WING DESIGN FOR SUPERSONIC CRUISE/TRANSONIC MANEUVER AIRCRAFT

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Abstract

An approach to multiple-design-point tactical aircraft wing development is discussed. Requirements for proposed tactical aircraft include both efficient supersonic cruise and acceleration and enhanced transonic maneuvering performance. A computational approach was developed to address the conflicting requirements of these conditions. The approach consists of developing two point designs: a transonic maneuver configuration with weak shocks and nearly attached flow and an optimum supersonic cruise design. A compromise is then developed in an iterative cycle which seeks to approach the point design flow quality through the use of variable camber. Computational results for representative tactical aircraft are presented to illustrate the process. Test experience is discussed to indicate the performance achieved with compromise designs relative to point-design configurations.

Introduction

The design of tactical aircraft presents a challenge because of the wide spectrum of operational requirements for typical military scenarios. A number of primary operating points exist throughout the subsonic-transonic-supersonic flow regime in addition to many off-design constraints that require new approaches and compromises. The goals for advanced tactical systems include efficient cruise at subsonic and supersonic mach numbers, superior maneuvering capability at subsonic and supersonic mach numbers, and rapid acceleration. The aerodynamic requirements for each condition often present conflicting requirements. The need for rapid acceleration to supersonic flight and efficient supersonic cruise emphasizes a low-aspect-ratio, highly swept wing with thin, low-camber airfoil sections. Efficient transonic maneuver requires higher aspect ratio planforms with moderate sweep and wing sections with increased camber for operation at elevated lift coefficients. These conflicts suggest, of course, the use of variable geometry. Even with a variable camber system, a compromise best satisfies the requirements of a multiple-design-point aircraft.

The development of lifting surfaces for fighter aircraft is accomplished through a series of computational designs and experimental verifications. Subsonic and supersonic cruise development is relatively straightforward due to the wide applicability of linear theory analysis, design, and optimization methods. In the transonic regime, particularly at high lift coefficients, the computational methods are less well developed. Additionally, viscous effects become important, particularly when moderate-to-strong embedded shocks are present. The use of transonic numerical methods is rapidly increasing due to the costs of wind tunnel testing.

The development of a suitable compromise is complicated computationally by the requirements to analyze nonsmooth geometries and to accept regions of separation larger than those for point designs. Thus, more uncertainty is introduced relative to the ability of the numerical analysis to simulate the flow fields, not only at transonic maneuver conditions, but also at supersonic cruise.

Background

Tactical aircraft designs may be categorized as point, point with optimization at a secondary condition using variable geometry, and compromise. For the first two categories, there is one primary objective. Off-design performance is a fallout for a fixed-geometry configuration. By using a variable camber system developed specifically for another point, off-design performance is improved without compromising the primary objective.

The characteristics of several point-design aircraft are presented in figure 1. Maximum lift-to-drag (L/D) ratios and L/D at typical maneuvering conditions are shown for a subsonic cruise design representative of current operational aircraft, a transonic maneuver design, (1) and a supersonic cruise design (2). Variable camber could be used to improve the off-design characteristics of each. In fact, for the transonic maneuver design, some variable camber was employed, but it did not impact the supersonic performance.

Numerical studies (3) have been conducted to define geometries for supersonic cruise and transonic maneuver configurations which achieve good

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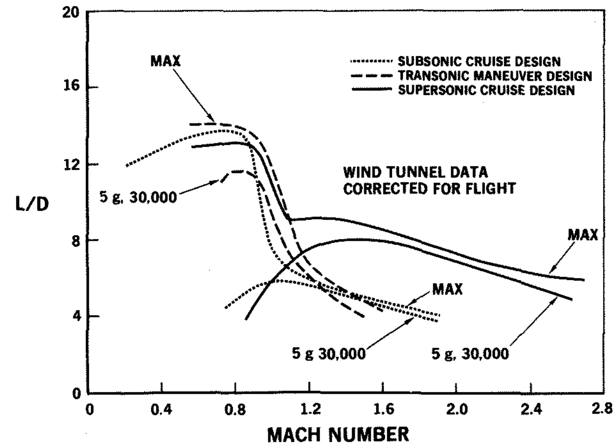

Figure 1. Fighter Efficiency Characteristics

off-design performance through implementation of variable camber systems. An optimum geometry was developed for a supercruise vehicle with a 3.5 aspect ratio, 55-degree sweep planform. Wing twist and camber, derived with a linear theory lifting surface optimization, are shown in figure 2. For a similar configuration, a transonic maneuver design was developed using a full-potential analysis (4) combined with a constrained minimization technique (5). At the maneuver operating condition ($M = 0.9$, $C_L = 0.8$), a weak, swept shock flow was obtained. The required wing twist and camber are presented in figure 3.

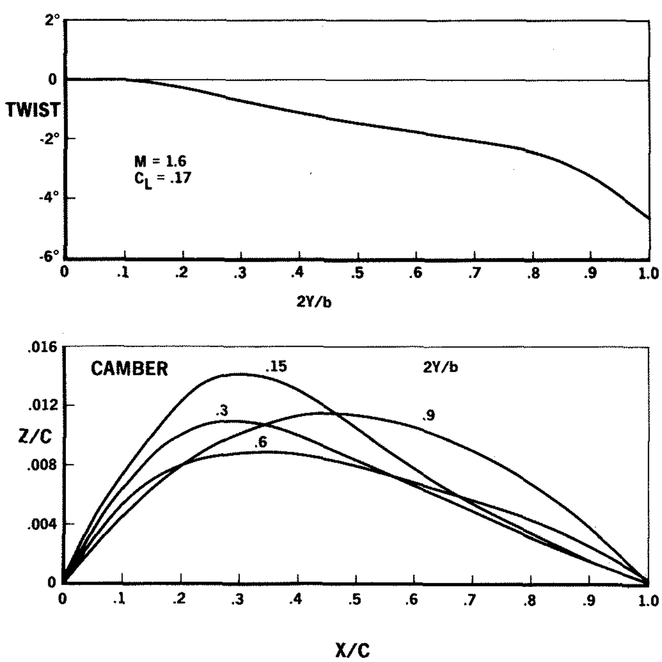

Figure 2. Supersonic Cruise Bias Geometry

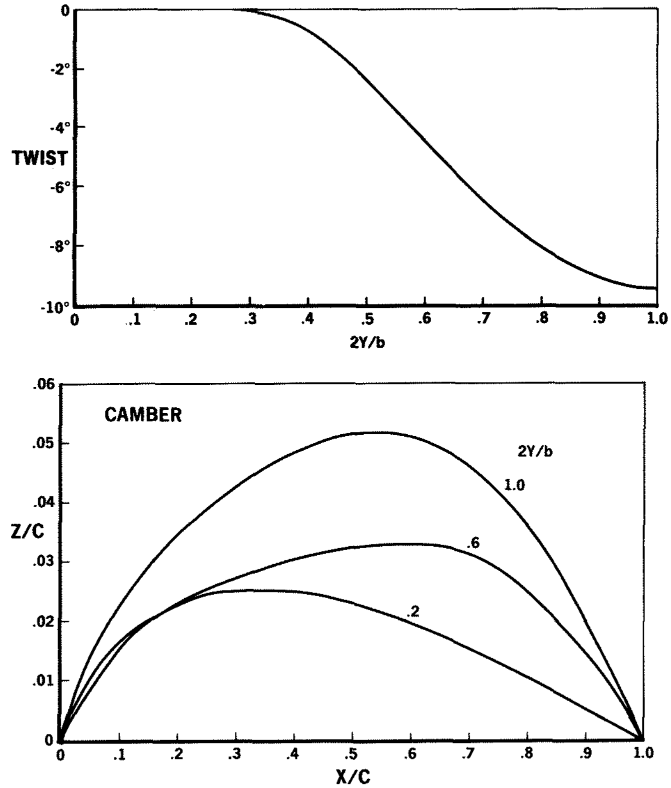

Figure 3. Transonic Maneuver Bias Geometry

Computational studies and test experience indicate the approach of developing an uncompromised point design and using simple flaps for off-design does not maximize all performance objectives. This results from the large mismatch of the required camber and twist distributions, as indicated in figures 2 and 3. In many cases, an adequate solution to the multiple-design-point problem can only be obtained by selecting an intermediate camber shape in addition to some variable geometry system. The variable camber system includes, as a minimum, trailing edge flaps and may encompass leading edge devices and aeroelastic tailoring. The extent of the system depends on the impact of aerodynamic improvements relative to structural and weight considerations.

Design Approach

The approach selected to minimize the drag due to lift at several operating points is to develop a compromise configuration which can be cambered for maneuver and decambered for cruise by use of variable geometry. The system includes leading and trailing edge flaps and aeroelastic twist from spar box bending and bending/torsion coupling.

Unconstrained point designs are obtained at the transonic maneuver condition and the supersonic cruise point. These designs provide upper and lower bounds for the required geometry. The maneuver design goals are a spanload that minimizes vortex drag and a controlled supercritical flow. Weak shocks are admitted, and strong shocks, which may induce separation, are confined to the trailing edge region. The unconstrained transonic maneuver design provides a measure of the flow quality which is ultimately sought in the compromise design cycle. The supersonic cruise design is relatively straightforward. Linear theory is used to minimize the far-field volume-dependent wave drag and the near-field lift-dependent drag. The design lift can be varied to determine a range of camber magnitudes and the corresponding drag-due-to-lift efficiency and sensitivity.

With the boundaries of the wing geometry established, a compromise design cycle is pursued to meet maneuver and cruise performance objectives. An initial variable camber system consisting of leading and trailing edge flaps is selected. Flap spanwise and chordwise extents and the segmentation are variables to be determined in the design cycle. Selection of a candidate camber compromise is based on experience. Some possible methods for this initializing step are addressed for the example design. Once a selection is made, a two-step design cycle is initiated. The variable camber devices are deflected, and the configuration is analyzed at the transonic maneuver point. The spar box shape and the deflections are modified as required to achieve a flow quality which approaches the uncompromised maneuver design. A supersonic optimization is conducted with the compromise shape to determine the zero-percent suction drag and pressure distributions. The two-step cycle is repeated for several variable camber system candidates. A matrix of design solutions is created which reflects the achievable flow quality at both design points relative to the complexity of the variable camber system.

Design Experience

The compromise design philosophy is examined relative to some current tactical aircraft designs. A wing-canard fighter configuration, shown in figure 4, was recently developed to obtain enhanced transonic (M = 0.9) maneuverability while retaining good supersonic cruise and acceleration capability.

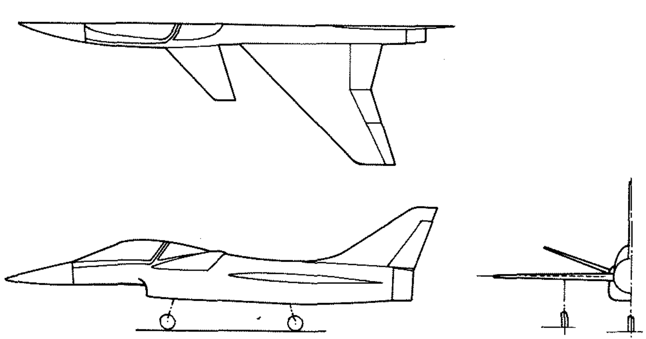

Figure 4. Advanced Fighter Configuration

Point Design

An unconstrained maneuver wing-canard design was developed for a lift coefficient of $C_L = 0.8$ at M = 0.9. A relatively flat supercritical pressure distribution which recompresses near the trailing edge was selected as a design objective. The intent is to limit separation to the trailing edge region. Reasonably good agreement between measured and predicted pressures was obtained for a similar wing designed for this type of pressure distribution. A modified small-disturbance calculation is compared with the experiment in figure 5.

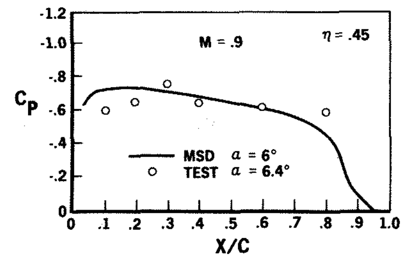

Figure 5. Maneuver Design Validation

With the design pressure prescribed, linear theory (6) is used to develop a wing-canard loading which is compatible with the selected chord-load shape. The loading at the maneuver condition satisfies the following conditions: the vortex drag is minimized, the vehicle is trimmed, and section lift coefficients are within the limits of current supercritical wing technology. The wing and canard section lift distribution which evolved from the linear design is shown in figure 6. The transonic chord-load shape is not directly imposed at this stage. Rather, a camber and twist is developed which nominally satisfies the section lift and moment requirements.

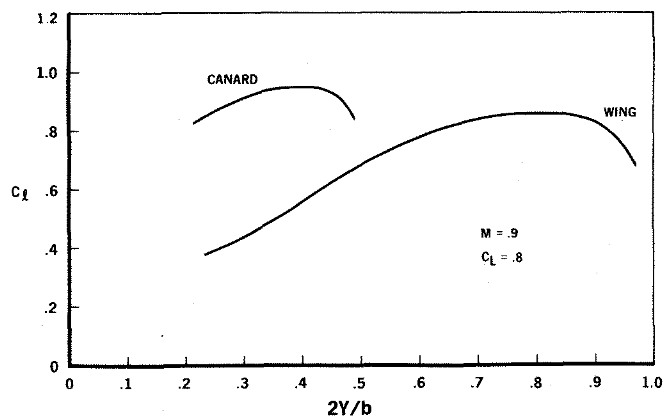

Figure 6. Design Section Lift

Analyses of the status wing-body and canard-body simulations were conducted at M = 0.9 with a modified small-disturbance code(7). Multiple-surface mutual induction effects in the presence of the body were calculated with linear theory and applied as twist increments to the preliminary geometry. The design pressure distributions were imposed, and an inverse option described in reference 8 was used to redefine the coordinates. Some smoothing of the geometry is required, with the result that the design pressures are approximated. Typical results are shown in figure 7 for the maneuver canard design.

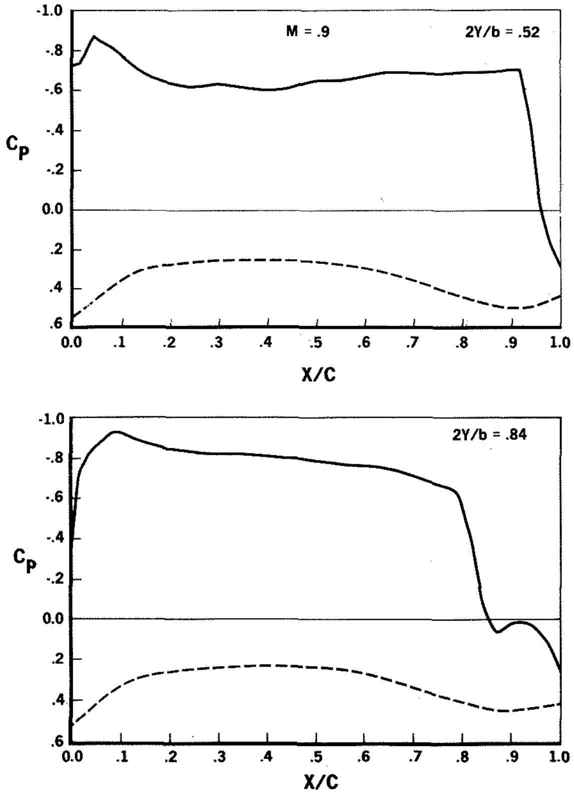

Figure 7. Maneuver Canard Design

An unconstrained supersonic optimization was obtained at M = 1.4, C_L = 0.05 to establish lower bound drag due to lift. Several additional optimizations were conducted varying the design lift, to provide sensitivity of lifting efficiency to the magnitude of camber.

<u>Compromise Design</u>

An initial variable camber system is selected, the geometry is sequentially modified, and the flow quality is examined at supersonic cruise and transonic maneuver. The variable camber system includes twist increments due to assumed aeroelastic effects and leading and trailing edge flaps as defined in figure 8. Trailing edge devices are 25-percent chord. The wing leading edge device consisted initially of two spanwise segments with an inboard single-segment flap of 10-percent chord and an outboard flap of 20-percent chord.

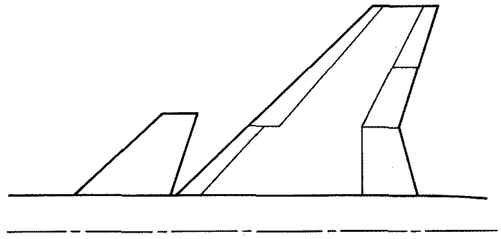

Figure 8. Variable Camber System

The selection of a compromise camber shape is, as noted previously, based on design experience. One possibility is to use an average of the point-design results. For the present study, the initial premise was to retain the maneuver wing shape in the spar box region. A supersonic optimization was conducted with the camber constrained to the maneuver shapes and with the twist and flap deflections as variables. The leading and trailing edge segments were then relaxed one-half of the optimum supersonic deflection. The camber was smoothed from the leading edge to slightly aft of the hinge line, and from just before the trailing edge device hinge line to the trailing edge, as illustrated in figure 9. New wing sections were defined for the modified camber distributions. The compromise was actually developed in two steps as discussed in the following paragraphs.

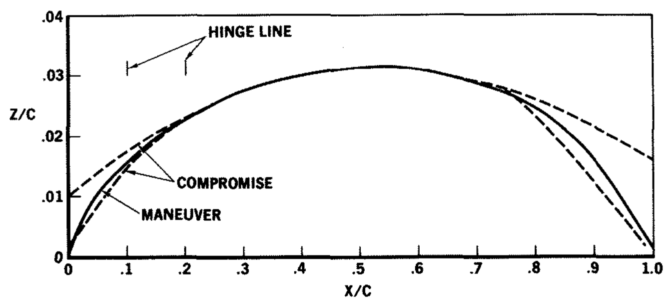

Figure 9. Wing Camber Compromise

The trailing edge compromise camber design was analyzed with the small-disturbance code at the M = 0.9 maneuver point (C_L = 0.8). Wing flap deflections were simulated by adding a step-function slope increment to the boundary conditions. Modification of the airfoils was made in the region forward of the hinge to reduce the expansion due to the discontinuity.

The compromise design cycle was continued with an evaluation of the status configuration at supersonic cruise conditions. Optimization results indicated acceptable cruise trailing edge deflections. The deflections were nominally half the values obtained for the uncompromised maneuver shape. Large leading edge deflections, in addition to the high curvature of the maneuver leading edge camber, resulted in linear theory chordwise pressure distributions shown in figure 10.

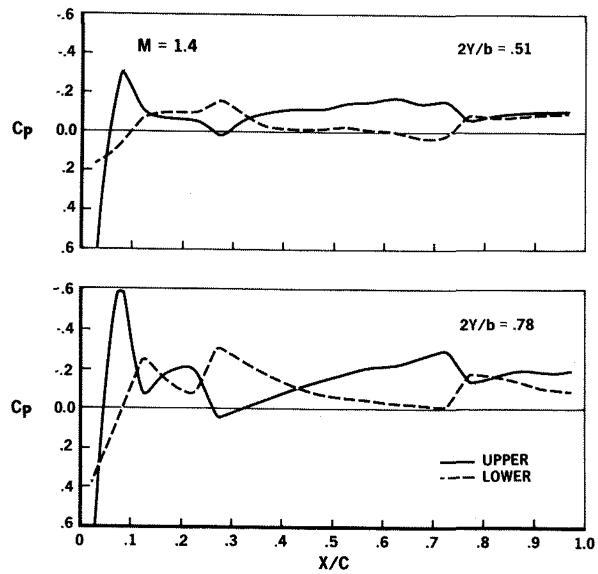

Figure 10. Cruise Pressure Distribution for Trailing Edge Compromise

In order to moderate the adverse gradients at the supersonic cruise condition, to reduce the potential for separation, a series of leading edge flap configurations was examined. The total chordwise extent, the ratio of the first element length to the total, and the number of chordwise segments were varied. None of the parametric variations was adequate in reducing both the camber drag and pressure gradients near the hinge lines. A leading edge camber compromise was subsequently considered as an alternative.

The transonic maneuver (M = 0.9) condition was evaluated first to determine if suitable hinge positions and deflections could be selected to maintain the maneuver flow quality. The leading edge camber was reduced as indicated in figure 9. Smooth airfoils were constructed with the compromise camber distribution. A number of solutions were then obtained for various hinge line positions and flap deflections. The best flow quality was obtained with a system consisting of two chordwise segments with hinge lines at 10- and 20-percent chord on the outboard segment. Typical conservative small-disturbance chordwise pressure distributions for the wing are shown in figure 11 for the configuration with leading and trailing edge deflections.

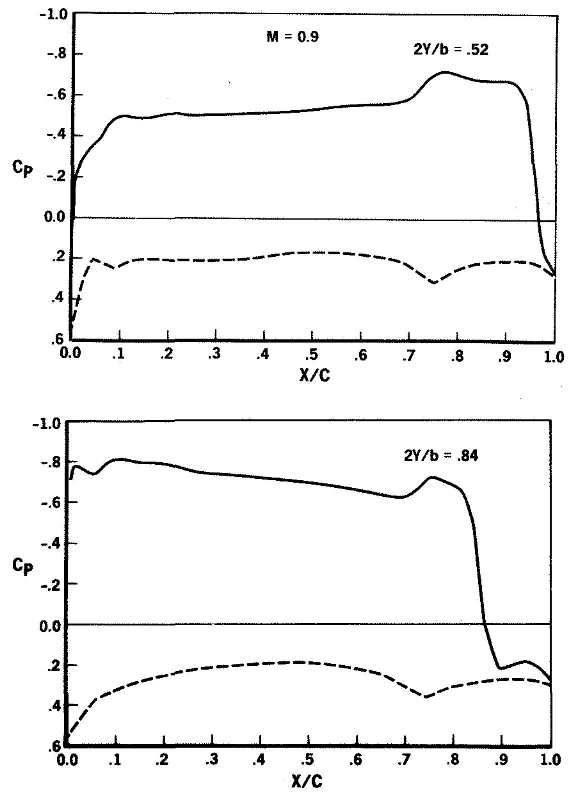

Figure 11. Compromise Design at Transonic Maneuver, Conservative Analysis

A three-dimensional boundary analysis[9] predicted separation at the foot of the shock. This situation precludes the use of weak-viscous interaction methods in the design cycle. There is presently no analysis for dealing with transonic three-dimensional strong-viscous interactions. Relative to experimental observations, inviscid conservative solutions usually overstate the shock strength, particularly for strong shocks. A nonconservative analysis was obtained for nominally the same lift. Pressure distributions (figure 12) indicate the outboard shock is weaker and more forward relative to the conservative results. This behavior simulates viscous effects, at least approximately. In either case, the shock position was deemed satisfactory, considering the design premise for the compromise wing.

A supersonic drag optimization was conducted for the revised compromise geometry. The zero-suction drag was reduced relative to the maneuver leading edge design, as indicated in figure 13. The required leading edge deflections were now half those for the previous solution. Corresponding

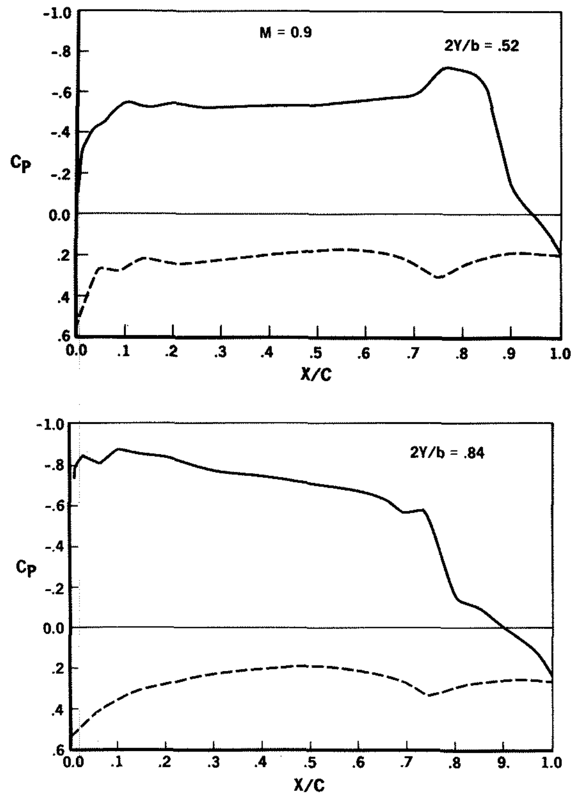

Figure 12. Compromise Design at Transonic Maneuver, Nonconservative Analysis

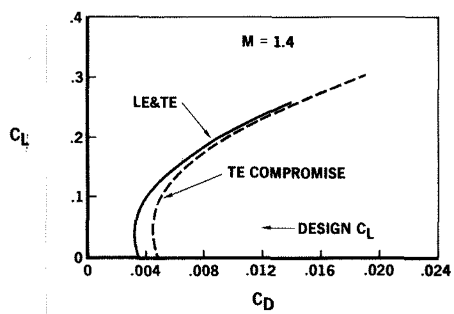

Figure 13. Supersonic Drag Due to Lift

wing pressure distributions at the supersonic cruise point are presented in figure 14. Adverse gradients were reduced to levels that were deemed acceptable based on three-dimensional boundary layer analysis.

Text Experience

Scale model force measurements are essential for evaluating the success of numerical design since calculation of drag suffers from an inability to reliably model three-dimensional viscous interactions. The interrelationship of shock strength and impact of the boundary layer on shock sweep inhibit accurate estimation of drag, even for the fully attached condition. Numerical design con-

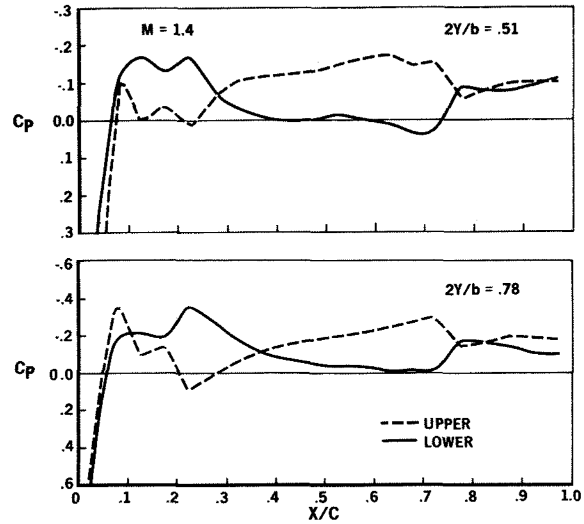

Figure 14. Cruise Pressure Distributions for Leading Edge Compromise

sequently emphasizes the management of pressure gradients to implicitly reduce drag by avoiding or controlling separation.

Point Design

In order to assess the computational design state-of-the-art, it is necessary to establish the lifting efficiency achievable in practice. For this purpose, consideration of point aerodynamic design is useful since it minimizes the impact of compromises which are a common feature of aircraft development. Two cases are considered in order to indicate the current level of achievement and the progress that has taken place in this regard. Potential lower bound (far-field) drag levels are used for comparison.

The Highly Maneuverable Technology (HiMAT) aircraft, currently undergoing flight test at NASA Dryden Research Center, provides one case for this purpose. It represents the first flight vehicle to use nonlinear three-dimensional transonic potential flow theory in the design process. The specific design objective was to achieve sustained 8 g maneuver capability using controlled supercritical flow. This goal has been successfully flight-demonstrated and represents a major advance over existing tactical aircraft.

It is informative to examine the HiMAT lifting efficiency relative to classical vortex drag levels. The wind tunnel drag due to lift at subsonic and transonic conditions is presented in figures 15 and 16, respectively. The former corresponds to primarily subcritical conditions, while the latter exhibits large extents of supercritical ($M_\ell \sim 1.4$) wing-canard flow at the maneuver condition. For comparison purposes, planar and nonplanar optimum vortex drag levels established from Trefftz plane analysis are indicated. The former corresponds to an elliptic spanload on the wing.

The bound $C_{L_\alpha}^{-1}$ corresponds to the efficiency expected for a thin uncambered surface of the same total planform. Examination of the results indicates potential for further improvement relative to the optimum lower bound using numerical analysis developments which have emerged since the HiMAT development.

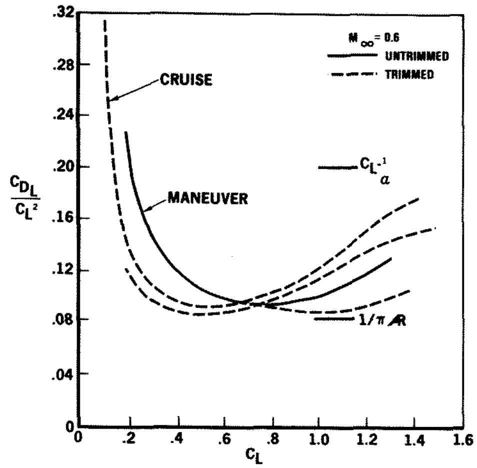

Figure 15. HiMAT Subsonic Test Experience

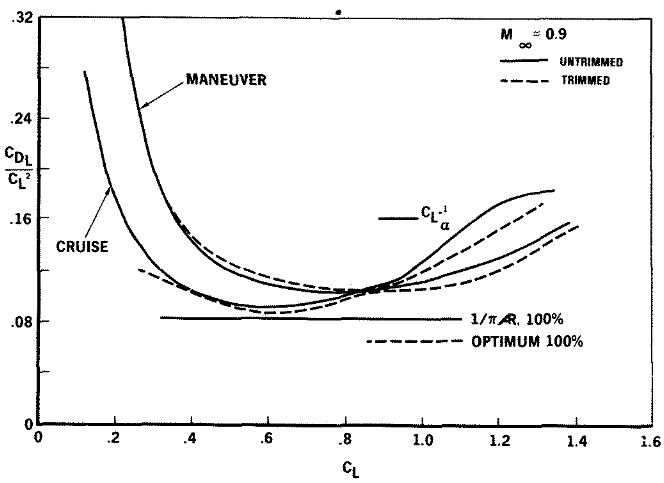

Figure 16. HiMAT Transonic Test Experience

A more recent case is examined in order to indicate transonic design point progress is not only possible but has been accomplished. For this purpose, a conservative full-potential analysis was used to develop a numerical transonic maneuver point design for an advanced tactical aircraft arrangement. A comparison of the measured lifting efficiency at subsonic and supersonic conditions is presented in figures 17 and 18, respectively. An improvement relative to lower bound vortex drag levels was achieved on the first wind tunnel entry and compares to five design/test iterations for the HiMAT maneuver wing development. The impact of numerical design is impressive in achievement of improved aerodynamic performance and reduction in development time and effort required for the point-design problem. Test results for a supersonic linear theory design are also presented for comparison purposes. Off-design conditions for either wing are indicated by dashed lines. As expected, the results indicate substantial potential for variable camber and twist. The reduced sensitivity of the maneuver wing to changes in operating C_L suggests a philosophy which uses deflectable leading and trailing edge devices to extend its high operating efficiency envelope.

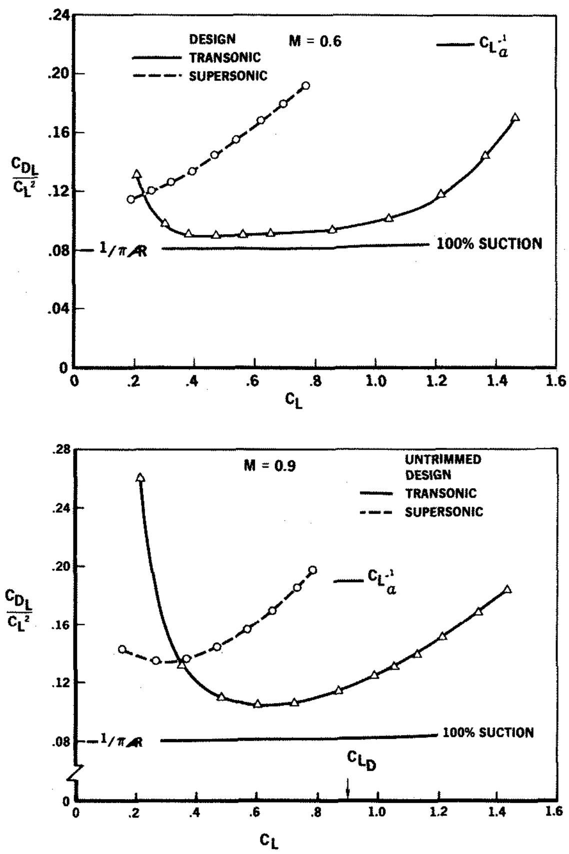

Figure 17. Point Design Subsonic Test Experience

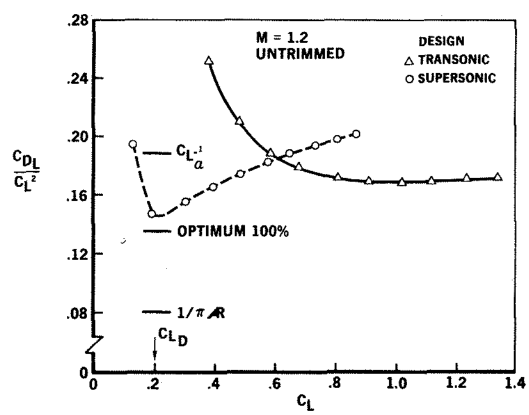

Figure 18. Point Design Supersonic Test Experience

Multiple Design Points

The previous development experience can be used to assess the computational state-of-the-art for aircraft design which typically requires consideration of two or more operating points. The various conditions assume different degrees of relative importance, depending on performance requirements and sensitivities. Conflicts normally necessitate the acceptance of compromises, resulting in greater drag, more extensive separation, etc. Numerical design for this situation is not as well developed and, consequently, more uncertainty is introduced concerning the test outcome. Progress in this regard will require incorporation of three-dimensional, strong-viscous interaction modeling into the design process. To date, principal effort has been directed to the precursor two-dimensional problem.

The first multiple-design-point case which will be considered has supersonic acceleration and transonic maneuver operating conditions. Typical point-design camber comparisons presented in figure 19 indicate high-aerodynamic-efficiency considerations dictate major differences in the region between the wing spars that are not particularly well managed by deflection of leading and trailing edge surfaces. An approach to this situation is to adopt a compromise between the two conflicting curvatures, as discussed previously in the paragraphs on design. Test results for a deflectable canard and wing trailing edge system are presented in figures 20 and 21. Comparison with the single-point-design case (figures 17 and 18), discussed previously, indicates the impact of the compromise is to increase maneuver drag (due to the existance of flow separation determined from oil flow and trailing edge pitot rake measurements). Transonic redesign must deal with reducing separation extent, which, typically, increases supersonic camber drag. Modeling strong-viscous interaction even approximately would be a substantial aid in systematizing design trade effort and reducing the number of test entries required to support the development.

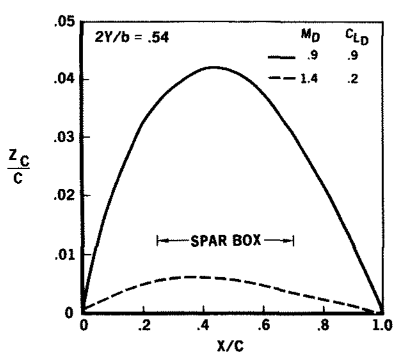

Figure 19. Design Camber Comparison

An ongoing supersonic cruise/transonic maneuver development is considered as a second multiple-design-point case. A compromise philosophy was again adopted for the reasons cited previously. A deflectable canard and wing leading

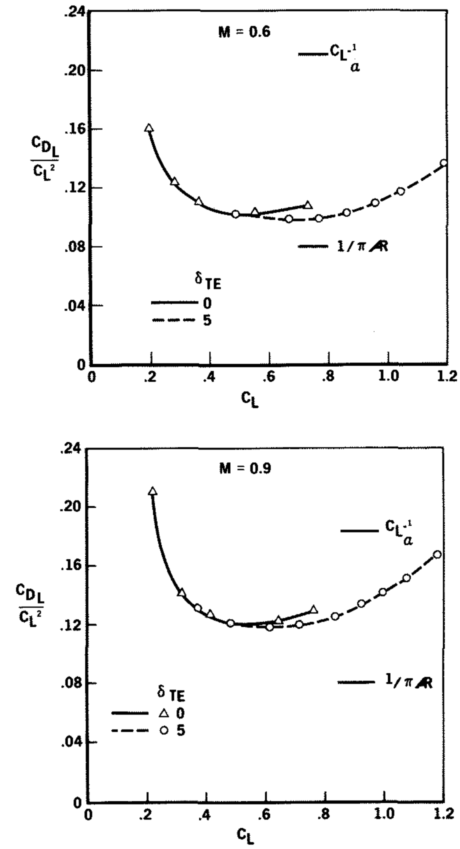

Figure 20. Compromise Wing Subsonic Test Experience

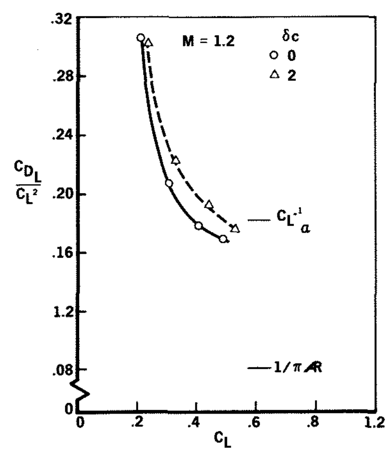

Figure 21. Compromise Wing Supersonic Test Experience

and trailing edge variable geometry system is employed. Design status is indicated in figures 22 and 23 for the maneuver and cruise condition, respectively. The former is compared to nonplanar optimum vortex drag levels, while the latter is compared to linear theory unconstrained 100-percent suction (far-field) levels. Improvements in relative lifting efficiency compared to the earlier compromise (figures 20 and 21) result from greater variability of the camber system.

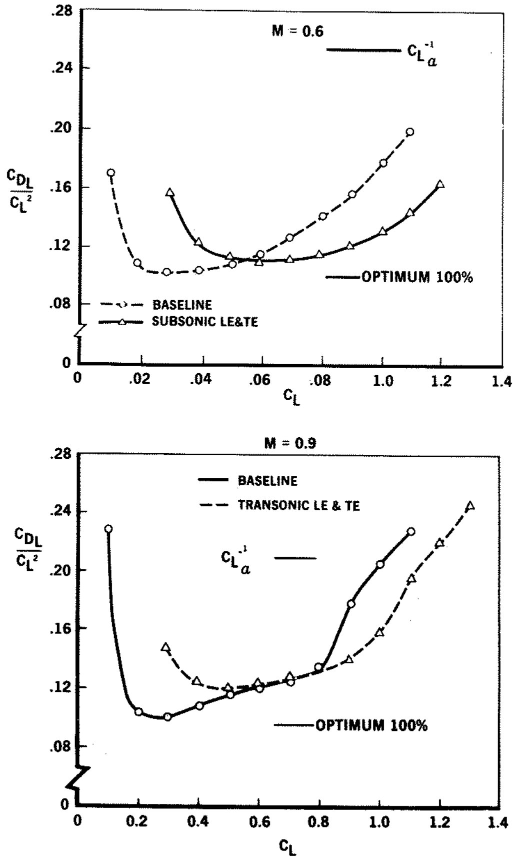

Figure 22. Compromise Design Subsonic Test Status

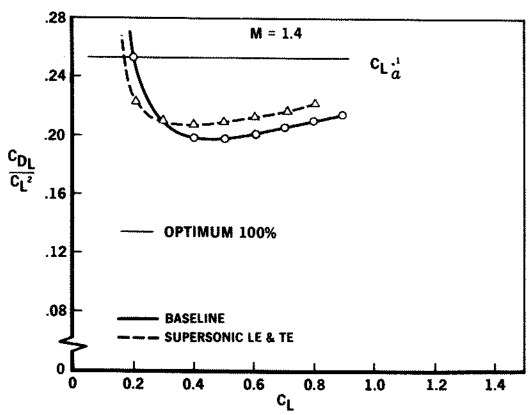

Figure 23. Compromise Design Supersonic Test Status

Concluding Remarks

In order to satisfy the multiple-design-point requirements of advanced tactical aircraft, compromises must be effected between optimum supersonic cruise and transonic maneuver designs. Point designs have been developed using state-of-the-art computational methods, and their aerodynamic efficiency has been verified experimentally. Although superior performance is obtainable at one operating point, off-design characteristics may be severely degraded.

A design philosophy has been developed to satisfy the multiple-operating-point problem. This approach accepts a compromise in camber between cruise and maneuver and seeks to maximize performance at these points through implementation of a variable camber system.

Computational and test experience has indicated that, at transonic maneuver, compromise designs will be subject to larger regions of separated flow than that existing for bias designs. This circumstance strains the capability of the available three-dimensional computational methods.

Supersonic cruise design is no longer straightforward when simple flaps are implemented in a variable camber system. Potential theory optimization may not be realized due to shock-induced separation for the deflected case.

Three-dimensional strong-viscous interaction models are consequently required for tactical aircraft aerodynamic design advances.

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