Abstract

This paper presents aerodynamic studies of a blended wing body (BWB) configuration within an European project, MOB. Firstly, the effects of spanwise distribution on the BWB aircraft aerodynamic efficiency were studied through an inverse design approach, combining both a low fidelity panel method and a high fidelity RANS method. Secondly, the BWB aerofoil profiles were optimised for improved performance. Finally, three-dimensional optimisation of the BWB twist and camber distribution were carried out based on continuous and discrete adjoint approaches.

1. Introduction

For conventional large transport aircraft, a substantial knowledge base exists for best practice in the wing design for transonic performance. Recently non-conventional aircraft designs, such as the blended wing body (BWB) aircraft\(^1\), have been proposed based on earlier flying wing designs for revolutionary improvement for future air transportation. Conceptually, the main aerodynamic advantages of the new BWB design are its lower wetted area to volume ratio and lower interference drag as compared to the conventional aircraft. Indeed, an increase in (L/D)\(_{max}\) of about 20% over the conventional design has been estimated for the blended wing body. However these benefits can only be realised as improved aerodynamic performance through careful and detailed aerodynamic shape design. Unfortunately, little is known regarding the best aerodynamic shape for BWB due to a large number of extra design variables and stronger coupling with the other disciplines such as structures and flight dynamics.

On the aerodynamic performance side, as pointed by Green\(^4\), the maximum lift-to-drag ratio (L/D)\(_{max}\) depends on the ratio of the aircraft span to the square root of the product of the induced drag factor and the zero-lift drag area, which is proportional to the wetted area of the aircraft. From this relation, one can see that larger span, smaller wetted area, lower skin friction (e.g. laminar flow technology), or less induced drag can all provide potentially substantial improvement in aerodynamic performance. In some of the recent BWB designs, e.g. Ref.3, a larger span was incorporated with an increase from the conventional 70-80m to 100m for the BWB. On the other hand, consideration of the current airport capability motivated other designers to limit the span to a slightly larger one (~85m) as in Ref.1 or within an 80m box as in Ref.2.

Although this paper concerns primarily the aerodynamic aspect, its interaction with structure through bending moment and flight dynamics through trim is also discussed. The aerodynamic studies and tools have been implemented in a multidisciplinary Computational Design Engine as described in Refs. 5 and 6.

2. Baseline BWB Model and Its Aerodynamics

Geometry and flow conditions

The baseline BWB geometry is defined in Ref.7 for the EU MOB project, which is based on a previous BWB design by a group of staff and MSc students headed by Dr Smith at Cranfield College of Aeronautics, Ref.2. The half geometry is composed of the central body, an inner wing and an outer wing to which a winglet is attached. They are “blended” to form the BWB geometry. The total span including the winglet is just under 80m. For the present study, the propulsion system and its integration with the BWB design is not included.

The design conditions considered correspond to the first segment of cruise as specified in Table 10 of Ref.5. Hence, to balance the weight, the design C\(_L\) is 0.41 based on the trapezoidal reference area of 842m\(^2\). All the aerodynamic coefficients presented in this report are based on this trapezoidal reference area. Unless otherwise stated, the cruise flow conditions are:

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\(^1\) Cranfield University UK, \(^2\) NLR Netherland, \(^3\) QinetiQ UK, \(^4\) SAAB Aerospace, Sweden
The baseline geometry has been studied using a high fidelity implicit multi-block Reynolds-averaged Navier-Stokes solver, MERLIN, developed at Cranfield in the Centre for Computational Aerodynamics and the NLR ENFLOW system, which supports aeroelastic deformation and can incorporate pitching moment trim$^6$. The BWB geometries were read in from the output of the ICAD model generator$^8$ to the grid generators. Structured multiblock grids were generated around the BWB geometry including the winglet.

**Grid Sensitivity**

To gain some insight into how much grid stretching was needed near the aircraft surface to obtain a good prediction of the aerodynamic coefficients, a grid sensitivity analysis was carried out in the direction $j$ normal to the surface. 5 different grids were created and a CFD analysis was performed on each of them to obtain the aerodynamic coefficients. The first 4 grids have the same number of points in the $j$ direction i.e. 60 but a different stretching which leads to a range of $y^+$ from 40 to 1 on the aircraft surface. The number of points for the fifth grid was doubled in the $j$ direction, resulting in a total grid number of one million, much more costly to run.

From the RANS simulations, the total drag comes from the integration of the pressure and the shear stress around the whole geometry surface. The former acts normal to the surface while the latter is a vector tangential to the surface. It is therefore obvious that the pressure drag defined above should include the induced drag (also known as vortex drag) due to lift generation, the wave drag due to shock generation, and the drag due to boundary layer displacement.

The results obtained with the different grids are shown in Table 1. Most noticeable is the severe under-prediction of the skin friction drag for grids without enough resolution in the boundary layer (with first cell distance $y_{max}^+=40$ or 13). The skin friction converges for $y_{max}^+=5$ as the grid is further clustered towards the surface. On the other hand, for a given number of grid in the wall normal direction, stronger clustering in the boundary layer implies less grid away from the near wall region. To investigate this effect, a finer grid solution is obtained, for which the resolution in the normal direction outside the boundary layer is doubled, while the first cell distance is kept to $y_{max}^+=1$. It is interesting to note that the skin friction becomes less sensitive to grid density for the three cases for $y_{max}^+=5$.

**Assessment of aerodynamic performance**

A series of computations at different incidences for M=0.85 were carried out in order to form a polar for the baseline BWB configuration, as shown in Fig.1. The different flow conditions and the corresponding aerodynamic coefficients are presented in Table 2. Computation at M=0.92 is also shown. The case at M=0.92 was carried out in order to investigate the behaviour of the aircraft at a speed nearer to the sonic speed outside the design conditions for certification requirement.

**Table 1. Grid sensitivity analysis M=0.85, $\alpha=3^\circ$**

<table>
<thead>
<tr>
<th>$J_{max}$</th>
<th>$y_{max}^+$</th>
<th>$C_L$</th>
<th>$C_D_{total}$</th>
<th>$C_D_{pressure}$</th>
<th>$C_D_{friction}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>40</td>
<td>0.336</td>
<td>0.0247</td>
<td>0.0244</td>
<td>0.00037</td>
</tr>
<tr>
<td>60</td>
<td>13</td>
<td>0.409</td>
<td>0.0285</td>
<td>0.0249</td>
<td>0.000365</td>
</tr>
<tr>
<td>60</td>
<td>5</td>
<td>0.414</td>
<td>0.0327</td>
<td>0.0250</td>
<td>0.000764</td>
</tr>
<tr>
<td>60</td>
<td>1</td>
<td>0.416</td>
<td>0.0330</td>
<td>0.0254</td>
<td>0.000763</td>
</tr>
<tr>
<td>120</td>
<td>1</td>
<td>0.421</td>
<td>0.0318</td>
<td>0.0241</td>
<td>0.000767</td>
</tr>
</tbody>
</table>

From the results, one can note that the design lift at M=0.85 is obtained at an incidence of 3 degrees. The total drag is composed of 77% pressure drag and 23% skin friction drag. The rate of lift increase reduces with the incidence while the rate of pressure drag increase goes up. These opposite trends result in a peak lift drag ratio at the design condition for the baseline BWB geometry at an unsatisfactorily low value.

**Table 2. Lift and drag coefficients for baseline BWB**

<table>
<thead>
<tr>
<th>M</th>
<th>$\alpha$</th>
<th>$C_L$</th>
<th>$C_D_{total}$</th>
<th>$C_D_{pressure}$</th>
<th>$C_D_{friction}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.85</td>
<td>0</td>
<td>-0.0144</td>
<td>0.01730</td>
<td>0.00937</td>
<td>0.007924</td>
</tr>
<tr>
<td>0.85</td>
<td>1.75</td>
<td>0.2305</td>
<td>0.02111</td>
<td>0.01326</td>
<td>0.007848</td>
</tr>
<tr>
<td>0.85</td>
<td>3</td>
<td>0.4136</td>
<td>0.03268</td>
<td>0.02504</td>
<td>0.007637</td>
</tr>
<tr>
<td>0.85</td>
<td>4</td>
<td>0.5229</td>
<td>0.04790</td>
<td>0.04045</td>
<td>0.007445</td>
</tr>
<tr>
<td>0.85</td>
<td>5</td>
<td>0.5690</td>
<td>0.06214</td>
<td>0.05483</td>
<td>0.007297</td>
</tr>
<tr>
<td>0.92</td>
<td>3</td>
<td>0.3761</td>
<td>0.06230</td>
<td>0.05483</td>
<td>0.007473</td>
</tr>
</tbody>
</table>

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Distributions of the spanwise local lift coefficient and spanwise loading for the various incidences are plotted in Figs. 2 & 3. Note that the winglet load is not shown in the plots and the 100% span corresponds to the junction between the outer wing and the winglet.

The distributions show that the outer wing is very highly loaded, where the chord is much shorter than the inner wing and the central body. At the design condition, i.e. the 3° case, the local lift for the baseline geometry peaks at about 80% of the span. On the other hand, the local lift for the central body is comparatively much lower than that on the outer wing.

The high demand on lift from the outer wing results in shock formation on the upper surface of the outer wing, which starts to appear at $\alpha=1.75^\circ$. This shock gets stronger as the incidence increases. At incidences higher than 3°, the outer wing can no longer sustain the high lift and the lift on this portion of the wing stalls, as shown in Figs. 2 & 3, due to shock induced flow separation revealed from the flow field solutions at $\alpha=4^\circ$ and $5^\circ$.

Fig. 4 shows the pressure contours on the upper surface of the baseline BWB at the design cruise condition (M=0.85, $\alpha=3^\circ$, $C_L=0.41$). Also shown are the pressure contours on both sides of the winglet.

A strong shock wave can be seen, extending from the junction of the central body and the inner wing to the outer wing tip. Although the central body has the greatest thickness, no significant shock can be observed on this part of the BWB due to the spanwise lift distribution (relatively low local lift) and the three dimensional effects of high leading edge sweep. A trace of a $\lambda$-shock is visible on the inner wing. The outer wing experiences the strongest shock due to the high local lift demand.

The shock wave extends to the inner side of the winglet and a relatively weaker shock also forms on the outer side of the winglet. Further flow separation is observed on the inner side of the winglet surface.

For the higher speed case at M=0.92 the lift stalls due to shock induced separation at $\alpha=3^\circ$ as shown.
in Table 2. At this Mach number, which could be encountered during manoeuvres, the shock wave is very strong and sits very close to the trailing edge on the outer wing in a region where control devices are supposed to be situated.

From the above assessment of the aerodynamic behaviour of the baseline geometry, it is revealed that the strong shock wave on the outer wing and the associated wave drag are crucial problems prohibiting high aerodynamic performance. In addition, from a structural point of view, the high outer wing loading also results in a high bending moment, which requires stronger and heavier structures. It is therefore desirable to shift the aerodynamic loading inboard for the baseline BWB in order to improve its aerodynamic performance.

3. Twist Inverse Design

This section addresses the effects of the spanwise lift distribution on aerodynamic performance for a fixed BWB planform and a given thickness distribution. Although the interaction of the lift distribution with the wing bending moment and trim will also be discussed, the discussion do not intend to cover the full multidisciplinary optimisation issues (see Refs. 5 & 6).

The baseline BWB spanwise lift (load) design adopted a near elliptic distribution for a large part of the wing through twist variation, with the centre part of the BWB (“body”) lightly loaded. This is typical of a lift distribution for a conventional aircraft with a wing/fuselage configuration. For such a design, a strong shock wave is present on the outer wing due to the high local lift at the design cruise condition at M=0.85, which results in a high wave drag and unsatisfactory aerodynamic performance.

To alleviate the high wave drag at the cruise condition, redistribution of the spanwise lift was studied through a twist redesign for the given planform and thickness distribution. A combination of low and high fidelity aerodynamic models was used for the study due to the efficiency of the low fidelity model. In order to shift the wing loading away from the outer wing, the distribution would have to be moved away from an elliptic distribution on the wing along. The low order aerodynamic model based on a panel method was used for the inverse design of the spanwise loading, shifting it from an elliptic distribution for the integrated BWB to a triangular distribution.

The redesigned twist distributions were then studied with a RANS solver (a Cranfield multi-block code MERLIN) to investigate the wave drag reduction due to the new designs. The spanwise loading from the high fidelity model proves the desirable shift of aerodynamic loading inboard. The wave drag components were extracted from the RANS solutions and a substantial reduction of the wave drag is observed through the twist redesign at the cruise condition.

A discussion of spanwise lift distribution

From the lifting line theory, an elliptic lift distribution was proved to produce minimum induced drag for a given lift and an aspect ratio. For a conventional aircraft, an elliptic lift distribution is normally targeted to minimise the induced drag produced by the wing. However, if the whole aircraft is treated as an integrated system, such an elliptic spanwise load distribution on the wing is no longer the optimum for minimum induced drag.

The spanwise load distribution is complicated by a number of factors as presented recently by Jupp of Airbus at the Royal Aeronautical Society in Ref.9. The effects of the winglet and the tailplane were discussed, linking the spanwise loading strongly with structural weight and aircraft balancing in addition to wing aerodynamics.

For a blended wing body, it is essential to treat the whole aircraft as an integrated system. Unlike the conventional aircraft, the spanwise distribution of a BWB includes the central body and the wing as a whole. For a conventional aircraft, the body does not contribute significantly to the lift generation. However, for a well designed BWB, the central body should be an intrinsic lift generating surface.

What is the best spanwise lift distribution for a BWB? Obviously there is no simple answer to this question. A practical solution will have to require multi-disciplinary teams to work together in an interactive way. The MOB team is working towards the development of such a computational design for the optimal BWB design.

Target spanwise loading distributions

From the aerodynamic assessment of the baseline BWB, it is desirable to shift the span load inboard in order to off-load the outer wing to reduce the shock strength and the wave drag. Such a move should also benefit from a reduced bending moment. For the current planform geometry, this also implies a
movement of the aerodynamic centre forward. According to the centre of gravity of the present design, this movement will result in a reduced trim, as shown in the results later.

Three lift distributions are imposed on the BWB apart from the winglet as target lift distributions at cruise condition. They are (1) an elliptic distribution, (2) an average of elliptic and triangular distributions and (3) a triangular distribution, as shown in Fig.5.

![Figure 5. Target lift distributions](image)

![Figure 6. Target aerodynamic loading](image)

![Figure 7. Spanwise twist distributions for the baseline and inverse designs](image)

The related targets in terms of section lift coefficient are shown in Fig.6. As expected, there is a substantial difference in the outer wing loading for the current BWB planform with the elliptic and the triangular loading at the two extremes.

**Inverse twist design for specified span loading**

From the baseline planform geometry without the winglet, a configuration without twist was initially derived. Panel method calculations for this untwisted geometry was then carried out at a series of different incidences. The local sections were then twisted to meet the specified local lift coefficient from the above calculations. The twist angles were derived at all the design sections and as a result a new span twist distribution is obtained. Since the geometry is a full three dimensional geometry, the geometry with the new twist distribution does not necessarily satisfy the specified spanwise lift distribution when it is analysed by the panel method. The discrepancies were then used to derive a correction of the twist distribution. An iterative procedure was set up to refine the twist distribution until the specified spanwise loading distribution is satisfied by the panel solution for the given twist distribution.

Fig. 7 plots the twist distributions obtained from the above inverse design procedure in comparison with the baseline geometry twist. Conventionally, a positive sign has been assumed for a downward twist of the leading edge in relation to the untwisted geometry. Therefore, in the original geometry the central body and part of the inner wing (0<y<0.45) are twisted downward in respect to the first segment (0.4<y<0.8) of the outer wing, which is rotated down again at the tip region. Note that all the twist is about the leading edge point.

In relation to the central body, all the three new designs twist downwards with the maximum twist at the tip of the outer wing.

The induced drag coefficients calculated for the low speed condition are listed in Table 3. As expected, the elliptic distribution gives the lowest induced drag among the candidates for this condition.

<table>
<thead>
<tr>
<th></th>
<th>baseline</th>
<th>elliptic</th>
<th>average</th>
<th>triangular</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{D_i}$</td>
<td>0.00333</td>
<td>0.00268</td>
<td>0.00325</td>
<td>0.00470</td>
</tr>
</tbody>
</table>
RANS Analyses of the New Designs

The inversely designed new twist distributions are then implemented in the RANS surface grid models. Multi-block structured grids were generated for the new geometries. Through running MERLIN for the new geometries at a series of incidences, the design lift condition can be simulated for each of the new geometries.

The new spanwise loadings obtained with the RANS calculations at the design M=0.85 and C_L=0.41 are shown in Fig.8, followed by the spanwise distribution of the local lift coefficient in Fig.9, in comparison with the baseline geometry. It is important to note that the RANS computations include the winglet, which is indicated in the lift distributions towards the outer wing tip.

![Figure 8](image1.png)

**Figure 8.** Comparison of spanwise loading at design C_L for M=0.85

In comparison, the baseline twist distribution has the highest outer wing loading and the lowest central body loading. In some way, this reflects a lift distribution of a conventional aircraft, where the wing is designed with a near elliptic loading and the central cylindrical body does not carry much lift.

![Figure 9](image2.png)

**Figure 9.** Comparison of spanwise local lift distribution at design C_L for M=0.85.

Aerodynamic performance of the new twist designs

Table 4 shows the drag coefficients for the new twist designs in comparison with the baseline geometry at the design lift condition (C_L=0.41) and the cruise speed (M=0.85).

To gain insight into the wave drag component, a method from the ESDU data sheet\(^{10}\) has been used to extract the wave drag from the RANS flow field solutions for the four different geometries. To calculate the total wave drag of the BWB geometries and their spanwise distributions, the program works on a series of wing sections along the span. For each wing section, it needs as input the geometry of the section to be able to calculate the curvature of the surface at the foot of the shock wave, the pressure coefficient just ahead of the shock, the chordwise location of the shock and the leading and trailing edge sweep angles. As output the method gives the local wave drag coefficient for each wing section and integrates along the span to give the total wave drag. This method does not include the boundary layer effects on the local surface curvature but should give reasonable estimates of the wave drag for the geometries considered here. The wave drag coefficients are also listed in Table 4 and the spanwise wave drag distributions are plotted in Fig.10. A significant reduction of the wave drag can be seen on the outer wing by the new twist distributions. Note that, although all the other drag

<table>
<thead>
<tr>
<th></th>
<th>C_D, total</th>
<th>C_D, pressure</th>
<th>C_D, friction</th>
<th>C_D, wave</th>
<th>M_max</th>
</tr>
</thead>
<tbody>
<tr>
<td>baseline</td>
<td>0.0327</td>
<td>0.0250</td>
<td>0.00764</td>
<td>0.00407</td>
<td>1.42</td>
</tr>
<tr>
<td>elliptic</td>
<td>0.0284</td>
<td>0.0203</td>
<td>0.00806</td>
<td>0.00209</td>
<td>1.36</td>
</tr>
<tr>
<td>averaged</td>
<td>0.0278</td>
<td>0.0201</td>
<td>0.00774</td>
<td>0.00180</td>
<td>1.30</td>
</tr>
<tr>
<td>triangular</td>
<td>0.0287</td>
<td>0.0208</td>
<td>0.00783</td>
<td>0.00161</td>
<td>1.25</td>
</tr>
</tbody>
</table>
coefficients include the whole BWB geometry, the wave drag shown in Table 4 and Fig.10 does not include the wave drag from the winglet. For all the cases, 6 drag counts were calculated from the winglet shocks on both sides.

Figure 10. Spanwise local wave drag distribution at design Cl for M=0.85

Generally, all the three new twist distributions substantially reduce the pressure drag partially due to the wave drag reduction and partially due to the induced drag reduction. As expected, the variation of skin friction with the span loading change is relatively small.

The comparison shows that, among all the four designs, the averaged elliptic/triangular distribution has the minimum total drag and therefore the highest aerodynamic efficiency, as shown in Fig.11, the lift to drag ratio being increased by 16% as compared with the baseline geometry. The pressure drag reduction of 49 drag counts comes from reduction in both the wave drag (23 drag counts) and the induced drag, Fig.11 indicates that the BWB operates around the drag rise point at the design lift condition at Cl=0.41.

Ideally, the elliptic loading should give the minimum induced drag associated with lift generation if there is no transonic shock on the wing, as shown in the panel calculations. The wave drag counteracts this potential benefit. On the other hand, the triangular distribution has the least wave drag but the pressure drag is higher than those from the elliptic and the averaged distributions. This is believed to come from the induced drag penalty. Therefore, from an aerodynamic performance point of view, the best spanwise loading distribution should be a fine balance of the induced drag and the wave drag at transonic conditions.

Also listed in the table is the maximum Mach number just ahead of the shock wave on the BWB surface. It is directly related to the wave drag for the corresponding geometry. Note that for a well designed transonic wing, the maximum Mach number should normally be below 1.2, implying that there is still scope for further wave drag reduction by optimising the sectional aerofoil profiles.

Interaction with structure and trim

In Ref.11, Iglesias and Mason concluded from their study that the wing weight decreases nearly linearly with reduced wing root bending moment, while the associated induced drag increases in a parabolic fashion. It is therefore worthwhile to move away from the minimum induced drag span loading with a small drag increase (near the starting point of the parabolic curve) for a substantial reduction in bending moment (weight) for the best aircraft performance. Similar argument applies in the present situation. When the structure is coupled to the aerodynamics through the bending moment, the triangular distribution, which implies less bending moment, may well be a better choice for the BWB design rather than the averaged elliptic/triangular distribution. As compared with the baseline geometry, all the new designs benefit from the structural point of view with much reduced bending moments.

Fig.12 shows the pitching moments about the centre of gravity (29.3m from the nose tip) for the BWB designs. Without a tail plane, a BWB needs to be trimmed by trailing edge devices to balance the aircraft. An extra important gain from the averaged distribution is that it requires the minimum trim at the design lift condition, implying a small performance penalty due to trim (trim drag).
4. BWB Aerofoil Profile Optimisation

The BWB aerofoil profiles were optimised for further improvement of the transonic aerodynamic performance. The three dimensional geometry and flow conditions were projected into local two dimensional aerofoil optimisation problems. The optimised profiles were then implemented in the 3D geometry, which is checked with the 3D RANS analyses.

An aerofoil optimisation was carried out by QinetiQ using the BVGK flow solver, coupling a full potential solution with a boundary layer solution, within QinetiQ’s optimisation package, CODAS. A recursive quadratic programming, RQPMIN, optimiser was used.

The initial shape is deformed by the addition of a perturbation that is defined by the design variables. Deformations are limited to the normal direction. The perturbation is defined by a Bézier-Bernstein parameterisation. 16 parameters were used to describe the aerofoil and 1 for the incidence. The baseline volume per unit span is set as a lower constraint. For an efficient optimisation, a multi-level approach (coarse grid Euler and fine grid RANS) incorporating high fidelity correction in the low fidelity steps is used.

The local lift requirement was based on the twist study of the previous section. For the given lift, the drag is minimized with or without constraints on the pitching moment. The design variables are the 6 camber parameters and the incidence. The chordwise and spanwise thickness distributions remain fixed during the optimisation.

The pitch moment constraint is important for trim requirement. Otherwise excessive trim may be necessary, introducing large trim drag, as for the baseline geometry shown in Fig. 12.

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Fig. 15 compares the drag convergence for the standard optimisation and the multi-level optimisation. The latter shows a significant improvement in efficiency. Fig. 16 shows the profile comparison with the baseline. Again increased camber is observed. The two optimised profiles are slightly different, especially for the lower surface, although the drag reductions were very similar. Fig. 17 plots the surface pressure, the shock wave has been eliminated in the new designs, hence eliminating the associated wave drag.

With the implementation of the optimised aerofoil section profiles, a further 14% improvement of the L/D ratio was obtained for the BWB aircraft.

Finally, the BWB geometry was optimised at the cruise condition using the Euler equation and adjoint methods to generate the required sensitivity derivatives for the gradient based optimiser.

SAAB Aerospace has performed a 3D Euler aerodynamic shape optimisation study of the MOB geometry within the MOB project using an optimisation system CADSOS at SAAB\textsuperscript{1415}.

The twist and camber distributions of the baseline wing (with BWB central body part fixed) were chosen as the design variables. All calculations discussed below were done for a cruising free stream Mach number $M=0.85$ and a lift coefficient $C_L=0.3$. The free stream angle of attack was adjusted during the calculations so that the prescribed value on $C_L$ was kept. A typical optimisation run consisted of 10-15 design cycles, which could be performed over night.

A third order polynomial was applied to describe the twist and camber modifications of the wing. These functions were combined with four functions (polynomials) in the span direction in order to get a smooth modification along the wing. In total 12 design variables were used to control the wing shape. The calculations were done on a grid consisting of 295,000 cells. Constraints were introduced on both the lift and pitching moment. A drag reduction by 0.0022 or 19\% was obtained as can be seen in Fig. 18. The optimum was reached after 9 design cycles. No further improvement was obtained performing more design steps. The results clearly show that the constraints $C_L=0.3$ and $C_M=0.51$ are fulfilled. The angle of attack was increased by 0.5° from 2.0° to 2.5°. This corresponds to a moderate global twist modification of the whole configuration. The pressure distribution over the
original and optimised aircraft shows the improved load distribution in the wing tip area. The decreased suction at the tip results in a lower load that is also of advantage from structural point of view. The profile shapes of the original and the optimised geometry at two span stations are finally shown in Figs 19 and 20.

Figure 18. Drag convergence history for the 3D aerodynamic optimisation

Figure 19. Twist and camber of the original and optimised wing at 60% of the wing span

Figure 20. Twist and camber of the original and optimised wing at 80% of the wing span

6. Conclusions

The importance of span loading distribution for BWB performance has been highlighted from the results of the present research. At the design transonic cruise and lift (weight) condition for the present BWB, wave drag has been found to be a significant component of the total drag. Therefore the span loading distribution giving minimum induced drag does not necessarily produce minimum total aerodynamic drag for a specified lift.

Although the triangular distribution gives the most wave drag reduction, the averaged elliptic/triangular distribution gives the best aerodynamic performance measured by the L/D ratio or the total drag at the design cruise condition. This is believed to be due to the less induced drag for the averaged elliptic/triangular distribution as compared to the triangular distribution.

Concluding from the above, the optimal spanwise lift distribution for best aerodynamic performance should be a fine balance of the vortex induced drag due to lift and the wave drag due to shock wave at transonic speed. For the whole BWB aircraft performance, this needs to be further balanced with a number of other disciplines, including structural weight through the bending moment and static stability (trim) through the pitching moment and the centre of gravity of the aircraft.

Aerofoil sections for the BWB shape have been optimised for given local lift and pitching moment. Further improvement in addition to the twist inverse design has been achieved.

With the development of the adjoint methods, it has become possible to optimise the 3D BWB shape for
aerodynamic performance. However, it is still very time consuming for practical use, especially for RANS based solvers.

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