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# APPLICATION OF A MULTIBLOCK CFD SYSTEM TO OBTAINING FLOWFIELD PREDICTIONS ABOUT WING BODY PYLON STORE CONFIGURATIONS

A J Baxendale
Aircraft Research Association Ltd, Bedford, UK

## ABSTRACT

The field of computational fluid dynamics (CFD) continues to develop rapidly, providing the aerodynamics engineer with increasingly powerful design tools. In this paper, the application of the currently most advanced CFD method available to the UK Aerospace Industry is described. The method, known as Euler Multiblock, has been used to analyse the flow about derivatives of a wing/body/pylon/store research model in the transonic flow region, making use of an extensive experimental data base to validate results. This data base was produced during wind tunnel tests to assess earlier pylon design techniques, which were guided by a transonic small perturbation code, with the coupled aim of providing experimental data against which to validate more advanced techniques as they become available. Following brief descriptions of the Multiblock system and the pylon design exercise, theoretical results are shown and discussed which demonstrate the ability of the system to predict the flow in regions of high interference such as close to wing pylon junctions, on pylons and on simple stores. The discussion is then broadened to describe, more generally, the potential of the Multiblock method for military aircraft design and development.

## 1 INTRODUCTION

Fig 1 illustrates the on-going approach to CFD development, evaluation and application adopted at ARA. As technology advances, the ability to predict complex flow patterns improves. The pace of development in this field is dictated by many factors which include for example the availability of powerful computers and physical data against which new methods can be judged. Therefore, when performing experiments, either to quantify the design predictions of an established code or to provide data against which to validate a newer code, it is important to maintain a long term view regarding the requirements for validation of CFD codes on the horizon. In 1983 a pylon design exercise was begun making use of a transonic small perturbation program (TSP[1]) to guide the design. Over the period of this work the CFD code on the horizon at ARA was Multiblock[2,3]. This was to be geared towards the development of a flexible method, for accurately simulating the compressible flow field about complex aircraft geometries. With this method in mind, extensive experimental pressures were measured for various model builds during the wind tunnel testing phase of the pylon design exercise. In addition to basic configuration forces, pressures were measured on the wing upper surface (8 stations), the wing lower surface (17 stations), on pylons (31 ports on each side) and on a tank (63 ports). The aim of these tests was to assess the merits of the design and provide data to test severely the Multiblock method when it became available.

Recently, the Multiblock method has been released in a form suitable for the use of CFD applications engineers and extensive evaluation work has already been carried out for supersonic flows about military aircraft configurations.[4,5] This paper illustrates some of the ways in which CFD can be combined with experiment, for the advancement of aerodynamic design, by describing the application of Multiblock to the transonic flow past wing/pylon/store installations.

## 2 THE EULER-MULTIBLOCK SYSTEM

Since an accurate prediction of the flow about a practical aircraft shape requires both flow algorithm accuracy and geometrical accuracy, research has concentrated on the development of a method which can go some way towards accurately representing geometrical features and solving the Euler flow equations. Fig 2 shows a schematic of the Multiblock system and illustrates how various elements combine to make up a complete CFD package.

The Multiblock method works by dividing the flow domain about a configuration into a number of blocks, known as the topology, with the constraint that only one type of boundary condition can be applied on any face of a block. Grid structures appropriate to each component can be generated, for example an 'O' grid about a body or store, a 'C' grid about a wing, pylon or canard with 'H' grids elsewhere. Structured grids are generated within each block and the way in which blocks are joined together dictates the quality and structure (eg 'C' grids or 'O' grids) of the final field grid.

One of the key elements in the grid generation process is the topology generation, since this forms the link between the geometrical complexity of the final field grid and the simpler block by block grid generation process. The process of topology generation is predominantly automated, requiring only a schematic representation of the configuration from the user and this considerably eases the task of analysing complex geometries. Fig 3 illustrates the automation of topology generation for an isolated wing type component. Initially, a Cartesian 'H' grid is constructed using the minimum number of blocks consistent with applying one boundary condition on each block face. If a 'C' grid is to be embedded about the aerofoil, then additional blocks are constructed as shown in steps 2 and 3 of Fig 3. A similar process is adopted for each component of a complete configuration, leading to grid structures appropriate to each component being embedded in an overall 'H' grid. The grid within each block is generated by solving a set of elliptic partial differential equations based on the ideas of Thompson, Thames and Mastin[6] and the control of grid quality via the positioning of grid points is based on the ideas of Thomas and Middlecoff[7]. To illustrate the concept of embedding grid structures appropriate to each component via topological block decomposition, Fig 4 shows a section through a field grid generated about a closely coupled wing canard combination. The block boundaries are also highlighted to show how the grids within each block combine.

The provision of the Jameson algorithm[8] for solving the Euler equations using a cell-centred finite-volume time marching scheme was taken up by British Aerospace (Filton) who initially developed the block structured Euler code EJ83. This program has been further developed at ARA and absorbed into the Multiblock suite to provide the flow solver of the Multiblock method.

## 3 PYLON DESIGN EXERCISE

The pylon design exercise was undertaken to assess the merits of designing the section shape of a pylon to reduce the interference with the wing lower surface flow with a symmetric pylon used as a datum for comparison. The research configuration used for this exercise, shown in Fig 5, featured a 25° sweep constant supercritical section wing of 8.5% thickness to chord ratio. The pylon design, designated a favourable interference pylon, was guided by using a transonic small perturbation code to calculate the streamline patterns about the wing plus body configuration. Using these patterns, a so-called 'zero interference pylon camber plane' was defined to minimise the interference between the pylon and the wing lower surface flow. In an attempt to increase the isobar sweep in the vicinity of the pylons, different thickness distributions were then added to the inboard and outboard sides of the pylon camber plane.

The Multiblock method was not available at the time of this exercise to develop further the pylon designs. However, design improvements were borne out by experiment. Fig 6 shows a comparison between the experimental pressure distributions on the wing lower surface, close to the pylon station ($\eta$ = 0.5), for the cases of no pylon present, single symmetric pylon and a single favourable interference pylon. The interference due to the symmetric pylon can be clearly seen, particularly on the inboard side where the high suction level is likely to result in early onset of shock induced separation. The results show that the favourable interference pylon design was successful in reducing the imbalance in suction peaks between the inboard and outboard sides of the pylon. This led to experimental observations of a delay in the onset of flow separation in the wing pylon junction as either Mach number was increased or incidence was decreased.

In order to provide a data base for the evaluation of new methods such as Multiblock, various model builds were tested including clean wing, single pylon ($\eta$ = 0.5), three pylons ($\eta$ = 0.3, 0.5, 0.7) and three pylons plus tank. These experimental results have been used to evaluate the Multiblock programs by comparing theoretical and experimental pressure distributions in regions of high interference and some of the results of this work are presented in this paper.

## 4 EVALUATION OF THE MULTIBLOCK SYSTEM

### 4.1 Accounting for Viscous Effects

Although useful results, particularly for military aircraft, can be obtained from inviscid calculations with no boundary layer representation, it can prove beneficial to take account of the boundary layer thickness to improve the accuracy and understanding of predicted results. The supercritical wing section of the model shown in Fig 5 exhibits significant viscous effects, particularly on the wing lower surface towards the trailing edge where there is a high degree of camber, resulting in an adverse pressure gradient (Fig 6). This leads to a rapid thickening of the boundary layer in this region and unless this is taken into account in the calculations, the comparison between theory and experiment is degraded. One common method of accounting for the boundary layer within an inviscid code is to use a boundary layer code to calculate the displacement thickness based on pressures input to the program. These pressures can either be experimental pressures on a similar wing (eg an earlier design variant) or the pressures obtained from an inviscid calculation. In the latter case a number of cycles is performed until the changes in displacement thickness are sufficiently small to ignore. Clearly this approach is only approximate but has the advantage that run times remain at the level of an inviscid calculation. The Multiblock system does not presently have a provision for viscous calculations and so it was necessary to adjust the geometry to take into account the results of boundary layer calculations. In the present case, this was done for the wing only since it was felt that, to the extent viscous effects could be reliably accounted for, they were most significant for the wing. For each build investigated, the experimental pressure distributions at M = 0.82, $\alpha$ = 0.0°, for various spanwise sections of the wing, were used as input to a swept integral boundary layer program[9]. Various values of the displacement thickness $\delta^*$ were obtained and these were used to obtain an analytic representation of the three dimensional shape of the boundary layer which was then used for all calculations. In this way, the smooth curvature distribution of the wing was retained and also the spanwise variation in boundary layer thickness close to a pylon station was represented. Fig 7 shows a comparison between the calculated variation of $\delta^*$ for the wing lower surface just inboard and outboard of the mid pylon location ($\eta$ = 0.5), for the single pylon and three pylons plus tank configurations. The effect of the tank on $\delta^*$ and the variation from one side of the pylon to the other can be clearly seen.

## 4.2 Generation of Grids

A field grid consisting of approximately 200,000 grid cells was generated about the wing body and favourable interference pylon and one consisting of approximately 275,000 grid cells was generated about the wing body, three favourable interference pylons and tank. Fig 8 shows a comparison between the model geometry and surface grid about the wing lower surface, mid pylon and tank and Fig 9 shows views through various sections of the field grid for this configuration. It can be seen from Fig 9 that wherever a 'C' or 'O' grid structure meets the 'H' grid structure further out in the field, a five point singularity is produced (also shown in Fig 3). Grid points tend to repel from these singular points and when defining the block dimensions which govern the overall density of the grid, it is beneficial to ensure that these singular points will be positioned sufficiently far away from the regions of high flow gradient not to degrade the solution.

## 4.3 Wing/Body/Single Pylon

Calculations were performed using the favourable interference pylon geometry for flow conditions which would test the ability of the programs to predict the regions of supercritical flow and shocks close to the pylon. Fig 10a shows the wing lower surface isobar pattern close to the pylon for $M = 0.82$, $\alpha = -1.0^{\circ}$, from which the extent of the interference local to the pylon can be seen. A detailed comparison of the calculated wing lower surface pressures with experiment, for stations just inboard and outboard of the pylon, is shown in Fig 10b. The pressures towards the trailing edge are not in good agreement with experiment which is presumably due to the pylon wake not being allowed for by theory. This conclusion is supported by the fact that the results for the two stations furthest away from the pylon, and hence furthest away from the pylon wake, are in closer agreement with experiment towards the trailing edge than the results for the two stations closest to the pylon.

Fig 11a shows the calculated isobar pattern on the inboard side of the pylon compared with experiment. Fig 11b shows a detailed comparison between the calculated pylon pressures and experiment, both close to the lower surface of the wing (A) and also towards the bottom of the pylon (B). Clearly, the results for the single pylon configuration demonstrate that reliable estimates of the suction peaks, shock strengths and shock positions were achieved. The next step was to see how accurately the code predicted the design improvements obtained compared with the symmetric pylon. Fig 12 shows the calculated wing lower surface pressures, compared with experiment, for the symmetric pylon and the redesigned pylon. It can be seen that the effects of the design changes are accurately predicted.

## 4.4 Wing/Body/Three Pylons plus Tank

The results for the single pylon configuration demonstrate that accurate pylon design work can be carried out using Multiblock. However, this case is still far removed from that of a fully laden military aircraft wing, a typical example of which is shown in Fig 13. Such a case poses an extreme challenge to CFD since the flow about store installations inevitably features some regions of separated flow together with rapid flow gradients associated with the small scale of parts of stores, for example, fins and arming vanes. Even with the flexibility of the Multiblock approach, it is not possible to accurately model a general store geometry and even if it were, extreme demands would also be made on the flow solver to obtain accurate results. Presently the most that can be expected of the inviscid Multiblock system applied to configurations such as illustrated in Fig 13, is that it predicts the gross features of the flow associated with the volume of stores beneath the wing. To simplify such a problem sufficiently to be able to demonstrate the state of the art regarding geometrical complexity and the accuracy of results, calculations were performed for three favourable interference pylons ($\eta = 0.3, 0.5, 0.7$) and a mid pylon mounted fuel tank. Once again, the experimental pressures provided an invaluable source of data for evaluation.

The experimental results at $M = 0.82$, $\alpha = -1.0^{\circ}$, showed that there was a large degree of separation at the foot of the shock inboard of the mid pylon and, as expected, the comparison between theory and experiment for this flow case was poor (Fig 14). The results at $M = 0.82$, $\alpha = 0.0^{\circ}$ (Fig 15), still represented a severe test case but with predominantly attached flow and the comparison between theory and experiment is significantly improved. Fig 16a shows the calculated isobar pattern around the wing lower surface pylons and tank from which the extent of the interaction between components can be seen. The accuracy of the results for the mid pylon and store is shown in Fig 16b,c,d. The results show that, apart from the separated flow towards the rear of the pylon, the flow pattern about the mid pylon and tank is accurately predicted. This provides a level of confidence that the mutual interference effects between components are being captured.

## 5 DISCUSSION

The theoretical results shown for the pylon design exercise demonstrate that pylon design work and associated flow field analysis can be carried out with some confidence using the Multiblock code. Although the onset of separated flow cannot be predicted by theory, it can be inferred to some extent, based on the levels of suction peaks and isobar sweep by, for example, comparing the theoretical results with the experimental results of an earlier design variant. The presence of large regions of separated flow about present military aircraft pylon and store installations suggests that there is scope for significant improvements, particularly bearing in mind that the installation of pylons and stores can double the drag of a configuration. The complexity of such flows means that wind tunnel tests will continue to play an important part in the overall design of a military aircraft, however, the usage of increasingly powerful CFD codes in conjunction with wind tunnel tests means that the design process can be accelerated and made more cost effective.

Underwing installations not only increase drag but also affect the performance characteristics of the wing and, if CFD is to be of use in assessing performance, the calculated pressure distributions must integrate to give reliable estimates of forces and moments. Multiblock has been used with some success to predict lift, drag and pitching moment variations for military aircraft research models, however, since the method is inviscid, only incremental variations in drag can be obtained. In spite of this, the programs have been used to optimise canard and trailing edge flap deflections to trim a model with minimum drag penalty(4) at M = 1.6. In addition, the method has also been used in support of experiment to identify the source of an anomalous reduction in the drag of an installation drag research model through the transonic flow regime(10).

Off-surface flow data is also required from both theory and experiment in support of store separation and store clearance work. To predict completely store separation by theory would be extremely computationally expensive, requiring a grid update and flow calculation at each time step as the store moves. To alleviate the difficulty of this task, work has concentrated on a semi-empirical approach, in which the interference flow field about a store is obtained from theory or experiment and is then used as input to a semi-empirical store loads program such as NUFA(11). If required, the predicted store loads can then be used as input to a store trajectory calculation. Following this procedure, various codes can be formally combined to yield a complete store trajectory calculation method. The requirements of the flow field calculation are for geometrical flexibility and ease of extracting flow field data in a form suitable for input to a store loads program. Presently, the British Aerospace (Brough) subcritical panel program SPARV(12) is used for this role since it allows complex geometries to be modelled, however, it is restricted to essentially subcritical flows. The Multiblock code features a powerful post processor developed at British Aerospace (Hatfield) which permits an arbitrary array of grid points to be defined, onto which the Multiblock flow field results can be interpolated. This, coupled with the ability to represent complex geometries, suggests that Multiblock may be useful for extending the range of applicability of store trajectory packages. Fig 17 illustrates the type of flow data which can be extracted from a Multiblock flow calculation and then used as input to a program such as NUFA to obtain the store loads.

Presently, the CFD method on the horizon at ARA is a further development of Multiblock, allowing the use of locally unstructured grids in the vicinity of very complex geometry such as about the stores shown in Fig 13(13,14). This will have the advantage of being based on a well established method and so can be viewed as providing potential improvements in efficiency and flexibility to the present system. Such improvements will then create a demand for detailed wind tunnel data for evaluation exercises similar to those described and discussed in this paper.

## 6 CONCLUDING REMARKS

1. The present Multiblock method provides a set of codes geared towards the use of CFD applications engineers rather than theoretical code developers.

2. The generation of grids about complex geometries is possible, however, there remains a considerable gap between what is a complex geometry for CFD calculations and the complex geometry of a heavily laden military aircraft.

3. Further Multiblock developments afoot to reduce this gap using locally unstructured grids will have the advantage of being based on an already well established method.

4. Evaluation work using Multiblock has shown that it has a powerful design potential, enabling wings and pylons to be modified to reduce some of the significant drag penalties associated with underwing installations.

5. Other evaluation work has shown that the code can provide valuable support to engineers involved in various projects, eg
    - interpretation of wind tunnel results
    - military aircraft performance estimation
    - installation drag and carriage load testing.

## 7 ACKNOWLEDGEMENTS

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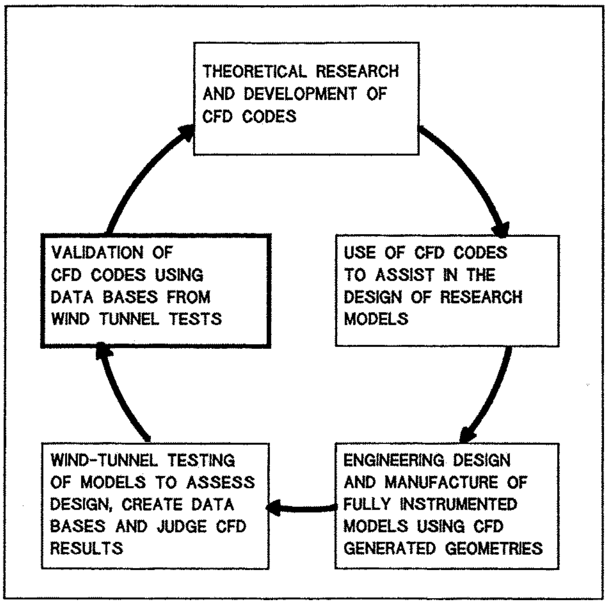



*FIG 1 ON-GOING APPROACH TO CFD DEVELOPMENT EVALUATION AND APPLICATION*

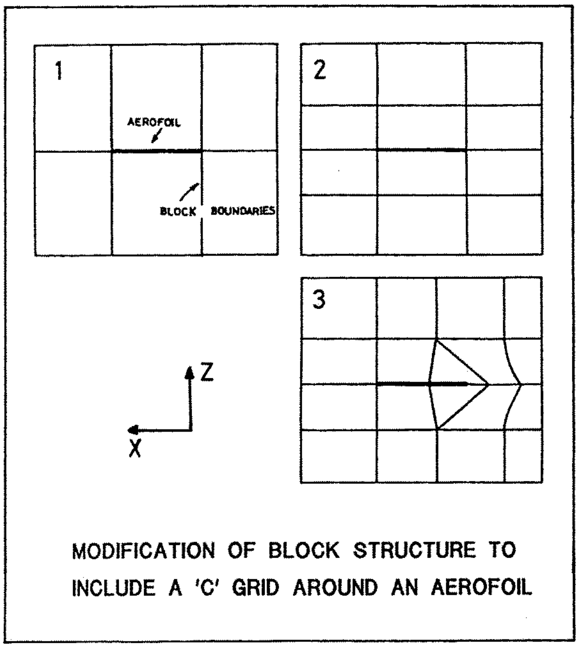



*FIG 3 TOPOLOGY CONSTRUCTION*

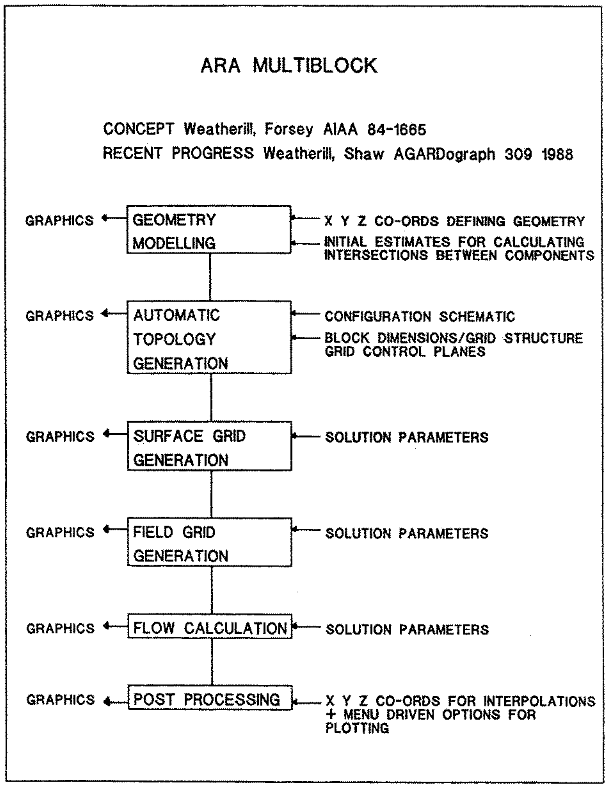



*FIG 2 PROGRAM ELEMENTS OF THE MULTIBLOCK SYSTEM*

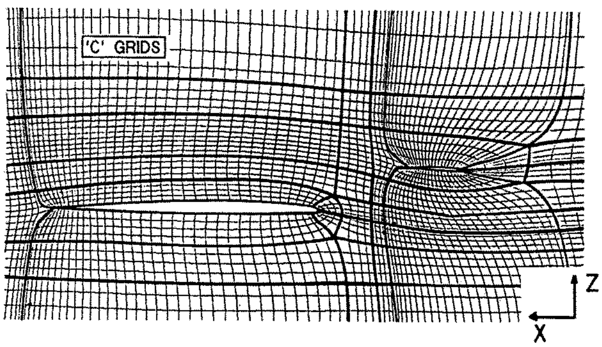



*FIG 4 SECTION THROUGH A FIELD GRID SHOWING BLOCK BOUNDARIES*

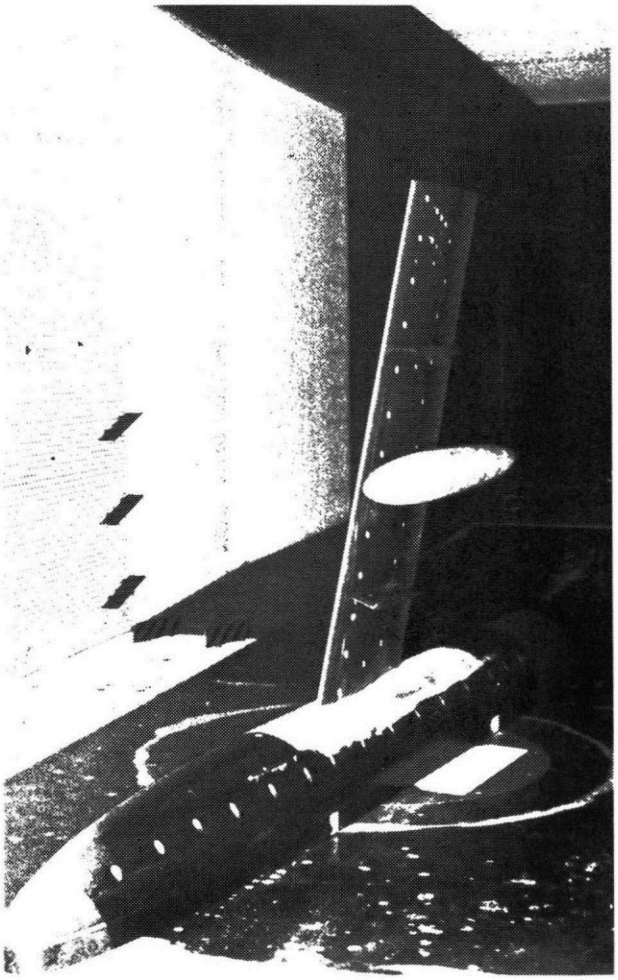


FIG 5 WING BODY PYLON STORE RESEARCH MODEL IN THE WIND TUNNEL

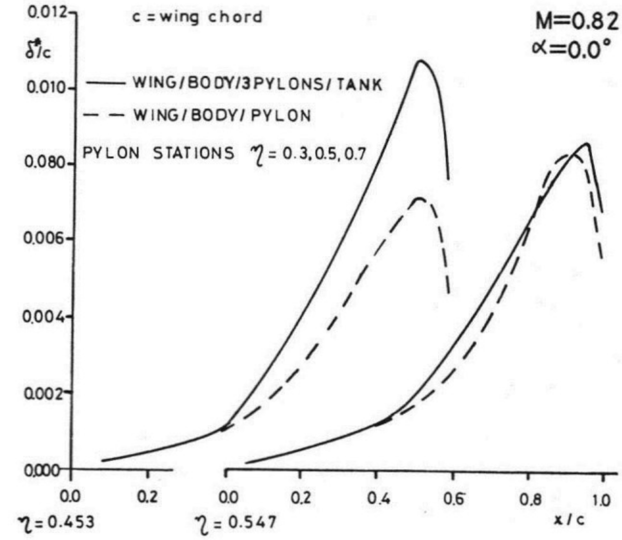



FIG 7 CALCULATED VARIATION OF $\delta^*$ ON WING LOWER SURFACE

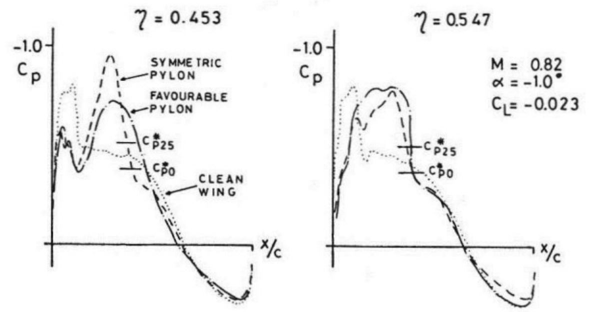



FIG 6 EFFECT OF PYLON DESIGN ON WING LOWER SURFACE PRESSURES

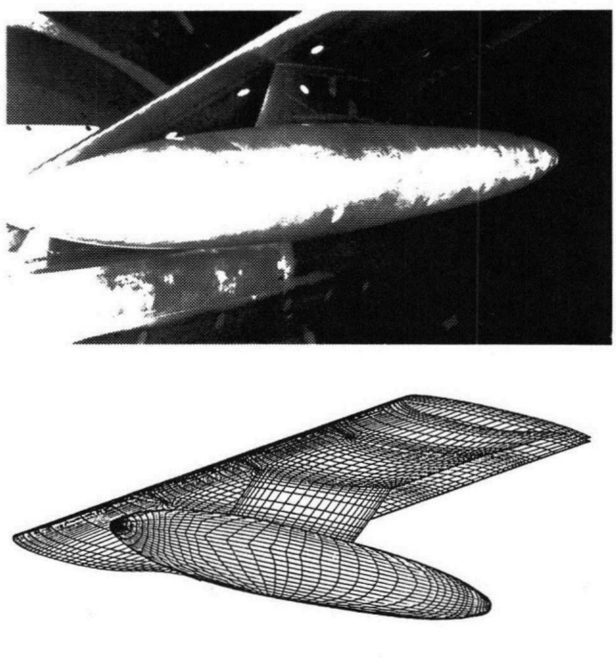


FIG 8 COMPARISON BETWEEN MODEL GEOMETRY AND MULTIBLOCK SURFACE GRID

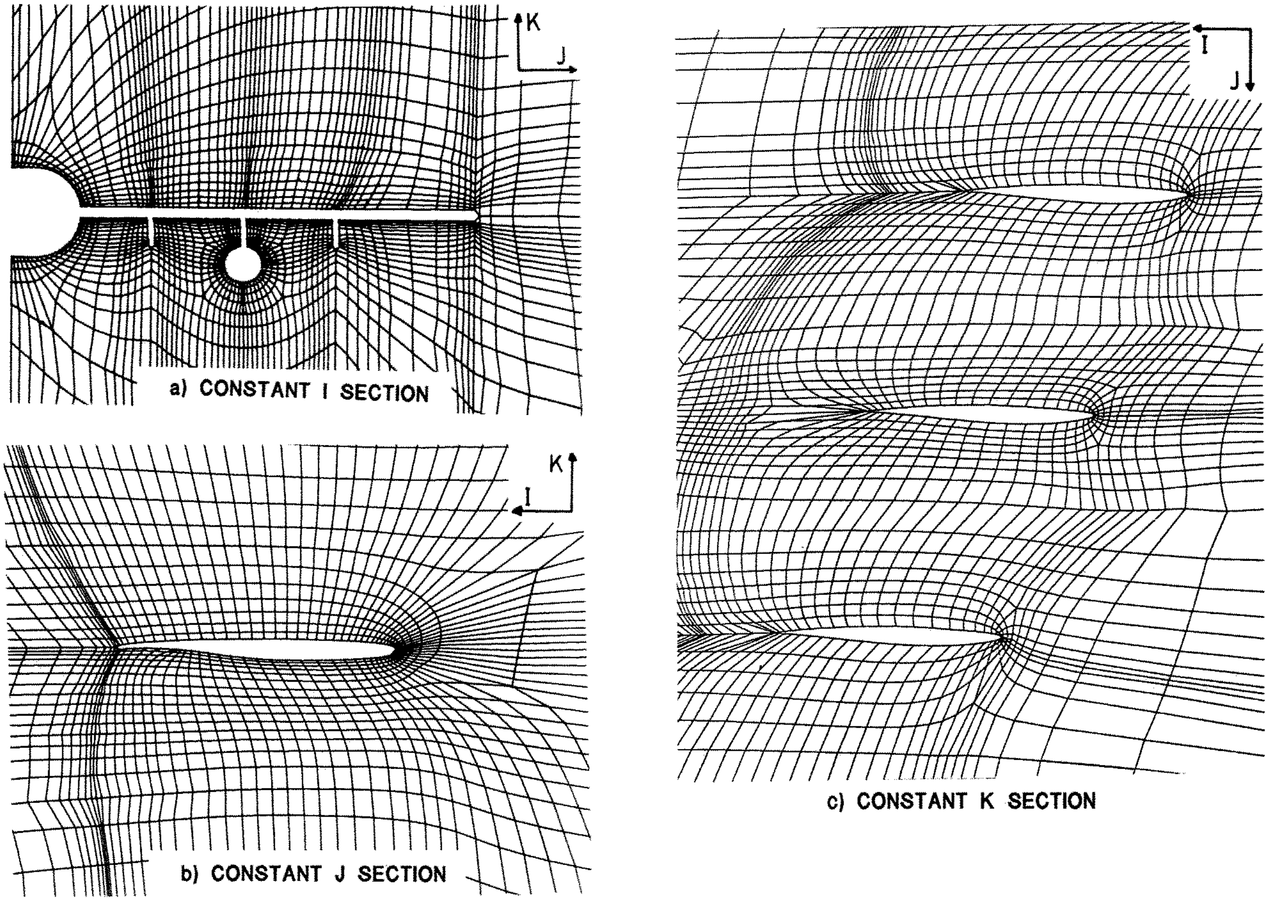



*FIG 9 VIEWS OF MULTIBLOCK FIELD GRID*

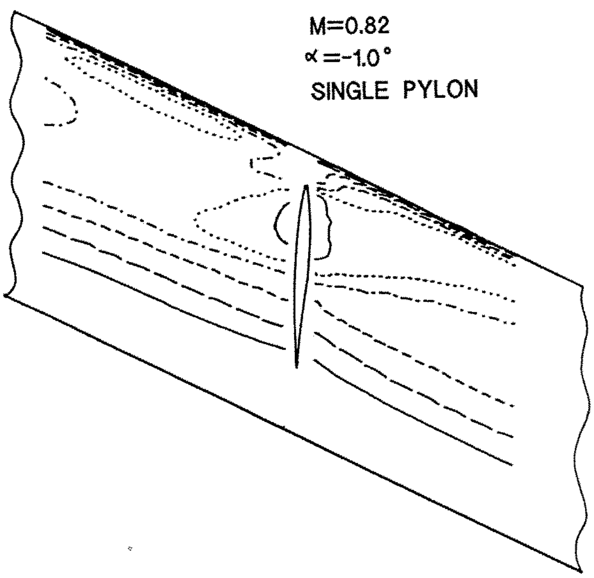



*FIG 10a CALCULATED WING LOWER SURFACE ISOBAR PATTERN*

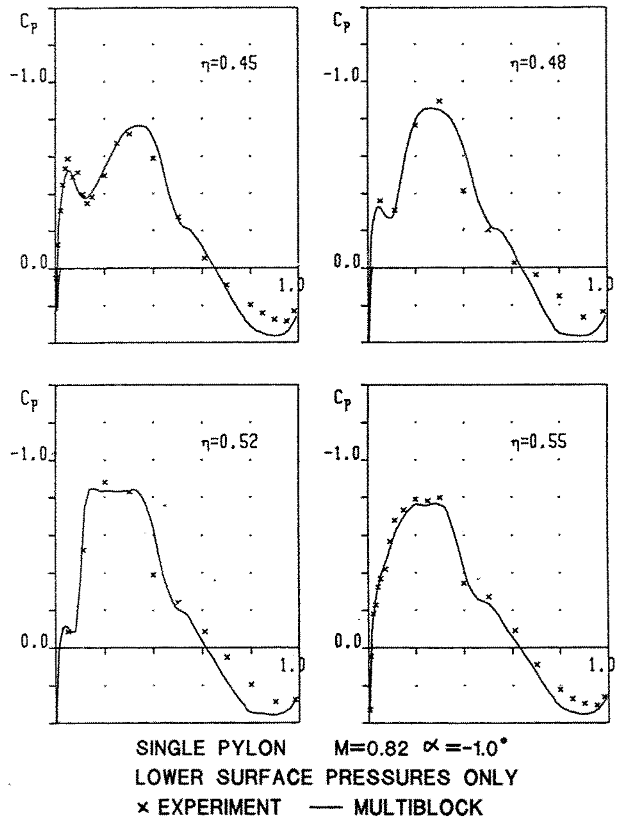



*FIG 10b COMPARISON BETWEEN THEORY AND EXPERIMENT CLOSE TO THE PYLON*

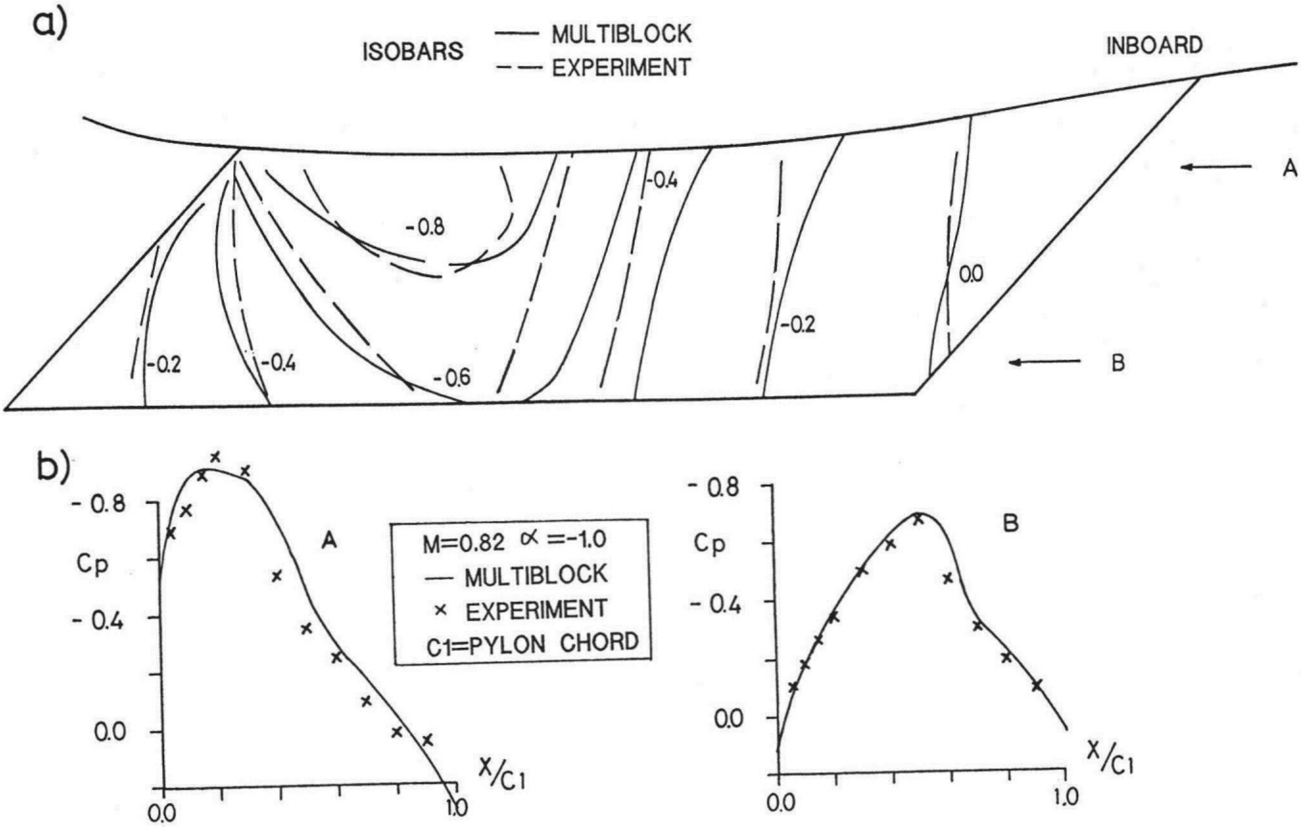
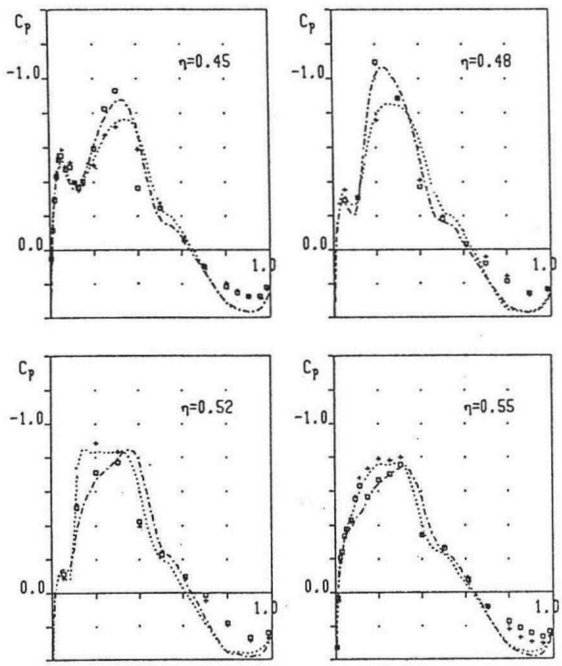



*FIG 11 FAVOURABLE INTERFERENCE PYLON PRESSURE DISTRIBUTIONS*




M=0.82 ∝=-1.0° LOWER SURFACE ONLY

THEORY (MULTIBLOCK) EXPERIMENT

-·-· SYMMETRIC PYLON ◻ SYMMETRIC PYLON

---- FAVOURABLE INTERFERENCE PYLON + FAVOURABLE INTERFERENCE PYLON

*FIG 12 COMPARISON BETWEEN THEORY AND EXPERIMENT FOR ALTERNATIVE PYLON DESIGNS*

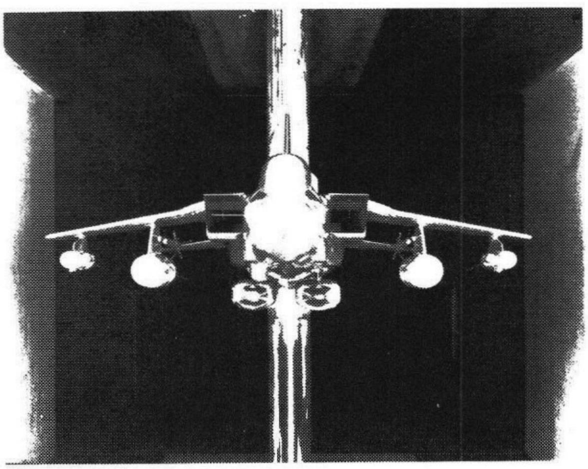
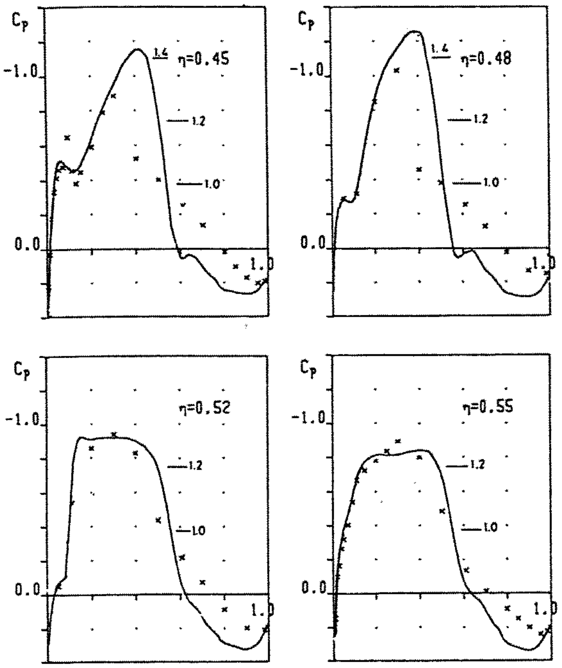


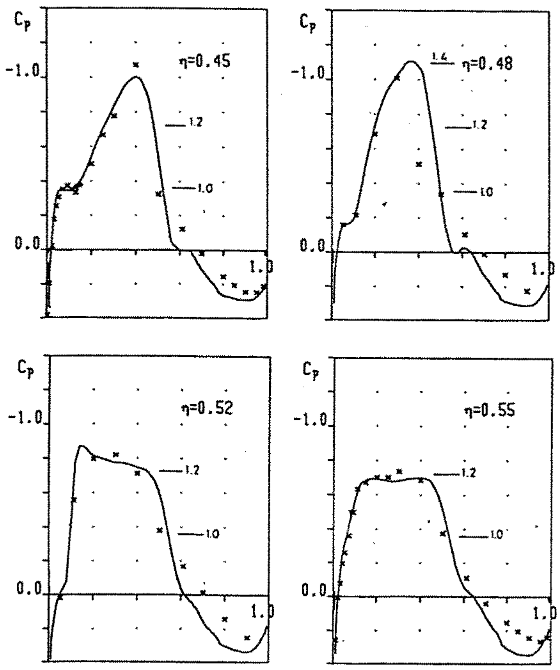
*FIG 13 HEAVILY LADEN MILITARY AIRCRAFT*




WING + 3PYLONS + TANK M=0.82 α =-1.0°
LOWER SURFACE PRESSURES ONLY
× EXPERIMENT —— MULTIBLOCK

LOCAL MACH NO'S SHOWN ASSUME AN UNSWEPT SHOCK

*FIG 14 WING LOWER SURFACE PRESSURE DISTRIBUTIONS*




WING + 3PYLONS + TANK M=0.82 α=0.0°
LOWER SURFACE PRESSURES ONLY
× EXPERIMENT —— MULTIBLOCK
LOCAL MACH NO'S SHOWN ASSUME AN UNSWEPT SHOCK

*FIG 15 WING LOWER SURFACE PRESSURE DISTRIBUTIONS*

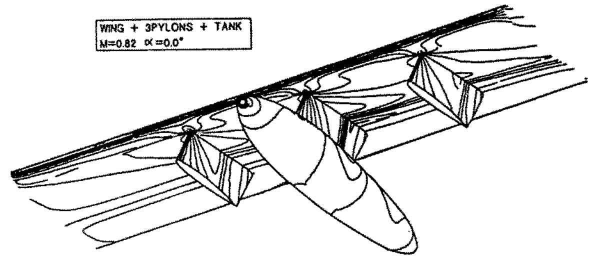



*FIG 16a CALCULATED ISOBAR PATTERN*

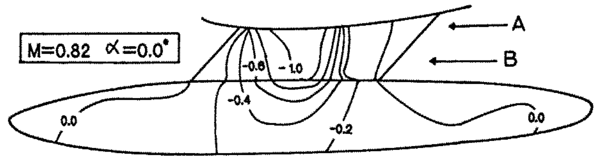



*FIG 16b CALCULATED ISOBARS ON INBOARD SIDE OF PYLON AND TANK*

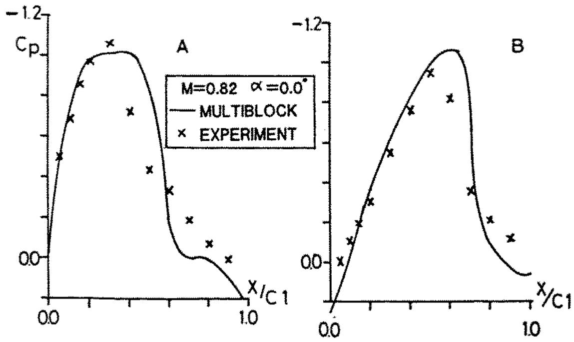
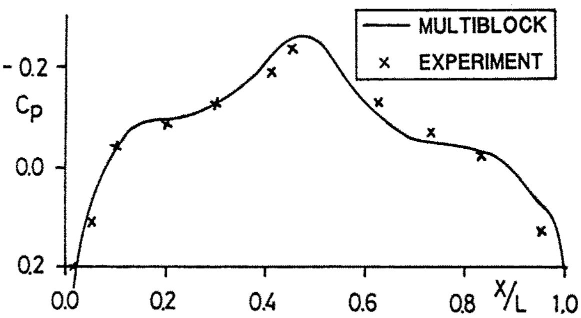



*FIG 16c PRESSURES ON INBOARD SIDE OF PYLON*




L=TANK LENGTH

*FIG 16d PRESSURES ON UNDERSIDE OF TANK*

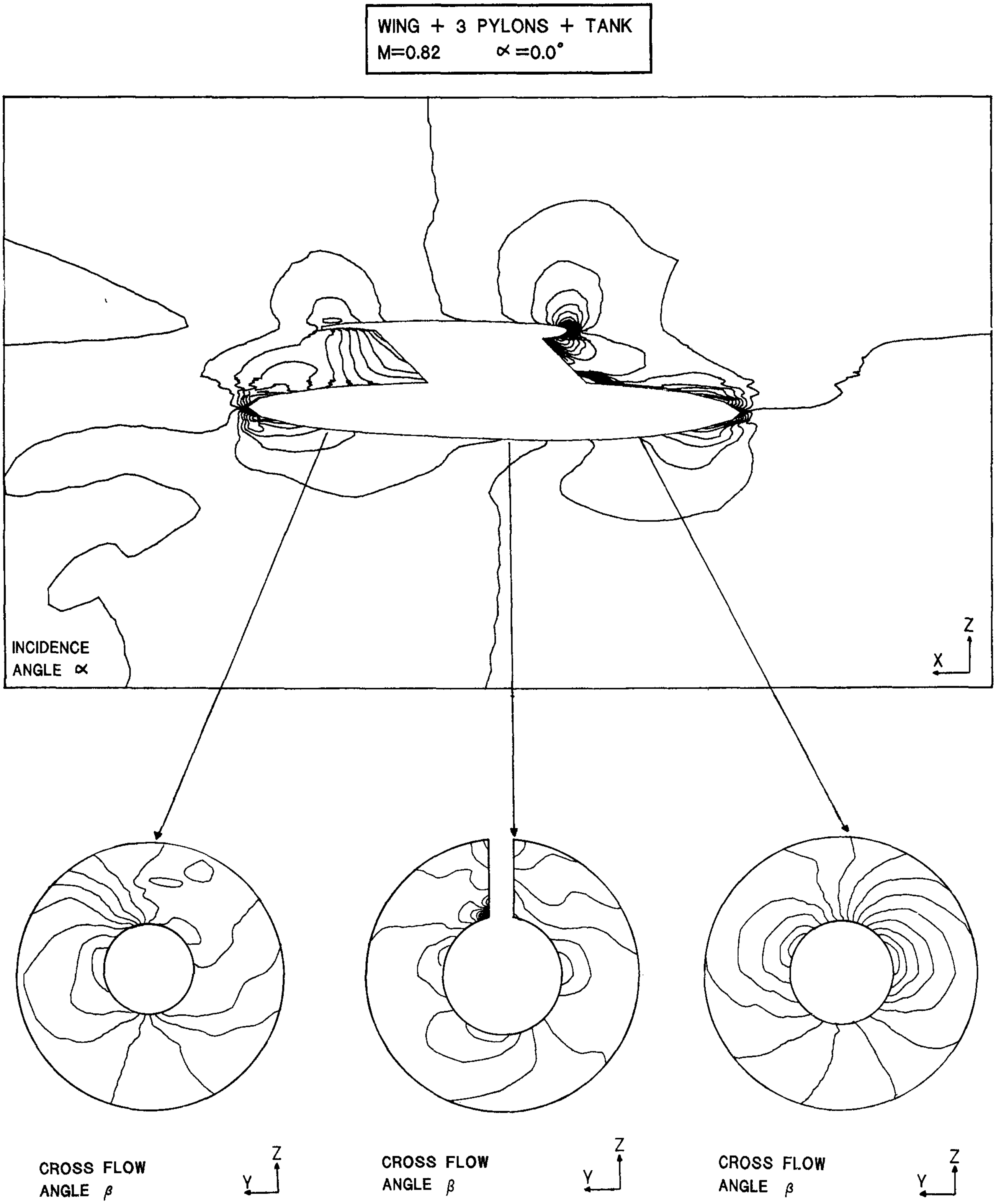



*FIG 17 FLOWFIELD DATA EXTRACTED FROM MULTIBLOCK FLOWFIELD CALCULATION*