Computational Aerodynamic Design of the Gulfstream IV Wing

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A wing has been designed for the Gulfstream IV aircraft with the objective of improving upon the aerodynamic performance of the Gulfstream III. Computational methods capable of simulating the flow about this configuration, complete with nacelles and winglets, were implemented to enhance the probability that the desired effects would be verified by wind tunnel experimentation. Test results confirmed all pretest predictions. The new wing has a weaker, more swept shock which results in a lower cruise drag. Other benefits include a lower root bending moment and a lower stall speed.

Introduction

DEVELOPMENT of the Gulfstream IV airplane was initiated in March 1983 as a re-engined, stretched fuselage derivative of the Gulfstream III. A decision to redesign the wing structure for weight reduction presented an opportunity for aerodynamic redesign to reduce cruise drag and increase range. Thus, the G-III design constraint of maintaining the G-II wing box structure[1] was lifted. This resulted in added freedom to make both camber and twist design refinements. However, it was judged to be cost effective not to alter the wing juncture region to obviate the need to redesign the fuselage structure. In addition, wing contour modifications had to be restricted to the forward 65% of wing chord so that no redesign of the control surfaces would be necessary.

The design problem is further compounded by the need to account for interference effects generated by the new Tay engines, which have about 50% more volume than the Spey engine used in the current airplane. Winglet performance benefits of the current airplane were also sought for the improved version. These constraints and goals resulted in a challenging design task.

Two computational methods were implemented to provide guidance in deriving wing contour modifications. Both techniques are capable of treating the complex wing-fuselage/nacelle/winglet arrangement. An advanced subsonic panel method[2] was used for low-speed analyses, while a transonic small disturbance method[3,4] provided predictions at high speeds.

Discussion

Aerodynamic characteristics of the current wing were examined to locate potential areas for improvement. The wing exhibited a relatively strong shock wave on the outboard regions at cruise conditions. This shock wave can be attributed to the aforementioned wing box constraint imposed. The inboard regions were shock free in the presence of the Spey engine nacelle mounted on the fuselage.

The nacelle diameter for the larger improved engine selected for the improved version is about 1.5 times that of the engine that powers the current airplane. (See Fig. 1.) The interference from this nacelle caused a significant reduction in lift at the inboard regions of the wing. Figure 2 compares the pressure distribution at a wing station below the nacelle for both the current and improved configurations (from preliminary wind tunnel tests). For a given cruise lift coefficient, this inboard lift loss must be compensated by an increase in angle of attack which would increase lift and strengthen the shock at the outboard regions.

This study suggested two ways of reducing wing drag. One method was to recontour outboard sections to reduce shock wave strength, the other was to recontour inboard sections to compensate for nacelle interference.

Outboard Wing Modification

Outboard wing modifications were aimed at reducing the peak subcritical pressure coefficient and moving it aft in an effort to reduce shock strength and increase shock sweep. These entail a reduction in incidence and an increase in camber of the tip airfoil. Tip airfoil modifications with various amounts of washout and camber were analyzed using the VSAERO code[2] and the model depicted in Fig. 3. In all cases, the airfoil section aft of 65% chord was unchanged and the leading-edge shape was copied from an existing wing section to preserve the smooth expansion at the leading edge that was characteristic of the current wing. Figure 4 shows the final tip airfoil selected. The subsonic pressure distributions at 95% span are shown for the original and modified wing in Fig. 5.

Inboard Wing Modification

Several modifications to the wing root section were considered to increase the lift at inboard stations and counteract the interference of the nacelle. Local modifications to the upper surface forward of 65% chord were attempted to compensate for the nacelle downloading. A leading-edge extension to form a glove appeared the more promising, since it increased both the lift and the isobar sweep near the root. However, this modification entailed a redesign of the fuselage floor structure, which was not acceptable. Consequently, attempts to modify the inboard region of the wing were abandoned.

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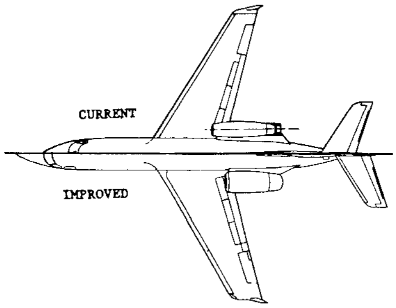

Fig. 1 General arrangement showing relative nacelle sizes.

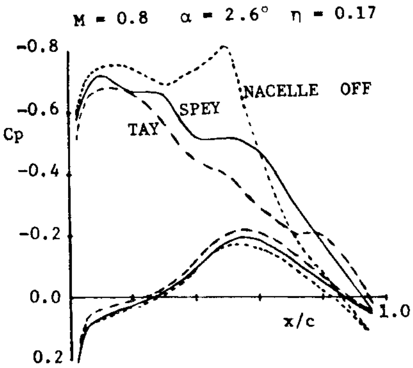

Fig. 2 Effect of nacelle on wing pressures at a station below the nacelle.

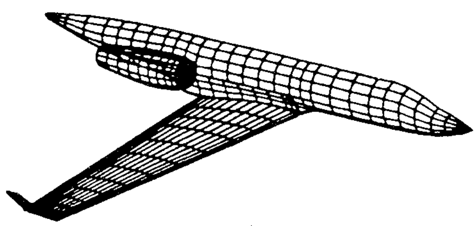

Fig. 3 VSAERO panel model.

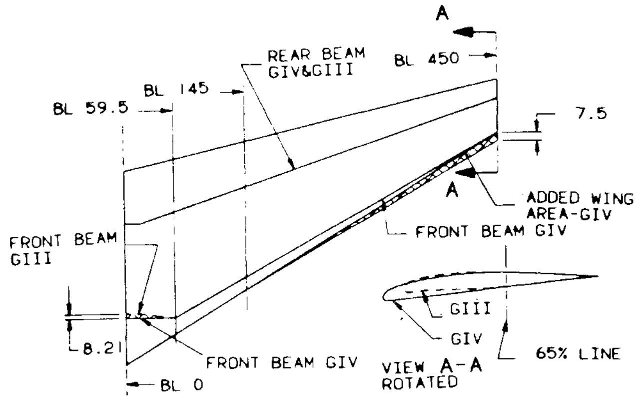

Fig. 4 Wing planform with leading-edge extension and modified tip airfoil.

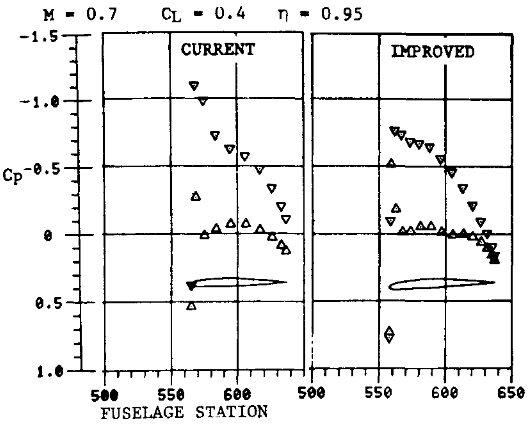

Fig. 5 Wing tip pressures, VSAERO analysis.

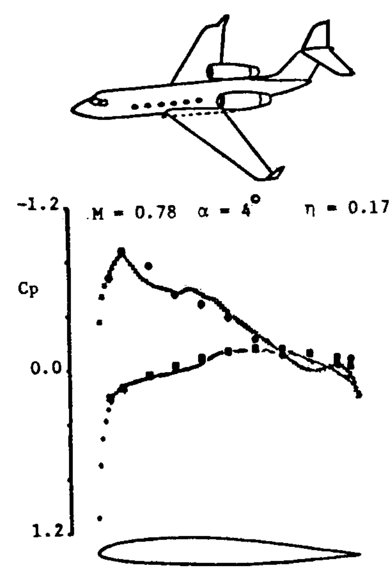

Fig. 6 Pressure correlation for current wing/new nacelle at a station below the nacelle.

Transonic Analysis

The wing shape derived using the low-speed VSAERO "panel" code was then modeled for an analysis using the WIBCO-PPW transonic wing/body code.[3,4] This was done to assess compressibility effects. In particular, the following items were of concern: whether the wing modification would have a favorable effect on shock wave strength and position, whether the winglet would still perform properly now that the wing tip shape/loading has changed dramatically, and whether the shock wave patterns that develop would alter the wing/nacelle interference effect.

A code comparison using the original wing and improved engine data already in hand provided confidence that the incremental effects caused by the wing modification would be properly simulated (see Fig. 6). Pressures predicted at a station near the tip are shown in Fig. 7 for the old and new wings. The improved wing has a weaker shock wave located further aft. Figure 8 shows the predicted isotach contours for the two wings at Mach 0.78. The new wing has lower supersonic velocities in the outboard region and the shock has a higher sweep.

Additional computations were performed to ensure that the new wing loading and shock wave pattern did not alter the winglet aerodynamic characteristics. Figure 9 shows predicted pressures for the wing tip and the winglet root in the juncture region. No flow separation problem was predicted for the wing or winglet and it can be seen that winglet pressures were not altered significantly. It was concluded that the winglet would perform properly with the new wing load distribution and shock wave pattern.

Pressure predictions near the new wing tip lower surface leading edge exhibited a pressure spike. Since this may have resulted in drag creep or separation, an attempt was made to minimize this gradient. Figure 10 shows the geometric wing tip shape modification implemented. This resulted in a small improvement in the pressure spike (Fig. 11).

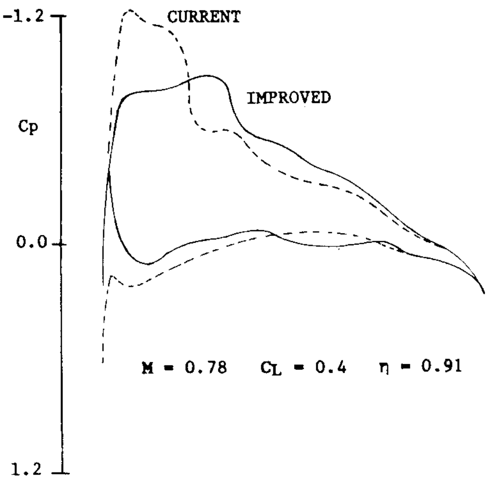

Fig. 7 Predicted effect of wing modification on wing shock strength and position.

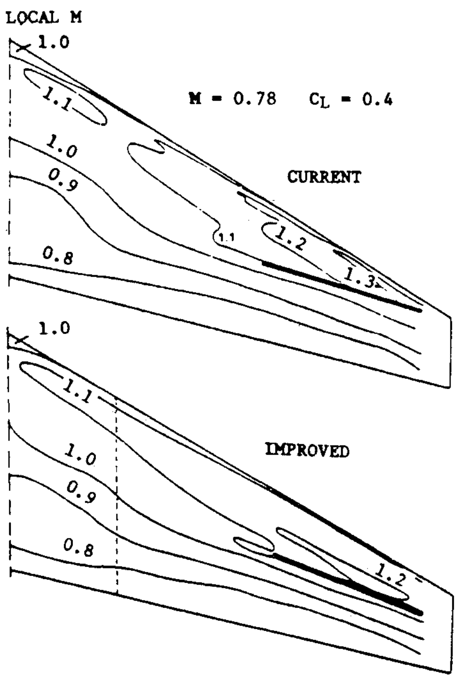

Fig. 8 Predicted wing upper surface isotach contours.

Wind Tunnel Test

A 1:8.8 scale reflection plane model of the airplane was tested in a transonic wind tunnel. The tunnel was a closed-circuit type with perforated walls at the 9×8 ft test section. The test Reynolds number was about 4×10^6. The model had Ballotini transition strips at 5% chord.

The measured pressure distribution over the wing correlated well with those computed by the subsonic code VSAERO (Fig. 12) and the transonic code WIBCO-PPW (Fig. 13) prior to the test. The test results verified the changes predicted by computational methods. The pressure distributions at 95% span (Fig. 14) and the upper surface isotachs (Fig. 15) indicate that the improved wing has significantly lower supervelocities and a higher shock sweep. There is good agreement between Figs. 8 and 15, which show the overall performance and the necessity to model the whole configuration.

Figure 16 shows the effects of the nacelle and wing changes on the spanwise wing loading. The larger new nacelle imposes a download on the inboard wing sections

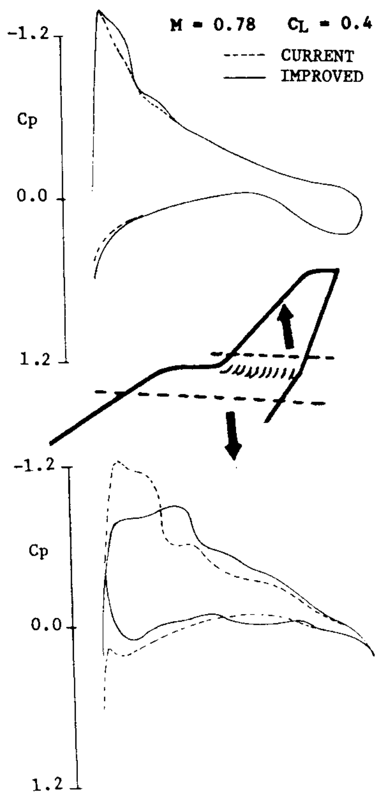

Fig. 9 Predicted wing/winglet pressures in juncture region.

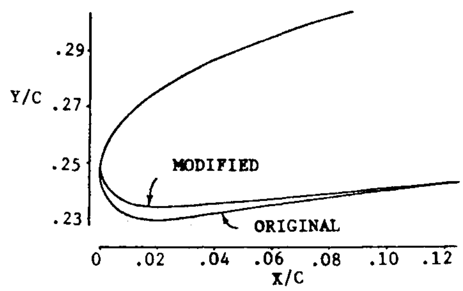

Fig. 10 Wing tip lower surface leading-edge refinement.

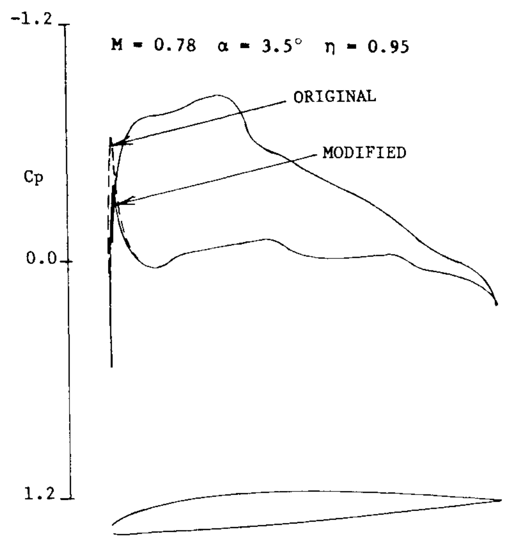

Fig. 11 Effect of wing tip leading-edge refinement on pressure spike.

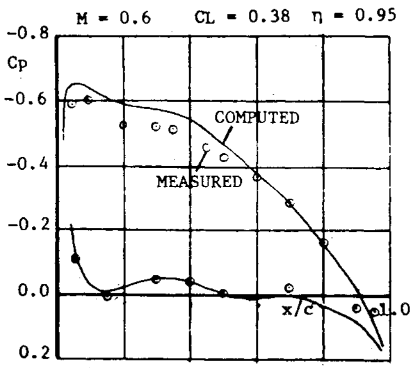

Fig. 12 Post-test correlation of VSAERO wing pressure predictions.

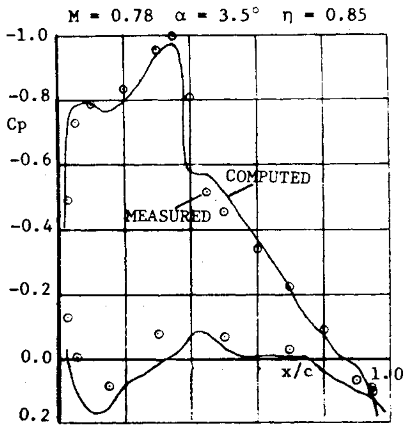

Fig. 13 Post-test correlation of WIBCO-PPW wing pressure predictions.

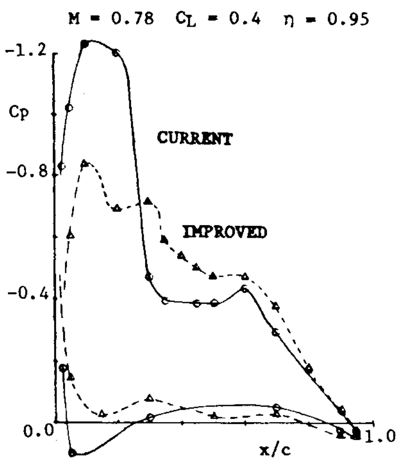

Fig. 14 Measured wing tip pressure fields showing reduced expansion/shock levels.

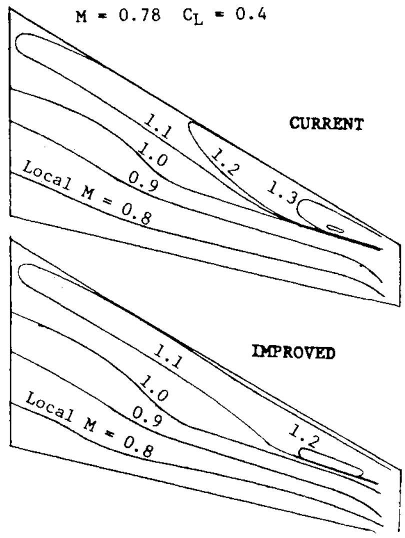

Fig. 15 Measured wing upper surface isotach contours.

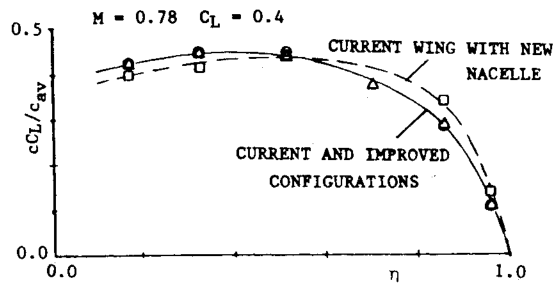

Fig. 16 Measured wing lift distributions showing effect of nacelle and wing changes.

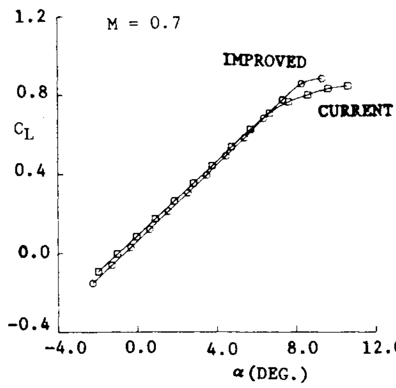

Fig. 17 Measured stall characteristics.

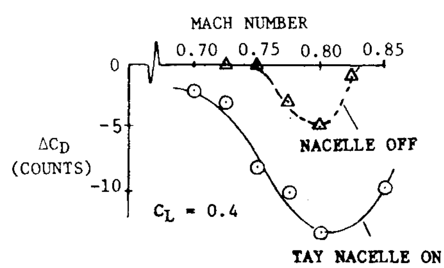

Fig. 18 Drag improvement realized by wing change.

that moves the spanwise center of pressure outboard on the original wing, resulting in a large root bending moment. The new wing has returned the loading to the current level. The increased camber and washout at the tip also improved stall characteristics (Fig. 17).

The drag improvement, obtained by replacing the old wing with the new, depended strongly on the presence of the nacelle (Fig. 18). The wing was optimized at Mach 0.78 in the presence of the nacelle and the drag improvement at this condition is nearly twice the drag improvement seen in the nacelle-off configuration. As a consequence, the installed drag (including interference) of the larger nacelle in the presence of the new wing is lower than that of the smaller nacelle in the presence of the old wing.

This demonstrates the significant wing/nacelle interference typical of airplanes with aft-fuselage mounted engines. For such configurations, it is important to include mutual interference effects when optimizing wing geometry and nacelle installation. Computational methods that accounted for the presence of nacelles were hence essential to the success of this design effort and outweighed using a more elegant but geometrically restrictive method.

Conclusions

An improved wing for the Gulfstream IV was designed with the aid of computational aerodynamics. A subsonic panel method and a transonic small disturbance code were used to analyze the complete wing/body/nacelle/winglet configuration and to predict the effects of geometry modifications in the presence of strong interference fields. Wind tunnel tests confirmed the improvements predicted by these computational methods. The new wing has lower upper surface supervelocities, yielding a weaker, more swept shock. This results in a significant drag reduction at cruise. The chord extension provides more fuel volume. The increase in washout reduces stall speed and relieves the root bending moment by moving the center of pressure inboard.

References

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