TRANAIR Applications to Engine/Airframe Integration

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The application of a three-dimensional, full-potential, finite-element method, TRANAIR, to the installation of turbofan engines on transport configurations is presented. An extension of the method, whereby regions of different total pressures and temperatures are modeled to simulate engine exhaust flows, is explained. This extension allows a transonic flow analysis of the mutual interference between turbofan exhaust flows and the nearby airframe. Computational results and comparisons with experiment are presented to illustrate the abilities of TRANAIR to adequately represent these complex geometry and flow phenomena. Results are presented for two isolated nacelles and three installed engine/airframe combinations. Comparisons of computed results with test data show good agreement.

Nomenclature

C_P = pressure coefficient
M = Mach number
p = static pressure
q = speed
r_P = ratio of local to freestream total pressure
r_T = ratio of local to freestream total temperature
x = streamwise coordinate
y = lateral coordinate
z = vertical coordinate
γ = ratio of specific heats
ρ = density

Subscript

∞ = freestream

Introduction

THE introduction of the full-potential, finite-element code, TRANAIR, with a newly developed capability of modeling regions of mixed total pressure and temperature has presented the design engineer with greatly enhanced analysis capability. The salient features of the code for the practicing engineer are that it computes transonic nonlinear flow phenomena, including engine power effects, using a grid generation scheme that provides timely construction of computational models.

Existing computational fluid dynamic (CFD) methods have been only partially effective in the calculation of underwing nacelle installation effects.[1-3] Panel methods, using linear potential equations, provide good geometric definition but do not treat transonic flows. Most full potential, Euler, and Navier-Stokes codes are not readily applicable to the geometric complexity of an airframe with an installed nacelle and strut. Previous efforts using full-potential equations and single flowfield total pressure and temperature to analyze turbofan exhaust effects on airframes have involved some method of determining the shape of the installed exhaust plume that was then modeled as a solid body. Solid plume modeling has had varying degrees of success.[1,2] Although some applications have provided good agreement with test data outside the exhaust plume, a solid plume does not allow evaluation of the effects of the airframe on the core cowl and fan exhaust flow. These shortcomings have been overcome with the modeling of regions of mixed total pressure and temperature in TRANAIR.

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Description of the Method

TRANAIR is a finite-element full-potential code for the analysis of transonic flows over completely general complex configurations. The difficulties of generating a surface-fitted grid to a complex geometry are avoided by the use of a hierarchically refined rectangular grid. A global box large enough to include all the embedded supersonic zones is first placed around the configuration. Rectangular grids within the box are generated by the program and automatically refined in a hierarchical manner near the configuration boundaries as a function of paneling density and a few user-specified controls. For areas where large variation of the velocity potential are expected, such as the wing leading edge, shock waves, exhaust flows, etc., additional local grid refinement can be specified by the use of special interest regions. Automatic adaptive flowfield grid refinement has been incorporated into the code but was not yet operational at the time this paper was written. The numerical problem is solved iteratively until either convergence is reached or the number of iterations has been exhausted. Six to eight orders of convergence are routinely achieved with the ability to go to machine accuracy if desired. Aerodynamic properties such as pressure coefficient and local Mach number are then computed at the input surface points and output as plotting files. Details of the methodology in TRANAIR are described in Refs. 4-6.

A recent extension involves flows with different total conditions such as those in an engine exhaust stream. The density and pressure are defined as

$$\{1+[1-(q/q_\infty)^2/r_T]M_\infty^2(\gamma-1)/2\}^{1/(\gamma-1)}r_P/r_T$$

$$\{1+[1-(q/q_\infty)^2/r_T]M_\infty^2(\gamma-1)/2\}^{\gamma/(\gamma-1)}r_P$$

where r_P is the local-to-total pressure ratio, and r_T the local-to-total temperature ratio for the specified regions.

Regions of different total conditions are bounded by user-specified, wakelike networks that define the exhaust plumes. The boundary conditions on these networks enforce continuous static pressure and represent conservation of mass across the plume boundary. Since these boundaries are permeable, the solutions are relatively insensitive to the shape of the defined plume. This means that the exhaust plume network can be defined in a simple manner (for example, maintaining constant exit area) and still provide a good solution for the mutual influences of the airframe and the operating engine.

Results

TRANAIR has been applied to engine/airframe integration for nearly a year. Several configurations have been analyzed to validate the code. TRANAIR has also been used for the analysis of some new installations. The results from selected cases are presented here to illustrate the functionality of the code.

Isolated Nacelles

Isolated axisymmetric turbofan nacelles were analyzed during development of the multiple total pressure and temperature region treatment for the simulation of exhaust flows as part of the code validation. Figure 1 shows the surface discretization (paneling) and longitudinal outline of an isolated, axisymmetric, turbofan nacelle used for static nozzle exhaust testing. Since TRANAIR is a three-dimensional code, two planes of symmetry have been specified to limit the analysis to one quadrant of the nacelle and flowfield. The high total pressure region of the fan exhaust requires dense grids, in any analysis code, to resolve the multiple shocks that may form. The adaptively refined computational grid generated by TRANAIR is shown in Fig. 2. Also shown are core cowl surface pressures from the experiment, TRANAIR, and an axisymmetric Navier-Stokes code PARC2D.[7] TRANAIR and PARC2D results match the experimental data reasonably well. The levels of the pressure peaks computed by TRANAIR match those from the experiment. The spacing of the multiple shocks is less well predicted. In this case, the dominant flow features are inviscid. The addition of viscous terms in the Navier-Stokes solutions only yields a slight improvement in the agreement with test data. The remaining discrepancy in the agreement with test data likely is due to an imprecise knowledge of the initial total temperature and pressure distributions of the exhaust flow. A uniform distribution at the advertised test conditions was used in both codes. Unlike many of the Euler and Navier-Stokes solvers, TRANAIR is capable of analyzing supercritical exhaust flows at essentially static ($M=0$) freestream conditions without difficulty.

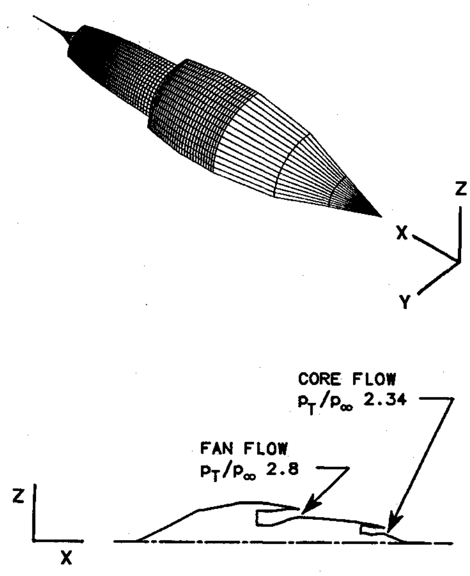

Fig. 1 TRANAIR model for an isolated nacelle.

Figure 3 presents TRANAIR results compared to those from an axisymmetric Euler code for an isolated turbofan nacelle with inlet. The freestream Mach number is a moderate 0.5, but the total pressure in the fan exhaust is high enough to generate a supersonic flow. The TRANAIR results agree quite well with those from the inviscid Euler code.

Installed Flow-Through Nacelles

A wind-tunnel model of the 747-200 with flow-through nacelles was analyzed using TRANAIR as a validation test case. The surface paneling used to define the airplane is shown in Fig. 4 and a close-up of the nacelle paneling in Fig. 5. In order to insure a good geometric definition, and since transonic flows are more sensitive to surface curvature and slope than subsonic flows, the body, wing, nacelle fan cowls, bifurcators, core cowls, and nacelle struts were all densely paneled. Approximately 23,000 panels were used for the definition. The TRANAIR field grid density is determined by the paneling density and user control. The accuracy and cost of a solution is determined by the number of grid points and level of convergence. Wing-presure distributions for this model at a low supercritical freestream Mach number $M=0.80$, where viscous interactions are weak, are presented in Fig. 6. Both TRANAIR and experimental results are presented at span stations just inboard and outboard of the two engine installations. Also shown are experimental data for the configuration without the nacelles and struts to illustrate the impact of the

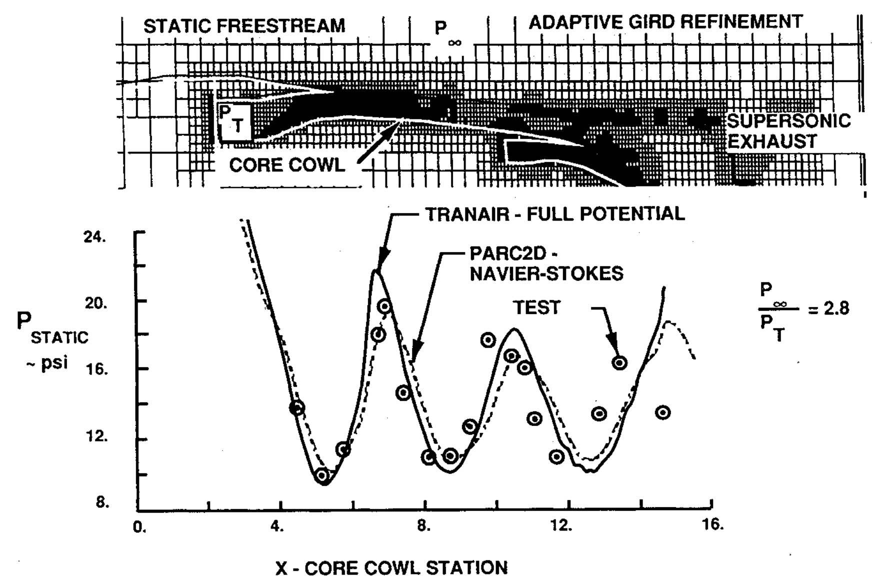

Fig. 2 TRANAIR grid and core cowl surface pressures.

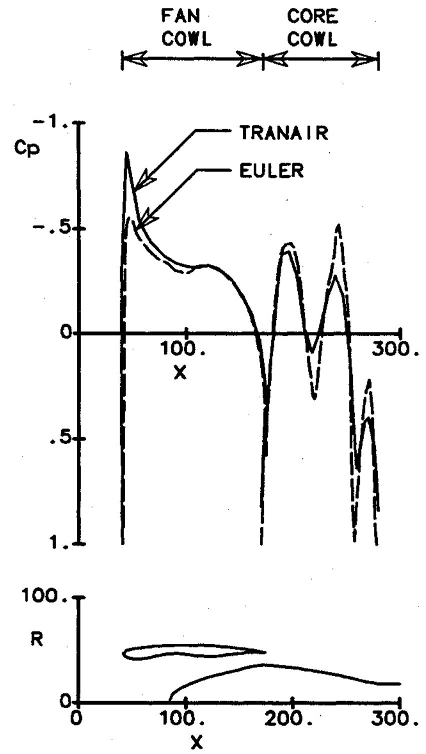

Fig. 3 Surface pressures on an isolated turbofan nacelle.

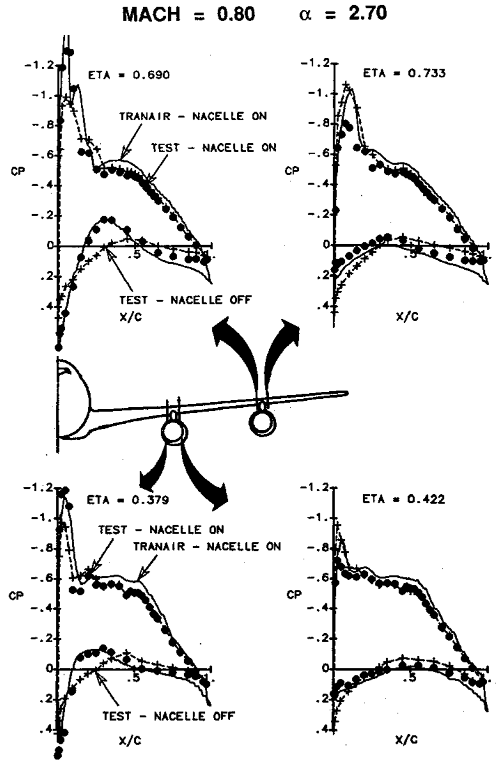

Fig. 6 Wing-surface pressure distributions.

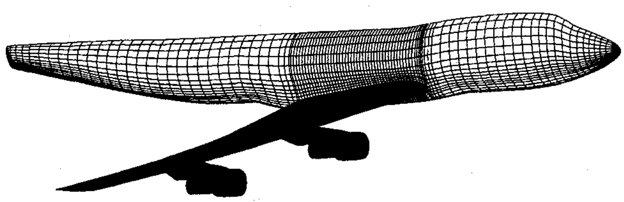

Fig. 4 747-200 TRANAIR model.

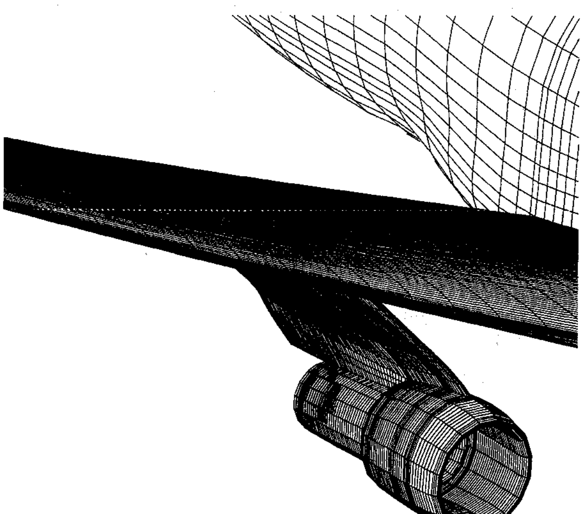

Fig. 5 Paneling details near inboard nacelle.

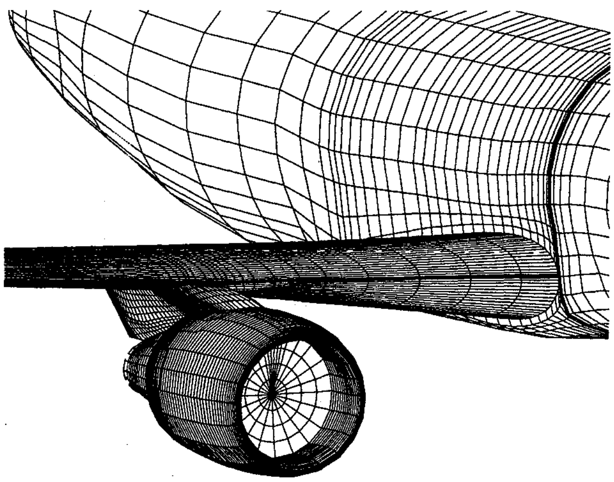

Fig. 7 Surface geometry of an installed short duct nacelle.

installation on the wing surface pressures. The TRANAIR results agree quite well with the nacelle-on wind-tunnel data.

Installed Short Duct Powered Nacelles

Several short duct engine installations on transport configurations with under-wing, strut-mounted nacelles have been analyzed using the option of specifying different exhaust total pressure and temperature ratios. The paneling for one of the configurations analyzed is shown in Fig. 7. The computational model included wing, body, strut, nacelle fan cowl and core cowl, and the internal fan exhaust duct as impermeable surfaces. A fan-face barrier inside the nacelle inlet allows control of inlet mass flow. Exhaust plumes define regions of specified total pressure and temperature to simulate the exhaust flow. Shed wakes from the wing and strut trailing edges are also defined as necessary. Approximately 12,000 panels were used to define the configuration and its resulting wakes and plumes.

Mach and pressure contours on the nacelle strut down in Fig. 8 illustrate the effect of the plume boundary conditions for an exhaust flow. The pressure isobars are continuous across the exhaust plume boundary, but the Mach contours are not. The line marking the discontinuity in the Mach contour plot is the plume boundary—since total pressure and temperature are discontinuous at this boundary, so is the Mach number distribution. By specifying inlet mass flow and ex-

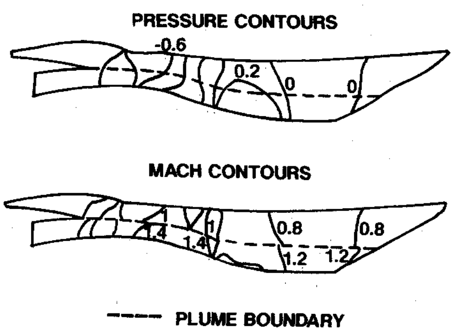

Fig. 8 Pressure and Mach contours on the strut.

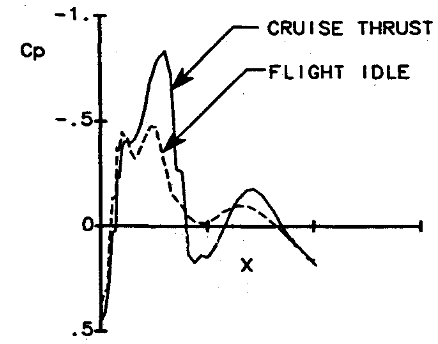

Fig. 12 Inboard side strut pressure distributions.

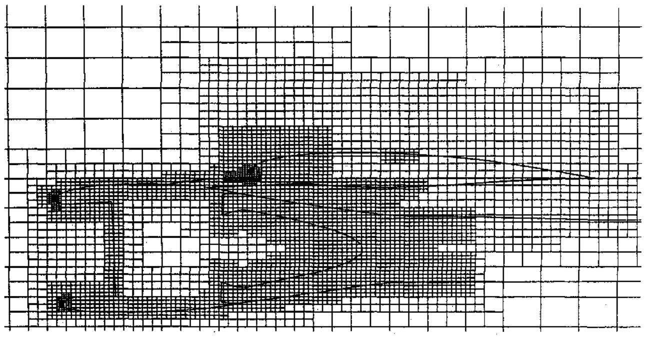

Fig. 9 TRANAIR grid—*X-Z* plane through wing, strut, and nacelle.

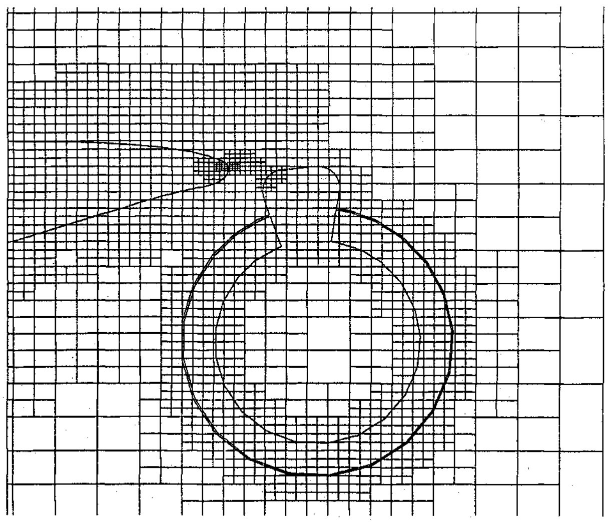

Fig. 10 TRANAIR grid—*Y-Z* plane through wing, strut, and nacelle.

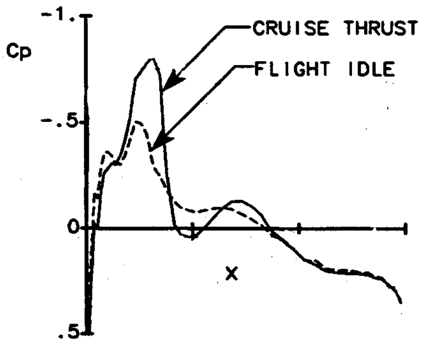

Fig. 11 Wing lower surface pressure distributions, inboard of strut nacelle.

haust total pressure and temperature ratios, actual flight conditions can be simulated.

Cross sections of the TRANAIR grid through the nacelle and parallel to the *X-Z* and *Y-Z* planes for one of the configurations analyzed are illustrated in Figs. 9 and 10. These examples illustrate the grid structure and density required for good resolution of an installed engine/airframe analysis. Approximately 300,000 grid boxes were used in these solutions. TRANAIR results are shown along a wing buttline just inboard of the nacelle strut in Fig. 11 and on the inboard side of the strut above the fan exhaust plume in Fig. 12. The configuration was analyzed with flight-idle and cruise-thrust simulations. The values of the total temperature and total pressure ratios necessary to simulate these two thrust conditions were obtained from engine manufacturers' published characteristics and from flight-test measurements. The results indicate a significant change in the surface-pressure distributions due to the increased thrust. The region of supersonic flow that develops at this condition is terminated by a shock. The "stairstep" variation in the pressure distributions shown in these figures is an artifact of the method by which the pressures calculated in the flowfield grid were transferred to the configuration surface at the time of this TRANAIR solution. The problem has since been rectified.

TRANAIR surface-pressure distributions for both "ram" (freestream total pressure and temperature) and cruise thrust are shown in Fig. 13 at several circumferential positions on a core cowl of an installed short duct turbofan nacelle. The influence of the nearby airframe is clearly evident in these results. The increase in engine thrust aggravates the variation of the pressure distribution around the exposed core cowl. The field grid for this case was not dense enough to capture the multiple shocks expected on a core cowl at cruise thrust, but the general features of the flow are believed to be representative. Requirements for dense wing grid combined with memory limitations of a CRAY X-MP 24 with a 128 Mword SSD prevented increasing the grid density in the exhaust plume at the time of this analysis. Recent improvements in TRANAIR operating and storage efficiency will now allow significantly more grid (~500,000 boxes).

Installed Long Duct Powered Nacelles

Several long duct mixer nacelle installations, similar to the configuration shown in Fig. 14, have also been analyzed at cruise flight conditions. One configuration proposed for a future wind-tunnel test had previously been analyzed in the linear potential code A502/PANAIR.[8-10] Figure 15 shows that although A502/PANAIR predicted a region of supersonic flow on the wing lower surface in the region of the strut/nacelle, it missed the level by a considerable amount compared to the TRANAIR predictions. Panel methods have been frequently used for this type of analysis because of their usability and their ability to accurately predict the onset of local supersonic flow. However, the limitations of linear theory prevent panel methods from accurately predicting what happens after the flow goes supersonic. Full potential codes do not have this

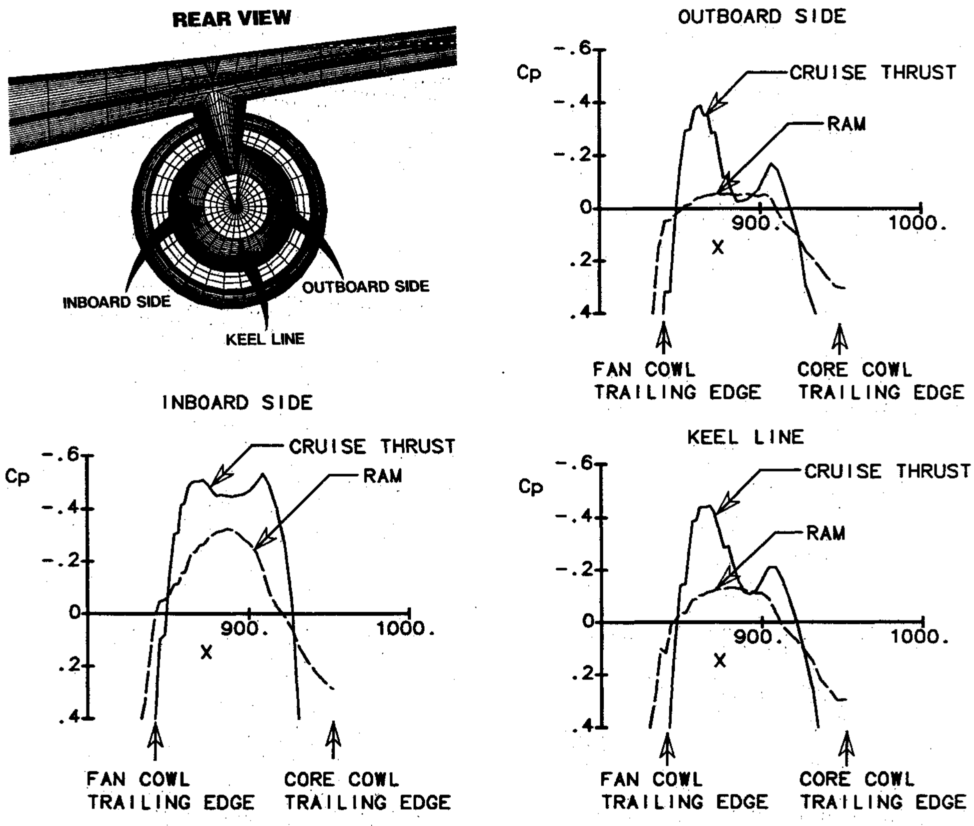

Fig. 13 Core cowl pressure distributions for an installed short duct nacelle.

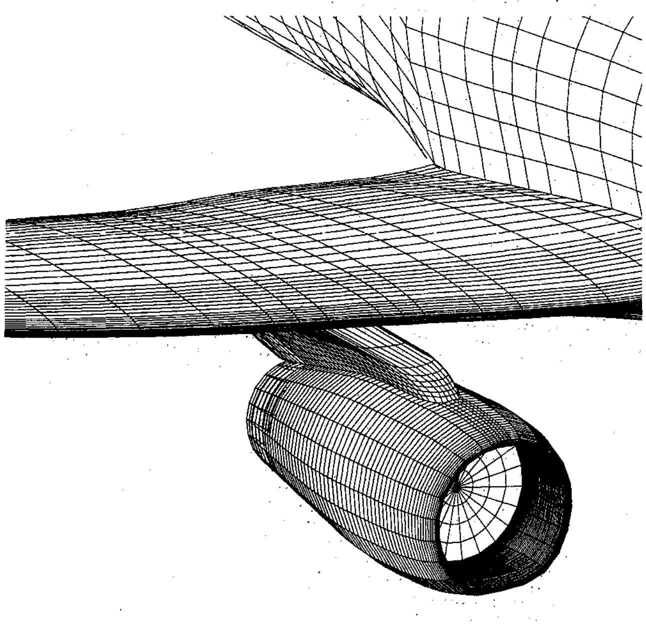

Fig. 14 Surface geometry of an installed long duct nacelle.

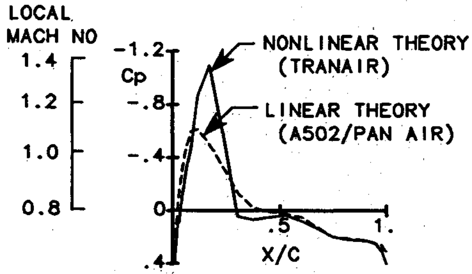

Fig. 15 Wing lower surface pressure distribution on a proposed installation.

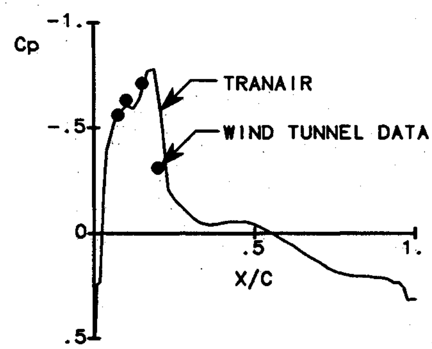

Fig. 16 Validation of wing lower surface pressure distribution.

limitation. TRANAIR predicted a rather strong shock on the wing lower surface, indicating an excessive installation drag. To gain confidence in the solution, a similar, previously tested configuration was analyzed. The TRANAIR computational model was modified within a few days to represent the test configuration. A comparison of the resulting TRANAIR solution with the experimental wing lower surface pressure distribution, shown in Fig. 16, sufficiently increased management's confidence in the TRANAIR predictions to discard the proposed configuration without the expense of a wind-tunnel test.

The CPU time for a solution with A502/PANAIR for one of these cases (four angles of attack) is approximately 1500 s on a CRAY X-MP. A typical TRANAIR solution (one angle of attack) for this type of case will take about 7200 s. The decision as to which code to use should not be made on the basis of computer cost, but rather accuracy needs. The cost of preparing the surface discretization (paneling) will greatly outweigh the computer cost of the solution. If all that is needed from the solution is an indication of the presence of local supersonic flow, then a linear solution will be adequate. If however, more detail of what the flow is doing in the supersonic regions, including those in the exhaust flow, is needed, then TRANAIR is the only choice. With TRANAIR all the nonlinear features of the inviscid transonic flow about a complex configuration can be calculated without the expense and flow time needed to construct a structured field grid. Additional examples of TRANAIR applications to complex configurations can be found in Ref. 11.

Conclusions

Although still under development, TRANAIR has been found to provide a greatly enhanced analysis capability for engine/airframe integration. Future engine installation design can benefit from an analysis using TRANAIR because of the following aspects of the code:

1) It treats complex geometries without the complexity of surface-fitted grid generation.

2) It treats transonic flows.

3) It treats regions of different total pressure and temperature allowing jet exhaust simulation.

4) It is usable in a time frame consistent with airplane development schedules.

Comparisons with other theoretical results and test data have shown good agreement. Continued development of TRANAIR, including the addition of viscous boundary-layer effects, will make it an even more useful tool to the aircraft design engineers.

Acknowledgments

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