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Aerodynamic performance of aerofoils obtained from a geometric offset applied to a given initial aerofoil

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Abstract: Many studies concerning morphing aircraft concepts in which enhanced performance and increased energy efficiency are two of the main goals have been recently conducted. Some of those concepts deal with wing span changes. In line with those, in a variable-span wing of the telescopic type, the cross-sections of the sliding panels, whether be two, three or more, must be made geometrically compatible among them. This requirement serves two purposes: to minimize the aerofoils’ geometric discontinuity which negatively affects wing drag and lift; and to provide a simple structural support between any two sliding panels. This paper describes the methodology employed to develop geometrically compatible aerofoils obtained from a constant geometric offset applied to a given initial aerofoil. This methodology is used to create inward offset aerofoils and outward offset aerofoils. The geometric and aerodynamic characteristics of the resulting offset aerofoils are compared with those of the original aerofoils. From the analysis of six different original aerofoils, strong trends in the geometric changes and in the aerodynamic characteristics of the resulting inward and outward offset aerofoils are observed. Ultimately, this study can help a telescopic wing designer decide whether an inward or an outward offset aerofoil is more appropriate for the specific design at hand.

Keywords: aerofoil offset; aerofoil geometry; aerodynamic analysis; morphing technologies; variable-span wing; XFOIL

1 Introduction

Morphing wing technologies for flight regime adaptation have received great attention in recent years and may become important for aircraft’s operations allowing near-optimal overall flight efficiency over different design points. Advances in these technologies enable new design approaches and improvements in multi-task flexibility, by considering wing geometric transformations. A thorough review of morphing concepts which thrived to be functional in flight is presented by Barbarino et al. [1] showing the huge effort that researchers have committed to developing efficient and reliable morphing aircraft systems.

From an aerodynamics perspective, the overall shape of the wing (including cross-section) is the most important design aspect for an aircraft so that there is usually an ideal single configuration of the aircraft suitable for each specific type of mission [2]. Therefore a non-morphing aircraft is highly efficient at some design flight condition while it becomes less suitable in others. Furthermore, morphing wing technologies contribute to efficient performance during distinct mission roles, or enable new multi-role missions that are not possible with a fixed geometry aircraft, as demonstrated by Tidwell et al. [3].

Many recent developments have focused on aircraft morphing concepts with the ultimate goal of enhancing performance and increasing energy efficiency of aircraft [4]. As these technologies are still recent and lack adequate maturity, their progress is an iterative process between design and experiment. Also, a large number of projects have produced extensive work on aerodynamic shape optimization of aerofoils and multidisciplinary design optimization of wing systems [5–8]. Methods of aerofoil and wing morphing can include thickness and camber change [9], variable twist, variable chord, sweep change, and variable span [5].

The motivation behind the present work lies in the desire to improve a variable-span wing (VSW) design of the telescopic type previously developed at the Aerospace Sciences Department of University of Beira Interior [8, 10, ...
This new VSW design makes use of purposely optimized aerofoil sections and also includes aerofoil camber changes. The variable span capability allows the wing to be fully extended for take-off and landing, in a configuration of high lift where the lift-to-drag ratio is improved, and provide reduced take-off and landing distances. The fully extended span configuration is also suitable for low speed loiters. On the other hand, with the outboard panel retracted, while in cruise or at high speeds, the wing planform area and aspect ratio are reduced, decreasing parasite drag for improved range and cruise efficiency [11].

In this manner, the layout of the VSW concept is based on a hollow inboard fixed wing (IFW) that is fixed to the fuselage inside of which an outboard moving wing (OMW) slides, actuated by an electromechanical mechanism.

The shape and size of the VSW is obtained through an in-house computational constrained aerodynamic shape optimization code, aimed at determining the wing mean chord and span values that minimize its drag for a specified mission profile. A detailed description of the aerodynamic optimization procedure is given by Albuquerque et al. [12]. As inputs to this optimization procedure, two aerofoil geometries must be provided. For such task, it is mandatory to design two geometrically compatible aerofoils, with the chord length of the IFW larger than that of the OMW, in order for the outboard wing panel to slide inside the inboard wing panel. Accordingly, both IFW and OMW wing panels have the design constraint of keeping chord and aerofoil geometry constants along each panel’s span, enabling proper fitting and support of the OMW.

Proper aerofoil design to ensure geometric compatibility and good aerodynamic performance is essential to guarantee improved overall variable-span wing performance over a conventional fixed wing. Thus, the main objective of this work is to develop aerofoils obtained from inward and outward geometric offsets applied to a given initial aerofoil to ensure geometric compatibility and to assess their resulting shape and aerodynamic characteristics compared with the original aerofoil. In the future, the methodology presented may help the designer decide whether inward offset or outward offset aerofoils are more suitable for a given application.

2 Offset Aerofoils

In a variable-span wing of the telescopic type, the cross-sections of the sliding panels, whether be two, three or more, must be made geometrically compatible among them. This requirement serves two purposes: to minimize the aerofoils geometric discontinuity which negatively affects wing drag and lift; and to provide a simple structural support between any two panels. As outlined in Mestrinho et al. [8], a convenient way to match the IFW aerofoil to the OMW aerofoil of a two-panel telescopic wing is to create an aerofoil for the IFW from a positive (outward) offset of the aerofoil selected for the OMW so that the smallest possible discontinuity between wing sections is obtained. However, it is not clear whether this procedure is the most appropriate for any given general situation where maximum aerodynamic performance is mandatory. Therefore, the need to validate the decision of selecting a more adequate combination between keeping an original aerofoil for the OMW and the corresponding modified aerofoil with an outward offset for the IFW or, alternatively, setting the original aerofoil for the IFW, modifying it with an inward offset for the OMW, has emerged.

Due to the geometric modifications obtained by offsetting the original aerofoil shapes, small geometric conflicts or imperfections need to be corrected in the aerofoil regions near the leading edge (LE) and the trailing edge (TE). Different mathematical representations are applied in order to improve the geometry of the LE and TE regions of the offset aerofoils and attain good aerodynamic performance.

This work is thereby divided into two parts. Firstly, two new aerofoils are mathematically created based on the modification of a given aerofoil selected for a specific application, with inward and outward offsets, where the size of the offset is usually selected based on structural considerations; and simultaneously, the LE and TE geometries are adjusted with some specified methods inserted in the main mathematical implementation. Secondly, a comparison of the aerodynamic performance of those two modified aerofoils relative to their respective initial aerofoil is performed. The algorithm to create the offset aerofoils is implemented in a computer code. The following information is required to build the offset aerofoils:

- Original aerofoil data points;
- Aerofoil’s chord length;
- Offset value;
- TE thickness; and,
- The desired point for the aerofoil’s LE (only applicable for the inward offset).

The output results are the inward and outward offsets of the original aerofoil, using different degree polynomial interpolation for expanding the outward offset aerofoil’s TE and different types of curves for rebuilding the inward offset aerofoil’s LE as described next.
3 Methodology

In the remaining of the document, all positions are relative to the chord length of the aerofoil unless otherwise specified.

3.1 Offset creation

In order to obtain the desired offset aerofoils, it is necessary to have the original aerofoil’s data points. Each of the inward or outward offset aerofoil points are created using a normal vector, that has a predefined length (the offset length) chosen by the user, which is perpendicular to the original aerofoil’s surface at any given point.

Each normal vector that gives the position of the respective offset point is defined by inverting the slope of the respective vector tangent to the original aerofoil (computed by central finite differences in the present case). This operation gives the slope of the normal vector. Knowing the position of each point of the original aerofoil, the slope of the normal vector and the desired offset length (negative for the inward offset and positive for the outward offset), the offset aerofoil points’ position can then be obtained from trigonometry.

3.2 Outward offset and trailing edge extension

In the case of the outward offset aerofoil, the critical situation lies in the creation of a TE. The TE of the outward offset aerofoil has to be extended so that the desired TE thickness is respected and the aerofoil’s surface is closed. Polynomial functions are used for this purpose, using interpolated points at the TE of the outward offset modified aerofoil. In small sized aerfoils it is often convenient to have a non-zero thickness TE to facilitate manufacturing and avoid damage during normal handling of the wings. This thickness is defined by the designer as a percentage of the chord according to specific requirements.

The original aerofoil is converted to unit chord if required and thus the offset value must be divided by the chord length before the desired offset geometry is calculated. The TE is created with different degree polynomials using the last points of the upper and lower surfaces of the aerofoil (starting from around 95% to 100% of the offset aerofoil’s chord). The polynomial interpolations can be of different degree (typically, first, second and third degree).

3.3 Inward offset and leading edge correction

As illustrated in Figure 2, the inward offset of an aerofoil creates a sharp LE due to the intersection of the normal offset of the upper and lower surfaces of the aerofoil. This critical situation imposes the creation of a new smooth LE. As mentioned previously, a distance from the original aerofoil LE must be provided indicating the new offset aerofoil LE position. Four different curves are used to create the desired smooth LE, such as a circular function, an elliptic function, a third degree polynomial and a fourth degree polynomial. All four methodologies are briefly described below.

The elliptic LE methodology consists of using two ellipse functions, one for the upper surface and another for the lower surface of the aerofoil, which must be tangent to the offset modified aerofoil and pass through the specified common new LE point. An example of this method is illustrated in Figure 3.

With this ellipse definition, three boundary conditions can be imposed, i.e., each ellipse function should: pass through a new LE point of the offset modified aerofoil defined by the user; be tangent to the offset modified aerofoil; and, be perpendicular to the horizontal axis at the same new LE point.
The height (semi-minor axis) of the ellipse, respectively.

\[ x = x_{LE} + a \left( 1 + \sqrt{1 - \left( \frac{z - z_0}{b} \right)^2} \right) \]  

In order to guarantee tangency of the new LE curve with the aerofoil’s surface, the derivative of Equation (2) with respect to \( z \) is required as follows

\[ \frac{dx}{dz} = -\frac{a (z - z_0)}{b \sqrt{b^2 - (z - z_0)^2}} \]  

Solving Equations (2) and (3) simultaneously with boundary conditions specified at a given point on the surface of the original aerofoil (\( x \) and \( z \) in the former and \( dx/dz \) and \( z \) in the latter), the only unknown variables, \( a \) and \( b \), can be computed. This is performed in turn for the upper and lower ellipses. In order to define the upper ellipse, a point on the upper surface of the aerofoil is selected and the boundary conditions \( x = x_U \) at \( z = z_U \) and \( (dx/dz)_U \) at \( z = z_U \) are applied. The lower ellipse is obtained by selecting a point on the lower surface and applying the boundary conditions \( x = x_L \) at \( z = z_L \) and \( (dx/dz)_L \) at \( z = z_L \). The functions \( z = z(x) \) or \( x = x(z) \) of both upper and lower surfaces are either known or interpolated from data points from the aerofoil geometry. The parameters \( a \) and \( b \) of the ellipses are obtained by iteratively changing \( x_{LE} \) and \( x_U \) (or \( x_L \)) to solve the system of equations in order to produce a few leading edge geometries which are then aerodynamically analysed. The best aerodynamic results, obtained from the different leading edges, reveal the best leading edge geometry, i.e. the best combination of \( x_{LE} \), \( a \) and \( b \) for the given modified aerofoil. Consequently, both elliptic functions defining the new LE can be created using Equation (2) for each modified aerofoil.

In the circular LE, only one circle is used. This circle must also pass through the leading edge point \( x_{LE} \) and be simultaneously tangent to the upper surface and the lower surface at the points \((x_U, z_U)\) and \((x_L, z_L)\), respectively. The centre of the circle is again at \( x_0 = x_{LE} + r \) and \( z_0 \). Equation (2) and Equation (3) are modified to have both semi-axes equal, \( a = b \), i.e. \( a = b \), to became the circle radius, \( r \). Thus, the circle curve is given by

\[ x = x_{LE} + r + \sqrt{r^2 - (z - z_0)^2} \]  

and its first derivative is obtained from

\[ \frac{dx}{dz} = \frac{(z - z_0)}{\sqrt{r^2 - (z - z_0)^2}} \]
Since the functions of the aerofoil’s upper and lower surfaces are not explicitly known, values for \( x_U \) (or \( z_U \)) and \( x_L \) (or \( z_L \)) are iteratively varied until all boundary conditions are fulfilled.

A different approach is used to build the polynomial LE curves. In this case the LE is given directly by the polynomial equation without the need for iteration. Initially, the aerofoil axes are rotated 90 degrees anti-clockwise and the general equation of the polynomial is written as

\[
x = \sum_{i=0}^{n} h_i z^i
\]

and its first derivative is given by

\[
\frac{dx}{dz} = \sum_{i=0}^{n} i h_i z^{i-1}
\]

where \( h_i \) is the \( i \)th coefficient of the polynomial of degree \( n \). In third degree polynomial LE case, the origin of both upper and lower surface polynomials is placed at \((x_U, z_L)\), zero slope is enforced at this origin and they are forced to pass at two other points selected on the aerofoil surface \( x_U \) (or \( z_U \)) and \( x_U + dx \) (or \( x_L + dx \)), where \( dx \) is a small increment in \( x \) selected by the user. For the upper surface, coefficients \( h_i, i = 0, 3 \), are calculated solving Equation (6) with \((z = z_0, z = x_L)\), \((z = z_U, x = x_U)\) and \((z = z_U + dx, x = x_U + dx)\) and Equation (7) with \((z = z_0, dx/dz = 0)\) simultaneously. In the fourth degree polynomial case, tangency is enforced at the point \( x_U \) (or \( x_L \)) and the point and \( x_U + dx \) (or \( x_L + dx \)) is not used. The coefficients \( h_i, i = 0, 4 \) and \( i \neq 3 \), are thus calculated.

The new leading edge point \( x_{LE} \) should be selected such that the gap between the original aerofoil and the inward offset aerofoil is not excessively large.

### 3.4 Aerodynamic analysis

The 2-dimensional (2D) aerodynamic coefficients as functions of the angle of attack, \( \alpha \), and Reynolds number, \( Re \), were obtained using XFOIL [13]. XFOIL is a panel method in which the steady Euler equations in integral form are used to represent the incompressible flow, and a compressible lag-dissipation integral method is used to represent the boundary layers and wake. The entire viscous solution (boundary layers and wake) is strongly interacted with the incompressible potential flow via the surface transpiration model, which permits proper calculation of limited separation regions. Data for the aerofoils lift coefficient, \( C_l \), curves, aerofoils parasite drag coefficient, \( C_d \), curves, including the non-linear regime, were obtained from this aerofoil aerodynamic analysis program. The aerofoils’ lift-to-drag ratio curves as functions of \( C_l \) were also obtained. XFOIL has been shown to adequately predict the shape of the aerodynamic curves \( C_l \times \alpha \) and \( C_d \times C_l \) at low \( Re \) and also their trends with varying \( Re \) for a variety of aerofoil geometries [14,15].

### 4 Case Studies and Results

In the study of a new high performing two-panel telescopic wing, three aerofoils are initially considered as suitable candidates: modified MH115, modified SG6042 and UBI-O3-012. These aerofoils are medium camber, low speed aerofoils with a good compromise between maximum lift coefficient, \( C_{l_{max}} \), maximum lift-to-drag ratio, \( (L/D)_{max} \), and low drag coefficient, \( C_d \), in the speed range from about 13 m/s to 30 m/s. The maximum thickness ratio, \( (t/c)_{max} \), of the modified MH115 is 11.3% whilst that of the other two aerofoils is 10%. Moreover, the concept applied to this study was based on the characteristics and flight conditions of a wing with a 280 mm mean chord and a 3 mm offset for the inward and outward modified aerofoils and a flow condition corresponding to a constant \( Re.C_{l_{max}}^{1/2} = 325,000 \).

The modified MH115 and modified SG6042 aerofoils are MH115 and SG6042 aerofoils, respectively, with their TE cut-off so that their thicknesses are 1 mm with the chord length of 280 mm mentioned above and are referred to as MH115-M and SG6042-M hereinafter.

Three further aerofoils are selected to complete the study and to provide a better understanding of the effect that the offset produces on the aerodynamic performance of the aerofoils. These three aerofoils are significantly different from the three mentioned above: one is a highly cambered aerofoil, the S1223, and the other two have very low camber values, the SD2030 and SD7090. The same TE thickness is applied to produce the modified aerofoils S1223-M, SD2030-M and SD7090-M. The maximum thickness ratio, \( (t/c)_{max} \), of the S1223-M aerofoil is 12.3%, that of the SD2030-M is 8.8% and the SD7090-M aerofoil has a thickness ratio of 10.2%.

The S1223-M aerofoil is a high lift aerofoil with the highest camber (8.27%) from the aerofoils studied, with a \( C_{l_{max}} \) greater than 2.3 and a \( (L/D)_{max} \) of 82 for a \( C_l \) of around 1.56. The MH115-M aerofoil exhibits the second highest camber, a \( C_{l_{max}} \) greater than 1.6 and has a \( (L/D)_{max} \) of 107 for a \( C_l \) of around 1.17. The SG6042-M aerofoil exhibits a \( C_{l_{max}} \) just over 1.5 and has a \( (L/D)_{max} \) of 108 for a \( C_l \) of around 0.93. The UBI-O3-012 aerofoil was devel-
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opened in house through an optimization procedure applied to the SG6042 aerofoil to increase its $C_{l_{\text{max}}}$ and reduce its drag coefficient, $C_d$, over a wider range of $C_l$ values. This aerofoil exhibits a $C_{l_{\text{max}}}$ just under 1.6 and has its $(L/D)_{\text{max}}$ of 111 for a $C_l$ of around 0.92. The SD2030-M aerofoil exhibits a $C_{l_{\text{max}}}$ just over 1.2 and has a $(L/D)_{\text{max}}$ of 94 for a $C_l$ of around 0.67. The SD7090-M aerofoil exhibits the lowest camber (1.79%), a $C_{l_{\text{max}}}$ of about 1.35 and has its $(L/D)_{\text{max}}$ of 76 for a $C_l$ of around 0.77.

### 4.1 Effect of trailing edge extension

The aerodynamic effect of the trailing edge extension formulation is studied using the outward offset aerofoil obtained from the MH115-M. In terms of geometry impact, of the three types of TE extension implemented, the third degree polynomial is the one that increases the aerofoil's camber the most whilst the linear extension is the one with the smallest effect closely followed by the second degree polynomial extension.

Those shape changes have an impact on the aerodynamic performance of the outward offset aerofoil as shown in Figure 4. These data were obtained for a flow condition corresponding to a constant $Re.C_{l_{1/2}}^1 = 325,000$. Maximum lift coefficient, $C_{l_{\text{max}}}$ = 1.71 and maximum lift-to-drag ratio, $(L/D)_{\text{max}} = 104.9$, of the linear extension aerofoil are lower than the values observed for the other two TE extensions. Better overall performance is obtained with the second degree polynomial extension though marginally better than the third degree polynomial extension, both for $C_{l_{\text{max}}}$ and $(L/D)_{\text{max}}$, with values of 1.79 and 108.5, respectively.

### 4.2 Effect of leading edge correction

The inward offset aerofoil obtained from the MH115-M aerofoil is also used to analyse the effect of different LE corrections on the aerofoil’s aerodynamic performance. Four mathematical formulations were used to perform the LE correction as described above: circular, elliptic, third degree polynomial and fourth degree polynomial. Each of these formulations was applied to the inward offset aerofoil using four different values of leading edge longitudinal position to chord ratio ($x_{\text{LE}}$). Figure 5 summarizes the main aerodynamic results.

These results show that, for all LE corrections in general, the increase in leading edge $x$-position will increase $C_{l_{\text{max}}}$ but will reduce $(L/D)_{\text{max}}$. Both $C_{l_{\text{max}}}$ and $(L/D)_{\text{max}}$ are essentially the same for $x_{\text{LE}} = 0.002$ maybe because the LE curvature is high in this region resulting in very small LE radii in all four cases. The circular LE correction produces somewhat smaller $(L/D)_{\text{max}}$ in all other values of $x_{\text{LE}}$ but, in the middle range of $x_{\text{LE}}$, it produces the highest values of $C_{l_{\text{max}}}$. However, unlike the other LE formulations, the circular LE correction produces an abrupt stall behaviour which is undesirable for the outboard part of any wing. The other three formulations present very similar performance regarding $(L/D)_{\text{max}}$ being the elliptic LE correction slightly better for $x_{\text{LE}} = 0.014$. Higher $C_{l_{\text{max}}}$ is achieved with the fourth degree polynomial LE.
Aerodynamic performance of offset aerofoils

Figure 5: Effect of leading edge correction and leading edge position on maximum lift coefficient and maximum lift-to-drag ratio of the inward offset obtained from the MH115-M aerofoil.

4.3 Aerofoil shape effect

The methodology described previously is applied, entering the original, non-modified, aerofoil coordinates and input data defined by the user. Novel aerofoils are created with the outward and inward offsets and the most adequate LE and TE representations. Based on the LE correction and TE extension studies, the 4th degree polynomial LE for the inward offset aerofoils and the second degree polynomial TE for the outward offsets produce the best aerodynamic performance. Furthermore, a leading edge position of 0.006 is used.

Figure 6 and Figure 7 show the aerofoil geometries ordered by decreasing camber value. Using the original aerofoil with unit chord (represented in black), the inward offset aerofoil was obtained (represented in green) together with the outward offset aerofoil (represented in red). In Figure 6 the aerofoils are represented to scale relative to the original aerofoil whilst in Figure 7 they are all illustrated with unit chord for better geometry comparison.

For all six original aerofoils, the offsets present identical trends. The inward offset produces an aerofoil with reduced maximum camber and reduced maximum thickness ratio, whose positions move aft in the former and move forward in the latter, and with increased incidence. One exception from the aerofoils analysed is the S1223-M which, due to the large reduction of the inward offset’s chord, has a higher thickness ratio than the original aerofoil. On the other hand, the outward offset produces an aerofoil with increased maximum camber and increased maximum thickness ratio, whose positions move aft in the former and move forward in the latter, and with increased incidence. It is observed that aerofoils with higher camber at the TE produce outward offsets with larger increases in incidence, as for S1223-M and UBI-03-012, and produce inward offsets with larger reductions in incidence, as for S1223-M. Other important aspects of the aerofoil geometry are the TE thickness and TE angle. It is observed that, the smaller the original TE angle, the greater will the variation in chord of the offset aerofoils be, provided the curvature of the upper and lower surfaces at the TE are not highly different as is the case with the UBI-03-012 or the SD2030-M aerofoils. In the former aerofoil, the higher negative curvature of its TE’s upper surface produced a shorter TE extension but, in the latter aerofoil, the small curvature of its TE’s upper surface resulted in a longer TE extension.

Another characteristic of the S1223-M aerofoil worth mentioning is its thin TE which extends forward over a significant portion of its chord. This produces a very short inward offset aerofoil which, in general, may not be appropriate due to large chord discontinuities between adjacent wing panels. In general, and from a structural point of view, thicker aerofoils are preferred for the inboard panels due to the higher structural depth, and higher TE angles result in stiffer offset TE’s and smaller variations in chord lengths.

Those geometric modifications also have strong effects on the aerodynamic characteristics of the resulting aerofoils and must be investigated. Figure 8 and Figure 9 illustrate the main aerodynamic characteristics of the studied aerofoils at \( Re_{C_{l}^{1/2}} = 325,000 \). In Figure 8 the lift curves (\( C_{l} \times \alpha \) curves) and the drag polars (\( C_{l} \times C_{d} \) curves) are shown whilst in Figure 9 the lift-to-drag ratio curves (\( L/D \times C_{l} \) curves) are represented.

From the lift curves of Figure 8, it is observed that the outward offset aerofoil produces an increase in \( C_{l_{max}} \) and in the lift coefficient at zero-angle of attack, \( C_{l_{0}} \). Its drag polar is moved to larger \( C_{l} \) values, resulting that \( (L/D)_{max} \) occurs at a higher \( C_{l} \) value, and the minimum \( C_{d} \) value is slightly increased. Not shown, but also an important result, the pitching moment coefficient becomes more intense in the outward offset aerofoil. The opposite is true for the inward offset aerofoil. These results were expected since the outward offset aerofoils’ mean camber and incidence were positively incrementated and the inward offset aerofoils’ mean camber and incidence were decremented. Larger variations on the lift and drag curves occur for larger geometric changes as is the case of the S1223-M aerofoil. Conversely, smaller variations on the lift and drag curves are observed for smaller changes in the aerofoil shape as for the SD7090-M aerofoil.
Figure 6: Original aerofoils and aerofoils obtained by inward and outward offsets shown to scale.
Figure 7: Original aerofoils and aerofoils obtained by inward and outward offsets with the aerofoils scaled to unit chord.
Figure 8: Lift curves and drag polars obtained for the original aerofoils and the aerofoils obtained by inward and outward offsets at $\text{Re} \cdot C_l^{1/2} = 325,000$. The angle of attack is in degrees.
Figure 9: Lift-to-drag ratio curves obtained for the original aerofoils and the aerofoils obtained by inward and outward offsets at $Re.C_{1/2}^1 = 325,000$. 

(a) S1223-M. (b) MH115-M. (c) SG6042-M. (d) UBI-O3-012. (e) SD2030-M. (f) SD7090-M.
It is interesting to point out that \((L/D)_{max}\) increases with the outward offset and decreases with the inward offset for the MH115-M, SG6042-M and SD2030-M aerofoils. The opposite effect is seen on the S1223-M and SD7090-M aerofoils, where \((L/D)_{max}\) decreases with the outward offset and increases with the inward offset. In particular, the lift coefficient for best \(L/D\) of the outward offset of the S1223-M aerofoil is very different from the original aerofoil which may reduce the interest in selecting this option. The same is not seen with the UBI-O3-012 aerofoil, where the larger \((L/D)_{max}\) occurs for the original aerofoil and not for the outward offset aerofoil, but its lowest value is still exhibited by the inward offset aerofoil. The reduced \((L/D)_{max}\) in the outward UBI-O3-012 offset aerofoil may be explained by the narrower laminar flow region observed in the drag polar curve, indicating that the laminar boundary layer in this case cannot extend so further aft at higher \(C_l\) values as with the other two aerofoils. Stall characteristics do not seem to be affected since the shape of the lift curves in the stall region do not present any significant differences among them.

5 Conclusions

A methodology for developing offset aerofoils given any existing aerofoil, including corrections for the leading edge and trailing edge geometries of the resulting aerofoils, was presented. The analysis of the offset aerofoils obtained from six initial known aerofoils enabled a better understanding of the geometric changes suffered by the offset aerofoils and the effect on their aerodynamic characteristics.

From the six aerofoils studied, the following trends could be observed. In terms of the geometric characteristics:

- The inward offset aerofoils have: reduced maximum camber at a further fore chord position; reduced \((t/c)_{max}\) at a further aft chord position; decreased incidence;
- The outward offset aerofoils have: increased maximum camber at a further aft chord position; increased \((t/c)_{max}\) at a further fore chord position; increased incidence.
- The smaller the trailing edge angle of the original aerofoil, the shorter and the longer will the inward and the outward aerofoils be, respectively.

The above geometric characteristics produce the following aerodynamic properties trends:

- The inward offset aerofoils have: reduced \(C_{l_{max}}\); reduced \(C_D\); reduced \(C_l\) for \((L/D)_{max}\); less intense pitching moment coefficient; reduced minimum \(C_d\) and corresponding \(C_l\);
- The outward offset aerofoils have: increased \(C_{l_{max}}\); increased \(C_D\); increased \(C_l\) for \((L/D)_{max}\); more intense pitching moment coefficient; increased minimum \(C_d\) and corresponding \(C_l\).
- The effect of the inward or outward offsets on \((L/D)_{max}\) does not present a consistent trend: \((L/D)_{max}\) depends greatly on the capability of the laminar boundary to still extend over a long distance on the upper surface and this is greatly affected by aerofoil LE and TE curvatures and also by thickness and camber distributions.

The present study gives important guidelines on the geometry and performance trends expected from the development of offset aerofoil designs intended to be applied to telescopic wings. Specific design situations must be analysed to select and/or develop an adequate set of aerofoils.

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Nomenclature

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<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>(a)</td>
<td>ellipse’s semi-major axis</td>
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<tr>
<td>(b)</td>
<td>ellipse’s semi-minor axis</td>
</tr>
<tr>
<td>(C_d)</td>
<td>drag coefficient</td>
</tr>
<tr>
<td>(C_l)</td>
<td>lift coefficient</td>
</tr>
<tr>
<td>(C_{l_{0}})</td>
<td>lift coefficient at zero-angle of attack</td>
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<tr>
<td>(C_{l_{max}})</td>
<td>maximum lift coefficient</td>
</tr>
<tr>
<td>(h_{11})</td>
<td>(n)th polynomial coefficient</td>
</tr>
<tr>
<td>IFW</td>
<td>inboard fixed wing</td>
</tr>
<tr>
<td>(L/D)</td>
<td>lift-to-drag ratio</td>
</tr>
<tr>
<td>((L/D)_{max})</td>
<td>maximum lift-to-drag ratio</td>
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<tr>
<td>LE</td>
<td>leading edge</td>
</tr>
<tr>
<td>(n)</td>
<td>degree of polynomial</td>
</tr>
<tr>
<td>OMW</td>
<td>outboard moving wing</td>
</tr>
<tr>
<td>(r)</td>
<td>circle radius</td>
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<tr>
<td>(Re)</td>
<td>Reynolds number</td>
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<tr>
<td>((t/c)_{max})</td>
<td>maximum thickness ratio</td>
</tr>
<tr>
<td>TE</td>
<td>trailing edge</td>
</tr>
<tr>
<td>VSW</td>
<td>variable-span wing</td>
</tr>
</tbody>
</table>
$x$  horizontal axis and coordinate

$x_0$  horizontal coordinate of the ellipse or circle centre point

$x_L$  horizontal coordinate of the lower surface tangent point

$x_{LE}$  horizontal distance from the leading edge of the original aerofoil to the leading edge of the modified aerofoil

$x_U$  horizontal coordinate of the upper surface tangent point

$z$  vertical axis and coordinate

$z_L$  vertical coordinate of the lower surface tangent point

$z_0$  vertical coordinate of the ellipse or circle centre point

$z_U$  vertical coordinate of the upper surface tangent point

$\alpha$  angle of attack

References


