THE AERODYNAMIC DESIGN OF AN INTEGRATED WING LOWER SURFACE AND PYLONS FOR REDUCED DRAG

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Abstract

The aerodynamic design of the wing for a military aircraft frequently concentrates on the clean wing performance, particularly the development of the upper surface flow at moderate and high incidence. The addition of underwing pylons and stores can cause a significant increase in drag, especially at the high subsonic Mach numbers and low incidences typical of 1'g' flight at low altitude. This paper describes the design modifications to the wing lower surface and pylons of a military aircraft research model, aimed at reducing the installed drag of the pylons and stores.

The redesign was carried out using the ARA Multiblock/Euler code to compute the flow around the fuselage/wing/pylon/store configuration. Geometric changes were specified using a simple relationship between the local surface curvature and the required change in surface pressure. Since the flow in the vicinity of the pylons and stores is highly viscous, the inviscid Euler code could not be relied upon to predict the drag differences between alternative designs. The success of the design modifications was therefore judged by the changes in surface pressure distributions, notably in the reduction in the shock strength on the wing lower surface. The redesigned wing/pylon combination has been tested in the ARA Transonic Wind Tunnel in conjunction with various store installations. The results demonstrate that a significant drag reduction can be achieved by redesigning the wing lower surface and pylons and a comparison with the predicted pressures shows that the CFD method has been successful in predicting the flow features accurately.

1 Introduction

A military aircraft is required to operate over a wide range of flight conditions, balancing the need for manoeuvre at high incidence with efficient 1'g' flight to minimise fuel usage in the cruise and high speed dash phases of the mission. The aerodynamic design of the wing frequently considers only the clean wing performance, particularly the development of the wing upper surface flow at moderate and high incidence. However, the requirement for high speed, 1'g' flight at low altitude emphasises the importance of the wing lower surface flow. The addition of underwing pylons and stores can cause a significant increase in drag, limiting the maximum Mach number at low altitude.

This paper describes the design modifications to the wing lower surface and pylons of a military aircraft research model with a moderately swept wing, typical of a subsonic, ground attack aircraft, Fig 1, aimed at reducing the installed drag of the pylons and stores. This model has a moderately thick wing (9% thickness:chord ratio) with an upper surface which was designed for a transonic manoeuvre design point with a region of supercritical flow which recompresses to give a weak shock at about 50% chord. The lower surface was designed to suppress the peak suctions which occur on the outer wing at low C_L as a result of the twist which is implicit in the upper surface design.

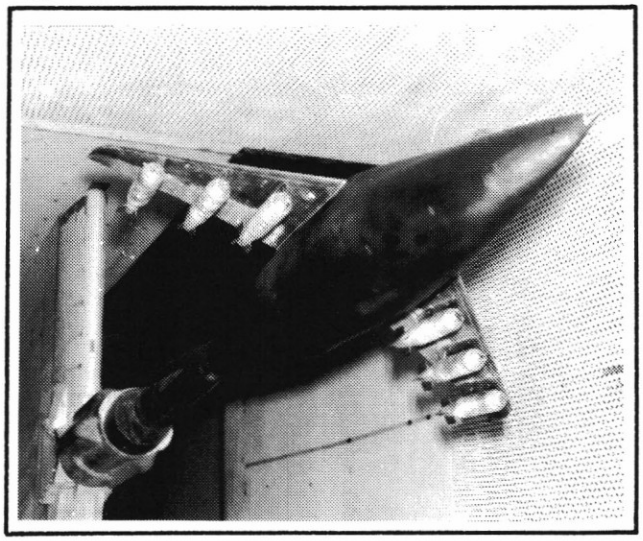

Fig 1 Military Aircraft Research Model in the ARA Transonic Wind Tunnel

The clean wing performance of the model is good, with a drag rise Mach number of approximately 0.88 at low and moderate C_L. However, the addition of pylons leads to strong, unswept shocks on the wing lower surface between the pylons with an extensive separation of the flow inboard of the outer pylon, Fig 2.

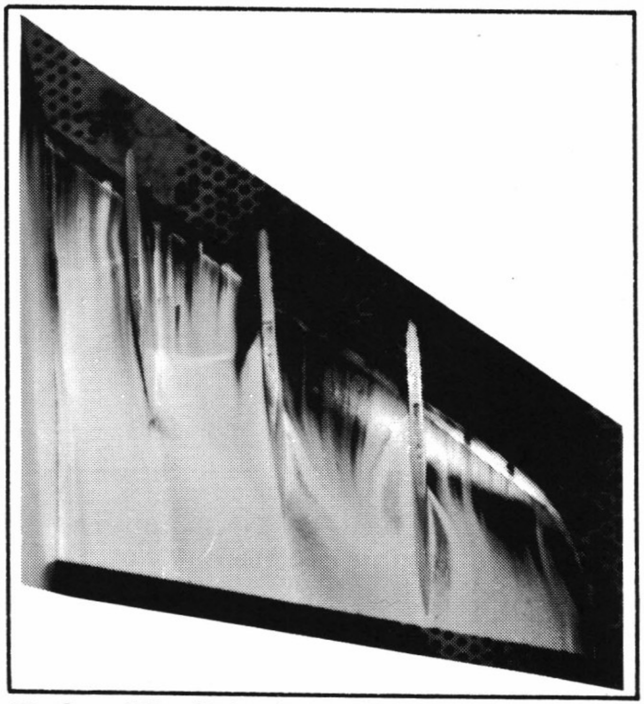

Fig 2 Wing/Pylon Lower Surface Flow Visualisation at $M = 0.8$, $C_L = 0.1$

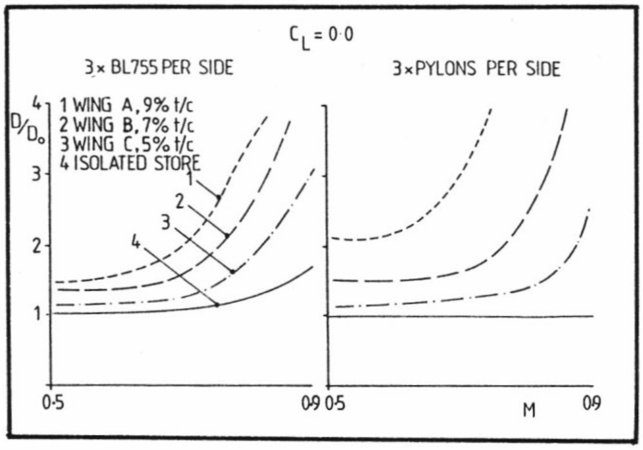

Fig 3 Incremental Drag due to the Same Stores Installed on Different Wings

2 Design Requirement

The installed drag of pylons and stores is dictated by the velocities on the wing lower surface. This, of course, means that the thicker wings typical of subsonic aircraft are susceptible to larger store drag increments. Fig 3 shows the incremental drag, normalised by the isolated drag at low Mach number, due to the same pylons and stores installed on different wings. It is apparent that the drag increment is significantly greater on the thicker wings, although it should be noted that the thinnest wing shown here has a lower surface design which incorporates upward deflections of the wing leading-edge and trailing-edge flaps to optimise the flow for low C_L. However, even this design demonstrates a significant increase in installed drag when compared with the isolated drag of the pylons and stores.

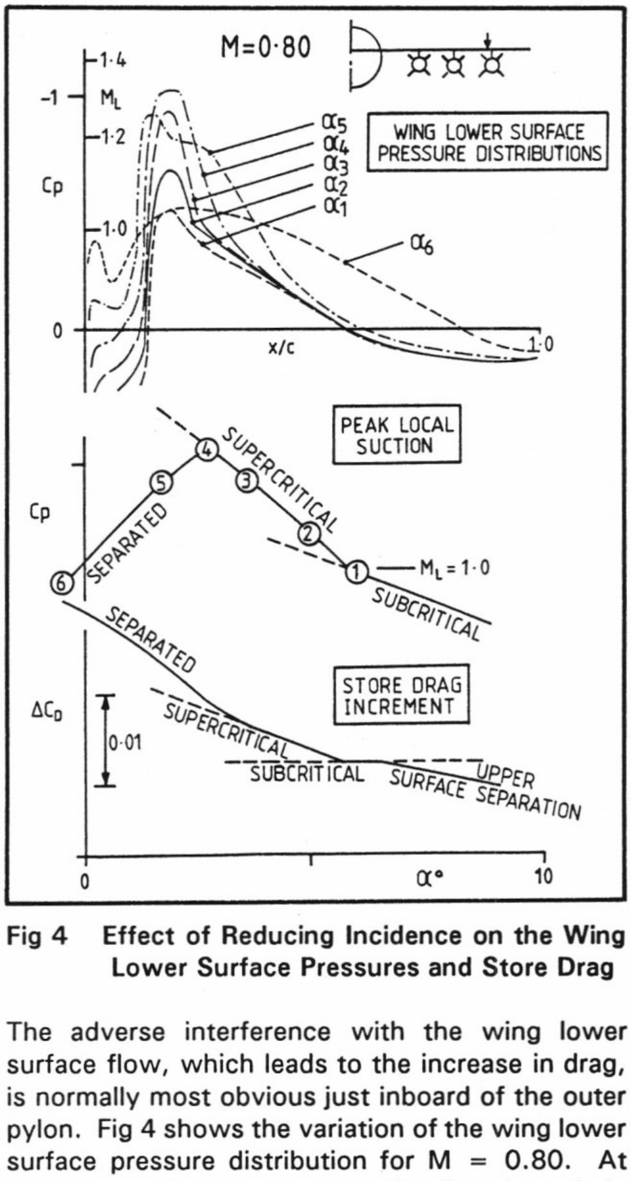

Fig 4 Effect of Reducing Incidence on the Wing Lower Surface Pressures and Store Drag

The adverse interference with the wing lower surface flow, which leads to the increase in drag, is normally most obvious just inboard of the outer pylon. Fig 4 shows the variation of the wing lower surface pressure distribution for $M = 0.80$. At moderate incidence, $\alpha = \alpha_1$, the flow is entirely subcritical and the peak suction increases slowly with reducing incidence. The onset of supercritical flow causes a more rapid expansion of the peak suction and a strong, unswept shock develops between the outermost two pylons with an associated increase in wave drag. Once the local velocity exceeds the level which can be sustained by attached flow, $\alpha < \alpha_4$, a separation develops downstream of the shock, such as that shown in Fig 2, with a rapid increase in drag at lower incidences. By α_6 the shock has collapsed and the flow is fully separated on the lower surface although the tendency to a trailing edge pressure divergence is less apparent than occurs on the upper surface because the low incidence and the concave curvature reduce the divergence of the separated streamline from the wing lower surface.

In order to reduce the influence of the flow breakdown at low C_L, we need to modify the wing lower surface and pylon design to reduce the strength of the shocks between the pylons and to increase the shock sweep, thus reducing the Mach number normal to the shock. Since this flow is dominated by the presence of the pylons and stores, it is apparent that these must be represented in the redesign process.

3 Design Procedure

The redesign of the wing lower surface and pylons was carried out using the ARA Multiblock/Euler suite of programs[1,2,3]. Inevitably, the representation of the configuration in the program requires some simplification of the geometry. In particular, since the principal effect of the stores is an increase in the local velocity due to their volume, the details of the store which are modelled in the experiment are ignored in the theoretical representation (Fig 5). These details will contribute a large proportion of the isolated store drag but they are viscous effects which do not have a significant contribution to the interference with the parent aircraft and would not be represented by the inviscid Euler code. Having specified the geometric representation of the datum configuration, surface grids were generated for each of the components of the configuration together with the far field boundaries and control planes within the field (Fig 6). The Multiblock approach then permits a surface conforming field grid to be obtained, using O grids around the fuselage and stores and C grids around the wing and pylons. Inevitably, some editing of the grid was required to achieve a satisfactory field grid for the complex configuration under consideration, but this was achieved fairly easily with approximately 1500 blocks and 500000 field grid cells (Fig 7).

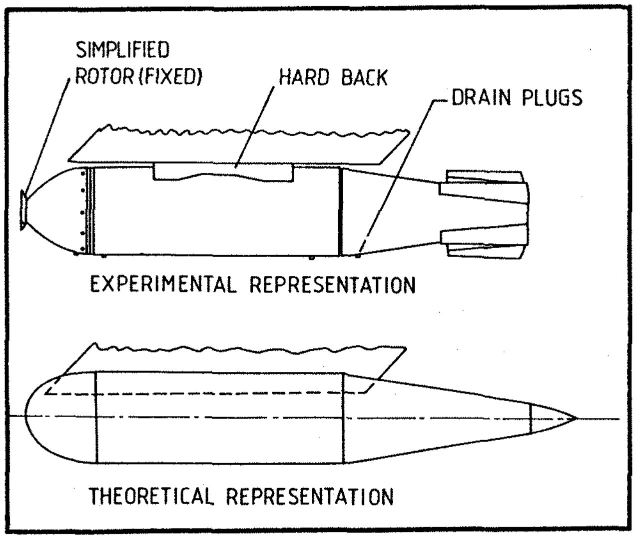

Fig 5 Comparison Between Experimental and Theoretical Representations of a BL755 Bomb

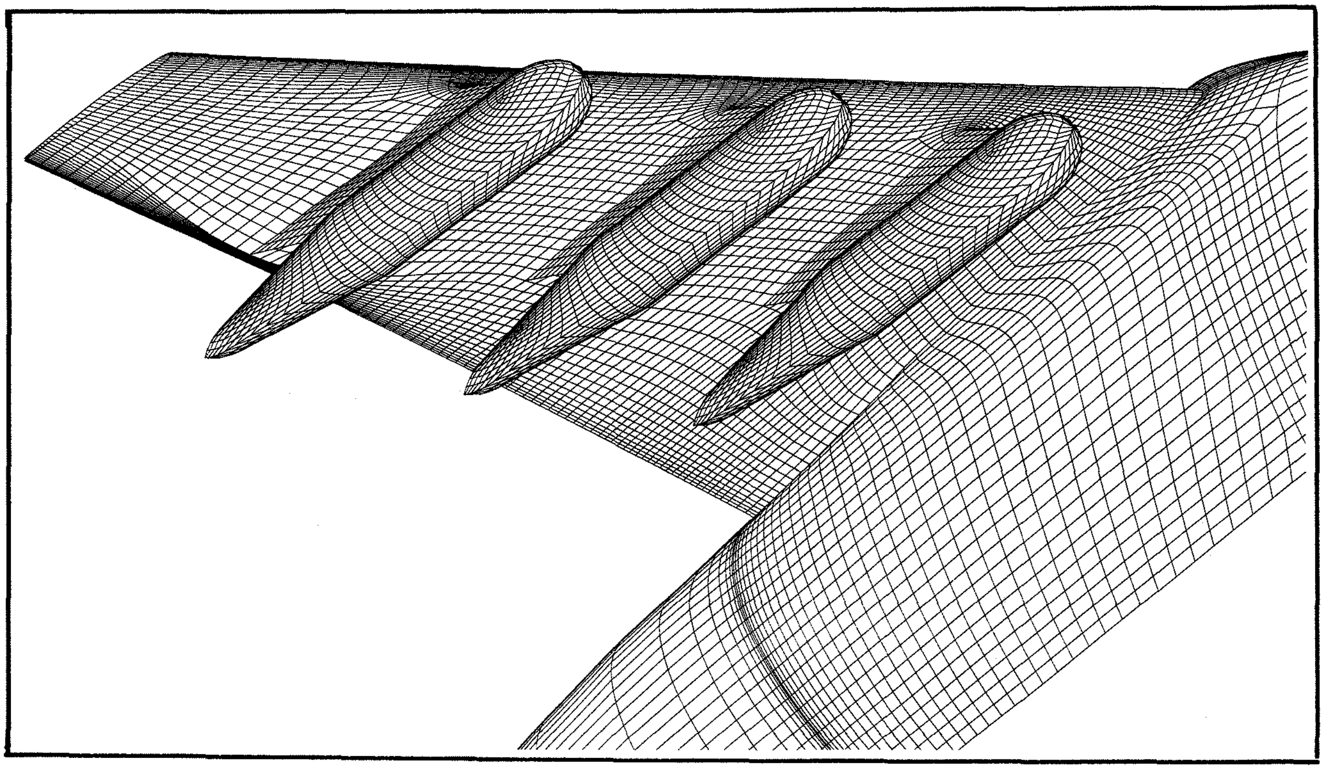

Fig 6 Surface Grid on a Multiple Pylon/Store Configuration

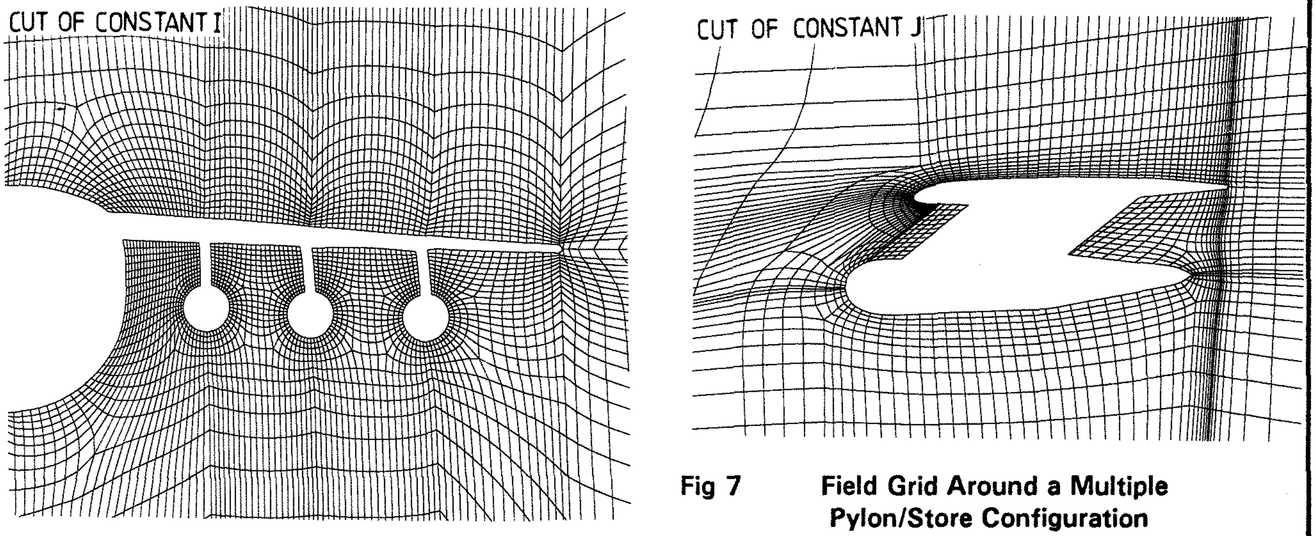

Fig 7 **Field Grid Around a Multiple Pylon/Store Configuration**

At this stage in the design process a comparison between the inviscid Euler calculation and the extensively separated real flow appeared meaningless (Fig 8). However, since the theory was predicting local Mach numbers in excess of 1.6, it was apparent that the real flow would be separated. The aim of the redesign was to modify the shape of the wing lower surface and pylons in order to reduce the shock strengths to levels which would not provoke separation and hence an improved comparison between theory and experiment would be expected following the redesign.

The design modifications to the geometry were generated following the two-dimensional method of Davies[4] to relate the required change in pressure coefficient to a change in the local curvature thus:

$$\Delta Z'' = \pi \Delta C_p [1 - M^{*2} + 1.2 M^{*2} C_p]^{1/2}$$

where $M^* = [1 - 1.2 C_p^*]^{-1/2}$

C_p^* = pressure coefficient for locally sonic flow

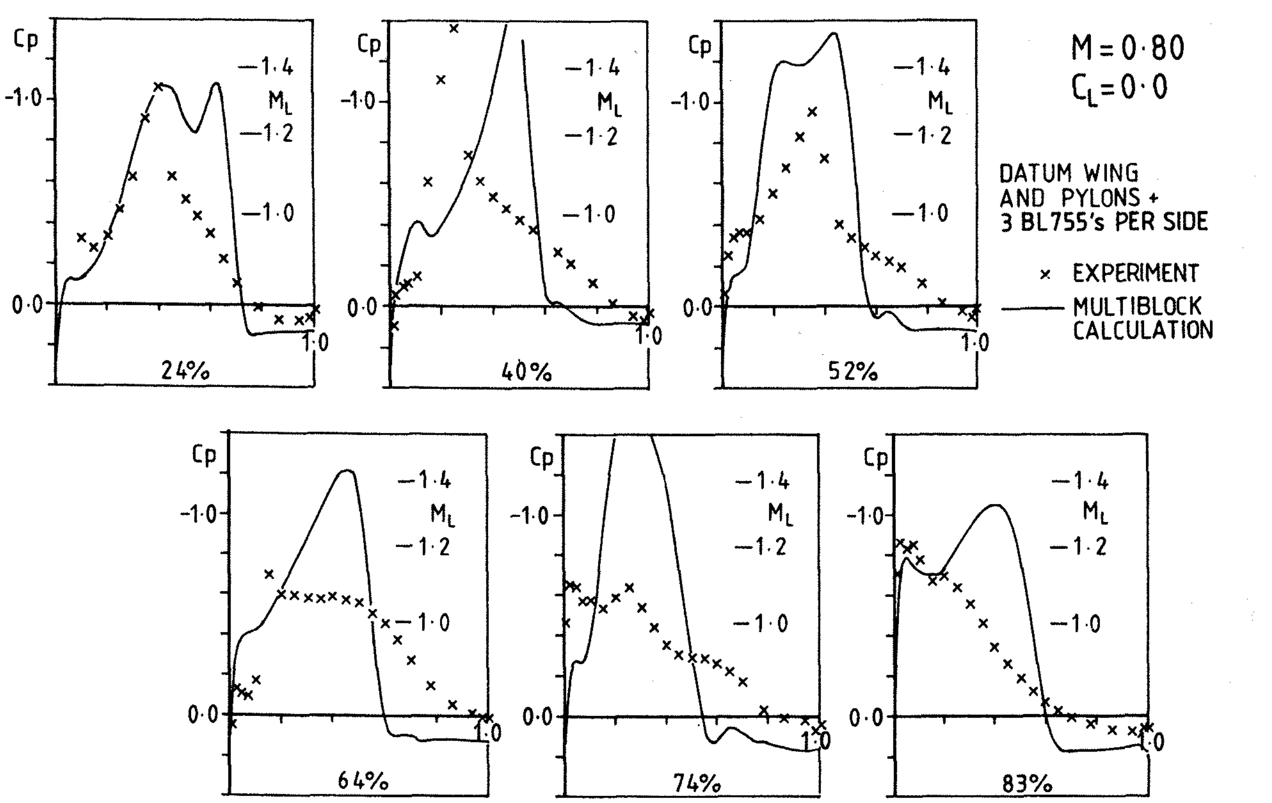

Fig 8 **Wing Lower Surface Pressure Distributions for the Datum Wing/ Multiple Pylon/Store Configuration**

Although Davies uses this expression for locally subsonic flow and has a modification to the first derivative for supersonic flow, experience has shown that these equations are sufficient to refine the surface geometry for this type of application.

In order to obtain a smooth variation in the surface shape between the pylons it is necessary to define the section at a large number of spanwise stations, with a smooth variation in ΔC_p. This was achieved by specifying an algebraic variation of ΔC_p in the spanwise direction, using a function f_0 which varied from a maximum value at the position of the peak suction x_m/c in the wing/pylon junction to zero at the adjacent control stations (Fig 9). Since the requirement was to modify only the lower surface of an existing wing, the chordwise function f_1 was also defined by an algebraic expression which reduced to zero at 5% chord and 90% chord. Thus, by defining values of $\Delta C_{p\ \max}$ and $x_{m/c}$ for each of the 3 pylon stations, a smooth distribution of ΔC_p over the wing lower surface could be obtained from

$$\Delta C_p = \sum_{i=1}^{3} f_o(i)\, f_1(i)\, \Delta C_{p_{\max}}(i)$$

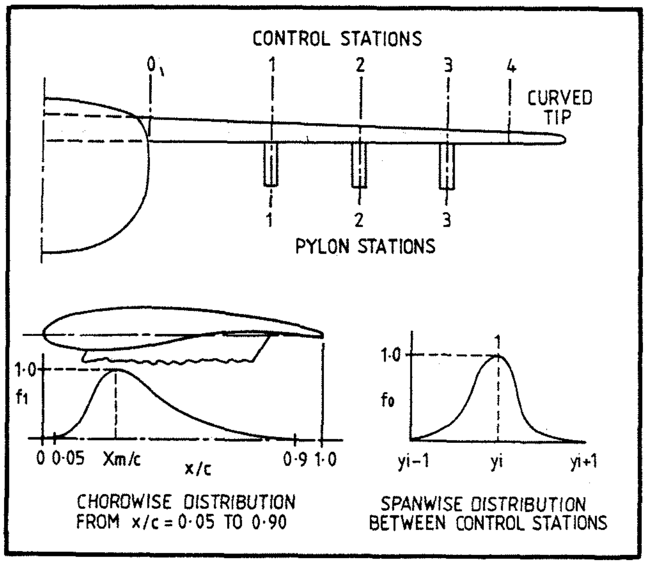

Fig 9 Incremental Pressure Distributions on the Wing Lower Surface

Modifications to the pylon section were also based on the Davies method, using functions f_0 and f_1 to specify the depthwise and chordwise variations from a maximum value at x_m to zero at the pylon foot and the leading and trailing edges of the pylons (Fig 10). This ensures that the intersection between the pylons and stores is unchanged by the design modifications.

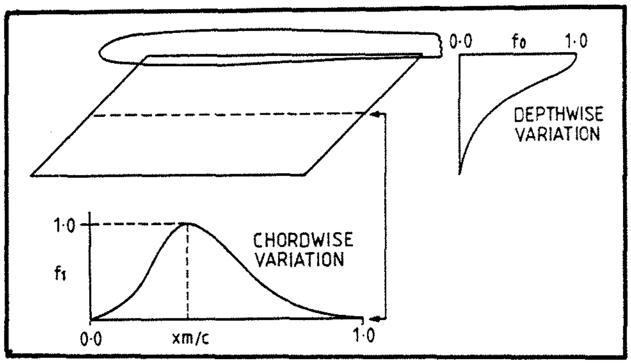

Fig 10 Incremental Pressure Distribution on the Inboard Side of the Pylon

Having revised the surface geometry of the wing and pylons through the second derivatives, it was necessary to obtain trailing edge closure. This was achieved by a simple linear variation in ΔZ over the wing lower surface and both inboard and outboard sides of the pylon, as shown in Fig 11. In addition the design modifications to the pylon were adjusted to ensure that the thickness was maintained.

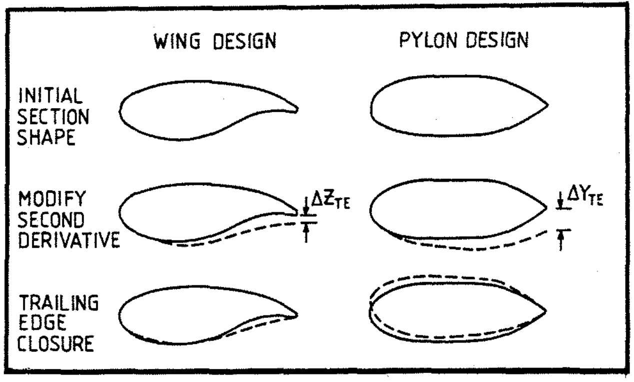

Fig 11 Design Modifications to the Wing Lower Surface and Pylons

Since the redesign of the wing and pylon was to be carried out using a number of analysis runs using the Multiblock suite of programs, a rapid turn-round was essential to minimise the elapsed time of the design process. The geometry modifications were incorporated into the Multiblock calculation using the remesh facility which permits small changes to the surface to be allowed for by regridding the blocks adjacent to the modified components. Since this results in a small change in the field grid, it was also possible to use the existing flow dump as an initial solution to obtain a reconverged solution in a small number of extra iterations of the flow solver. In this way a complete design cycle from the analysis of the existing flow solution using the Multiblock post processing package, through the geometry modifications and regridding, to a new flow solution could be achieved on a daily basis.

Having carried out a number of design cycles to modify the wing lower surface and the pylons, the pressure distribution inboard of the outer pylon was modified as shown in Fig 12. Whereas the strength of the shock on the datum wing cannot be sustained by a real flow and the flow separates, the weaker shock on the redesigned wing, where the local Mach number is less than 1.4, is unlikely to provoke a separation.

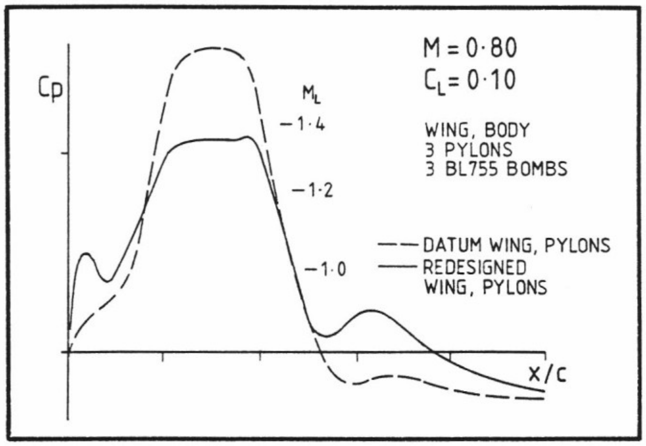

Fig 12 Predicted Pressure Distributions Inboard of the Outer Pylon

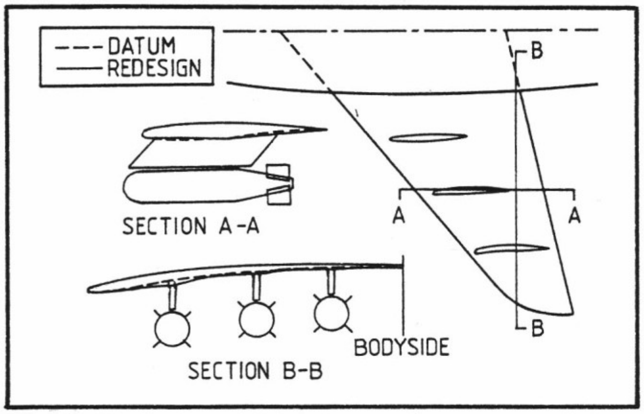

Fig 13 Redesigned Wing Lower Surface and Pylons for Reduced Installed Pylon/Store Drag

The design modifications to the wing lower surface and pylons are shown in Fig 13. It is apparent that the surface geometry varies rapidly in the vicinity of the pylons, thus:

a) the curvature of the wing lower surface near the peak suction is reduced to oppose the acceleration of the flow around the pylon leading edge.

b) the rear loading on the wing is removed at the pylon stations. In fact this would be contrary to the upper surface design requirement for transonic manoeuvre and a compromise solution is likely to require the use of the trailing edge flap to modify the camber such that the wing upper surface is designed for manoeuvring whilst the lower surface is designed for 1'g' flight at sea level.

c) the pylons have a significant camber with the leading edge set toe-out, particularly outboard.

4 Experimental Results

The existing research model was modified to incorporate the redesigned wing lower surface by removing metal near the wing leading edge and increasing the thickness near the trailing edge, most notably in the vicinity of the pylons. A set of cambered pylons was manufactured with the same planform and a similar thickness to those used for the datum configuration. In addition, a set of bodies of revolution was manufactured to test the validity of the simplification used in the theoretical modelling of the BL755 bomb, shown in Fig 5. The redesigned configuration was tested in the ARA Transonic Wind Tunnel over the Mach number range 0.5 to 0.95, using the store installations shown in Fig 14 and up to 1.35 for the clean wing and pylons alone configurations.

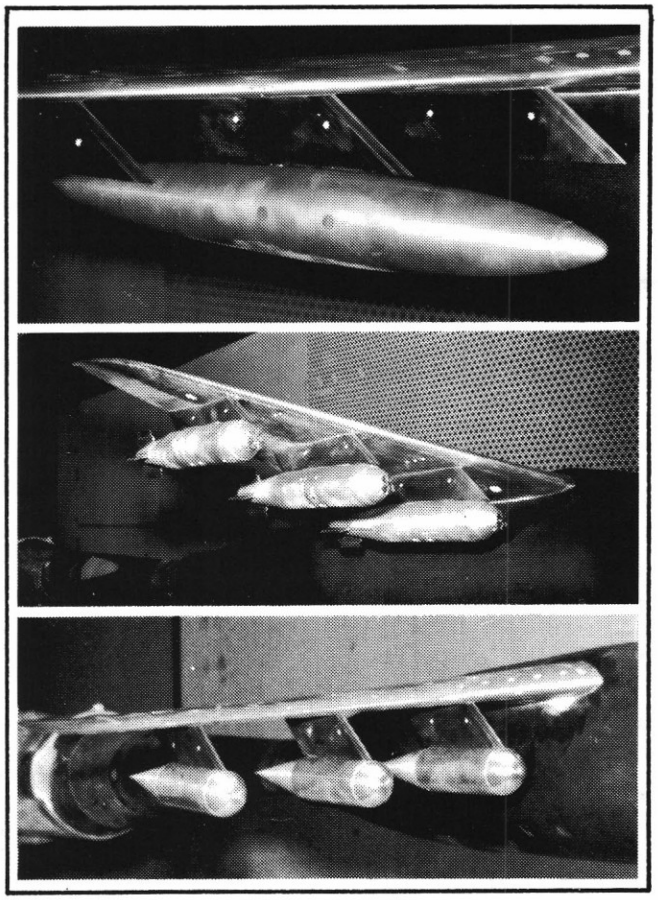

Fig 14 Alternative Store Installations on the Redesigned Wing

Fig 15 shows the drag variation with Mach number of the redesigned wing fitted with the alternative store installations, in comparison with the same stores fitted to the datum wing. The clean wing comparison shows that there is only a very small increase in drag due to the modified lower surface at low Mach number and a significant reduction in drag at and beyond the drag rise Mach number. This is a little surprising in that the redesigned wing has a wavy lower surface which is optimised for the pylon-on configurations. The configurations with pylons and stores show the anticipated improvement in both the installation drag at low Mach number and the drag rise Mach number. At M = 0.80, there is a 45% reduction in the pylon drag increment and a 30-40% reduction in the additional drag due to the stores. In each case there is an improvement in the drag rise Mach number of approximately 0.05.

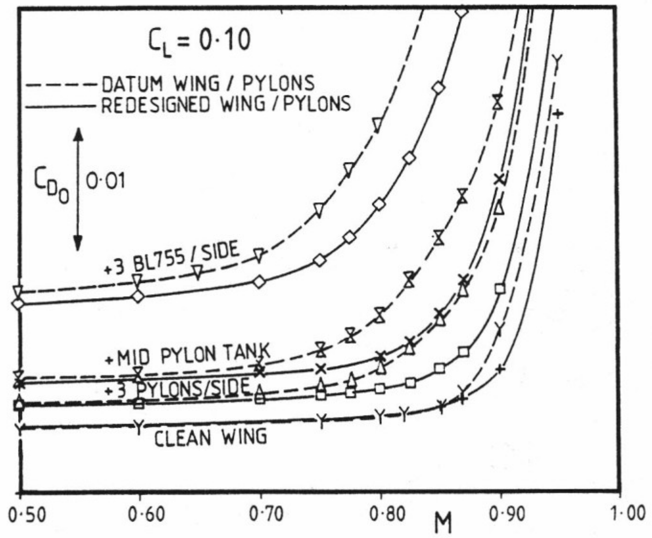

Fig 15 Effect of the Wing/Pylon Redesign on the Drag at low Lift

As would be expected from the reduction in rear loading associated with the redesign of the wing lower surface, there is some degradation of the manoeuvring performance of the clean wing at moderate and high C_L (Fig 16). However, this effect is less significant with the pylons on and the addition of stores shows a drag improvement over much of the range of C_L. Since this degradation in performance can be attributed to the removal of the rear loading on the wing lower surface, this could largely be retrieved by the incorporation of manoeuvre flaps into the design process. Experience has shown that the use of a small downward deflection of the trailing edge for the upper surface design point with an upward deflection for the lower surface design point (Fig 17) permits a near-optimum pressure distribution to be achieved in both cases. The concave corners, which appear on the opposite surface to that being designed, occur in a region of subcritical flow which does not degrade the efficiency of the design pressure distribution. However, the constraints imposed by the use of an existing model precluded a more extensive redesign in this case.

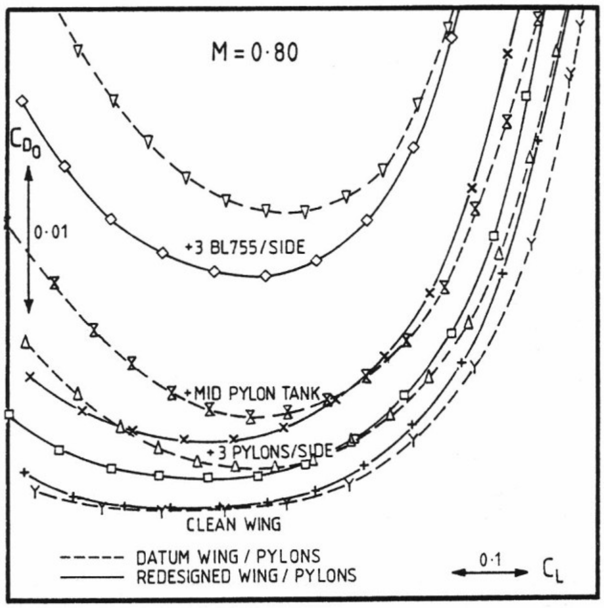

Fig 16 Effect of the Wing/Pylon Redesign on the Drag Variation with Lift

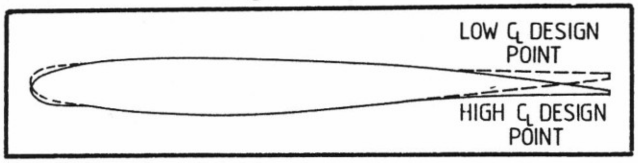

Fig 17 Incorporation of Flap Deflections into the Wing Design Process

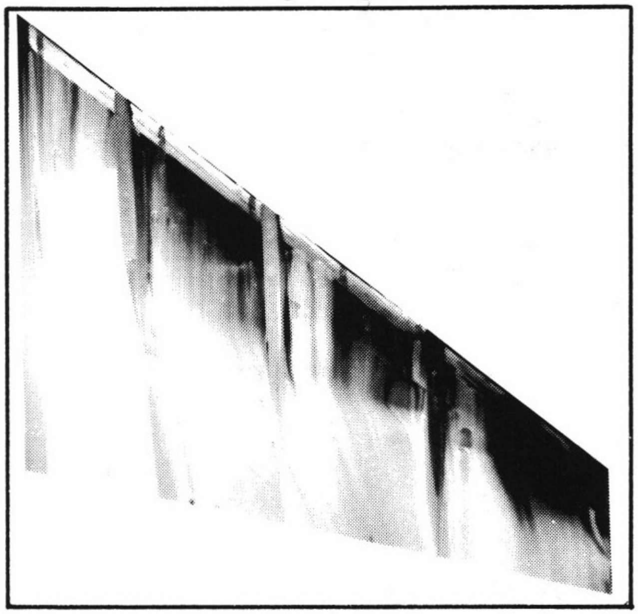

Fig 18 Redesigned Wing/Pylon Lower Surface Oil Flow Visualisation at M = 0.8, C_L = 0.1

The reason for the drag reduction at low C_L can be seen in the oil flow visualisation at $M = 0.80$, $C_L = 0.1$, shown in Fig 18, in comparison with that for the datum wing in Fig 2. Whereas the datum configuration has strong, unswept shocks on the inner wing with extensive separations around the outer two pylons, the redesigned wing shows a more benign flow in that the separations are largely suppressed and moderately swept shocks are obtained between the pylons.

The wing lower surface pressure distributions for the configuration with 3 bombs installed on each wing, Fig 19, now shows a more satisfactory comparison between theory and experiment in contrast to that shown earlier for the datum wing design (Fig 8). It is apparent that, whilst the theory does not give a precise prediction of the pressures, it has been instrumental in guiding the redesign of the wing lower surface and pylons for a complex configuration. The discrepancies between theory and experiment which remain can be attributed to the weaker viscous effects which are still present and it is anticipated that the Navier-Stokes codes being developed[5,6] will refine the modelling of this type of complex flow.

Having established a satisfactory comparison of pressure distributions between theory and experiment for the redesigned wing, it is now a more realistic proposition to consider the forces, obtained from the theory by an integration of surface pressures, in comparison with the balance measurements in the experiment.

Fig 20 shows the lift curves predicted by the Multiblock code in comparison with the experimental data. It is apparent that the theory provides a very encouraging prediction of the results for the pylon/store configurations, bearing in mind the differences which would be expected between an inviscid calculation and experimental results. That is, there is a small increase in lift at zero incidence and a slightly greater lift curve slope predicted by the theory. However, the results for the clean wing are less satisfactory in that the comparison with the pylons-on configuration is incorrect. This can be attributed to the complexity of the clean wing lower surface, particularly in the vicinity of the pylon locations. A relatively sparse computational grid in the spanwise direction means that the variation in flow in that direction is not adequately modelled for the clean wing. With the pylons present a boundary condition is imposed at each of the pylon stations and an extra C-grid is introduced around each of the pylons to ensure a more precise representation of the flow.

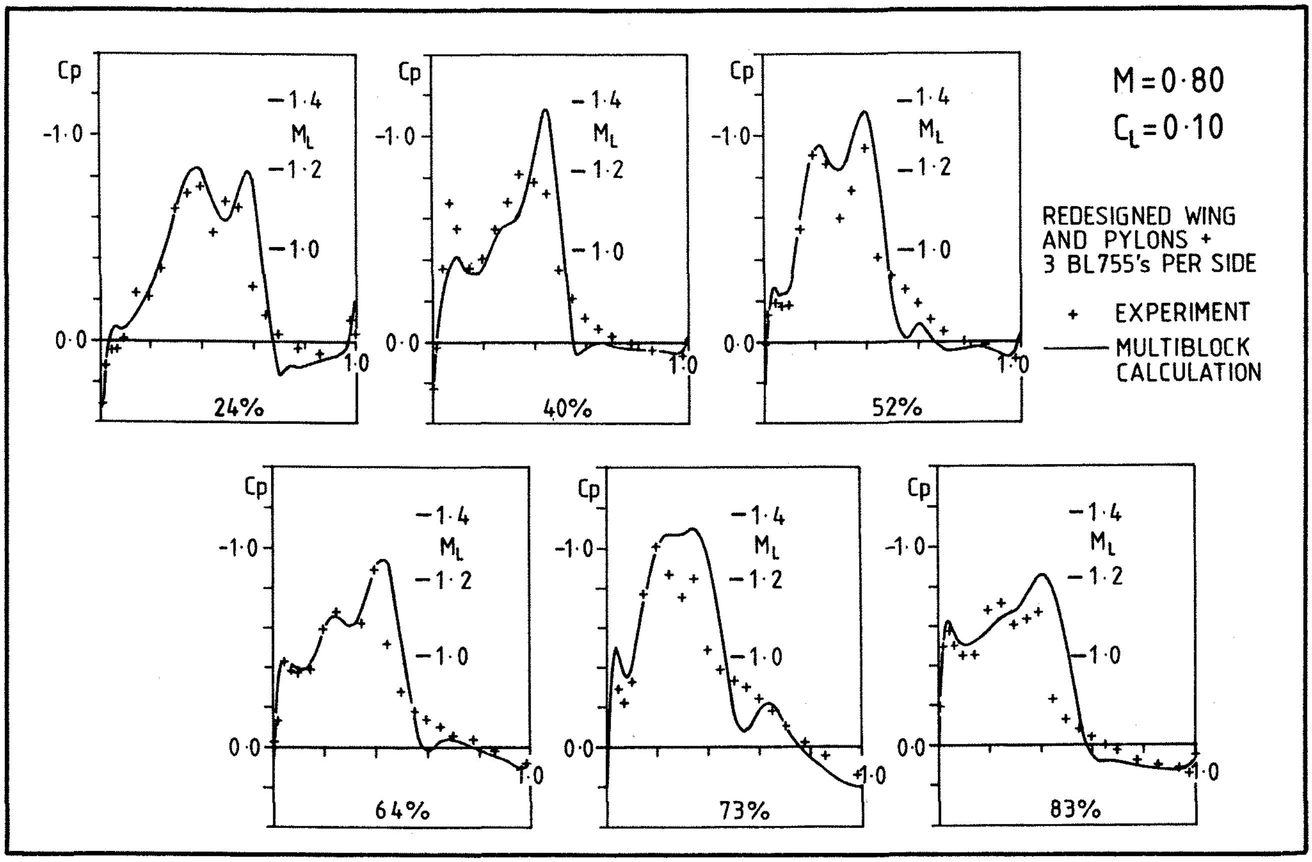

Fig 19 Comparison of Experimental and Theoretical Wing Lower Surface Pressure Distributions

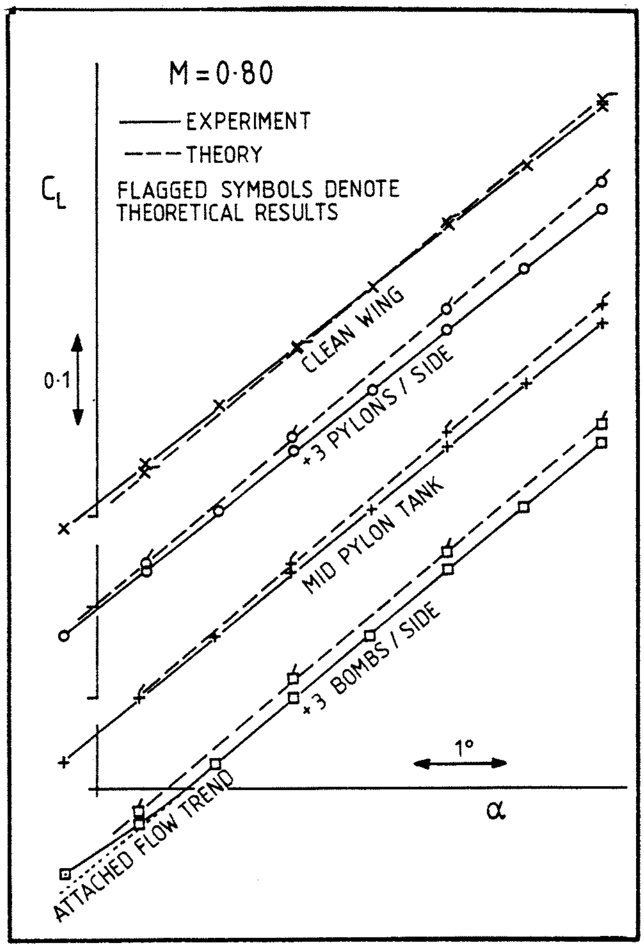

Fig 20 Comparison of Experimental and Theoretical Lift Curves

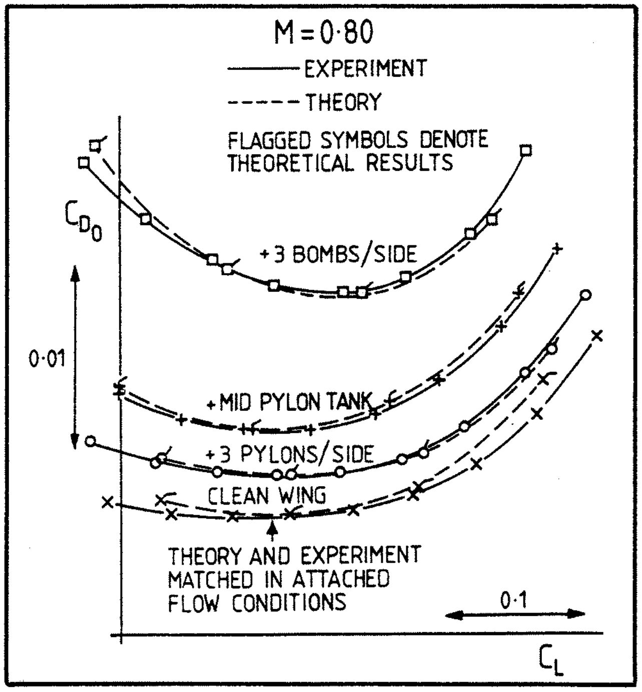

Fig 21 Comparison of Experimental and Theoretical Drag Variation with Lift

Finally the predicted drag is compared with experiment in Fig 21 using the parameter $C_{D_0} = C_D - C_L^2/\pi A$ to remove most of the drag variation with lift and hence to permit the results to be plotted at a larger scale. Since an inviscid code has been used for the flow solution, the theoretical drag has been adjusted to match the experiment at $C_L = 0.2$ and hence this can only be considered a comparison of the drag variation with lift. These results show a very satisfactory match for the pylon/store configurations although once again the clean wing comparison is less good, with the theory overestimating the drag variation with lift.

5 Conclusions

The purpose of this paper has been twofold; to demonstrate the potential benefits of redesiging the wing lower surface and pylons to reduce the installed drag of pylons and stores for reduced drag at low incidence and to show the value of a CFD code which is capable of predicting accurately the flows around such complex configurations.

A design procedure has been developed, using the ARA Multiblock/Euler suite of programs with a simple design rule to modify the geometry of the wing lower surface and pylons to achieve a required change in the pressure distribution. Since an inviscid flow code was being used, the success of the redesign was judged by the change in the predicted pressure distributions, notably the shock strength inboard of the outer pylon where the real flow on the datum wing separates, causing a large increase in drag at low C_L.

The redesigned wing and pylons have been tested in the ARA Transonic Wind Tunnel, demonstrating a large reduction in drag at the wing lower surface design point. The results show a 45% reduction in the pylon drag increment at $M = 0.80$, $C_L = 0.10$ with a 30-40% reduction in the additional drag of pylon mounted stores. In each case there is an improvement in the drag rise Mach number of approximately 0.05. There is a very small increase in the drag of the clean wing at low Mach number but, surprisingly, the redesigned clean wing shows an improvement of approximately 0.02 in the drag rise Mach number.

At high C_L there is some degradation of the manoeuvring performance of the clean wing due to the reduction in rear loading implicit in the redesign. However, this effect is less pronounced with pylons on and there is an improvement over most of the C_L range with stores on.

Comparison between the measured and predicted pressure distributions on the redesigned wing shows that the Multiblock/Euler code has been instrumental in guiding the redesign of the wing lower surface and pylons for a complex configuration. Having established a predominantly attached flow on the redesigned wing, a surface pressure integration has been used to compute the predicted lift and drag of the configurations. The results for the clean wing show that the complexity of the wing lower surface geometry in the spanwise direction is not captured adequately by a relatively sparse grid. However, with the pylons present a boundary condition is imposed at each of the pylon stations and a very satisfactory comparison between theory and experiment is obtained.

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