AN EVALUATION OF THE RELATIVE MERITS OF WING-CANARD, WING-TAIL, AND TAILLESS ARRANGEMENTS FOR ADVANCED FIGHTER APPLICATIONS

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ABSTRACT

The relative merits of wing-canard, wing-tail, and tailless arrangements for advanced fighter applications were addressed in two wind tunnel studies. Variable camber by means of automatically scheduled leading- and trailing-edge flaps was a primary consideration in both studies. In the first study, a canard was evaluated with respect to a tail on a modified F-16 transonic fighter model at subsonic, transonic, and supersonic speeds. Both arrangements were tested in enough detail to address the effects of scheduled flaps and static margin on trimmed polar shape, along with stability and control considerations at high angles of attack. In the second study, General Dynamics and NASA/LRC conducted a series of generic wind tunnel tests to provide the data base needed for a more general understanding of the aerodynamic/performance comparisons between wing-canard, wing-tail, and tailless arrangements. Both a 60-degree leading-edge-sweep delta wing and a 44-degree leading-edge-sweep trapezoidal wing were tested, at subsonic and supersonic speeds, to address configurations dominated by vortex flow and by attached flow, respectively. Sufficient data were obtained to provide trimmed drag polar comparisons for all wing-canard, wing-tail, and tailless arrangements with optimally scheduled flaps at various stability levels. The importance of these aerodynamic comparisons was placed in perspective by evaluating their impact on takeoff gross weight (TOGW) in the design of an advanced fighter. From the results of both studies, several general conclusions were reached. (1) For highly efficient, variable-camber wings, large negative stability levels are required to achieve small subsonic polar shape benefits for wing-canard arrangements, as compared to wing-tail arrangements. However, these large negative stability levels are accompanied by reduced maximum lift for canard arrangements along with potential stability and control problems at high angles of attack. The need for large negative stability levels with a wing-canard diminishes as the main wing efficiency is decreased. (2) Subsonic polars for canard and tailless arrangements are more sensitive to subsonic static margin than those of wing-tail arrangements. (3) At supersonic speeds, the canard arrangements show some advantage because their polar shapes optimize at higher subsonic stability levels than wing-tail or tailless arrangements. (4) The minimum drag and weight advantages of tailless delta arrangements can overcome polar shape deficiency to provide a TOGW advantage for typical advanced fighter mission/performance requirements. (5) Static margin limit is a critical issue in control surface (canard, tail, tailless) selection.

I. Introduction

Requirements for superior combat performance at subsonic and supersonic speeds have led to a widespread integration of variable-camber systems in advanced fighter designs. By contrast, the control surface selection issue (canard, tail, or tailless) has been a subject of considerable disagreement. The purpose of this paper is to investigate some key aspects of this controversial issue with special emphasis placed on considering the effects of trim and variable camber, obtained by means of automatically scheduled flaps.

II. Transonic Fighter Model Analysis

A series of wind tunnel tests was conducted by General Dynamics during 1977 and 1978 to evaluate the relative merits of canard and tail arrangements in conjunction with a larger wing on the F-16. The canard and tail arrangements shown in Figure 1 were tested in enough detail to address the effects of scheduled flaps (leading- and trailing-edge) and static margin on both trimmed polar shape and stability/control characteristics at high angle of attack.

The initial section contains an overview of some primary factors that affect trimmed polar optimization with a well-designed variable-camber wing. This discussion contains some explanatory-type conclusions that were drawn only after careful analysis of all data obtained. This information is presented up front to provide some preliminary insight that will aid the reader in understanding data comparison trends as they are presented in subsequent sections of this report.

DRAG POLAR OPTIMIZATION WITH SCHEDULED FLAPS

Before drawing comparisons between the wing-canard and wing-tail arrangements of Figure 1, it is useful to review some fundamental aerodynamic considerations that govern drag polar optimization in various flow regimes for a well designed fighter. A trimmed subsonic polar can be optimized by use of scheduled flaps combined with proper CG placement, as illustrated for the wing-tail arrangement in Figure 2.

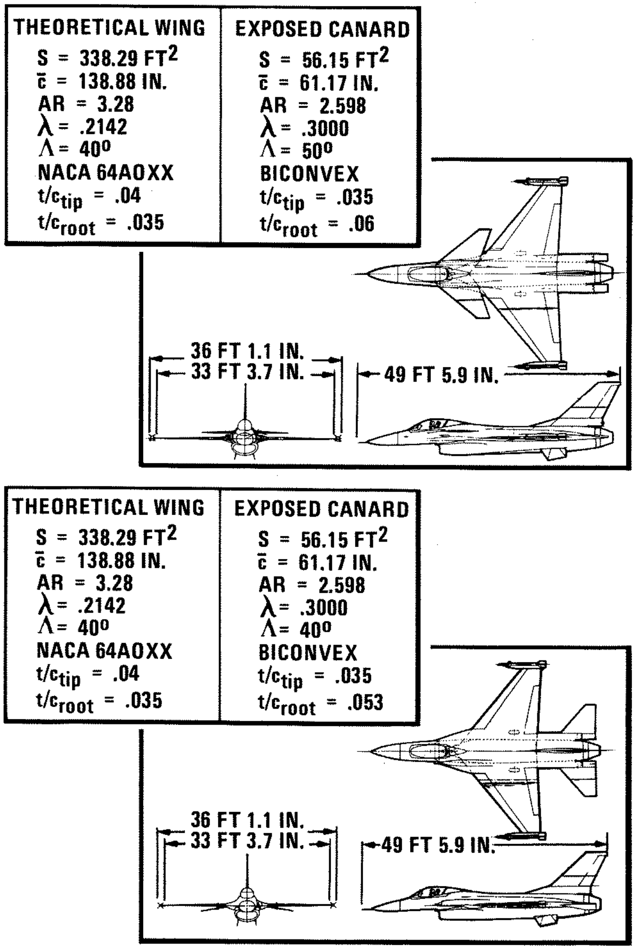

Figure 1 Canard and Tail Arrangements Evaluated on Modified F-16

In the low-to-moderate lift range, labeled Regime I in Figure 2, the leading- and trailing-edge flaps are scheduled to maintain attached flow over the wing. Here the drag polar is nearly optimized by carrying all lift in the main wing rather than in any control surface (tail or canard). This is possible only if the CG is located at the wing-body center of pressure so that, with scheduled flaps, the wing-body is simultaneously trimmed and optimized.

In the higher lift range, labeled Regime II in Figure 2, the wing becomes less efficient due to flow separation and loss of leading-edge suction. Here the trimmed polar is enhanced by carrying small to moderate uploads in the control surface (tail or canard). This trim requirement in Regime II is satisfied only if the CG is located aft of the wing-body center of pressure for a wing-tail or forward of the wing-body center of pressure for a wing-canard. A well designed controlled separation device, such as a strake or a fixed canard, will provide both favorable interference and wing load relief to further enhance the polar in Regime II.

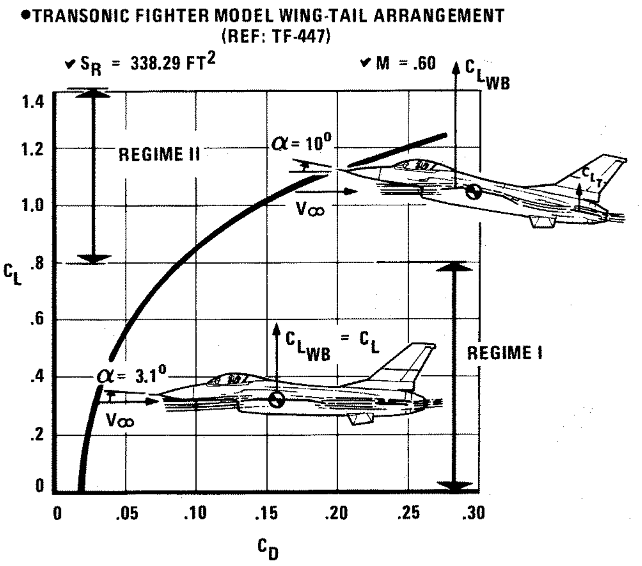

Figure 2 Subsonic Polar Optimization with Scheduled Flaps and CG Placement

Wing-body drag polars and pitching moment data are presented in Figure 3 for a series of flap deflections on the transonic fighter model at .6 Mach. These data show that with the CG properly located, in this case at 44%c̄, it is indeed possible to achieve optimum trim requirements. For the optimum flap schedule shown in Figure 3, the wing is simultaneously optimized and self-trimmed in Regime I; however, nose-down control moments are required in Regime II. This nose-down control requirement in Regime II can be satisfied with either an uploaded tail, which enhances the polar, or a downloaded canard, which degrades it.

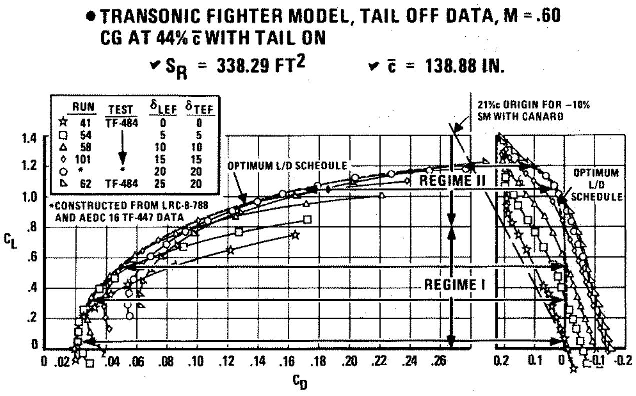

Figure 3 Optimum CG Location for Variable Camber Wing as Derived from Wing-Body Aerodynamics

Following this rationale, a CG location of 44%$\bar{c}$ is expected to provide a near-optimum trimmed polar for either the canard or tail arrangement in Regime I. It may also be expected that this CG location provides a near-optimum trimmed polar for the tail arrangement in Regime II; however, for the canard arrangement no single CG location will provide an optimum trimmed polar in both Regime I and Regime II.

The control surface trim requirements at higher Mach numbers can be compared with those at .6 Mach by inspection of wing-body pitching moment curves, as shown in Figure 4, for the same CG location of 44%$\bar{c}$. With the optimum flap schedule indicated by the dashed lines, it is apparent that the .9 Mach trim requirements are quite similar to those at .6 Mach. At 1.5 Mach the flaps are fixed at zero and the wing-body is self-trimmed up to a lift coefficient of 0.8. In the supersonic Mach range, referred to as Regime III in Figure 4, the polar shape is optimized by carrying a small fraction of the overall lift in the control surface (tail or canard), as will be shown in the generic research model analysis. It will also be shown that the subsonic/transonic Regime I polar is slightly enhanced by carrying a small fraction of the total lift in the control surface. Therefore, considering only the Regime I and Regime III cases, it may be expected that the canard arrangement will optimize with a CG location slightly forward of 44%$\bar{c}$ while the tail arrangement optimizes slightly aft of 44%$\bar{c}$.

●TRANSONIC FIGHTER MODEL, TAIL-OFF DATA

S_R = 338.29 FT^2 $\bar{c}$ = 138.88 IN.

SYM	LEF	TEF
☆	0.0	0.0
□	3.6	3.2
△	5.0	5.0
◇	10.0	10.0
○	15.0	15.0
▽	25.0	20.0

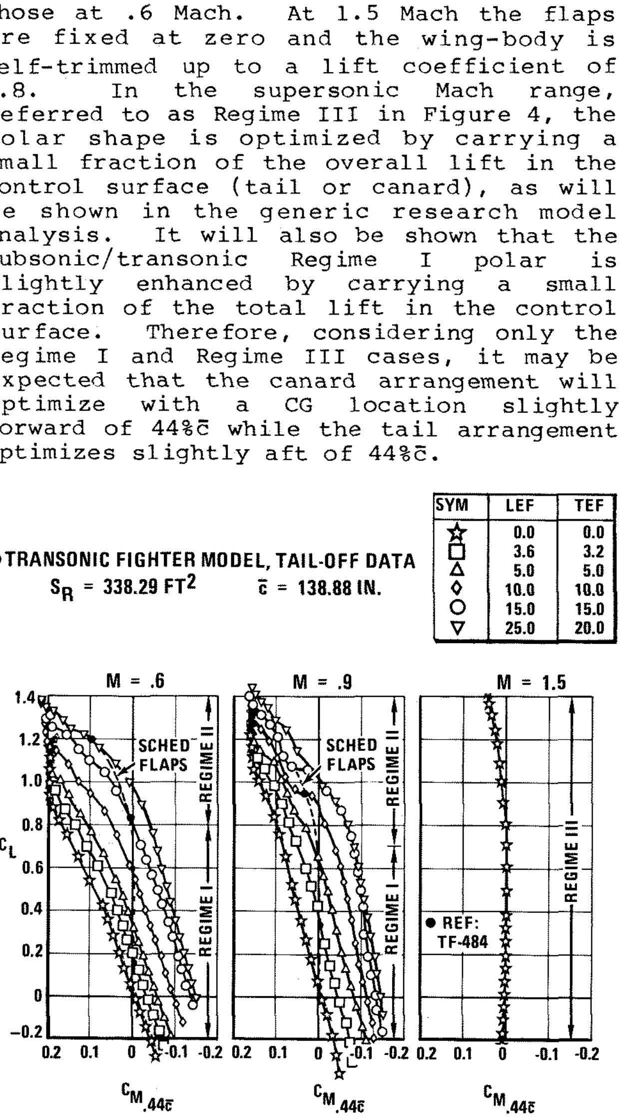

Figure 4 Criteria for Optimization of Trim Surface Requirements Across the Mach/Lift Flow Regimes with Scheduled Flaps

This set of wing-body data indicates that, with scheduled flaps and proper CG placement, the trim surface requirements can be nearly optimized across all three flow regimes for the wing-tail case. However, for the wing-canard case, the CG location that provides near-optimum trim requirements in Regimes I and III is aft of an optimum placement for Regime II. A CG location of 44%$\bar{c}$ provides a self-trimming wing with optimally scheduled flaps in Regime I, and is very close to an optimum location for both the canard and tail arrangements in Regime I, as will be shown in the following two sections.

The longitudinal stability effects of integrating both canard and tail control surfaces with the wing-body are compared in Figure 5 for the near-optimum CG location of 44%$\bar{c}$. The wing-body subsonic static margin is nominally -18%$\bar{c}$ as defined in the low-lift coefficient range from 0 to 0.4. Addition of the tail, which is located in the wing downwash field, causes the aerodynamic center to shift aft 8% to give a subsonic static margin of -10%$\bar{c}$. Since the canard is added in an upwash field caused by the wing and forebody, it produces a more powerful aerodynamic center shift of 15% forward to give a subsonic static margin of -33%$\bar{c}$. This large forward aerodynamic center shift coupled with the near-optimum CG location of 44%$\bar{c}$ is an illustration of the fundamental reason why efficient wings with scheduled flaps require more negative stability to optimize in Regime I with a canard than with a tail.

●TRANSONIC FIGHTER MODEL DATA

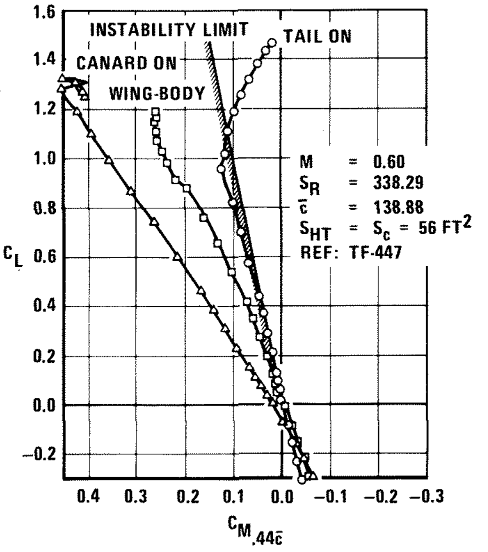

Figure 5 Longitudinal Stability for Canard and Tail Arrangements with Near-Optimum CG Location

The actual negative static margin limit for each arrangement will be set by stabilty and control considerations that address high angle of attack (roll-pitch coupling, deep stall, and lateral/directional) characteristics along with control system (pilot-in-loop handling qualities with real-time actuation rates) and flexibility limits. For this transonic fighter model, these considerations drove the static margin limit to -10%$\bar{c}$, as indicated in Figure 5. This translates into an aft CG limit of 44%$\bar{c}$ for the wing-tail versus

21%c̄ for the wing-canard. The wing-tail provided fully satisfactory stability and control characteristics at this subsonic static margin limit of -10%c̄; however, the wing-canard encountered both longitudinal control and directional stability problems, described later, which were not resolved during this study.

In spite of these unresolved stability and control problems for the wing-canard, trimmed polar comparisons were made at a subsonic static margin of -10%c̄ as shown in Figure 6. These comparisons indicate substantial polar shape advantages for the wing-tail arrangement at subsonic speeds along with nearly identical supersonic polars.

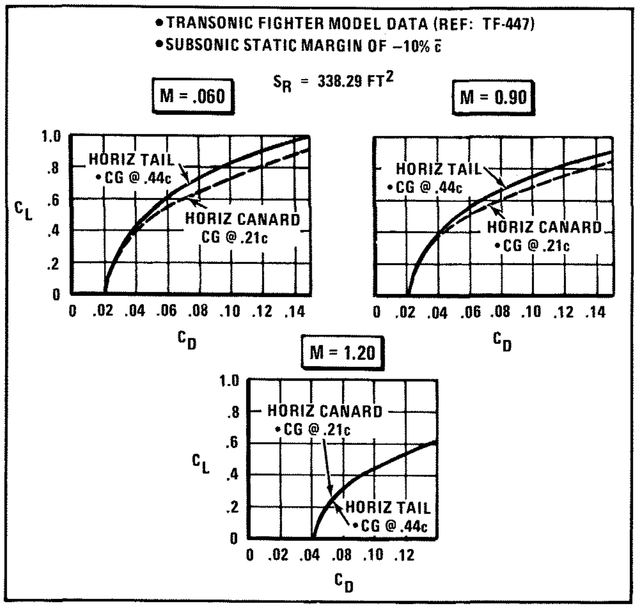

Figure 6 Trimmed Polar Comparison Between Canard and Tail Arrangements at a Subsonic Static Margin of –10% c̄

The trimmed polar advantages for the wing-tail at subsonic speeds can be best understood by referring back to Figure 3. With the origin for a CG location of 21%c̄ (a subsonic static margin of -10%c̄ for the wing-canard) superimposed on the wing-body pitching-moment curves, it is evident that the wing-canard polar shape must be compromised in Regime I. If the optimum wing-body flap schedule is maintained, large canard uploads are required for trim. These canard uploads can be reduced only by backing off from the optimum flap schedule for the wing-body. The wing-canard envelope polars shown in Figure 6 were defined by passing a minimum-drag fairing tangent to the family of trimmed polars for the various flap deflections. These trimmed envelope polars are optimum for the wing-canard with a subsonic static margin of -10%c̄.

SCHEDULED FLAP AND TRIM EFFECTS

The use of scheduled flaps can have a significant impact on control surface selection as illustrated by the trimmed drag polars shown in Figure 7 for a subsonic static margin of -10%c̄. With flaps fixed at zero, no significant difference occurs between the wing-canard and wing-tail arrangements. This is because the wing is very inefficient with zero flaps and under this condition favorable interference and load relief is provided by a lifting surface located forward of the wing. Both the forebody strake and the uploaded canard perform this function in a similar manner. However, for the optimum scheduled flap case shown in Figure 7, the wing-tail shows a definite advantage over the wing-canard. This is because with scheduled flaps the wing is potentially very efficient and the polar is optimized with practically no lift carried in the control surface. With a static margin of -10%c̄, the wing-tail arrangement is capable of maintaining the optimum wing-body flap schedule while minimizing control surface lift; however, the wing-canard does not provide this capability (for reasons described in the previous section).

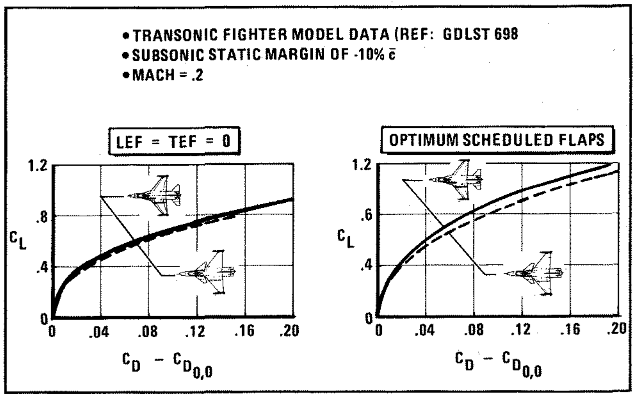

Figure 7 Scheduled Flap Effect on Polar Comparisons Between Canard and Tail Arrangements at a Subsonic Static Margin of –10% c̄

Trimmed polar comparisons must be carefully considered in the process of evaluating various control surface options (or any other configuration option). Furthermore, these trimmed polar comparisons must be made at stability levels that are appropriate for each control surface concept. The importance of this kind of comparison is illustrated in Figure 8. For the untrimmed case, virtually no polar shape difference occurs between the wing-canard and wing-tail with scheduled flaps. However, the trimmed polar comparisons at discrete static margins show quite different results. The wing-tail shows a definite advantage at neutral stability but is nearly identical to the wing-canard at a static margin of -15%c̄. With the static margin fixed at -30%c̄, the wing-canard shows an advantage over the wing-tail. However, this is not an appropriate comparison because the wing-tail polar is optimized at a static margin of -15%c̄, and -30%c̄ is not achievable for

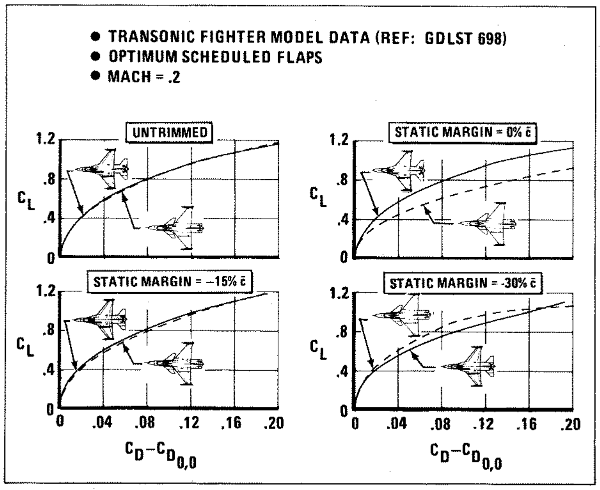

Figure 8 Trim Effects on Polar Comparisons Between Canard & Tail Arrangements at Various Subsonic Static Margins

either arrangement, as will be shown in the next section. The important point is that trimmed polar comparisons should be made at stability levels that are at least achievable and optimum (if possible) for each control surface arrangement.

STATIC MARGIN SENSITIVITY AND LIMITS

The subsonic polar of the wing-tail shows significantly less sensitivity to static margin than that of the wing-canard, as shown in Figure 9. This comparison also shows that the wing-tail polar is optimized in Regime I at a more positive stability level (i.e., −15%c̄ for the wing-tail versus −30%c̄ for the wing-canard). A comparison of the wing-canard and wing-tail polars at their optimum static margins (see Figure 10) shows a small advantage for the wing-canard up to moderate lift coefficients. For both arrangements, the optimum polars are achieved by carrying a very small fraction of the total lift in the control surface. This is evident if one recalls that the self-trimming wing condition, discussed previously, is achieved with the CG at 44%c̄, which corresponds to static margins of −33%c̄ for the wing-canard and −10%c̄ for the wing-tail. It is also apparent from Figure 9 that the wing-canard optimum static margin for the moderate-lift regime is significantly more negative than that for the high-lift regime (i.e., −30%c̄ versus −20%c̄). With the CG located for a static margin of −30%c̄ on the wing-canard, the low-to-moderate lift regime is optimized because the wing is lifting efficiently and practically no canard lift is required for trim. However, this CG location results in trim requirements for download in the canard at higher lift coefficients rather than the moderate canard uploads that would enhance the polar in this regime.

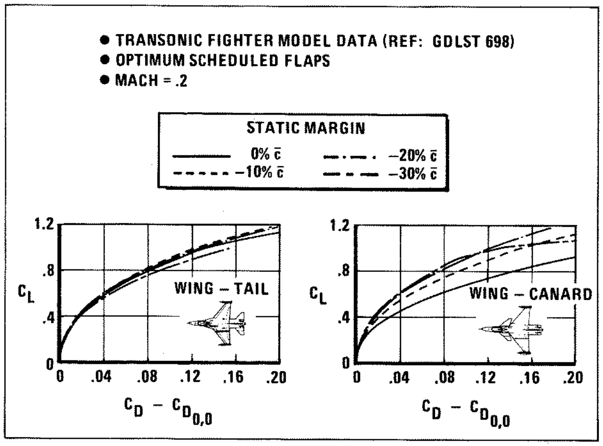

Figure 9 Subsonic Polar Sensitivity to Static Margin for Canard and Tail Arrangements

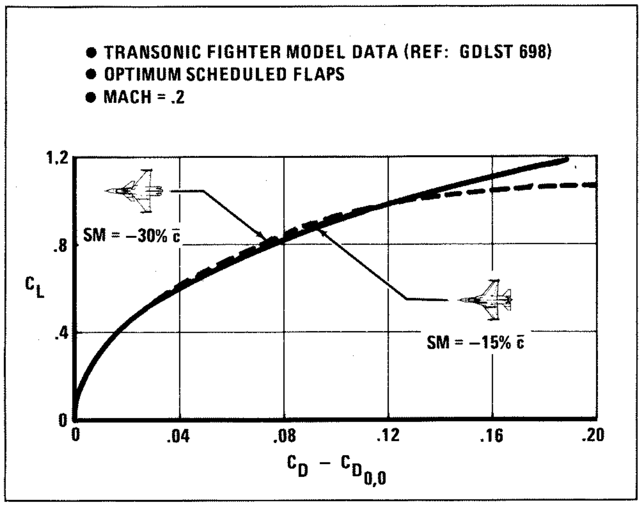

Figure 10 Polar Shape Comparison Between Canard & Tail Arrangements at Optimum Static Margins

The aft CG limits for this transonic fighter model were set by longitudinal control and directional stability characteristics at high angles of attack. These characteristics for the wing-canard and wing-tail arrangements are compared in Figure 11.

The longitudinal control power must be sufficient to satisfy a dynamic roll/pitch coupling requirement. In other words, for a required roll rate of 50 deg/sec in this case, sufficient nose-down control must be available to overcome both static and inertial forces. This requirement is nominally satisfied if the CG is located such that, with maximum nose-down control, the pitch-

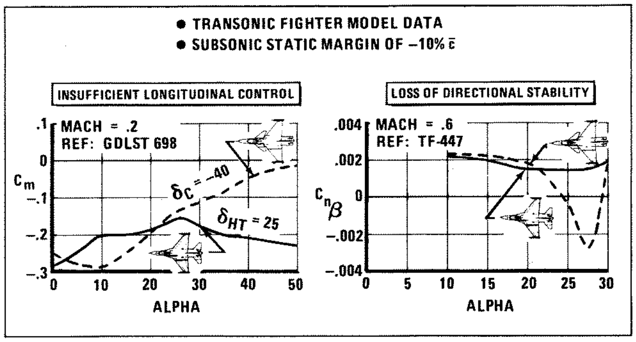

Figure 11 Comparison of Maximum Nose-Down Control and Directional Stability Characteristics for Canard and Tail Arrangements

ing moment coefficient is less than -0.1 up to high angles of attack. With the static margin set at -10%$\bar{c}$, the wing-tail satisfies this roll-pitch coupling requirement; but the wing-canard lacks sufficient nose-down control at angles of attack above 32 degrees, as shown in Figure 11.

The directional stability comparison of Figure 11 shows the wing-canard to be unstable between 24 and 29 degrees angle of attack. This problem was apparently caused by an adverse interference of the canard wake with the vertical tail. Increased canard dihedral caused the same problem to occur at lower angles of attack. The wing-tail directional stability was considered acceptable for a negative static margin of -10%$\bar{c}$.

Some attempts were made to correct the longitudinal control and directional stability problems associated with the wing-canard; however, no satisfactory solutions were found during this study. Based on an assumption that these problems could be resolved with further analysis and test efforts, a decision was made to compare trimmed polars at a static margin of -10%$\bar{c}$ for both the wing-canard and the wing-tail. Even though this assumption may be optimistic for this wing-canard configuration, the trimmed polars for the wing-tail still provide a significant advantage over those for the wing-canard as shown previously in Figure 6.

The longitudinal control characteristics for the wing-canard and wing-tail are compared in Figure 12 with their CG's located to provide a subsonic static margin of -10%$\bar{c}$. From these pitching moment curves, it is evident that further aft movement of the CG's would result in trim requirements for increased upload in the tail versus reduced upload in the canard. These contrasting trim requirements result in a fundamental trend toward increased maximum lift for the wing-tail versus decreased maximum lift for the wing-canard with reduced stability, as shown in Figure 13.

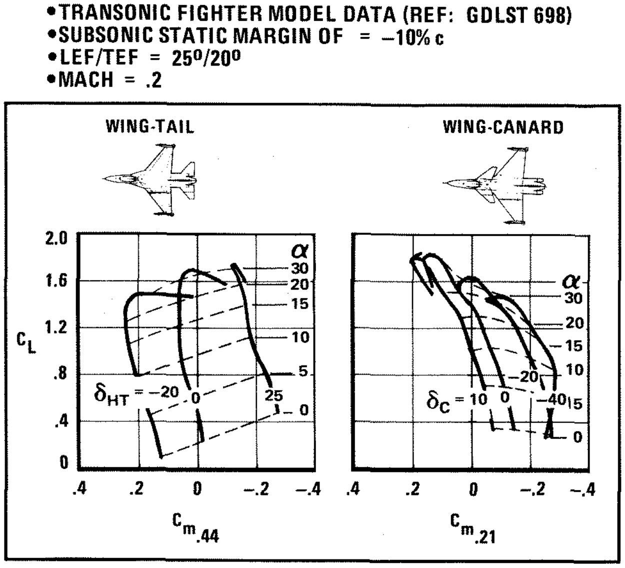

Figure 12 Comparison of Longitudinal Control Characteristics for Canard and Tail Arrangements

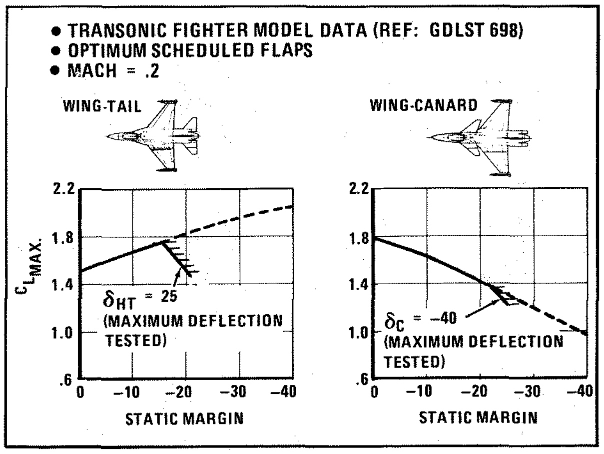

Figure 13 Effect of Subsonic Static Margin on Maximum Lift for Canard and Tail Arrangements

III. Generic Research Model Analysis

The preceding transonic fighter model analysis represents a re-evaluation of wind tunnel data taken during 1977 and 1978 on two modified versions of the F-16 aircraft. The task of re-evaluating this data was undertaken during 1981 in light of current interest in wing-canard arrangements for advanced fighter applications. Conclusions from this analysis indicate that a wing-tail provides a better solution than a wing-canard for a modified F-16 application. Some questions remained, however, as to whether these conclusions had general relevance or were restricted to and possibly driven by the particular configuration characteristics of the F-16. Literature surveys, conducted by both General Dynamics and NASA/LRC, showed no other comparative testing that addressed the canard-versus-tail issue in a systematic way with consideration for the effects of trim and scheduled flaps. The joint GD/NASA research program described herein was initiated in 1982 to address this database deficiency.

During 1982 and 1983, General Dynamics and NASA/LRC conducted a series of wind tunnel tests on a generic configuration matrix, shown in Figure 14. The purpose of this test program was to provide the data base needed for a more general understanding of aerodynamic/performance comparisons between wing-canard, wing-tail, and tailless arrangements. Both a 60-degree leading-edge-sweep delta and a 44-degree leading-edge-sweep trapezoidal wing were tested to address configurations dominated by vortex flow and by attached flow, respectively. The data obtained were sufficient to provide trimmed polar comparisons at various subsonic static margins for the configurations of Figure 14 with optimally scheduled flaps.

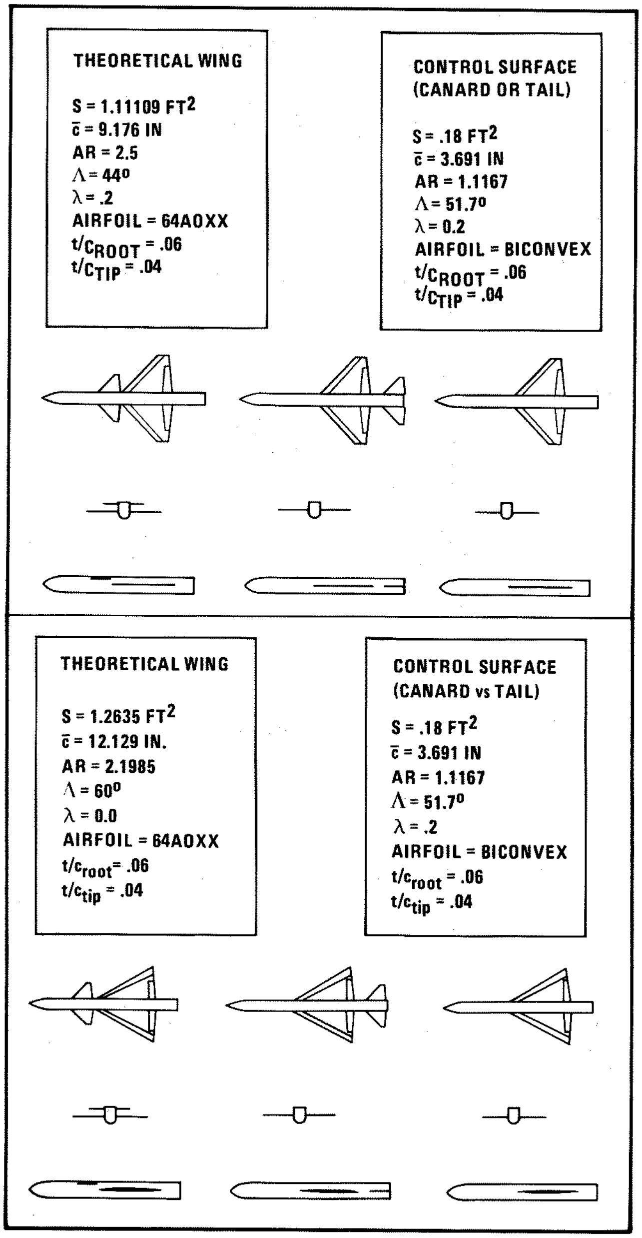

Figure 14 Generic Research Model Configuration Matrix

This generic model is appropriate for addressing trimmed polar shape characteristics up to moderate lift coefficients, where the polar shape is primarily a function of wing and control surface geometry. However, stability and control characteristics at high angles of attack tend to be highly dependent on more subtle configuration details and cannot be appropriately addressed in such a generic sense. Therefore, the testing was limited to longitudinal data up to moderate lift coefficients, as required for performance comparisons. This generic test series was conducted in the LRC 7- by 10-foot transonic tunnel at Mach numbers of 0.4 and 0.8 and in the LRC 4- by 4-foot supersonic unitary tunnel at Mach numbers of 1.6 and 2.0. A dual-balance system was housed within the fuselage to provide the capability of isolating forebody forces while obtaining force data on the total configuration. The following discussion is limited to summary data comparisons that reflect the major conclusions derived from the study. Wind tunnel data from these tests are available in Reference 1, along with a more detailed presentation of analytical results.

TRAPEZOIDAL WING

It was previously observed that the subsonic drag due to lift is nearly optimized with the control surface unloaded, provided that the main wing is lifting efficiently. Therefore, the first step in this study was to investigate the effects of scheduled flaps, both with and without a strake, on the wing-body envelope polar efficiency. As shown in Figure 15, the scheduled leading- and trailing-edge flaps provide this wing with a highly efficient subsonic polar. However, when combined with a strake (defined in Reference 2 as AD 22), the polar improvements achieved with scheduled flaps are significantly degraded. This strake effect tends to support the idea of carrying lift exclusively in the main wing in the attached-flow regime. In order to maximize wing-body efficiency, the strake was removed for all the following trimmed polar comparisons.

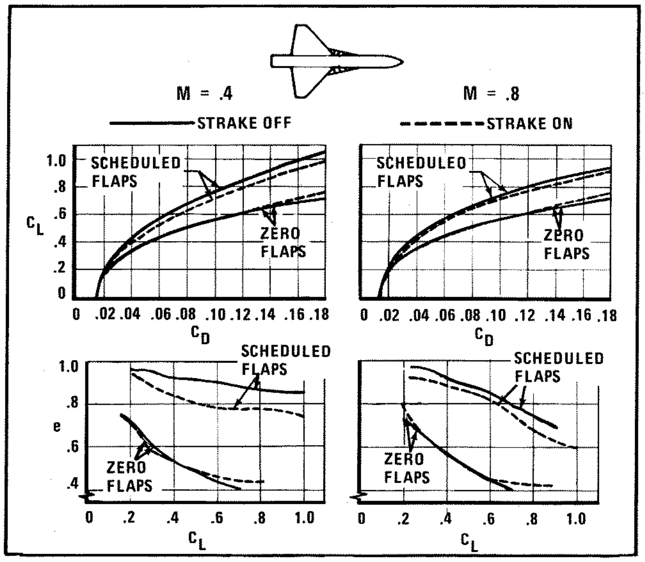

Figure 15 Scheduled-Flap and Strake Effects on Wing-Body Polars of the 44-Degree Sweep Trapezoidal Wing

A summary comparison of wing-canard, wing-tail, and tailless data is presented in Figure 16 as the variation of trimmed envelope polar drag with subsonic static margin for lines of constant lift coefficient. The leading- and trailing-edge flaps were optimally scheduled to minimize drag for the wing-canard and wing-tail. For the tailless arrangement, the subsonic data were insufficient to define trimmed polars; at supersonic speeds, trailing-edge flap deflections were naturally governed by trim requirements rather than by drag optimization.

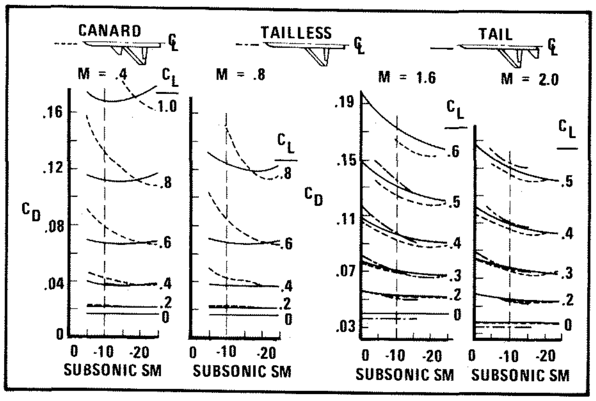

Figure 16 Summary Trimmed Drag Comparison of Canard, Tail and Tailless Arrangements with the 44-Degree Sweep Trapezoidal Wing

At subsonic speeds, large negative static margins are required to achieve small polar benefits for the wing-canard as compared to the wing-tail. The wing-tail drag is optimized with subsonic static margins in the range of -10 to -15%$\bar{c}$. This nominal level of instability is considered achievable because of satisfactory high-angle-of-attack stability and control characteristics observed on the transonic fighter model. Furthermore, the drag penalties for slightly increased stability on the wing-tail are not severe. The wing-canard subsonic drag polar appears to be approaching optimum with a subsonic static margin of -25%$\bar{c}$, and increased stability is accompanied by severe drag penalties. The risk associated with an aircraft designed for this level of instability is significant, and the potential drag benefits appear to be small. It is also apparent that the subsonic polar shapes of both the canard and tailless arrangements are far more sensitive to subsonic static margin variations than those of the wing-tail.

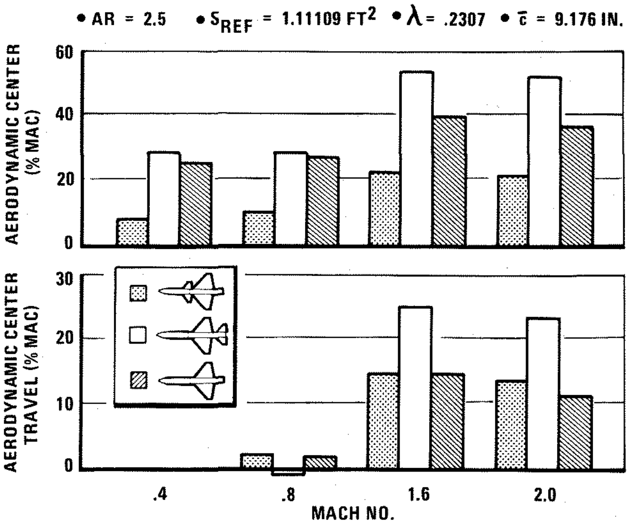

Figure 17 Variation of Aerodynamic Center with Mach Number for Canard, Tail and Tailless Arrangements with the 44-Degree Sweep Trapezoidal Wing

At supersonic speeds, static margin sensitivity is roughly similar for the canard, tail, and tailless arrangements. Here, the optimization comparison between canard and tail is somewhat reversed, with the subsonic static margin being optimum at -15%$\bar{c}$ to -20%$\bar{c}$ for the wing-canard versus approaching optimum at -25%$\bar{c}$ for the wing-tail. The reason for this reversal is associated with aerodynamic center (defined with all surfaces fixed at zero-deflection) travel from subsonic to supersonic speeds, which is greater for the wing-tail than for the wing-canard, as shown in Figure 17. This happens because the fraction of total lift carried by the tail increases significantly as the wing downwash field decreases from subsonic to supersonic speeds. However, because of its forward location, the canard experiences relatively little variation in the fraction of total lift that it carries between subsonic and supersonic speeds. Therefore, for a fixed level of subsonic stability, the wing-body is more stable at supersonic speeds for the wing-tail than it is for the wing-canard. It is this supersonic wing-body stability that determines canard or tail trim requirements. Both the wing-canard and the wing-tail optimize with approximatley 12% of the total lift carried in the control surface, as shown for 1.6 Mach in Figure 18. This optimum control-surface/wing lift ratio is achieved with a subsonic static margin of nominally -21%$\bar{c}$ for the wing-canard versus -27%$\bar{c}$ for the wing-tail. The net result is that, at supersonic speeds, the wing-canard provides a small drag advantage over the wing-tail with a reasonable level of subsonic static margin (i.e., -10 to -15%$\bar{c}$).

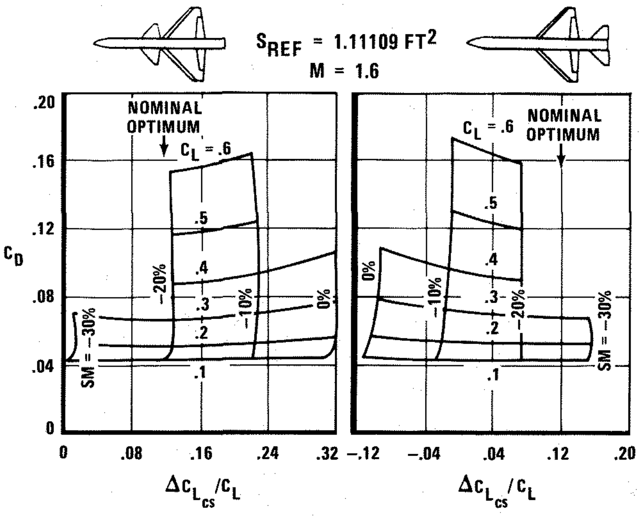

Figure 18 Effect of Control Surface Lift on Trimmed Supersonic Drag for Canard and Tail Arrangements with the 44-Degree Sweep Trapezoidal Wing

DELTA WING

The effect of various flap schedules on subsonic polar efficiency of the wing-body is shown in Figure 19. Although the scheduled flaps provide a large polar shape improvement, this wing is not as efficient as the 44-degree-sweep trapezoidal wing (see Figure 15).

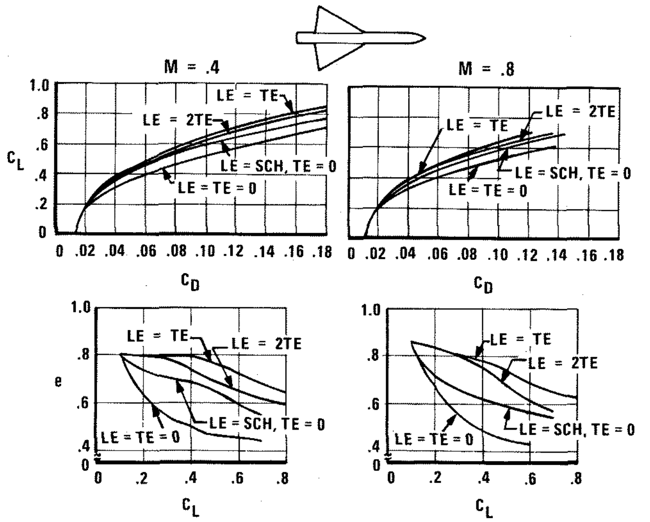

Figure 19 Scheduled Flap Effects on Wing-Body Polars of the 60-Degree Sweep Delta Wing

A summary comparison of wing-canard, wing-tail, and tailless data is presented in Figure 20 as the variation of trimmed envelope polar drag with subsonic static margin for lines of constant lift coefficient. The leading- and trailing-edge flaps were optimally scheduled to minimize drag for the wing-canard and wing-tail. For the tailless arrangement, the leading-edge flaps were optimally scheduled; however, trailing-edge flap deflections were naturally governed by trim requirements that were generally inconsistent with drag optimization.

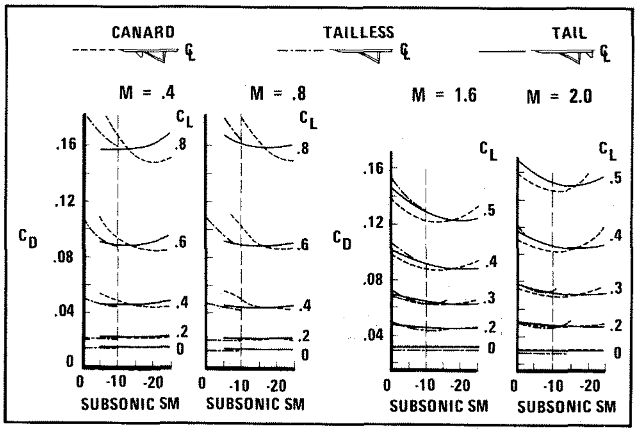

Figure 20 Summary Trimmed Drag Comparison of Canard, Tail and Tailless Arrangements with the 60-Degree Sweep Delta Wing

As might be expected, the decreased efficiency of this wing, with respect to the trapezoidal wing, causes both the wing-canard and wing-tail to optimize with larger control surface uploads at subsonic speeds. This results in polar optimization with more positive stability for the wing-canard and more negative stability for the wing-tail. Still, the wing-tail provides lower subsonic drag than the wing-canard at subsonic static margins more positive than $-15\%\bar{c}$. Also, as in previous cases, the wing-tail subsonic polar shapes are far less sensitive to subsonic static margin variations than those of the wing-canard and tailless arrangements.

The wing-tail subsonic drag is optimized with subsonic static margins in the range of $-10\%\bar{c}$ to $-15\%\bar{c}$ and the drag penalties for slightly increased stability levels are not severe. This result is similar to both of the previous wing-tail arrangements. Furthermore, stability and control characteristics of the transonic fighter model at higher angles of attack indicate that this nominal level of instability is achievable for a wing-tail.

The wing-canard subsonic polar is optimized with a subsonic static margin of approximately $-20\%\bar{c}$ and, as for previous wing-canard cases, slightly increased stability levels are accompanied by large drag penalties. At a subsonic static margin of $-20\%\bar{c}$, the wing-canard provides a small drag advantage over the wing-tail. However, the additional risk that would accompany this small benefit does not appear to be warranted. At a subsonic static margin of $-15\%\bar{c}$, the wing-canard subsonic polar is comparable to that of the wing-tail. The wing-canard also shows a small supersonic advantage over the wing-tail at this level of instability. An increased supersonic polar advantage for the wing-canard is seen at a subsonic static margin of $-10\%\bar{c}$; however, at this stability level the wing-tail provides a significant subsonic advantage.

The subsonic polars for the tailless arrangement are roughly comparable to those of the wing-tail at subsonic static margins approaching $-10\%\bar{c}$. However, recent tailless aircraft experience by General Dynamics on the F-16XL indicates that this level of instability is probably not achievable. At supersonic speeds, the tailless arrangement provides a significant minimum drag advantage that could compensate for polar shape penalties associated with more positive stability levels.

At supersonic speeds, the static margin sensitivity is roughly similar for the canard, tail, and tailless arrangements. Here, the wing-canard optimizes at a more positive subsonic static margin than the wing-tail (nominally at $-13\%\bar{c}$ versus $-20\%\bar{c}$). This trend is reversed from the subsonic case, where the wing-canard optimized at a subsonic static margin of $-20\%\bar{c}$ versus $-10\%\bar{c}$ for the wing-tail. The reason for this reversal was described for the trapezoidal wing case, where the same trend was observed. The aerodynamic center travel from subsonic to supersonic speeds is greater for wing-tail than for the wing-canard, as shown in Figure 21. Both the wing-canard and wing-tail optimize with approximately the same percentage of total lift carried in the control surface (i.e.,

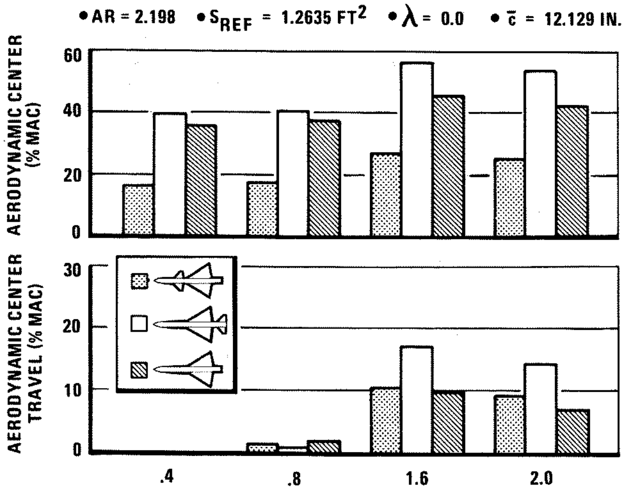

Figure 21 Variation of Aerodynamic Center with Mach Number for Canard, Tail and Tailless Arrangements with the 60-Degree Sweep Delta Wing

14% for the wing-canard versus 13% for the wing-tail), as shown for 1.6 Mach in Figure 22. These optimum control-surface/wing lift ratios are achieved with a subsonic static margin of nominally -14%c̄ for the wing-canard versus -20%c̄ for the wing-tail. As was the case for the 44-degree-sweep trapezoidal wing, the net result is that, at supersonic speeds, the wing-canard provides a small drag advantage over the wing-tail with a reasonable level of subsonic static margin (i.e., -13%c̄).

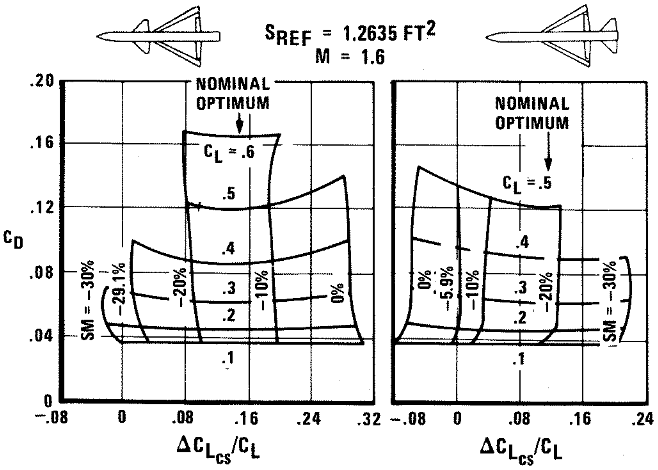

Figure 22 Effect of Control Surface Lift on Trimmed Supersonic Drag for Canard and Tail Arrangements with the 60-Degree Sweep Delta Wing

AIRCRAFT DESIGN IMPLICATIONS

The importance of these aerodynamic comparisons can be placed in proper perspective by evaluation of their impact on the design of an advanced fighter aircraft. This was accomplished by simulating the polar shape characteristics shown in Figures 16 and 20 in the General Dynamics Conceptual Design Synthesis Procedure (CDSP, Reference 3) and optimizing airfoil thickness, wing area, and fuselage size for various levels of mission/performance requirements while holding planform shape constant. The minimum drag of the baseline fuselage and external stores was also held identical for all configuration arrangements in order to isolate the effects of drag due to lift, camber, and trim.

Results of this analysis are presented in Figure 23 in terms of relative takeoff gross weight (TOGW) versus subsonic static margin for both the trapezoidal and the delta wing arrangements. The sizing mission was held constant while the effect of three levels of combat performance was evaluated. The middle two comparison plots are representative of a desired level of combat performance, whereas the upper two plots are representative of excessively high supersonic maneuver requirements and the lower two plots are representative of reduced subsonic and supersonic combat performance requirements.

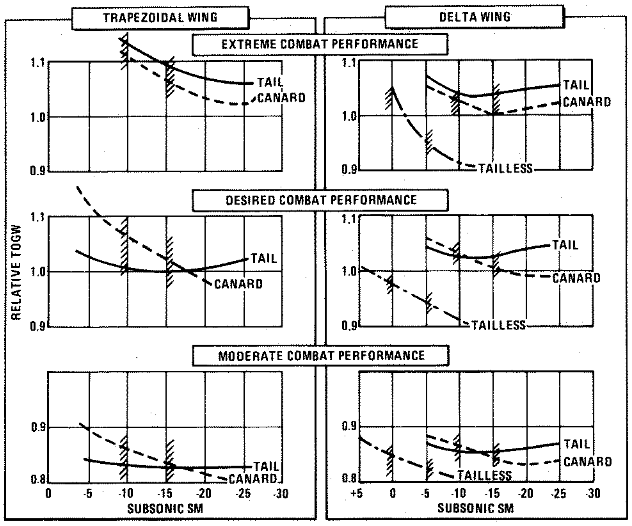

Figure 23 Summary of Aircraft Sizing Analysis Based on Trimmed Polar Shapes of Generic Research Model

For both the desired and moderate performance cases, the subsonic polar shape characteristics are dominant factors and the canard-versus-tail TOGW trends are remarkably similar to the trimmed drag comparisons of Figures 16 and 20. More-negative static margins are required to show a TOGW advantage for the canard, and the canard TOGW is more sensitive to subsonic static margin than the tail at these performance levels. The crossover point for the wing-canard occurs at a more positive subsonic stability level for the delta wing (-12%c̄) than for the trapezoidal wing (-17%c̄). This is attributed to the relatively lower aerodynamic efficiency of the delta wing. At subsonic static margins of -10 to -15%c̄, which are considered potentially achievable for canard and tail arrangements, the trapezoidal wing shows a TOGW advantage for the tail; however, the TOGW difference between canard and tail arrangements is not significant for the delta wing.

For the case of extreme supersonic high-g performance requirements, the supersonic polar shape advantage of the canard becomes significant and provides the canard an advantage with respect to the tail for both the delta and trapezoidal wings.

It is unlikely that a tailless arrangement can tolerate subsonic static margins of less than $-5\%\bar{c}$. However, it is interesting to note that, even at neutral stability, the tailless delta is competitive with both the canard and tail arrangements at a subsonic static margin of $-10\%\bar{c}$. This is attributed to the minimum drag and weight advantages of the tailless delta, since both the tail and canard arrangements have superior polar shapes. Unfortunately, subsonic test data was insufficient to simulate a tailless trapezoidal-wing arrangement.

IV. Concluding Remarks

The generic test data analysis provides a better understanding of issues that affect control surface selection for advanced fighter applications. Furthermore, no basic contradictions with regard to the canard versus tail issue, were found between the generic study and the modified F-16 study. Based on these two studies, it was generally concluded that the key considerations for control surface (canard, tail or tailless) selection are scheduled flap and trim/static margin effects along with high angle-of-attack stability and control characteristics. The general conclusions resulting from this work are summarized as follows:

- For highly efficient variable-camber wings, large negative subsonic static margins are required to achieve subsonic polar shape benefits for wing-canard arrangements with respect to wing-tail arrangements. However, these large negative static margins are accompanied by reduced maximum lift for canard arrangements along with potential stability and control problems at high angles of attack, as shown for the modified F-16 case with a subsonic static margin of $-10\%\bar{c}$.
- Subsonic polar shapes for canard and tailless arrangements are more sensitive to subsonic static margin variations than those for tail arrangements. As stability of the wing-canard is increased from its optimum level, the optimum wing-body flap schedule must be compromised to avoid excessive trim/interference drag penalties associated with carrying large trim uploads in the canard.
- Supersonic polar shapes for canard arrangements optimize at more positive subsonic static margins than those for tail arrangements. This results in a supersonic polar shape advantage for the wing-canard. However, mission/performance analysis shows that, for the trapezoidal-wing case, supersonic performance requirements must be pressed to extreme levels to take advantage of this benefit; the canard versus tail sensitivity to supersonic performance requirements is considerably reduced for the delta wing case.
- The minimum drag and weight advantage of tailless delta arrangements can overcome polar shape deficiencies to provide TOGW advantages for typical advanced fighter mission/performance requirements.
- Static margin limit is a critical issue in control surface selection. This limit is governed by consideration of high angle-of-attack stability and control characteristics, control system considerations, and control-surface/flexibility characteristics.

It was also noted throughout the comparisons between wing-canard and wing-tail arrangements that,

- If the main wing is performing efficiently, the subsonic polar shape is nearly optimized with no lift in a canard or tail. Full optimization for an efficient wing requires that a very small fraction of the total lift be carried in the control surface; the optimum ratio of control surface to wing lift increases as the wing becomes less efficient.
- Unloading a canard requires more negative stability than unloading a tail because of the forward aerodynamic center shift caused by adding a canard. This factor drives efficient variable-camber wings toward requiring large negative static margins to optimize with a canard; the need for large negative static margins diminishes as the main wing efficiency decreases.
- An uploaded canard enhances the polar at angles of attack above the main wing polar break. However, this improvement is achievable only if a canard upload is required for trim. Such a trim requirement is not consistent with the large negative static margin required to optimize an efficient variable-camber wing in the attached-flow regime.
- At supersonic speeds, canard arrangements optimize at more positive subsonic stability levels than wing-tail arrangements. The reason for this trend is that the aerodynamic center travel from subsonic

to supersonic speeds is greater for the wing-tail than for the wing-canard. Both arrangements optimize with approximately the same fraction of total lift carried in the control surface at supersonic speeds (nominally 12% to 14% for the arrangements tested).

For advanced fighter applications, where a highly efficient, variable-camber wing is employed, no significant wing-canard advantage was found that would warrant the additional risk (associated with increased negative stability, increased sensitivity of subsonic polar shape to CG location, and potential stability and control problems at high angles of attack) over a conventional wing-tail arrangement.

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