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T. L. Williams, Northrop Corporation, Hawthorne, California
W. P. Nelms
D. Smeltzer, Ames Research Center, Moffett Field, California

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field California 94035

TOP-MOUNTED INLET SYSTEM FEASIBILITY FOR TRANSONIC-SUPERSONIC FIGHTER AIRCRAFT APPLICATIONS

T.L. Williams and B.L. Hunt

Northrop Corporation, Aircraft Division
One Northrop Avenue
Hawthorne, California 90250, USA

D.B. Smeltzer and W.P. Nelms

NASA Ames Research Center
Moffett Field, California 94035, USA

SUMMARY

Top inlet flow field and engine-inlet performance data for an advanced fighter aircraft configuration were obtained over the Mach 0.6 to 2.0 range. These studies not only provided extensive data for the baseline arrangement, but also evaluated the effects of key aircraft configuration variables - inlet location, canopy-dorsal integration, wing leading-edge extension (LEX) planform area, and variable incidence canards - on top inlet performance. In order to set these data in the context of practical aircraft systems top inlet performance is compared with that of more conventional inlet/airframe integrations.

The results of these evaluations show that, for the top inlet configuration tested, relatively good inlet performance and compatibility characteristics are maintained during subsonic and transonic maneuver. However, at supersonic speeds, flow expansion over the forebody and wings causes an increase in local inlet Mach number which subsequently reduces inlet performance levels. These characteristics infer that although top inlets many not pose a viable design option for aircraft requiring a high-degree of supersonic maneuverability, they have distinct promise for vehicles with subsonic and transonic maneuver capabilities.

NOMENCLATURE

AR	Wing aspect ratio	$\bar{P}_{T2}$	Average total pressure at engine compressor face
FRP	Fuselage reference plane	ΔP_{T2}	Maximum total pressure variation at Engine compressor face
FS	Fuselage station (inches)	$\bar{P}_{TRMS}$	Average root-mean-square of total pressure fluctuation (turbulence)
IDC	Engine fan instantaneous circumferential distortion index	α	Angle of attack
IDC_{limit}	Maximum allowable instantaneous circumferential distortion index for a typical low-bypass fighter aircraft engine	β	Angle of sideslip
		δ_c	Canard deflection angle
M_L	Local inlet Mach number	δ_f	Trailing-edge flap angle
M_0	Free-stream Mach number	δ_n	Leading-edge flap angle
$\bar{P}_{T1}$	Average total pressure at inlet highlight	Λ	Leading-edge sweep angle
ΔP_{T1}	Maximum total pressure variation at inlet highlight	Γ	Dihedral angle

1.0 INTRODUCTION

Recent advanced fighter aircraft technology studies have shown that mounting the engine-inlet above the fuselage can afford a variety of potential advantages relative to more conventional inlet locations. These advantages include:

- Unobstructed lower-fuselage for weapons integration (inlet isolated from weapons, thereby eliminating engine-inlet compatibility problems during weapons carriage and delivery)
- Virtual elimination of hot gas reingestion problem associated with VSTOL aircraft
- Reduced incidence of engine foreign object damage (FOD) problems during takeoff and landing
- Superior ground-level access to most aircraft sub-systems
- Reduced aircraft structural weight due to characteristically short inlet duct length
- Reduced frontal aspect radar cross-section (RCS) due to the inherent forebody/wing shielding of the inlet system from low-altitude and ground-based radars.

Despite this attractive list of advantages, top inlet systems have not yet been applied to production fighter aircraft, primarily because of concerns over inlet flow field quality at angle of attack. However, several recent experiental studies (References 1-5) have shown that the upper-fuselage region poses a potentially favorable inlet location for fighter aircraft configurations employing vortex lift enhancement. This is due to the action of the strong, counter-rotating vortex pair produced by the wing leading-edge extensions (LEX's) which effectively inhibits upper-fuselage flow separation. These vortices inhibit separation by entraining high-energy free-stream air into the upper-fuselage region and sweeping low-energy boundary layer air outwards.

Past top inlet studies have been limited to subsonic flow field and engine-inlet performance evaluations (References 1, 2 and 3) and transonic and supersonic upper-fuselage flow field surveys (References 4 and 5). Those programs have established a valuable initial data base, but have left a need for inlet performance measurements at higher speeds to provide a firmer data base for aircraft design studies. In addition, previous work has identified several potential problem areas on which further information is needed. First, ingestion of wake flow from the canopy can occur, so that the integration of the canopy with the fuselage appears to be important to top inlet performance. Second, sharply degraded inlet performance can be produced by ingestion of vortex flow into the inlet, either because of vortex bursting or because, in sideslip, the vortex migrates into the inlet. Third, at supersonic flight speeds, expansion of the flow field over the forebody and wings at angle of attack produces local elevations in Mach number and consequent increases in inlet shock losses. The objectives of the study reported on herein are to meet the need for high-speed performance data and to shed further light on the known problem areas.

The test program on which this paper reports was conducted under contract by Northrop Corporation to NASA's Ames Research Center and the David Taylor Naval Ship Research and Development Center*. Top inlet flow field and engine-inlet performance data were obtained for an advanced top-inlet fighter aircraft configuration over the Mach 0.6 to 2.0 range and for angles of attack and sideslip up to 27° and 12°, respectively. In addition to extensive evaluation of the baseline configuration performance characteristics, these tests also investigated the influence of several key aircraft configuration variables.

This paper provides a summary and evaluation of significant test results from this program and, in addition, compares selected top inlet performance data with those of more conventional inlet/airframe arrangements.

2.0 TEST PROGRAM

2.1 Test Vehicle

Top inlet performance evaluations were conducted utilizing a 0.095-scale model based on Northrop's Vertical Attitude Takeoff and Landing (VATOL) configuration. This vehicle, depicted in Figure 1, was designed as an advanced, supersonic, air-to-air fighter with operational capability from ship-board platforms. The vehicle is launched and retrieved utilizing an unusual tail-sitting takeoff and landing procedure from a vertical platform. This launch and retrieval technique imposed special constraints on the design of the inlet which ultimately played a major role in the selection of a top inlet configuration. The inlet employed on this configuration is a two-dimensional fixed geometry design with a 7° external compression ramp, and was sized for shock-on-lip at Mach 2.0. The wing is a clipped delta planform with a 50° leading-edge sweep angle and includes an integral wing leading-edge extension (LEX). Further details concerning the design of this configuration may be obtained in Reference 6.

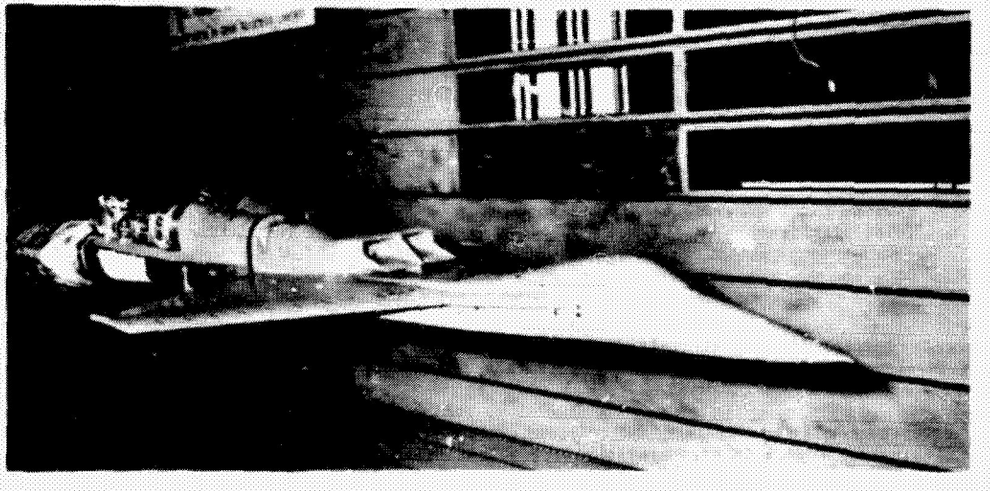


FIGURE 1. VATOL 0.095 SCALE INLET PERFORMANCE MODEL

* NASA Study Contract NAS2-10384, "Study of Top Inlet Technology"

The subsonic diffuser utilized in the inlet/airframe performance model was modified from the original VATOL design to enable fore and aft movement of the inlet. By eliminating almost all diffuser offset in the diffusion plane (profile view), as is shown in Figure 2, the entire inlet assembly, consisting of the inlet, diffuser and mass flow control plug assemblies, could be positioned at any one of three predetermined locations. Although duct offset was not accurately simulated, other diffuser parameters such as duct aspect ratio and diffusion ratio were retained relative to the initial VATOL design. Inlet mass flow was regulated through the use of two remotely controlled plugs located in the duct exits (see Figure 2).

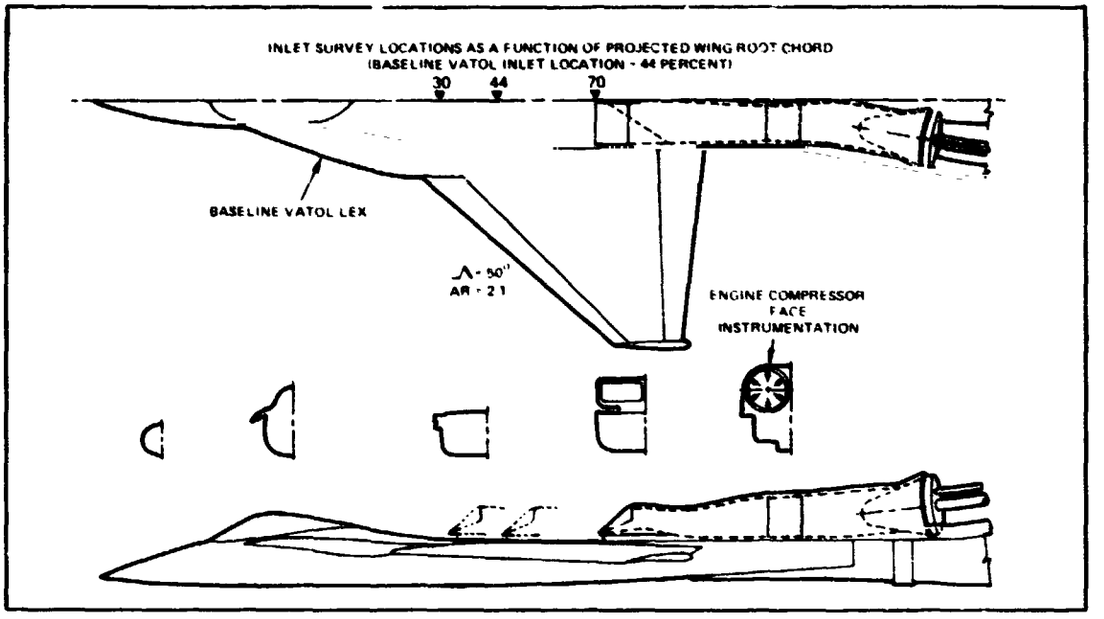


FIGURE 2. VATOL INLET/AIRFRAME PERFORMANCE MODEL LAYOUT

The model was also designed to enable evaluation of the effects of other key aircraft configuration variables, in addition to inlet location, on top inlet performance. Details concerning these configuration options, which included changes in canopy-dorsal integration, wing leading-edge extension (LEX) planform area variations, and replacement of the LEX by a variable incidence canard, are given in Section 3.2.

2.2 Instrumentation

The model was instrumented to enable evaluation of the ingested inlet flow field and engine-inlet performance parameters. Flow field instrumentation spanned both the left and right inlets systems and was located immediately upstream of the compression ramp leading-edge, as is shown in Figure 3. This instrumentation package included an array of pitot and 5-hole cone probes from which local inlet flow field parameters including total pressure, Mach number, and flow angularity were determined. To eliminate interference effects during acquisition of engine-inlet performance data the entire inlet flow field rake assembly was removeable. Unfortunately, cone probe flow angularity and Mach number data were not available at the time of printing of this paper; however, cone probe pitot pressure measurements are included in the flow field total pressure data presented herein.

Determination of engine-inlet performance parameters over the Mach 0.6 to 2.0 range required the use of two different instrumentation systems, one applicable to the subsonic and transonic range and another for supersonic speeds. For free-stream Mach numbers less then 1.4, inlet performance parameters were evaluated at the engine compressor face station (see Figure 2). Due to the small scale of the model [7.3cm (2.9in) compressor face diameter] instrumentation at the engine face was limited to 12 total head pressure probes, 6 "Kulite" transducers (capable of measuring both steady-state and dynamic pressures), and 4 wall static taps. This arrangement can be seen in Figure 4. The 18 probes were mounted in 3 circumferential rings, each containing 6 probes: The spacing corresponded to the centroids of equal areas. This instrumentation package enabled evaluation of inlet total pressure recovery, steady-state distortion, and turbulence.

At supersonic speeds above Mach 1.4, evaluation of inlet performance characteristics at the engine compressor face posed a problem. The small scale of the model did not allow for incorporation of an active boundary layer control system. Thus, there was no means of controlling the shock induced boundary layer separation which results from the interaction of the inlet terminal shock and ramp boundary layer. Inlet performance parameters measured at the engine compressor face are thus masked by the resulting separation region. To counteract this problem "quasi" inlet performance parameters were measured at the inlet entrance plane using a "clipped-cowl" inlet, shown in Figure 5. The rationale behind this arrangement is as follows: Clipping the inlet cowl moves the terminal shock downstream of the true inlet lip location. An array of pitot probes can then be mounted in the inlet entrance plane, upstream of the terminal shock and the resultant separation region. The probes give readings of local pitot pressure which are assumed equal to the corresponding total pressures at the true inlet face. Hence, the mean total pressure recovery and steady-state distortion levels at the

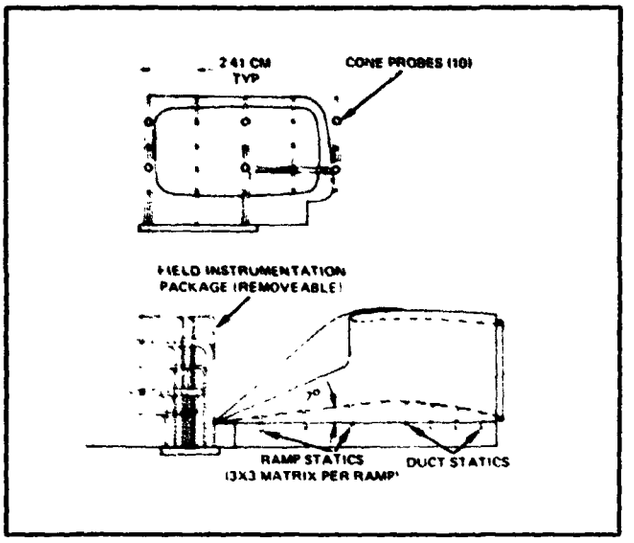


FIGURE 3. EXTERNAL FLOW FIELD INSTRUMENTATION

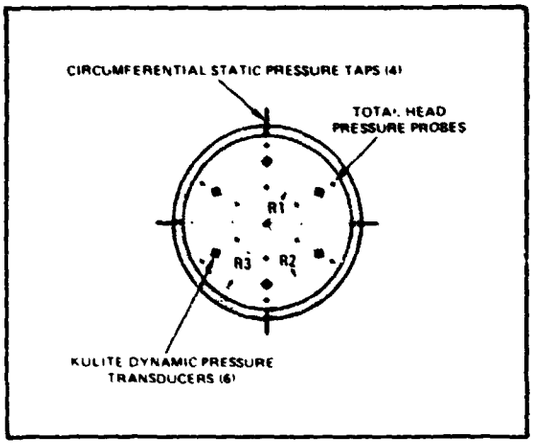


FIGURE 4. ENGINE COMPRESSOR-FACE INSTRUMENTATION

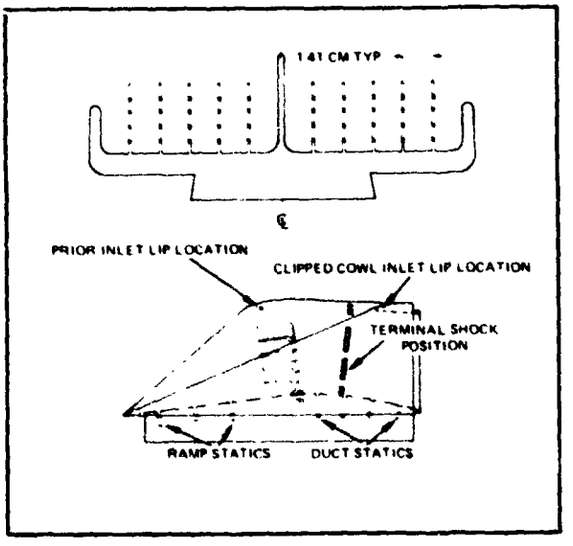


FIGURE 5. CLIPPED COWL INLET SYSTEM

inlet entrance plane can be determined. Diffuser loss characteristics can then be used to estimate the mean compressor face total pressure recovery levels.

The inlet was also instrumented with surface static pressure taps on the ramp and along the upper- and lower-centerlines of the duct for diagnostic purposes (see Figure 5).

2.3 Test Particulars

Top inlet flow field and engine-inlet performance evaluations were conducted in the 11-Foot (3.4m) Transonic and 9-by 7-Foot (2.7m x 2.1m) Supersonic Unitary Plan Wind Tunnel Facilities at NASA's Ames Research Center.

Testing in the 11-Foot Wind Tunnel was conducted at the primary test Mach numbers of 0.6, 0.9 and 1.2 at a fixed Reynolds number of 9.8×10^6/m (3×10^6/ft). Maximum angle of attack was limited to 27° by sting divergence criteria. The support system enabled survey of a ± 15° circular angle of attack and sideslip envelope, which was centered at 12.5° angle of attack and 0° sideslip. This gave an angle of attack capability -3° to 27° at zero sideslip and correspondingly reduced ranges of angle of attack at non-zero sideslip angles. Testing was conducted at fixed sideslip angles of 0°, 4°, 8° and 12°. Limited testing was also conducted at negative sideslip angles to determine the effect of possible model asymmetries on inlet performance. The test envelope surveyed can be seen by looking ahead to Figure 14.

In the 9-by 7-Foot Wind Tunnel, the primary test Mach numbers were 1.6 and 2.0, again at a Reynolds number of 9.8×10^6/m (3×10^6/ft). An angle of attack range of -4° to 15° was surveyed at fixed sideslip angles of 0°, 4° and 8°.

In both tunnels, the influence of inlet mass flow ratio on inlet performance was examined at predetermined angle of attack and sideslip conditions, however, all data presented in this paper are for the maximum engine airflow condition. To ensure turbulent boundary layers on the model, transition strips were fixed to the aircraft nose, wing leading-edges, and canard leading-edges during all testing.

3.0 DISCUSSION OF RESULTS

The following sections present and discuss some of the more significant results from this test program. First, selected results obtained for the baseline configuration will be described. Then, in Section 3.2, the influence of certain configuration variables on inlet performance will be considered. Finally, in Section 3.3, the inlet performance characteristics obtained for the baseline configuration are compared to those of more conventional inlet installations.

3.1 Baseline Configuration Inlet Performance Characteristics

Screening tests were initially conducted to determine the impact of inlet location on engine-inlet performance, and to aid in the selection of a baseline inlet arrangement for future comparative purposes. The results of these tests, however, showed little discernable difference in inlet performance as a function of inlet location over the entire test envelope surveyed. In the absence of any decided preference, based on engine-inlet performance data, the mid-inlet location was selected as the baseline arrangement since it corresponded with the VATOL inlet design location. Similar screening tests were also conducted to assess the influence of leading-edge flap deflections ($0° \leq \sigma \leq 30°$) on inlet performance. Test data showed that only marginal improvements in inlet performance were obtained with leading-edge flaps deployed, thus for all ensuing performance evaluations the zero degree leading-edge flap setting was used. In addition to incorporating a mid-inlet arrangement and zero degree leading-edge flaps, the baseline configuration as defined employed the baseline VATOL LEX, shown in Figure 2, and was tested with trailing-edge flaps undeflected.

Performance characteristics associated with the VATOL inlet/airframe model diffuser system were evaluated during subsonic and transonic wind tunnel testing. The results of these studies show that there is a marked thickening of the boundary layer along the upper- and lower-centerlines of the duct, which adversely effects inlet recovery and distortion. Surface static pressure instrumentation located along the upper-centerline of the duct indicates that this growth is not attributable to boundary layer separation, but rather to the adverse pressure gradient created by the high local wall angles (7° maximum diffuser half-angle as opposed to accepted optimum value for an ideal diffuser of 3.5° to 3.5°). Conversely, surface static pressure instrumentation along the lower-centerline of the duct indicates that there may be a zone of separation and re-attachment immediately downstream of the inlet throat (high turning region shown in Figure 3). Comparison of these data with Northrop experimental data for a similar top inlet diffuser with offset indicates, that VATOL inlet performance levels could have been improved by 0.5 to 0.8 percent had the model diffuser design not been constrained by a fore and aft movement requirement.

3.1.1 Subsonic-Transonic Performance

Subsonic and transonic inlet performance characteristics for the baseline arrangement are presented in Figure 6 in terms of average total pressure recovery, distortion, and turbulence, which is a measure of the total pressure fluctuation. Each of these parameters is presented as a function of angle of attack at zero sideslip for Mach 0.6, 0.9, and 1.2. In addition to the typical maximum minus minimum total pressure, steady-state distortion parameter ($\Delta P_{T_2}/P_{T_2}$), an estimate of maximum instantaneous fan distortion has been provided to enable a preliminary assessment of engine-inlet compatibility. The instantaneous distortion parameter presented (IDC/IDC_{limit}) is an estimate, based on steady state distortion and root-mean-square turbulence data, of the maximum instantaneous circumferential fan distortion normalized by a representative maximum allowable (limiting) value for a typical low-bypass ratio fighter aircraft engine (this value has not been quoted due to its proprietary nature).

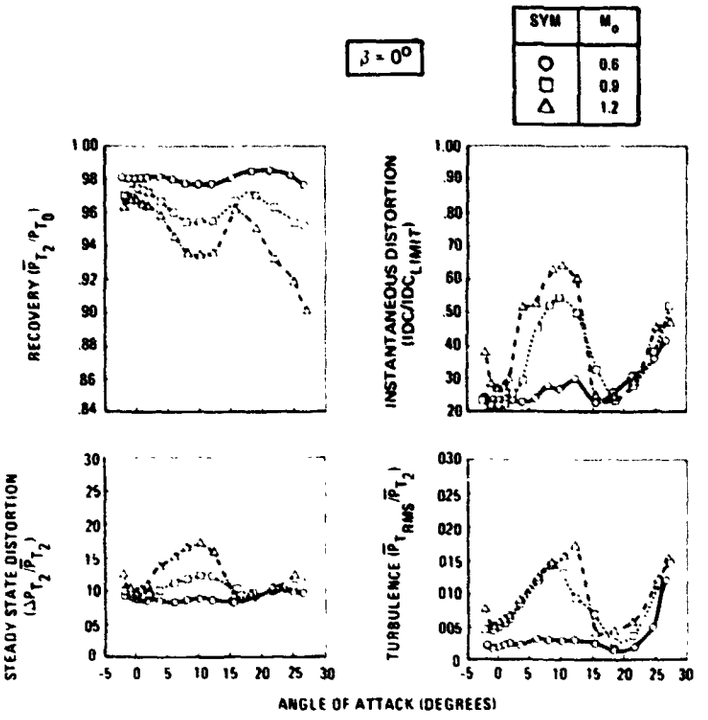


FIGURE 6. SUBSONIC AND TRANSONIC INLET PERFORMANCE CHARACTERISTICS AT ANGLE OF ATTACK ($\beta = 0^0$)

It can be seen from Figure 6 that in the lg level flight domain, $1° < \alpha < 3°$, the top inlet system exhibits high total pressure recovery levels, notwithstanding decreases in performance with increasing Mach number. These decreases in performance with Mach number, at low to moderate angles of attack, are attributable to increased incidence of canopy-dorsal separation. This highlights the importance of careful canopy-dorsal integration for top-mounted inlet installations. As angle of attack is increased from 3° to 10° a general deterioration in inlet recovery, distortion, and turbulence is experienced, independent of Mach number. This performance degradation is not the result of increased canopy-dorsal separation, but rather is traceable to ingestion of low-energy flow emanating from the juncture of the wing leading-edge extension and forebody. This is illustrated in Figure 7, where Mach 0.9 inlet flow field total pressure contours are presented in conjunction with corresponding water tunnel flow visualization photographs for a similar top inlet configuration. In fact, Figure 7 shows that at 10° angle of attack the wake shed from the canopy-dorsal is no longer evident, due to the entrainment action of the LEX vortex system. Above 10° angle of attack, a general improvement in inlet performance is noted to levels near those obtained at 0° angle of attack. This effect is ascribed to the increased sweeping action of the LEX vortex with angle of attack, which entrains the low-energy, LEX/body juncture flow out of the inlet flow field. Improvements in recovery are realized until α exceeds 15° to 20°, dependent on free-stream Mach number. Above this angle of attack range there is a reduction in inlet recovery accompanied by increases in distortion and turbulence. This is caused by the movement of the LEX vortex system burst point ahead of the inlet entrance plane. The burst phenomenon described results in a rapid expansion in the diameter of the low-energy turbulent core of the vortex, which is subsequently ingested by the inlet (see Figure 7, $\alpha = 27°$). It can also be seen in Figure 6 that the burst point moves ahead of the inlet at progressively lower angles of attack with increasing Mach number. This phenomenon is believed to be attributable to changes in the strength of the wing leading-edge vortex system and the magnitude of the LEX/body juncture low-pressure region with Mach number. As Mach number increases the wing leading-edge vortex system strength decreases, while the magnitude of LEX/body juncture flow region increases, thus having a resultant destabilizing action on the wing LEX vortices.

In sideslip, the top-mounted inlet system exhibits performance trends which are diametrically opposed to those of most conventional twin-inlet installations for low to moderate angles of sideslip ($\beta < 12°$). For top-mounted inlet installations, as is shown in Figure 8, it is the windward inlet which experiences the most noticeable degradation in inlet performance. Although Figure 8 presents data only for the Mach 0.9 condition, the trends shown are indicative of those exhibited over the entire Mach 0.6 to 1.2 test envelope.

The leeward inlet initially experiences an improvement in recovery and distortion characteristics, over most of the positive angle of attack spectrum, at low sideslip angles ($\beta = 4°$). This improvement is due to migration of the LEX/body wake out of the inlet flow field, as is illustrated in the total pressure contours of Figure 9. At higher sideslip angles, leeward inlet performance deteriorates as a result of ingestion of low-energy flow from the windward LEX/body juncture. Only a small amount of this low-energy flow is ingested at 8° sideslip, whereas at 12° the entirety of the low-pressure region is ingested, thus accounting for the marked differences in performance shown. The dramatic improvement in inlet performance which occurs at 12° sideslip and 21° angle of attack, shown in Figure 8, is believed attributable to the favorable influence of the LEX vortex entrainment mechanism.

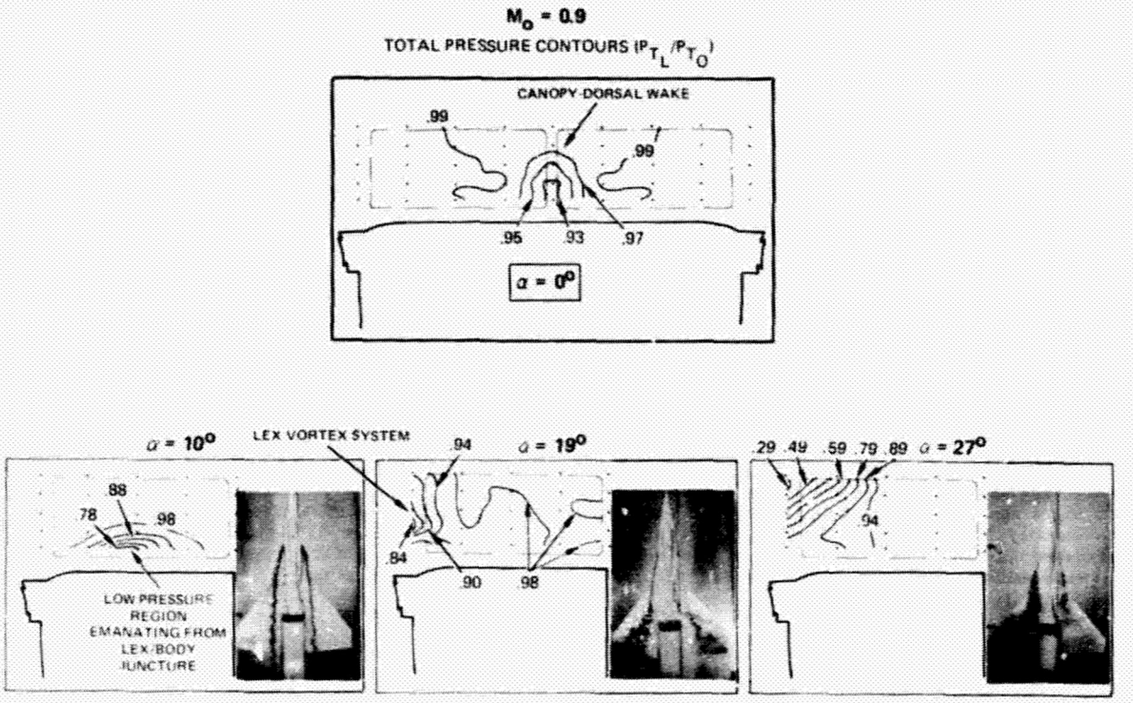


FIGURE 7. TRANSONIC INGESTED INLET FLOW FIELD CHARACTERISTICS AS A FUNCTION OF ANGLE OF ATTACK ($\beta = 0^o$)

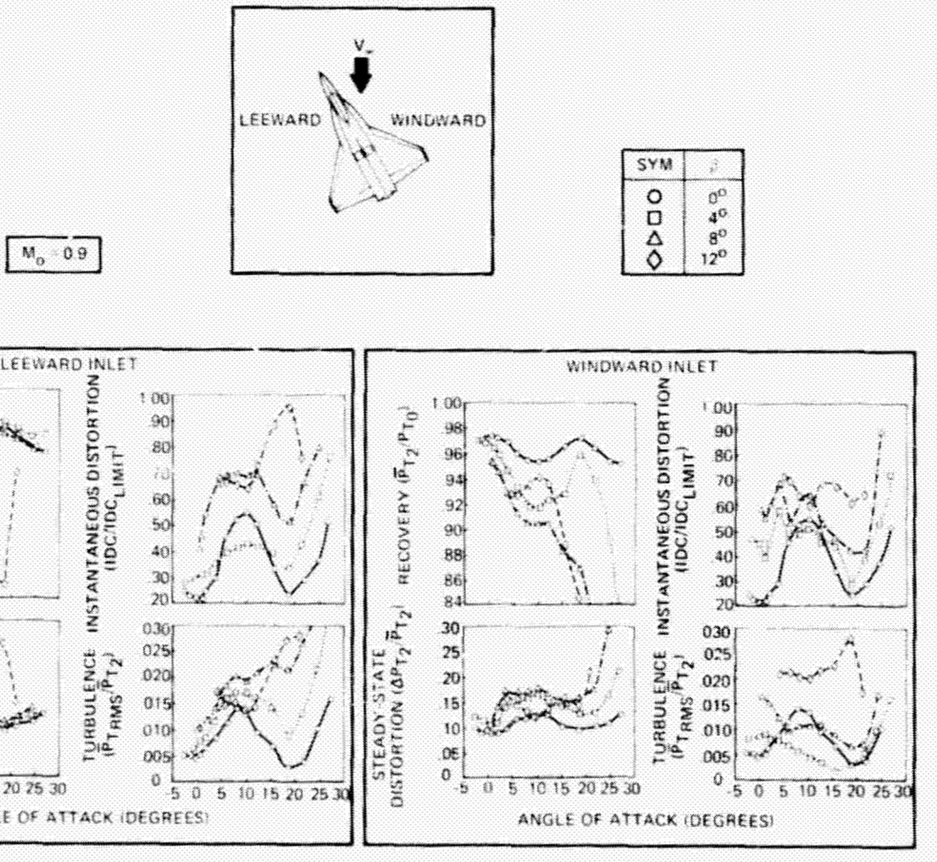


FIGURE 8. EFFECT OF SIDESLIP ON TRANSONIC INLET PERFORMANCE (M_0 = 0.9)

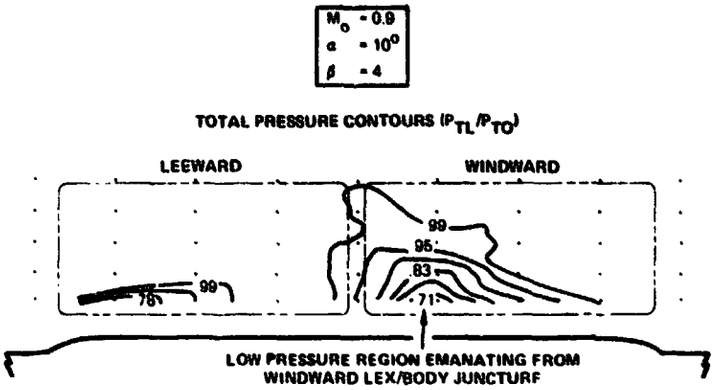


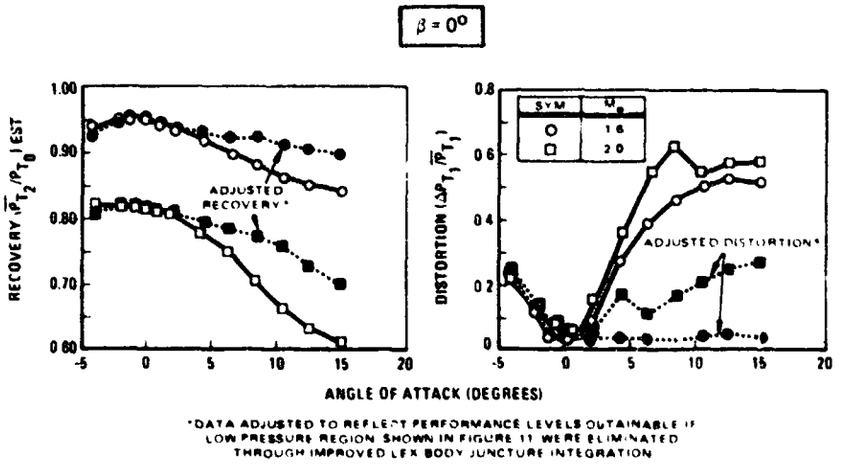
FIGURE 9. IMPACT OF SIDESLIP ON INGESTED INLET FLOW FIELD

In general, windward inlet performance decreases with increasing sideslip. This can be related to increased low-energy flow buildup from the windward LEX/body juncture at low angles of attack, and to migration of the windward LEX vortex system into the inlet flow field at higher angles of attack. An anomaly in this trend is exhibited at 12° sideslip. At this angle, low-pressure flow from the windward LEX/body juncture migrates out of the windward inlet flow field, thereby explaining the improvement in performance observed in Figure 8, relative to the 8° sideslip condition, at low to moderate angles of attack.

3.1.2 Supersonic Characteristics

During supersonic testing, ingested inlet flow field quantities were again evaluated, however, as commented in Section 2.2 "quasi" inlet performance parameters were measured at the inlet entrance plane. The inlet aperture total pressure data were used to estimate average compressor face recovery levels $(\bar{P}_{T_2}/P_{T_0})_{EST}$ and to determine steady-state, maximum minus minimum, distortion levels $(\Delta P_{T_1}/\bar{P}_{T_1})$ measured at the inlet entrance plane. Estimated compressor face recovery levels were obtained by subtracting an allowance for the diffuser losses from the measured inlet aperture recovery levels. The total pressure loss attributed to the diffuser was 1.9 percent; this value was computed from subsonic test data for the baseline configuration. No attempt was made to estimate compressor face distortion levels from the inlet aparature data as the impact of the diffuser on distortion varies (it can increase or decrease distortion) dependent on the inlet entrance profile.

Values of estimated recovery and measured distortion are presented in Figure 10 as a function of angle of attack at zero sideslip for Mach 1.6 and 2.0. A comparison of the estimated recovery levels in Figure 10 with corresponding transonic values in Figure 6 shows the same initial fall in recovery levels but without the leveling off and subsequent increase seen above 10° at transonic speeds. A direct cause of this difference in behavior is the larger scale and reduced pressures of the low-energy region generated by the LEX/body juncture at supersonic speeds as compared to transonic speeds. This effect can be seen by comparing the pitot pressure contours of Figure 11, which are for Mach 2.0 and 10° angle of attack, with the 10° angle of attack, Mach 0.9 total pressure contours of Figure 7. It can be seen that based on the pitot pressure contours at Mach 2.0 the low-energy region from the LEX/body junction is more extensive and contains lower total pressures in Figure 11 than in Figure 7. This is reflected in the inlet aperture (total pressure) distortion values presented in Figure 10, which show a marked increase with angle of attack. The reason for this increased effect of flow from the LEX/body juncture is believed to be due to a loss in strength and effectiveness of the LEX vortices at supersonic speeds: Such a loss in strength at supersonic speeds is characteristic of leading-edge vortices, as is discussed in (Reference 7).



*DATA ADJUSTED TO REFLECT PERFORMANCE LEVELS OBTAINABLE IF LOW PRESSURE REGION SHOWN IN FIGURE 11 WERE ELIMINATED THROUGH IMPROVED LEX BODY JUNCTURE INTEGRATION

FIGURE 10. SUPERSONIC INLET PERFORMANCE CHARACTERISTICS AS FUNCTION OF ANGLE OF ATTACK

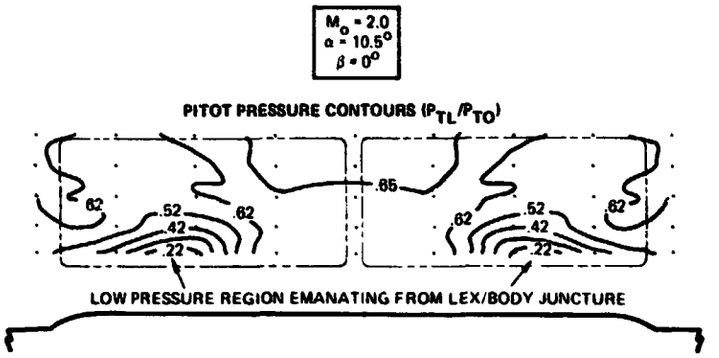


FIGURE 11. SUPERSONIC INGESTED INLET FLOW FIELD AT ANGLE OF ATTACK

The magnitude of the wake generated by the intersection of the wing leading-edge extension with the forebody is believed to be directly related to the shaping of this region*. Hence, it is possible that this low-pressure region could be reduced or eliminated and inlet performance improved by suitable design change. To estimate the relative levels of improvement possible, inlet recovery and distortion levels were recomputed from inlet entrance plane data with the region affected by the wake removed. These values are presented in Figure 10 where they are denoted as "adjusted" recovery and distortion. Significant improvements in recovery and distortion over the unadjusted values are realized over most of the positive angle of attack range tested. These data further highlight the importance of careful LEX/forebody integration with respect to top inlet vehicles.

The adjusted curves of Figure 10 show that there is still a reduction in recovery with increasing angle of attack, even in the absence of the low-pressure region. This is due to supersonic flow expansion over the forebody and wings, which increases the local inlet Mach number and hence increases shock losses. The variation in average local inlet Mach number with angle of attack for zero sideslip at Mach 2.0 is presented in Figure 12. These data have been computed from total head pressure measurements made at the inlet entrance plane and assume that the inlet shock system is purely two-dimensional. Also shown for comparison are corresponding values derived from the data of Reference 5 and the local Mach number for flow over an infinite flat plate, derived from Prandtl-Meyer theory. The VATOL data presented and those of Reference 5 are in generally good agreement, and both give substantially lower local Mach numbers than would be found for a flat plate at angle of attack. Nonetheless, the local inlet Mach number is elevated by approximately 13 percent at 15° angle of attack.

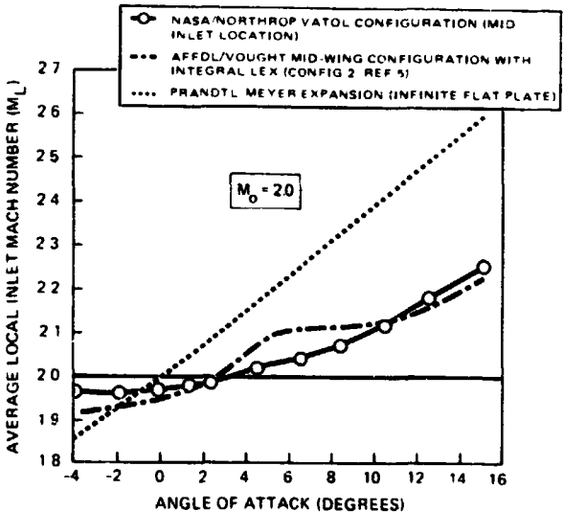


FIGURE 12. EFFECT OF ANGLE OF ATTACK ON LOCAL INLET MACH NUMBER ($\beta = 0^o$)

The impact of sideslip on inlet performance at Mach 2.0 is examined in Figure 13. These data show trends which are similar in nature to those exhibited transonically in Figure 8. Supersonically, leeward inlet performance improves in sideslip over most of the positive angles of attack range (note the dramatic improvement in distortion at 4° sideslip). This is due to the migration of the LEX/body juncture wake out of the inlet flow field. The windward inlet, as is shown in Figure 13, experiences marked deteriorations in performance, particularly at higher angles of attack. This performance reduction is attributable to the increased ingestion of low-energy flow from the LEX/body juncture and the eventual migration of the windward LEX vortex system into the inlet.

* Evidence supporting this contention is given in Section 3.2.1

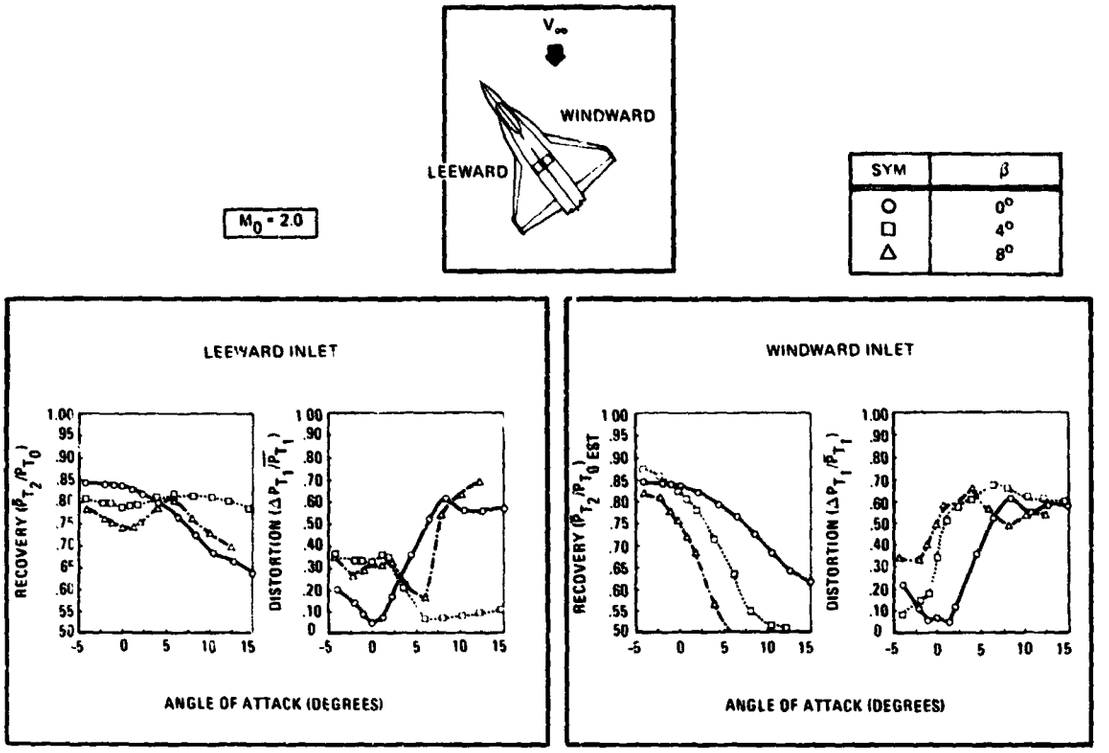


FIGURE 13. EFFECT OF SIDESLIP ON SUPERSONIC INLET PERFORMANCE

3.1.3 Engine-Inlet Compatibility

Compatibility of an aircraft inlet with the engine is crucial since it defines the functional limits over which the engine will operate. Indeed, for instantaneous maneuver, the thrust levels are relatively unimportant and the requirement for the inlet is that it should deliver flow to the engine at sufficiently low distortion levels to prevent engine stall. Normally, engine-inlet compatibility is defined in terms of both instantaneous circumferential and radial distortion. However, prior studies have shown that instantaneous circumferential distortion used alone serves as a good preliminary indicator of engine-inlet compatibility.

Utilizing the estimated instantaneous circumferential distortion parameter defined in Section 3.1.1, Figure 14 shows the conditions at which the estimated instantaneous distortion levels exceed a typical engine stall-free limit over the subsonic and transonic test envelope surveyed. Also shown are fixed-throttle maneuver envelopes characteristic of an air-to-air tactical fighter over the Mach 0.6 to 0.9 range and at Mach 1.2. It can be seen that the compatibility limit was exceeded for only three test conditions: these were all at Mach 1.2 and well outside the corresponding maneuver envelope. A complete assessment of engine-inlet compatibility over the entire $0.6 \leq M_o \leq 0.9$ maneuver envelope was not possible since the test envelope was limited to 27° angle of attack (see Section 2.3).

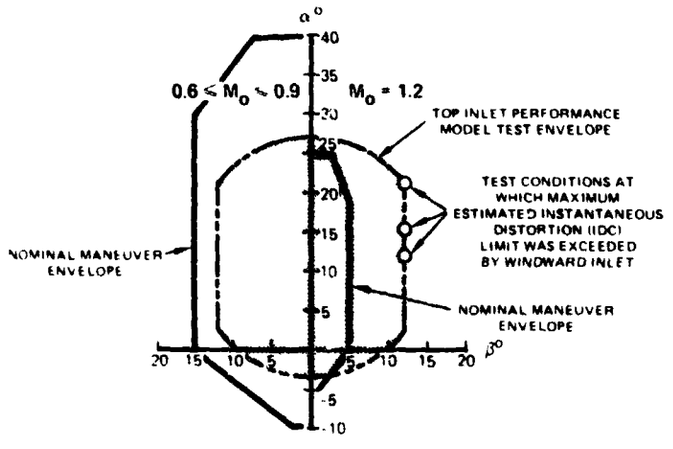


FIGURE 14. TRANSONIC TEST ENVELOPE AND TYPICAL FIXED THROTTLE MANEUVER ENVELOPES

Although no compressor face measurements or dynamic data were obtained at supersonic speeds, some indication of engine-inlet compatibility can be obtained from the steady-state distortion data measured at the inlet entrance plane (Figure 10). Using an allowable total pressure distortion limit of 30 percent, which is the typical compressor face value ($\Delta P_{T_2}/\bar{P}_{T_2}$) at which instantaneous distortion limits are exceeded (IDC/IDC$_{limit}$ >1)*, the "unadjusted" values exceed the compatibility bounds at a rather modest 4° angle of attack. However, these high distortion levels are directly related to degraded flow from the LEX/body juncture: thus, if this low-pressure region could be reduced or eliminated, the "adjusted" values shown in Figure 10 indicate that the inlet would not experience any compatibility problems over the entire -5° to 15° angle of attack range at zero sideslip.

3.2 IMPACT OF KEY AIRCRAFT CONFIGURATION VARIABLES ON TOP INLET PERFORMANCE

In order to establish guidelines for the design of future fighter aircraft incorporating top-mounted inlet systems, the impact of several key aircraft configuration variables on top inlet performance was examined. A summary of the variables investigated is presented in Table 1.

TABLE 1. CONFIGURATION VARIABLES

- INLET LOCATION (FORE-MID-AFT)
- LEX PLANFORM AREA
  - BASELINE LEX
  - REDUCED PLANFORM AREA LEX
  - LEX-OFF
- CANOPY DORSAL INTEGRATION (CANOPY ON-OFF)
- VARIABLE INCIDENCE CANARDS
- LEADING AND TRAILING-EDGE FLAPS ($0^\circ \leq \delta_n \leq 30^\circ, 0^\circ \leq \delta_f \leq 30^\circ$)

As described in Section 3.1, the influences of inlet location and leading-edge flap deflections was investigated during screening tests and found to have limited impact on inlet-performance. Subsequent tests evaluated the influence of trailing-edge flap deflections and also showed little or no impact. This section presents results for configuration variables which were found to have a more significant influence on inlet performance. These parametric evaluations were conducted with the inlet mounted in the mid location and leading- and trailing-edge flap deflections held fixed at zero degrees.

Only inlet total pressure recovery data are presented for the comparisons which follow. This parameter was selected as it serves as a good general indicator of inlet performance trends (typically losses in recovery are accompanied by increases in inlet distortion and turbulence).

3.2.1 Canopy-Dorsal Effects

The integration of the canopy with the fuselage takes on a new importance in the case of a top inlet aircraft since low-energy flow shed from the canopy-dorsal region may now be ingested by the inlet. This leads to a reduction in inlet recovery and increases the potential for engine-inlet compatibility problems.

The baseline VATOL configuration tested in this study highlights this problem. Since the vehicle was designed for an air-to-air mission, a full 360° field-of-visibility was required, causing the crew module to be elevated. This results in a high canopy-dorsal aft slope, which is responsible at low angles of attack for the low-pressure region and consequent reductions in inlet performance, which have already been pointed out in connection with Figures 6 and 7.

To examine the effects of reducing the canopy-dorsal aft slope, a "canopy-off" block, shown in Figure 15, was fitted in place of the baseline canopy. To limit the extent of the modifications, the dorsal, which comprises part of the center-fuselage, was retained and the canopy-off block faired to it. Thus, even with the canopy-off block in place, some aft slope remains and the resultant configuration is perhaps more indicative of a canopy-dorsal integration which might be employed on an Air-to-Surface aircraft, with its reduced rearward visibility requirement.

The impact of re-configuring the canopy-dorsal on inlet performance can be seen in Figure 16. At Mach 0.9, significant improvements can be seen in the recoveries at low to moderate angles of attack. This improvement is related to two different effects. At low angles of attack ($\alpha < 5^\circ$) corresponding flow field total pressure contour data confirm that there is a considerable reduction (but not elimination) of the wake from the canopy-dorsal. For moderate angles of attack, the baseline performance is degraded by the low-energy flow associated with the LEX/body juncture (see Figure 7), but the canopy-off block reduces the severity of the corner created by the junction of the LEX with the forebody(canopy), thus reducing or eliminating the low-pressure region. As the angle of attack is increased to approximately 20°, the benefit of the improved canopy integration is lost because the increasingly powerful LEX vortices become more effective in sweeping away the LEX/body juncture low-pressure region even from the baseline arrangement. At Mach 1.6, Figure 16 shows that inlet

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* This correlation is based on subsonic and transonic inlet performance data.

total pressure recovery continues to improve relative to the baseline configuration with angle of attack. Indeed, comparison with Figure 10 shows that the canopy-off results are almost identical with those of the "adjusted recovery" values obtained for the baseline arrangement. This indicates, that the wake from the LEX/body juncture (see Figure 11) has been significantly reduced or eliminated from the ingested inlet flow field via the smoother blending of the LEX and forebody which results from the use of the canopy-off block.

The reduced effect of the low-pressure region from the LEX/body juncture with canopy-off block confirms that the problems experienced with the baseline arrangement due to this flow phenomenon are configuration-dependent and can be significantly reduced or eliminated by appropriate LEX/body integration.

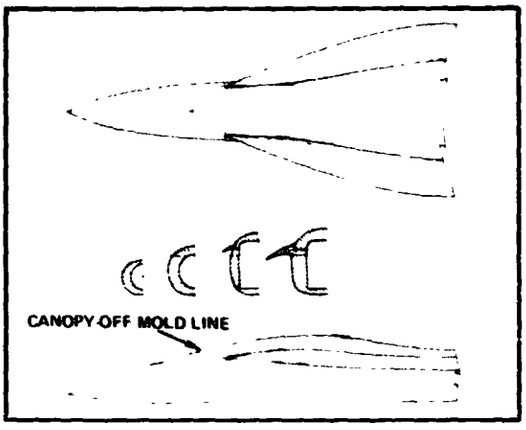


FIGURE 15. CANOPY-OFF BLOCK

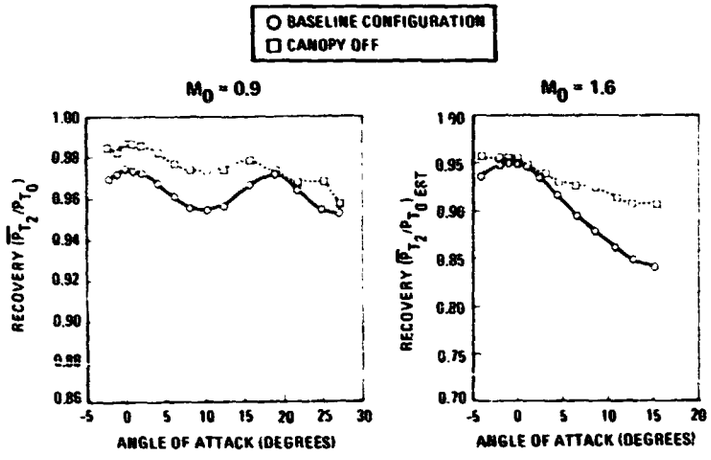


FIGURE 16. IMPACT OF CANOPY-DORSAL ON INLET RECOVERY AT ANGLE OF ATTACK ($\beta = 0^0$)

3.2.2 Wing Planform Effects

Earlier top inlet studies (e.g. References 1 and 4) have shown the importance of the LEX vortex system in counteracting the effects of upper-fuselage flow separation. These studies have also shown a direct correlation between LEX vortex system effectiveness and LEX planform area (size) and shape. A further examination of the effects of LEX planform area variation was conducted during this study. This was achieved by testing the model, as is illustrated in Figure 17, with the baseline LEX, a reduced planform area (alternate) LEX, and with wing leading-edge extensions removed. The alternate LEX retains the baseline LEX shape but has a 40 percent reduction in exposed planform area.

Comparisons of inlet pressure recovery for these three wing leading-edge extension arrangements at transonic and supersonic speeds are presented in Figure 18. It can be seen that the alternate LEX performs nearly as well as (and in some instances better than) the baseline LEX, despite a 40 percent reduction in planform area. This result differs from the findings of Reference 1 which shows a direct correlation between improved inlet performance and increased LEX planform area. A possible explanation for this behavior is that the alternate LEX forms a more favorable junction with the body, thus reducing the amount of low-energy flow buildup. In addition, this low-pressure region may be positioned further outboard on the upper-fuselage, since the intersection of the LEX and forebody moves farther out on the fuselage (see Figure 17). Thus, the consequent reduction in the extent of the low-pressure region entering the inlet would compensate for the reduced LEX vortex strength. Verification of this explanation will be possible when the inlet flow field contours become available for the alternate LEX configuration.

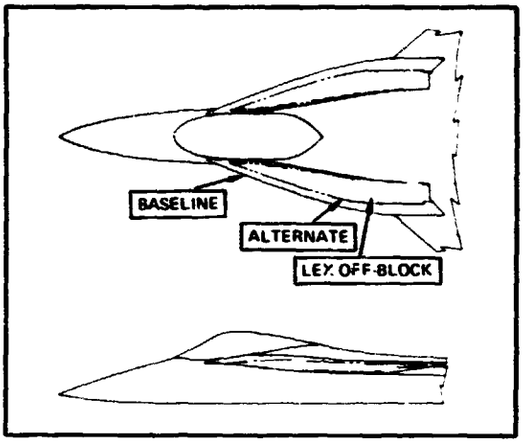


FIGURE 17. WING LEADING-EDGE EXTENSION (LEX) PLANFORM OPTIONS

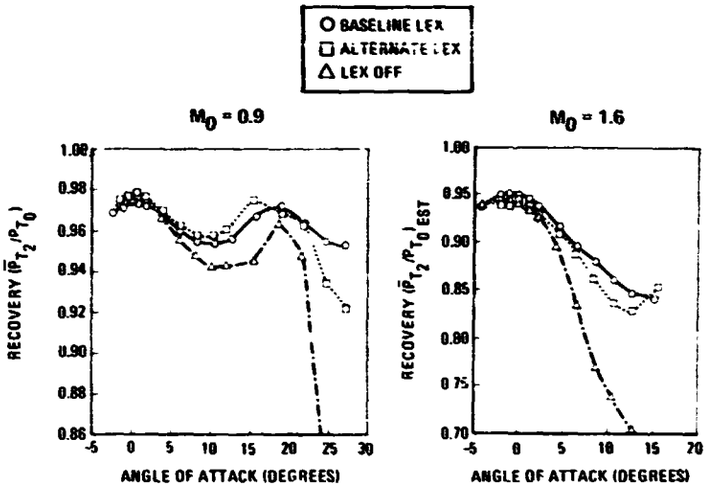


FIGURE 18. EFFECT OF WING PLANFORM VARIATIONS ON INLET RECOVERY AT ANGLE OF ATTACK ($\beta = 0^0$)

The LEX-off results of Figure 18 show a number of interesting features. First, at Mach 0.9 the LEX-off recoveries are lower, but not drastically so, than the LEX-on values, except above about 20° of angle of attack. This is due to the strong wing leading-edge vortex system, generated by the 50° swept wing, which is nearly as effective as the LEX vortices in controlling the upper-fuselage flow. However, above 20° angle of attack, the wing is stalled and the LEX-off recoveries fall rapidly. Another striking feature of Figure 18 is that at Mach 1.6 the LEX-off recovery levels continue to decrease relative to the baseline configuration with angle of attack, despite the elimination of the low-pressure region from the LEX-body juncture. Thus, the wing vortices must be much less effective in controlling upper-fuselage separation than the LEX vortices at supersonic speeds. A possible explanation for this is that, while the strengths of both vortex systems are reduced supersonically, the wing leading-edge vortex system experiences a greater reduction in strength as the wing has a lower sweep angle and hence a higher effective leading-edge normal Mach number.

At Mach 0.9 and 4° sideslip, the LEX planform has a strong effect on the windward inlet recovery, as can be seen in Figure 19, but relatively little impact on the leeward inlet performance, until 20° angle of attack, when the wing without LEX stalls. At this sideslip angle, low-energy flow from the LEX-body junction is ingested by the windward inlet but migrates outboard of the leeward inlet, thus explaining the resultant trends in inlet performance. It should also be noted, that on the windward side of the vehicle the boundary layer buildup from the LEX-body juncture is more severe in sideslip while the effective leading-edge sweep angles of the windward LEX and wing are reduced, resulting in weaker vortices and lower inlet total pressure recoveries. It can be seen that at this sideslip angle the windward vortex generated by the wing alone (LEX-off) becomes almost totally ineffective.

As sideslip angle was increased, the larger vortex from the baseline LEX was found to enter the windward inlet first, hence diminishing the advantage of the baseline LEX. Thus, in the integration of the wing planform with the inlet, it is critically important that the design achieve maximum entrainment with minimum vortex ingestion.

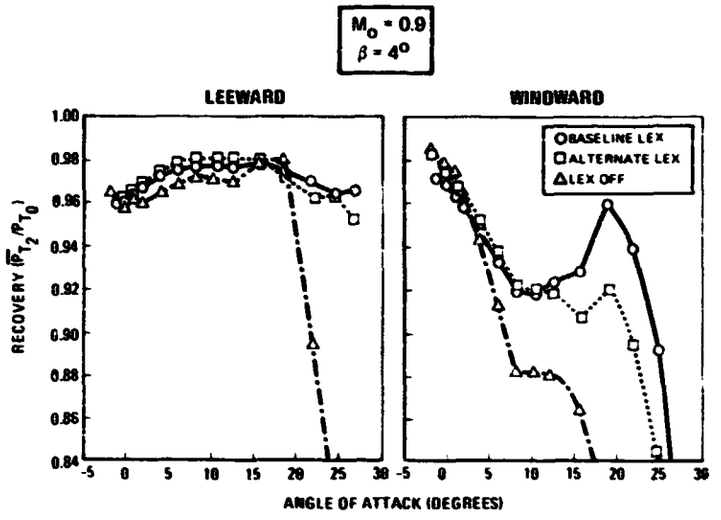


FIGURE 19. WING PLANFORM EFFECTS AT SIDESLIP

The test model did not provide the capability of examining the effect of wing planform variations. However, an indirect evaluation of this parameter is possible by making use of the flow field data of Reference 5 (AFFDL/Vought test program). These data were acquired utilizing a 35° leading-edge swept wing model with a 3.8 wing aspect ratio, which is depicted in Figure 20. Figure 21 compares inlet flow field total pressure recovery values calculated from the AFFDL/Vought data with similar values obtained for the VATOL model, which has a wing leading-edge sweep of 50° and an aspect ratio of 2.1. Data derived for the aft-survey location on the VATOL model were used, in order to obtain the closest correspondence with the flow field survey location used in Reference 5 (see Figure 20). The most important point of difference between the two curves of Figure 21 is the greater angle of attack capability exhibited by the VATOL configuration: The AFFDL/Vought model experiences a rapid decrease in recovery near 15° angle of attack whereas the VATOL configuration gives only a moderate reduction at 25° angle of attack. This difference is ascribed to the following: The VATOL wing has a significantly lower aspect ratio than the AFFDL/Vought Configuration but a similar LEX to wing planform area ratio. Thus, at given angle of attack the adverse pressure gradient associated with the VATOL wing is less than that of AFFDL/Vought configuration. This results in increased LEX vortex system stability for the VATOL configuration and, hence, increases the angle of attack at with the burst point moves ahead of the inlet.

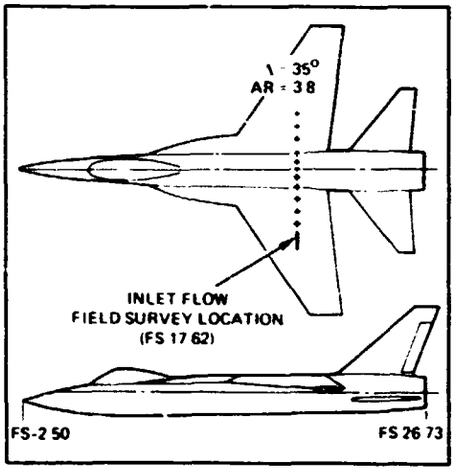


FIGURE 20. AFFDL/VOUGHT TEST CONFIGURATION

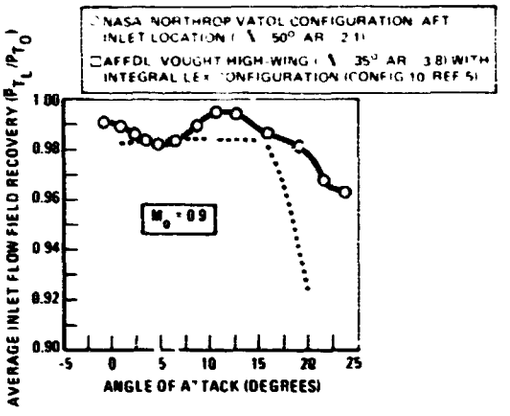


FIGURE 21. WING LEADING-EDGE SWEEP EFFECTS ON INGESTED INLET FLOW FIELD RECOVERY (β = 0°)

3.2.3 The Effect of Canards

Canards are a configuration option which are employed on a number of advanced fighter aircraft concepts, therefore, it was of interest to determine the impact canards would have on inlet performance if integrated into a top inlet configuration. Variable incidence canards were integrated into the VATOL model by replacing the wing leading-edge extensions with canards having a leading-edge sweep of 60° and a dihedral of 20°, see Figure 22. Although not typical of most canard integrations, this arrangement was selected so as to couple the canard leading-edge vortex system with the wing flow field, thus providing for vortex lift enhancement. In addition, it was desired to create a strong vortex system above the wing in order to establish a similar sweeping action to that provided by the wing leading-edge extensions.

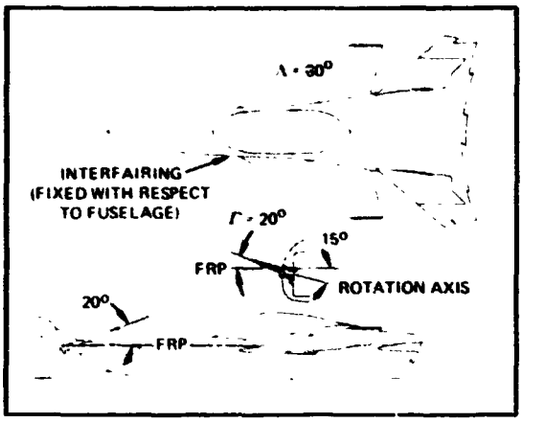


FIGURE 22. CLOSE-COUPLED VARIABLE INCIDENCE CANARDS

Figure 23 compares inlet total pressure recovery characteristics for the canard and baseline configurations at Mach 0.9 and 1.6. Curves are only shown for the undeflected canard condition (δ_c = 0°). At Mach 1.6, a zero degree canard deflection approximates the angle required for trim; but at Mach 0.9, where the aircraft has a negative static margin, quite large negative deflections are required for trim. Inlet recovery levels which would be obtained if the canards were scheduled are shown in Figure 23 for the Mach 0.9 condition at three different angles of attack.

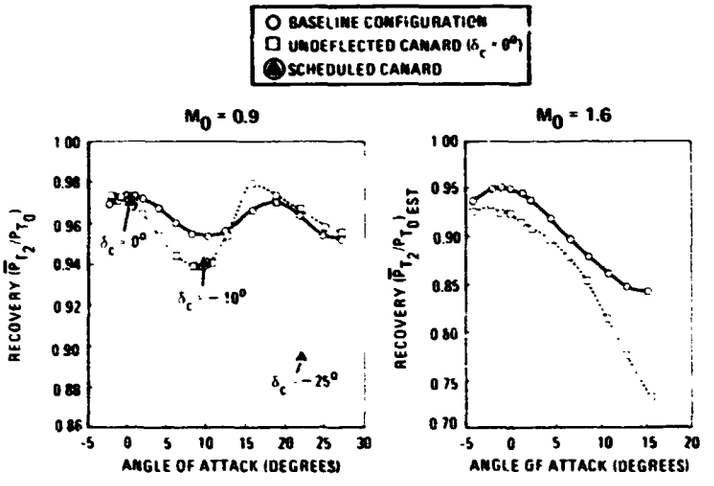


FIGURE 23. EFFECT OF CANARDS ON INLET RECOVERY AT ANGLE OF ATTACK (δ = 0°)

The Mach 0.9 data, shown in Figure 23, indicate that the canards are not effective, over the 0° to 10° angle of attack range, in controlling the upper-fuselage flow field, but at higher angles of attack, the vortex from the fixed canard improves inlet recovery, yielding values higher than those obtained with the baseline configuration. However, the scheduled canard at 22° angle of attack (δ_c = -25°) experiences a large loss in inlet performance, down to the level of the plain wing (compare Figure 18). At Mach 1.6, the canard vortices increase inlet recovery above the wing alone (LEX-off) levels but are not as effective in improving inlet performance as the baseline LEX vortices.

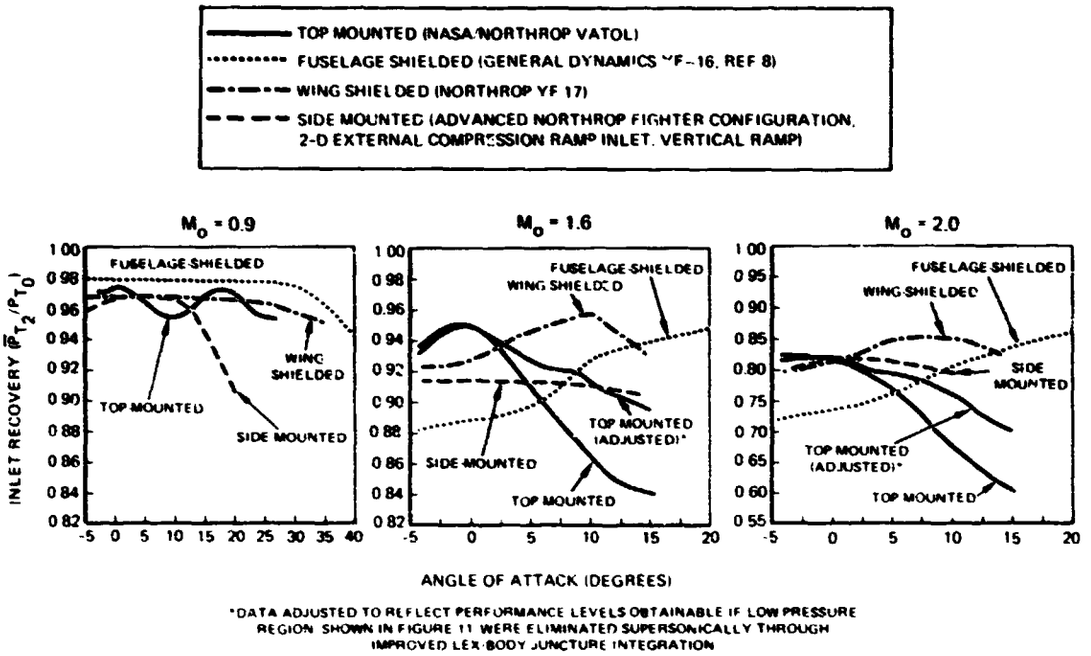
3.3 COMPARISON WITH MORE CONVENTIONAL INLET INSTALLATIONS

In order to set the results from the VATOL inlet/airframe model into the context of practical aircraft systems, VATOL top inlet performance (recovery) data have been compared with typical performance data for fighter aircraft employing more conventional inlet installations. The aircraft utilized in these comparisons are the YF-16 (Reference 8), which has a fuselage-shielded inlet system, Northrop's YF-17 prototype (wing-shielded inlet), and an advanced Northrop fighter configuration with side-mounted, two-dimensional external compression inlets with fixed, vertical ramps.

Figure 24 presents comparative results at Mach numbers of 0.9, 1.6 and 2.0. The results reflect differences in inlet design and mission requirements and do not allow a precise determination of the relative merits of the different integration options. They do, however, show the following: The VATOL inlet provides recoveries at least comparable to those of the other aircraft over the cruise range of angles of attack ($0° < \alpha < 3°$). At the transonic operating condition shown, the top inlet performance levels are competitive out to at least 25° angle of attack. Supersonically, top inlet performance deteriorates with angle of attack, primarily due to increases in local inlet Mach number (high shock system losses). In contrast, the performance of the fuselage- and wing-shielded inlets improves with

angle of attack because of the precompression provided by the forebody and/or wings. Supersonic angle of attack capability for fighter aircraft is typically limited to less than 15° angle of attack at Mach 1.6 and to approximately 10° at Mach 2.0, based on load factor constraints. Figure 24 shows that the top-mounted inlet at these angle of attack conditions gives "adjusted" recoveries which are distinctly, but not drastically, lower than those of the other inlet installations.

It is perhaps apropos to comment that the VATOL inlet system has not undergone the many hours of developmental testing that each of the other inlet systems presented in Figure 24 has, thus, the performance of the VATOL inlet system could most likely be improved through similar development efforts.



*DATA ADJUSTED TO REFLECT PERFORMANCE LEVELS OBTAINABLE IF LOW PRESSURE REGION SHOWN IN FIGURE 11 WERE ELIMINATED SUPERSONICALLY THROUGH IMPROVED LEX-BODY JUNCTURE INTEGRATION

FIGURE 24. COMPARISON OF INLET RECOVERY CHARACTERISTICS FOR TOP AND CONVENTION INLET INSTALLATIONS

4.0 CONCLUSIONS

The study described in this paper has generated extensive data on top-inlet flow field and engine-inlet performance characteristics at subsonic, transonic, and supersonic speeds. From an initial assessment of the data the following conclusions can be drawn.

- The VATOL top-inlet configuration maintains relatively good subsonic and transonic inlet performance characteristics at zero sideslip over the entire -3° to 27° angle of attack range tested. In sideslip top inlet performance in general deteriorates, but a preliminary assessment of engine-inlet compatibility shows no apparent problems over the subsonic and transonic ($0.6 \leq M_0 \leq 1.2$) test envelope.

- For the configuration tested, ingestion of low-energy flow from the LEX/body juncture serves as a major contributor to inlet performance losses. This highlights the importance of attention to detail when integrating the LEX into the forebody, especially during the preliminary design process.

- Top inlet performance is sensitive to canopy-dorsal integration and the location and strength of the wing leading-edge extension (LEX) vortices.

- The sweeping action of the wing leading-edge extension (LEX) vortices can significantly enhance top inlet performance characteristics at angle of attack. In addition, available data indicate that the effectiveness of these vortices can be extended to higher angles of attack by employing wing planforms with low adverse pressure gradient, which delay the onset of LEX vortex burst.

- Supersonically, top-mounted inlet systems experience an inherent increase in local inlet Mach number at angle of attack. This undesirable characteristic reduces inlet performance and may prohibit application of this concept to vehicles which require a high-degree of supersonic maneuverability. However, the prospects of creating designs with subsonic and transonic maneuver capabilities appear promising.

The foregoing conclusions demonstrate the highly configurational-dependent nature of top-mounted inlet systems. This indicates that major components of the airframe design must be evolved interactively with the inlet system not only in the preliminary design process, as is conventional, but also during the inlet/airframe development testing phase. The parametric studies reported on in this paper together with previous work (References 1-5) will, however, provide valuable design guidance for fighter aircraft incorporating top-mounted inlet systems.

5.0 REFERENCES

1. Williams, T. L. and Hunt, B. L., "Top Inlet System Feasibility for Transonic-Supersonic Fighter Aircraft Applications," AIAA Paper 80-1809, August 1980.

2. Prince, S. W., "A Flow Field Study for Top-Mounted Inlets on Fighter Aircraft Configurations," David Taylor Naval Ship Research and Development Center Report ASED-79/03, January 1979.

3. Ridder, S. O., "Wind Tunnel Test at Low-Speed of a Dorsal Air Intake on a Fighter Configuration," AGARD-CP-247, January 1979.

4. Surber, L. E. and Rhoades, W. W., "Top-Mounted Inlet Flow Field Testing for Future Fighter Aircraft," AIAA Paper 79-1147, June 1979.

5. Rhoades, W. W., "Experimental Definition of Top-Mounted Inlet Flow Fields," AFFDL-TR-79-3088, Volume I, August 1979.

6. Gerhardt, H. A. and Chen, W. S., "Study of Aerodynamic Technology for VSTOL Fighter/Attack Aircraft - Vertical Attitude Concept," NASA CR-152131, May 1978.

7. Kuchemann, D., "The Aerodynamic Design of Aircraft," First Edition, Pergamon Press, 1978.

8. Hawkins, J. E., "YF-16 Inlet Design and Performance," Journal of Aircraft, Volume 13, Number 6, June 1976.

6.0 ACKNOWLEDGEMENTS

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