly due to their extreme anisotropy, allowing for high stiffness in one direction, whilst being compliant in another. This allows the skin to simultaneously take the aerodynamic loading and transfer it to the internal structure, whilst allowing for spanwise extension and retraction of the wing.

A purely structural optimisation of the corrugations will drive towards a high depth of corrugations, to give the minimum stiffness in the spanwise direction. However, it is likely the case that this will be aerodynamically poor due to the large increase in area over which skin friction can act compared to an uncorrugated aerofoil. The effect of corrugation profile on aerodynamic performance is also not usually considered; a trapezoidal corrugation might be appealing from a structural point of view, but the sharp edges used in such corrugations may cause separation of the flow in cross-flows, such as at a slip angle \( \beta \), or near the wingtip where the tip vortex induces a spanwise component of velocity.

B. Problem definition

In this paper, spanwise corrugations are examined in both 2D and 3D using the CFD tool OpenFOAM. Due to the method of corrugation employed, sharp leading edges are produced in the troughs of the corrugations. Two methods of rounding these leading edges are used, and their aerodynamic performance examined. The effect of different corrugation depths on aerodynamic performance is also analysed, as well as the effect of corrugation wavelength. The RANS results from OpenFOAM from two different turbulence models are compared to each other to provide a useful comparison in cases with some degree of flow separation.

II. Corrugation Shapes

The design of corrugated skins is a challenging task which requires thorough trade-off studies between the conflicting requirements. To simplify the problem, the analysis is split into two studies: structural and aerodynamic. A structural study was conducted by Xia et al. [6] where they developed an aero-structural design suite. The suite consisted of ANSYS 14.5 integrated into a Genetic Algorithm (GA) optimiser. Representative aerodynamic loads are extracted from a vortex lattice method and then refined by XFOIL (2D potential solver) before being applied to the corrugated skin modelled in ANSYS 14.5. The aim of the structural study was to minimise the axial stiffness of the skin while allowing it to withstand aerodynamic pressure without excessive deformations. From a systems level point of view, the actuators' force and weight are dependent on the axial stiffness. Therefore, it is highly desirable to minimise the axial stiffness of the corrugated skin to minimise the overall weight of the morphing wing. The outcomes of the structural study showed that the optimiser maximises the height and number of corrugations up to a point where the out-of-plane deformation constraints are violated.

In this aerodynamics paper, corrugations are produced by projecting perpendicularly inwards a given distance from the surface of a baseline aerofoil. In general, the NACA 0012 aerofoil is used as the baseline in this paper, though 2D results are also presented for a NACA 6510 aerofoil. When projecting inwards from the upper and lower surface, two new surfaces are generated. However, at the leading and trailing edges, the two projected surfaces will tend to cross each other, as shown in Figure 1.

![Projected surface crossing at the LE and TE](image)

Figure 1. Projected surface crossing at the LE and TE

Once the projected surfaces are cropped to lie between their intersection points, the resulting cross-section is likely to have a sharp leading edge. A CFD analysis of this leading edge shape is performed in Section
IV A, but at this stage it can be hypothesised that a sharp leading edge is likely to lead to flow separation at even moderate angles of attack. This will lead to a loss in lift, and increased drag. Due to the periodic variation in sharpness of the LE across the span of the wing, this stall should be progressive rather than sudden, and may be tolerable from a handling qualities point of view, but the associated loss in performance should be avoided if possible.

Two methods for rounding of the leading edge are examined in Section IV A. The first method uses a moving average (low-pass) digital filter to smooth the leading edge and reduce its sharpness. The amount of smoothing can be controlled by changing the size of the moving average stencil. In the second method, a circular arc of specified radius is fitted to the leading edge such that it is tangential to the upper and lower surfaces to which it adjoins. Examples of the two methods are shown in Figure 2.

![Figure 2. Methods of producing a rounded leading edge](image)

The trailing edge is produced simply by cropping the crossed surfaces to their rear-most intersection point. Figure 1 shows that in general this new trailing edge is a much larger distance from the baseline trailing edge than the corrugation depth.

Figure 3 shows examples of two aerofoils generated using the method described above, with circular leading edges. Note that not only has the aerofoil generated from the NACA 6510 baseline been truncated to shorter chord length than its 0012 equivalent, but since the trailing edge ends up being more heavily cropped than the leading edge, the angle of attack of the NACA 6510 derivative has changed relative to its baseline. It can be expected that this will shift the zero-lift drag angle (see Section IV A), as well as reducing the lift of the overall section relative to an uncorrugated section. In order to negate this effect, the section would have to be flown at a higher angle of attack to reach the same lift coefficient of an uncorrugated section, likely leading to a reduction in overall lift-to-drag ratio.

![Figure 3. Examples of two aerofoil sections generated, both using circular leading edge corrections](image)
A different method for producing the corrugated unit cell would be to project outwards rather than inwards. In doing so, the leading edge would remain rounded, taking on a similar profile to the baseline aerofoil without modification. However, the trailing edge would be open and need closing in some manner. Only the inwards projection method is examined in this paper.

For three-dimensional simulations, the surface is produced by taking the baseline cross-section, and gradually increasing the depth of projection across the span of the section, essentially performing the 2D method outlined previously a number of times across the span. The surface is then described by splines that pass through similar points in the spanwise direction; e.g. the leading edge spline is the locus of points passing through the forwards-most point in each cross-section. An schematic diagram of an example 3D section is given in Figure 4. The figure shows half of a corrugation unit cell, from peak to trough aerofoils. For the 3D CFD calculations, only half of a unit cell is used because the cell shape is symmetric; a symmetry plane condition can be used with the half-model in the solver to reduce the computational effort required to reach a solution.

III. Software Definition

The CFD simulations presented later in this paper are solved using OpenFOAM, a numerical solution suite with contains a large number of modules used to build solutions for different types of numerical problem.

`simpleFoam` is the solver chosen for the results presented in Section IV. This is the standard OpenFOAM solver used for steady incompressible turbulent problems. For the 2D results, turbulence is modelled using the included \( k - \omega \) SST model, which follows Menter’s formulation [7] with some tweaks [8]. This turbulence model is known for good stability, and its two equation formulation should provide for accuracy in relatively complex flows. The Spalart Allmaras turbulence model is additionally used in the 3D results to provide a comparison as the two models can have a tendency to predict separation differently. Transition is not captured accurately in these models, and so the boundary layers produced will be turbulent essentially from the leading edge of the section.

In addition to the turbulence model, the user must state the desired numerical schemes for terms in the equations such as spatial gradients and time derivatives. For this work, only steady-state solutions are sought, so the time derivative is not required, whilst the spatial gradients are calculated with a linear (2nd order accurate) estimation, and convection terms are calculated with second order schemes. Relaxation factors are required for the SIMPLE algorithm, and are chosen to give the best balance between stability and time to convergence.
Meshing is achieved using the OpenFOAM utility \textit{blockMesh}. This utility is used to create multiblock structured meshes of hexahedral cells, allowing for high mesh quality at the cost of a large number of cells, but also allowing for control over the cell spacing within the blocks. Careful block spacing then permits good control of the overall cell spacing, especially in the near-wall region. The process is automated using a wrapper for \textit{blockMesh} written in MATLAB. A functional representation for the aerofoil surface shape is used, allowing for mesh generation within a few seconds from a simple set of parameters.

The resulting meshes are comprised of between 1M and 3.5M cells, with the farfield extending approximately 30 chord lengths away from the wing section. A cutaway of a mesh can be seen in Figure 5.

![Figure 5. Cutaway of the mesh, showing the upper aerofoil and back surfaces](image)

IV. Results

A. Two-dimensional simulations

Three-dimensional simulations, even of a single unit-cell of corrugation, are computationally expensive, and would not be feasibly incorporated into an optimisation loop. It may, however, still be possible to learn something of the flow over the unit cell by means of two-dimensional simulations. At the deepest part of the trough, the leading edge is at its sharpest and this region will have the largest effect upon the flow. Additionally, due to the symmetric nature of the unit cell, the deepest part lies at the symmetry plane, and so the flow in this plane should be closest in nature to that from a two-dimensional simulation. Different leading edge profiles are studied here so that one suitable profile can be selected for the three-dimensional study performed in Section B.

Simulations are run at 60m/s freestream velocity, with a kinematic viscosity of $\nu = 1.4813 \times 10^{-5}$m$^2$/s, giving a Reynolds number based on chord length of $4.05 \times 10^6$. Freestream turbulence intensity is taken to be 5%, which is used to calculate values for $k$ and $\omega$ needed for the turbulence model at the upstream boundary.

Lift and drag polars for aerofoils derived from the NACA 0012 baseline with three leading edge profiles and two corrugation depths are shown in Figure 6. In 6(a) and (b), the blue line represents the polars for the baseline aerofoil. From Figure 6(a), one can see a reduction in the lift-curve slope from the baseline...
aerofoil. This is most significant for the sharp leading edge case, whilst both methods of rounding the leading edge (either by smoothing or circularising) have been similarly effective at recovering some of the lost lift. The drag for the three derived aerofoils is significantly increased from the baseline aerofoil, and grows progressively worse as the angle of attack is increased. The sharp leading edge, however, performs very significantly worse than the two rounded leading edges; although both perform similarly well, the smoothed LE shows better drag performance than the circularised LE.

In the case of the deeper corrugation, shown in Figure 6(b), similar trends are seen. There has been a reversal in performance of the smoothed and circularised leading edges, however, with the circularised one now performing better in both lift recovery and drag reduction when compared to the smoothed leading edge.

Subfigures 6(c) and (d) show the same data as (a) and (b), but with the derived aerofoil performance normalised by the baseline aerofoil performance to give an indication of the percentage of performance lost. In the case of lift, the first point at zero-degrees angle of attack has been omitted; since the aerofoil is symmetric, the lift at this condition is essentially zero for both the baseline and derived aerofoils, leading to spurious results when normalised.

Figure 7 helps to indicate the difference in lift and drag shown between the sharp and circular leading edges in Figure 6(a) and (c). There is clear evidence of separation from the sharp leading edge, even at this modest angle of attack of 6 degrees. Additionally, the velocity over the upper rear surface of the aerofoil is in general lower, and a greater area of low-speed flow exists near the trailing edge. In the case of the greater depth of corrugation, the advantage of the circular leading edge is seen in Figure 8, which indicates the more gradual acceleration of the flow over the nose, and the slightly greater suction that is maintained over a greater portion of the upper surface.

The same analysis is performed on the NACA 6510 aerofoil and derivatives for the same two corrugation depths and LE generation methods; Figure 9 shows the results. As was hypothesised in Section II, alteration of the baseline aerofoil to produce its derivatives has shifted the lift-curve line vertically. This is due to the change in effective angle of attack of the aerofoil to form the derivatives; by trimming the TE more than the LE, the new aerofoil has effectively been pitched down.

In Figure 9(a), for shallower corrugations, the lift-curve slope at positive lift coefficient appears to be largely unaffected. Figure 9(b) indicates that the lift-curve slope is slightly reduced from the baseline aerofoil when corrugation depth is increased. For a range of positive lift coefficients, drag of the derivative sections appears similar to the baseline aerofoil at a given lift coefficient, and at a given angle of attack (without accounting for the effective rotation due to truncation), the drag value is lower than the baseline aerofoil. Within the limitations of this two-dimensional analysis, this may indicate that a corrugation cell based upon a NACA 6510 baseline might not suffer from greatly increased drag; whilst lift is lost, drag is also reduced, and the two effects will go some way to counterracting each other.

Both figures, however, indicate unfavourable behaviour at high negative angles of attack (spanning negative lift coefficients) where the data suggest the occurrence of stall. Drag increases rapidly as \( \alpha \) becomes progressively more negative, and the lift-curve begins to roll off. This stall is clearly visible in Figure 10, which shows a NACA 6510 derivative aerofoil with a 0.02\( c \) corrugation depth and circularised leading edge.

B. Three-dimensional simulations

The two-dimensional analysis performed in Section IV A has identified that leading edge shape is highly important to aerodynamic performance of the trough aerofoil. However, this analysis neglected the effect of the spanwise shape in three-dimensions; this is addressed in this section with a series of CFD simulations of half-unit-cells in 3D. These computations are naturally more resource intensive, and thus a smaller test-matrix has been designed in an attempt to identify the importance of three-dimensional effects on the flow.
(a) Polar from aerofoils derived from the NACA 0012 with a corrugation depth of 0.02 c

(b) Polar from aerofoils derived from the NACA 0012 with a corrugation depth of 0.03 c

(c) Normalised polar from aerofoils derived from the NACA 0012 with a corrugation depth of 0.02 c

(d) Normalised polar from aerofoils derived from the NACA 0012 with a corrugation depth of 0.03 c

Figure 6. NACA 0012 derived aerofoils
Figure 7. Flow over sharp and circular leading edges

Figure 8. Pressure coefficient over NACA 0012 derived aerofoils with corrugation depth = 0.03 c
(a) Polar from aerofoils derived from the NACA 6510 with a corrugation depth of 0.02c

(b) Polar from aerofoils derived from the NACA 6510 with a corrugation depth of 0.03c

(c) Normalised polar from aerofoils derived from the NACA 6510 with a corrugation depth of 0.02c

(d) Normalised polar from aerofoils derived from the NACA 6510 with a corrugation depth of 0.03c

Figure 9. NACA 6510 derived aerofoils
A baseline design is produced based upon a NACA 0012 aerofoil section, with a corrugation depth that varies sinusoidally from 0 to 0.02 $c$. This is equivalent to the shallower derived aerofoil in Section A, whose performance was shown in Figure 6(a). This figure indicated that the smoothed leading edge style outperformed the sharp style by a very large margin, and the circularised leading edge by a small margin, and so was picked for the three-dimensional baseline section.

Simulations of a sharp leading edge section are also performed as a comparison to determine the overall importance of the leading edge shape in 3D; although the 2D cases indicated a large impact, in the 3D section, only a small portion of the section is particularly sharp. Also simulated are wide versions of the baseline section (which is of the same corrugation depth, but twice the corrugation wavelength), and a deep section of corrugation depth 0.03$c$ (50% greater than the baseline). This deep corrugation section follows the wide format rather than the baseline format. This was done to avoid high surface angles that introduce large amounts of non-orthogonality in the computational mesh.

Unfortunately, it is not possible to truly decouple the effects of these design variables from each other. Increasing corrugation depth not only reduces the thickness and chord of the trough aerofoil, but increases the maximum surface angle. Increasing corrugation wavelength does not affect thickness and chord, but reduces maximum surface angle. Due to this coupling, it will be difficult to draw quantitative results from the data, but some qualitative conclusions will be reached.

Both the Spalart Allmaras (one-equation) and Menter’s SST (two-equation) turbulence models will be compared. Since separation is expected to occur in some of the runs, especially in those with sharp leading edges, it is sensible not to rely too heavily upon one model as the behaviour of different turbulence models can be quite different in the prediction of separation.

To keep computational costs down, two angles of attack are examined: 0 degrees and 4 degrees. The former provides results at zero lift, which is useful for determining the zero-lift drag coefficient so that it can be compared to uncorrugated sections. The latter represents a modest angle of attack for the NACA 0012 section and between the two, a reasonable estimate for the lift-curve-slope should be produced. Additionally, any three-dimensional effects that might increase drag (e.g. production of vortices within the trough sections) will begin to show in the 4 degrees results without being drastically hampered by separation.

The results from this series of simulations are presented in Figure 11. The naming convention used is as follows: the first digit represents the corrugation depth as a percentage of chord length; the second digit is the leading edge style (0 for sharp, 1 for smoothed; no circular leading edges were used in the 3D simulations); and the third digit represents angle of attack in degrees. The presence of a ‘W’ indicates that it is a wide section of double corrugation wavelength, whilst the final tag indicates the turbulence model used.

Ignoring the top-left subfigure for now (which represents lift at zero-degrees angle of attack, and is essentially zero), the upper-right subfigure shows the zero-lift drag for the various sections. The baseline section, represented by the left-most two bars, has the highest drag of all sections tested at some 10% higher than the minimum drag section: the 3-1-0-W. In general there is reasonably good agreement between the two turbulence models at this angle of attack.
Figure 11. Lift and drag in 3D for various sections

Turning to the bottom two subfigures, representing 4 degrees angle of attack, the 3-1-0-W section which had previously performed the best at 0 degrees, is now the worst performing section. It produces the lowest lift (some 6% lower than the 2-1-4-W case) with higher drag than some other sections. However, the agreement in drag results between the two turbulence models here is much poorer, with the SST model predicting significantly higher drag values than the SA model by approximately 15% in each case.

Perhaps surprisingly, increasing the corrugation wavelength appears to have reduced the lift of the section (bottom left subfigure), though drag is also reduced such that the lift to drag ratio of the two is nearly identical. From this it may be concluded that within the limits examined here, corrugation wavelength does not have a very large effect upon aerodynamic performance (lift to drag ratio), whereas increasing corrugation depth can have a more significant impact. This is unfortunate, as from a structural point of view, it is preferable to maximise corrugation depth.

In all cases, the drag is significantly higher than that of an unmodified NACA 0012 section (see Figure 6), and more closely follows that of the derived (trough) aerofoils examined in Section A. This may indicate that, at least in the cases studied here, the aerodynamics is dominated by the flow in the corrugation trough. It can certainly be expected that any separation occuring in this 0012 section is most likely to develop in the trough section due to its greater leading edge sharpness.
Figure 12 shows the surface pressures of the 2-1-4 3D section at the leading edge. Notable here is the change in $z$ position of the leading edge stagnation point (the yellow band that runs left to right), as well as the sharp and clearly defined suction peak (the dark blue patch) just aft of the leading edge in the corrugation trough; despite the smoothing of the leading edge, the pressure gradients near the leading edge of the trough aerofoil are still significantly higher than that at the peak (baseline) section.

![Figure 12. Surface pressures at the leading edge](image)

This region is associated with a small bubble of separation which soon reattaches and does not appear to significantly affect the flow. This is shown in Figure 13(a), and can be contrasted to the sharp leading edge 3D simulation in 13(b), which shows a larger separation region that reattaches further downstream.

The change in $z$ position of the stagnation point at the leading edge can also clearly be seen in the streamlines plotted in Figure 14. The streamlines near the leading edge of the corrugated section split, with those near the trough passing over the upper surface, and those near the baseline section passing underneath. The streamlines over the upper surface also appear to roll up into the bottom of the corrugation. However, they do not appear to be rolling into a fully formed vortex, and do not continue to rotate within the wake region. Nevertheless, this rolling up of the flow will still be contributing to the drag of the section.

V. Conclusions

Corrugated skins for span changing morphing aircraft show good potential from a structural point of view, due to their high anisotropy in stiffness. Corrugations produced through projecting perpendicularly from a baseline aerofoil surface produce either a sharp leading edge, or an open trailing edge; only the former has been examined in this paper. Two-dimensional simulations of these derived aerofoils showed that sharp leading edges lead to poor aerodynamic performance at angles of attack. Two methods for rounding the leading edge have been investigated: low pass filtering and fitting a circular arc both proved to be effective at reclaiming lost aerodynamic performance for both uncambered and cambered baseline aerofoils. Corrugating a cambered aerofoil leads to a rotation of the chord line, causing a shifting of the lift-curve slope, as if the
Figure 13. Flow in the trough region of 3D simulations with smooth and sharp leading edges

Figure 14. Streamlines over the 3D section
angle of attack had been changed.

Three-dimensional simulations were performed which identified that the overall force coefficients approximately followed that of the derived aerofoils investigated in two dimensions previously, suggesting that the overall aerodynamics are dominated by the trough (or worst-case) sections. Changing the wavelength of corrugation appeared to reduce both lift and drag at a given angle of attack, although the overall lift to drag ratio remained relatively constant, suggesting that from a practical standpoint, wavelength has little effect and may be chosen for structural reasons. Increasing corrugation depth did reduce aerodynamic efficiency by reducing lift generation, whilst having little effect upon drag.

From these results, one might conclude that the aerodynamic penalty of corrugations may be too large to be practical without some kind of compliant skin covering the corrugations; such a design would incur penalties in both weight and actuation energy to overcome the stiffness of the skin during span morphing.

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References


