Subsonic/Supersonic Aeropropulsive Characteristics of Nonaxisymmetric Nozzles Installed on an F-18 Model

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The Langley Research Center has conducted an experimental program on a model of the F-18 airplane to determine the performance of nonaxisymmetric nozzles relative to the aircraft's baseline axisymmetric nozzle at Mach numbers from 0.60 to 2.20. The performance of a two-dimensional convergent-divergent nozzle, a single expansion ramp nozzle (ADEN), and a wedge nozzle were compared to the baseline axisymmetric nozzles. The nonaxisymmetric nozzle did not have these capabilities. The comparisons presented here are for the nozzles in their full forward thrust mode and for the aircraft at zero angle of attack. The results demonstrate that nonaxisymmetric nozzles can be installed on a close-spaced twin-engine fighter with equal or higher performance than the axisymmetric nozzle over the range of Mach numbers tested.

Nomenclature

A/B = afterburner
A_e = nozzle exit area
A_t = nozzle throat area
$C_{D,a}$ = afterbody drag coefficient
D_a = afterbody drag
F = thrust along stability axis
F_g = gross thrust
F_i = ideal thrust
FS = fuselage station
M = Mach number
NPR = nozzle pressure ratio
Δ = increment in afterbody performance or afterbody drag coefficient (nonaxisymmetric-axisymmetric)
ϵ = nozzle expansion ratio $= A_e/A_t$

Introduction

NONAXISYMMETRIC nozzles and their application to both current and advanced tactical aircraft have received considerable attention in recent years.[1-8] This nozzle concept is geometrically amenable to improvements in nozzle/airframe integration which achieve installed drag reduction, thrust vectoring for maneuver enhancement and short-field takeoff and landing, and thrust reversing for increased agility, ground handling, and reduced landing ground roll.

This paper will summarize the results of two wind tunnel studies of nonaxisymmetric nozzles installed on a 10% scale F-18 jet effects model at Mach numbers from 0.60 to 2.20. The objective of this investigation was to determine the performance of the nonaxisymmetric nozzles relative to the aircraft's baseline axisymmetric nozzle. Three different nonaxisymmetric nozzle concepts, a two-dimensional convergent-divergent (2-D C-D), a single expansion ramp (ADEN), and a wedge, were tested. All three had vectoring capabilities and the 2-D C-D and wedge nozzles also incorporated thrust reversers.

The transonic investigation conducted at the NASA Langley Research Center was a joint NASA Langley/U.S. Navy program with the participation of Northrop, General Electric, and Boeing. The results of this investigation, which included the effects of thrust vectoring and reversing, are contained in Refs. 9 and 10. A system study to determine the feasibility of integrating the ADEN nozzle concept on a YF-17 airplane was conducted for the NASA Dryden Flight Research Center by Northrop,[11] using the data of Ref. 9. The supersonic study[12] conducted at AEDC was a joint NASA Langley/USAF Flight Dynamics Laboratory program with the participation of Northrop; all the nozzles were in the nonvectoring, nonreversing mode.

Apparatus and Model Description

Wind Tunnels

This investigation was conducted in the Langley Research Center 16-Foot Transonic Tunnel (16FTT) and the Arnold Engineering and Development Center 16-Foot Supersonic Tunnel (16S). Tests were made in the 16FTT at Mach numbers from 0.60 to 1.20 at Reynold's numbers per foot from 3.2×10^6 to 4.0×10^6. In the 16S, the Mach number range was 1.6-2.2 at Reynold's numbers per foot of 1.4×10^6 to 1.5×10^6. Failure of one motor in the tunnel main drive precluded running at a higher Reynold's number. Nozzle pressure ratio was varied up to about 20 depending upon Mach number. Angle of attack, nozzle vector angle, and horizontal tail incidence were held at zero degrees in the investigation at the 16S. The effects of varying these parameters in the 16 FTT are reported in Ref. 9.

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Model

An existing 0.10-scale F-18 afterbody jet effects model was utilized in this investigation and is shown in the sketch of Fig. 1 and photographs of Figs. 2 and 3. This model was wing-tip supported. Afterbody (including tails) forces and moments were measured with a six-component force balance. The shaded portion of the model shown in Fig. 1 is metric. The outer wing panels were modified, as shown in Fig. 1, in order to provide structural integrity of the wind tunnel model. The support system used in the 16FTT is shown in Fig. 2. A similar higher strength wing-tip support system (Fig. 3) was utilized in the 16S because of unstart load considerations. The boom semispan was 18.66 in the 16S, whereas in the 16FTT, the boom semispan was 19.53 in.

An external high-pressure air system provided a continuous flow of clean, dry air at a controlled temperature at the nozzles of 70°F in the 16FTT and 120°F in the 16S. The air was ducted to the model through the wing-tip support booms and the wing. This high-pressure air is then transferred into the metric portion of the model by means of the two flow transfer assemblies. Additional details concerning the model and calibration procedures can be found in Ref. 9.

Nozzle Designs

The baseline F-18 axisymmetric nozzle and three nonaxisymmetric or 2-D nozzle concepts were tested. The 2-D nozzles represent three generically different types: 1) two-dimensional convergent-divergent (2-D C-D); 2) single expansion ramp (ADEN); and 3) wedge with combined internal/external expansion. Each 2-D nozzle type was integrated into the F-18 model so that realistic external lines were established which were expected to minimize external flow separation in the transonic speed range. Internal clearance between the engine and airframe skin needed for structural frames, engine installation and removal, engine-bay cooling air, nozzle actuation equipment, and other required accessories within the airplane afterbody were considered in establishing these realistic external lines. The dry power throat aspect ratio of the nonaxisymmetric nozzles was selected to be 4 in order to provide a good integration with the F-18 airplane.

Each afterbody/nozzle combination was then tested in the Northrop diagnostic water tunnel in order to determine and fix regions of separated flow. The configuration with the baseline axisymmetric nozzles was used as a calibration standard to adjust nozzle exhaust velocity. Nozzle exhaust velocity was adjusted to give the same nozzle flow separation pattern at angle of attack as observed in tests previously conducted at transonic speeds.

For installation of the 2-D nozzles, modifications were made to the model afterbody starting at about fuselage station 66.0. This modification consisted of filling in the engine/nozzle interfairing that began at this fuselage station and adding filler at the fuselage corners for smooth transition to the rectangular shaped 2-D nozzles. Photographs of the various nozzle installations are shown in Fig. 4. Only the metric portion of the model (including tails) is shown for each of the nonaxisymmetric nozzles. Figure 5 presents a sketch showing a profile view of all the nozzles tested.

Two nozzle power settings were investigated representing a dry or cruise power setting with a model throat area of 2.50 in.^{2} and an afterburning (A/B) power setting with a throat area of 4.00 in.^{2} The effects of nozzle expansion ratio, thrust vectoring and reversing were studied for the nonaxisymmetric nozzles in the NASA Langley 16-Foot Transonic Tunnel and these results are presented in Ref. 9. In the AEDC 16S investigation, only one expansion ratio for each of the dry and A/B dry power settings was tested. The nozzle expansion ratios chosen were the largest of those tested at Langley. Table 1 summarizes these configurations.

The ADEN and wedge nozzles have external expansion ramps and can be considered to have both internal and external area ratios. The values quoted in Ref. 9 are internal

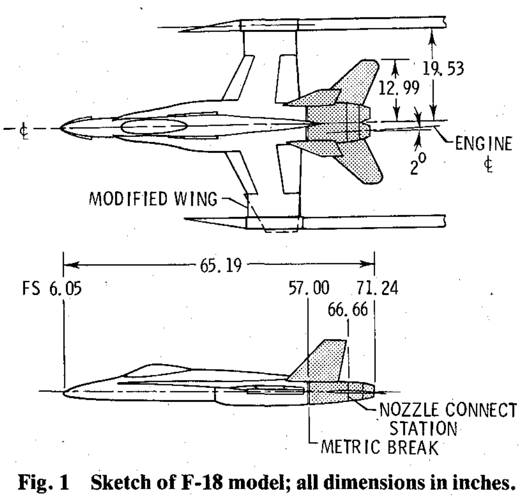

Fig. 1 Sketch of F-18 model; all dimensions in inches.

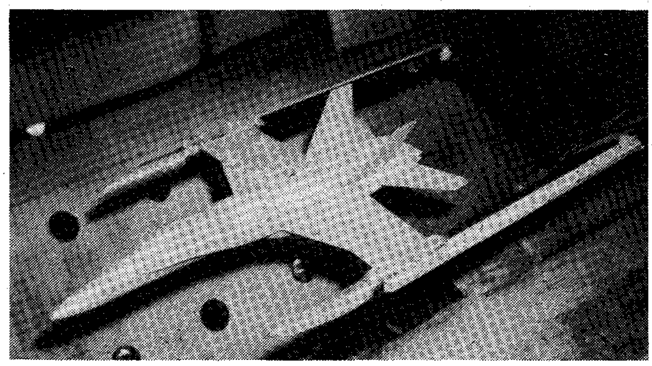

Fig. 2 F-18 model mounted in Langley 16 FTT.

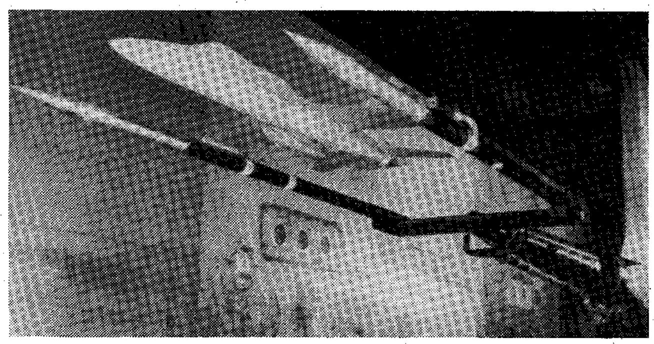

Fig. 3 F-18 model mounted in AEDC 16S.

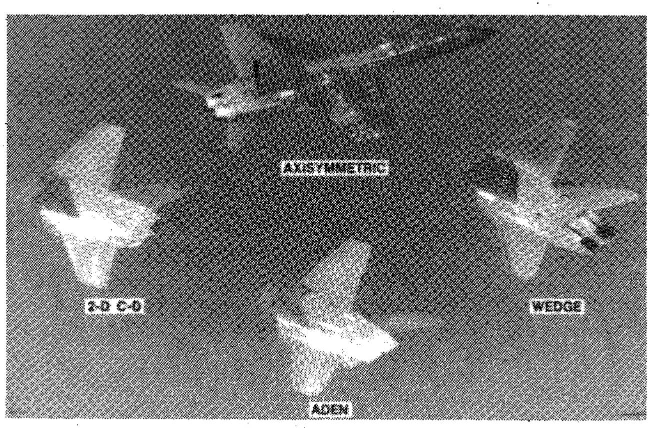

Fig. 4 Various nozzle installations.

Table 1 **Nozzle parameters**

Nozzle	A_e/A_t	Facility 16FTT	Facility 16S
Axisymmetric			
Dry	1.28	⊗[a]	⊗
A/B	1.56	⊗	⊗
2-D C-D			
Dry	1.15	X	
Dry	1.65	⊗	⊗
A/B	1.15	⊗	
A/B	1.65		⊗
ADEN			
Dry	1.06	X	
Dry	1.15	⊗	⊗
A/B	1.19	X	
A/B	1.36	⊗	⊗
Wedge			
Dry	1.10	X	
Dry	1.30	⊗	
Dry	1.50	⊗	⊗
A/B	1.20	X	
A/B	1.40	⊗	⊗

[a] ⊗ Denotes data presented herein.

ratios based on the flow areas at the end of the shorter expansion surfaces.

Baseline Axisymmetric Nozzle

The baseline axisymmetric nozzles installed on the F-18 model are shown in the photographs of Fig. 4. This axisymmetric exhaust nozzle represents a hinged-flap, variable-position, convergent and divergent nozzle. Both the convergent and divergent portions of the nozzle are conical.

Two-Dimensional Convergent-Divergent Nozzle

The 2-D C-D nozzle installed on the F-18 model is shown in the photograph of Fig. 4. The 2-D C-D nozzle is a variable-area, internal expansion exhaust system which is a three-flap design between fixed sidewalls. The 2-D convergent flap controls the nozzle-throat area. The 2-D variable-position divergent flap and external boattail flap assembly controls both the nozzle-exit area and thrust vector angle independently of throat area.

The two-dimensional nozzle shape blends well with airframe contours and the nozzle aspect ratio (dry cruise throat width/height ratio) of 4 was selected to fill the area behind the engine. In addition, sidewall thickness has been minimized by locating actuation hardware in available area on top of the exhaust duct. This permits the side-by-side nozzles to be toed-in so that only a small extension of the sidewall is required to provide an "interfairing." The result is a nozzle installation that minimizes drag-producing base regions.

Initially, the exit of the 2-D C-D nozzle was fixed at the same fuselage station as the axisymmetric nozzle. However, tests conducted in the Northrop water tunnel indicated a flow separation problem at about FS 66.66 due to locally higher afterbody slopes. This flow separation was eliminated by extending the nozzle throat aft 1.00 in.

ADEN Nozzle

The ADEN nozzle[4] installed on the F-18 model is shown in the photograph of Fig. 4. The ADEN nozzle is a 2-D, variable-area, external expansion exhaust system. Basic components consist of: 1) a transition casing from a round cross section at the tail pipe connect flange to a two-dimensional cross section at the nozzle throat station; 2) a two-dimensional variable-geometry convergent-divergent flap assembly; 3) a two-dimensional variable ventral flap; and 4) a two-dimensional external expansion ramp which can be fixed or variable depending on specific installation requirements.

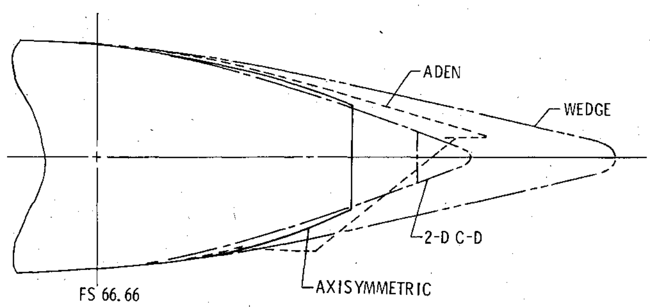

Fig. 5 Composite view of nozzles tested.

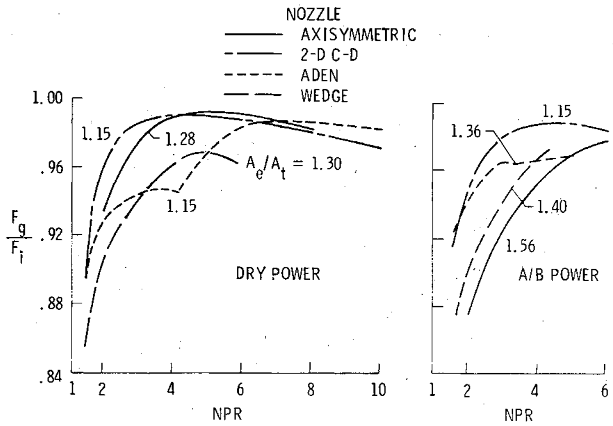

Fig. 6 Nozzle static performance.

Nozzle area control is achieved by the variable convergent-divergent flap assembly. The variable ventral flap located downstream of the throat controls nozzle expansion area ratio as required over the range of operating pressure ratios. Note that the throat is forward of the ventral flap such that nozzle area is independent of the ventral flap position. As in the case of the 2-D C-D design, the ADEN nozzle throat aspect ratio (4) and sidewall thickness were designed to provide an exhaust system that blends well with the aircraft afterbody contours and minimizes base area.

Wedge Nozzle

The wedge nozzle installed on the F-18 model is shown in Fig. 4. The wedge nozzle is a 2-D, variable-area, internal/external expansion exhaust system. The nozzle has a collapsing wedge centerbody and a fixed external nozzle flap or boattail.[5]

F-18 Model Aeropropulsive Characteristics

This section presents static nozzle performance and wind tunnel measurements of thrust-minus-drag characteristics for the range of Mach numbers from 0.60 to 2.2 for the model at zero degrees of angle of attack. The nonaxisymmetric nozzles are in the nonvectoring nonreversing mode.

Static Performance

A comparison of the static performance of each of the nozzles is presented in Fig. 6 for both dry and A/B power settings at selected expansion ratios. The performance levels shown are typical for these type nozzles. Static internal performance of the 2-D C-D nozzles ($\epsilon = 1.15$) and of the ADEN ($\epsilon = 1.15$) at NPR > 6.0 is competitive with the axisymmetric convergent-divergent nozzle at dry power setting (see Fig. 6). Performance of the wedge nozzle ($\epsilon = 1.30$) and of the ADEN at NPR < 6.0 generally is 2 to 4% below the axisymmetric nozzle at dry power setting. Both the ADEN and wedge nozzles, however, have external expansion surfaces; thus internal performance will be altered by external flow effects at forward speeds. At A/B power, all three nonaxisymmetric nozzles have higher performance than the axisymmetric nozzle, with the 2-D C-D nozzle ($\epsilon = 1.15$) exhibiting the highest performance. However, it should be noted that the axisymmetric nozzle expansion ratio tested at A/B power is much higher than the nozzle expansion ratios tested for the nonaxisymmetric nozzles. A lower nozzle expansion ratio for the axisymmetric nozzle should produce internal performance levels similar to that obtained for the 2-D C-D nozzle.

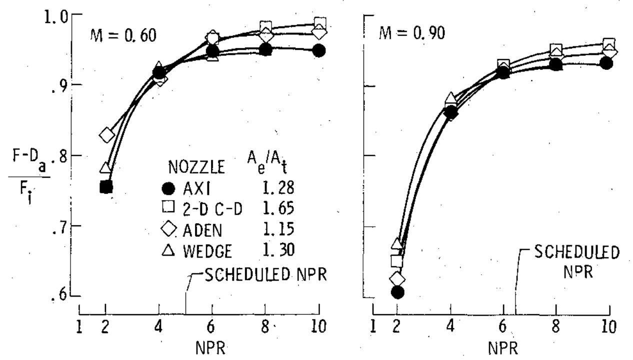

Fig. 7 Subsonic afterbody aeropropulsive performance, dry power, tails metric.

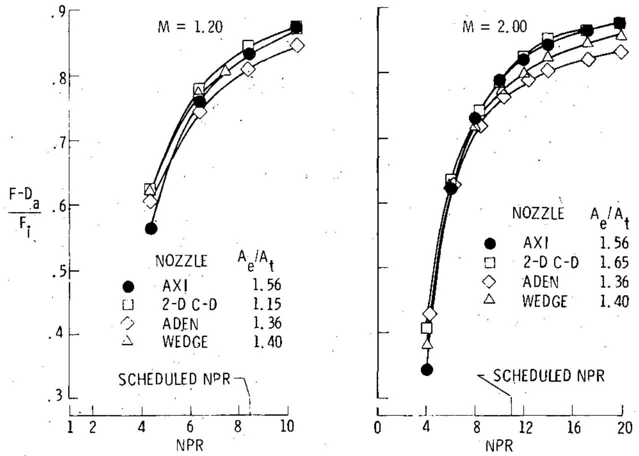

Fig. 8 Supersonic afterbody aeropropulsive performance, A/B power, tails metric.

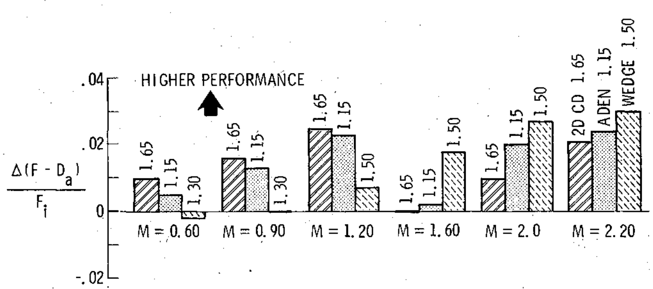

Fig. 9 Incremental afterbody aeropropulsive performance, dry power, at scheduled NPR. Values indicate nozzle expansion ratios.

Forward Flight Characteristics

Typical F-18 aeropropulsive afterbody characteristics are presented in Figs. 7 and 8 for the dry and A/B dry power settings respectively. The aeropropulsive parameter $(F-D_a)/F_i$ is shown as a function of nozzle pressure ratio, where $F-D_a$ is the thrust minus afterbody drag, and F_i is the ideal thrust. Also indicated on these figures are the typical operating or scheduled pressure ratios for the F-18 aircraft at each Mach number.

An incremental afterbody performance parameter is summarized in Figs. 9 and 10 for both nozzle power settings over the range of Mach numbers tested. This incremental afterbody performance is the difference between performance for the F-18 with nonaxisymmetric nozzles and that for the baseline axisymmetric nozzles. A positive increment indicates higher performance for the F-18 with nonaxisymmetric nozzles installed. Nozzle area expansion ratios are given on Figs. 9 and 10.

Dry Power Performance

Afterbody aeropropulsive performance is equal to or higher for the F-18 with the 2-D C-D nozzle ($\epsilon = 1.65$) than for the configuration with the axisymmetric nozzle ($\epsilon = 1.28$). This higher performance occurs over most of the nozzle pressure ratio range (Fig. 7) and Mach number range tested (Fig. 9). Subsonic and transonic performance characteristics are presented for the 2-D C-D nozzle with the 1.65 expansion ratio because this was the same nozzle configuration tested at AEDC 16S. However, the F-18 with the 2-D C-D nozzle at an expansion ratio of 1.15 also has higher performance than the axisymmetric nozzle with an expansion ratio of 1.28 over the NPR range tested at Mach numbers from 0.60 to 1.20.[9,10] Performance for the 2-D C-D nozzle followed trends with varying expansion ratios that are typical for an internal expansion nozzle. That is, low nozzle expansion ratios generally produce higher performance at low nozzle pressure ratios, and high nozzle expansion ratios generally produce higher performance at high nozzle pressure ratios. Since actual nozzle flight hardware would be continuously variable within mechanical constraints, nozzle expansion ratio would be programmed, as closely as possible, for optimum performance over the operating range of nozzle pressure ratios.

The performance of the dry power 2-D C-D nozzle at $M \leq 1.2$ can be estimated for the same expansion ratio as the axisymmetric nozzle by using the results of Ref. 9. This would result in an increase of $\Delta(F-D_a)/F_i$ of about 0.005 at $M = 0.60$ and a decrease of this parameter of 0.004 and 0.008 at $M = 0.90$ and 1.20, respectively. At $M = 1.60$ to 2.20, the axisymmetric nozzle has larger underexpansion losses than the 2-D C-D nozzle because it is operating at a less than optimum expansion ratio for the operating NPR associated with these higher Mach numbers.

Afterbody aeropropulsive performance at $M = 0.90$ of the F-18 with the ADEN nozzle ($\epsilon = 1.15$) at the dry power setting (Fig. 7), is nearly the same as with the axisymmetric nozzle for NPR < 6.0; for NPR > 6.0, ADEN performance is slightly higher than the axisymmetric nozzle. Although the ADEN static performance at NPR = 4.0 is about 4% less than either the axisymmetric or 2-D C-D nozzle, favorable external flow recompression effects on the free expansion surface are enough to make its performance at forward speeds comparable.

Consistent trends with expansion ratio for the ADEN were not evident from the NASA 16FTT investigation.[9] As just noted, the external expansion surface is affected by external flow and thus the "internal" performance of this nozzle is dependent on Mach number, angle of attack, NPR, and configuration external geometry. For ADEN-type nozzles (internal/external expansion type), internal performance is influenced by both the internal (at low NPR) and external expansion ratio (at high NPR). The external exit area is that area at the end of the external flow expansion ramp.[13] At NPR > 7, the ADEN has the highest static performance of the nozzles tested (Fig. 6), since internal performance at the higher NPR is primarily influenced by the external expansion ratio. Consequently, at the scheduled nozzle pressure ratios, the dry power ADEN configuration has higher performance over the Mach number range (Fig. 9) than the axisymmetric nozzle even though its internal expansion ratio is less than the axisymmetric nozzle. These results illustrate that comparisons of performance between internal and internal/external expansion nozzles cannot necessarily be made for nozzles at the same expansion ratio. It may also be possible to operate an ADEN-type nozzle at a fixed internal expansion ratio, with a resulting savings in both nozzle weight and complexity by not having to actuate the lower nozzle ventral flap.

The dry power wedge nozzle installed on the F-18 had higher performance at subsonic speeds for NPR < 5 (Fig. 7), and generally higher performance at supersonic speeds (data not shown) than the axisymmetric nozzle. At the scheduled NPR, the dry power wedge nozzle has higher performance than the axisymmetric nozzle at supersonic Mach numbers (Fig. 9). As with the ADEN, external flow recompression effects on the wedge are beneficial enough to overcome the lower static performance of this nozzle.

Afterburner Performance

As in the case of the dry power settings, aeropropulsive performance at A/B power for the F-18 with the 2-D C-D nozzle ($\epsilon = 1.65$) is equal to or higher than the configuration with the axisymmetric nozzle (Fig. 8). Figure 10 indicates that the 2-D C-D nozzle configuration has the highest A/B power performance of all the configurations tested over the entire Mach number range tested. At $M = 0.60$ to 1.20, this higher performance can be attributed to the fact that this nozzle is at a lower expansion ratio (1.15 compared to 1.56) than the axisymmetric nozzle (1.65 expansion ratio not tested in the 16FTT). At $M = 1.60$ to 2.20, the effect of the small difference in expansion ratio (1.65 compared to 1.56) should have little effect on performance.

The configuration with the A/B power ADEN nozzle generally has lower performance than that with the axisymmetric nozzle over either the NPR range (Fig. 8) or Mach number range (Fig. 10) tested. This lower performance may result from two factors. First, contrary to dry power results, there may be an adverse instead of beneficial effect of the external flow interacting with the external expansion ramp. In addition, there is a thrust loss due to a nonoptimum alignment of the resultant gross thrust vector relative to the aircraft body axis for the nozzle in the nonvectored mode. Reference 13 indicates that the resultant thrust angle for the A/B power ADEN varies linearly from about 0 deg at NPR = 4 to about 6.5 deg at NPR = 6. For the dry power nozzle, this angle varies from −4 deg at NPR = 4 to 4 deg and NPR = 10. References 13 and 14 indicate that this flow angle usually increases in a linear fashion from about NPR = 4 to 20. For the ADEN at A/B power, the resultant thrust angle at NPR > 8 is from about 12 to 16 deg. The magnitude of the reduction in $(F-D_a)/F_i$ for a 12-deg misalignment of the thrust vector is 0.022, which is significant but not enough to account for all the differences seen in Fig. 10. Nonetheless, optimum alignment of the ADEN resultant thrust vector angle to minimize this thrust loss would result in higher performance. This could be accomplished by varying the external expansion ramp flap that is normally used for thrust vectoring. Control of the external expansion ramp flap angle through an integrated flight/propulsion control system could maximize ADEN aeropropulsive performance and also eliminate either nose-up or -down pitching moments that would occur from the nonaligned gross thrust vector.[14]

In general, the A/B power wedge nozzle has somewhat higher performance than the axisymmetric nozzle at NPR < 6 (Fig. 8). This nozzle, however, has lower performance than the axisymmetric nozzle at the scheduled NPR over the Mach number range tested (Fig. 10). As with the ADEN, this nozzle's performance is also a function of the external expansion ratio and it may be that the internal expansion ratio of this nozzle is too high. Unfortunately, research has not been conducted to optimize the performance of these types of nozzles at supersonic speeds.

These results are significant because they demonstrate that 2-D C-D nozzles can be installed on a twin-engine fighter aircraft with higher installed thrust-minus-drag characteristics than the baseline aircraft axisymmetric nozzles which have been refined through a complete development program. The ADEN and wedge nozzles also show advantages under certain flight conditions and may be capable of considerable further improvement.

Afterbody Drag Characteristics

Typical F-18 afterbody drag characteristics are presented in Figs. 11 and 12 as a function of nozzle pressure ratio for the same power setting and Mach numbers as shown in Figs. 7 and 8. The afterbody drag coefficient of Figs. 11 and 12 were obtained by determining the components of thrust in the axial and normal directions and subtracting these values from the measured afterbody forces. The thrust components at for-

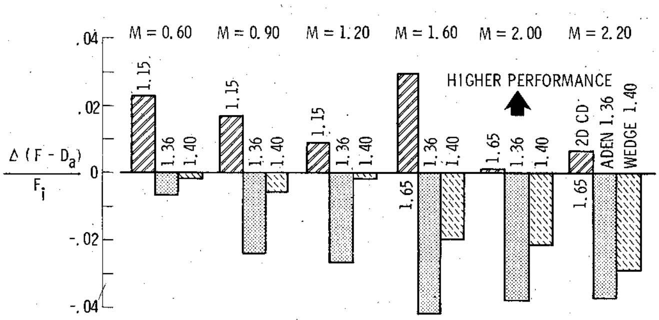

Fig. 10 Incremental afterbody aeropropulsive performance, A/B power, at scheduled NPR. Values indicate nozzle expansion ratios.

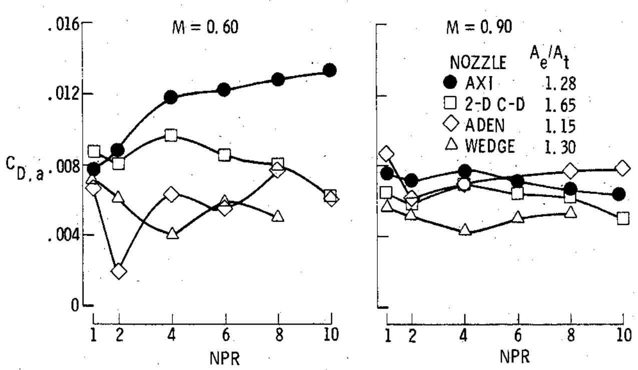

Fig. 11 Subsonic afterbody drag characteristics, dry power, tails metric.

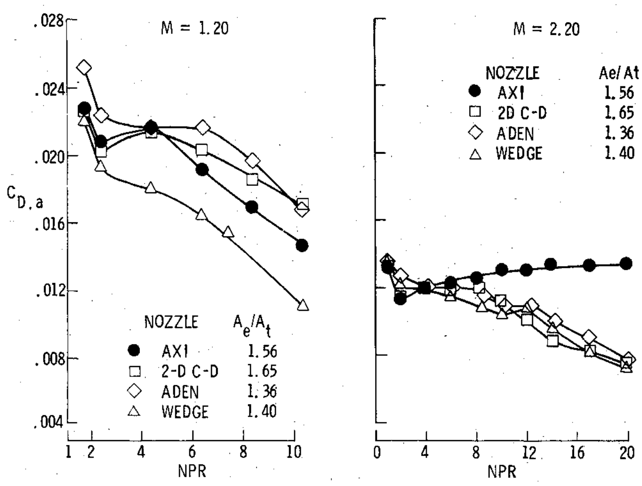

Fig. 12 Supersonic afterbody drag characteristics, A/B power, tails metric.

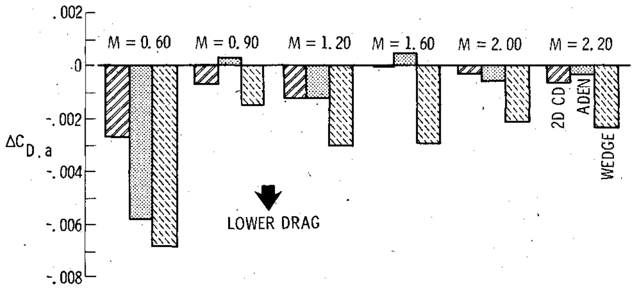

Fig. 13 Incremental afterbody drag characteristics, dry power, at scheduled NPR.

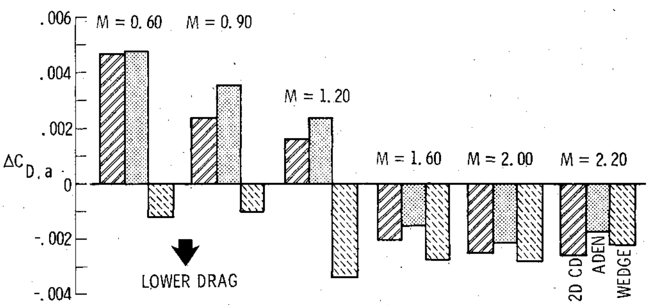

Fig. 14 Incremental afterbody drag characteristics, A/B power, at scheduled NPR.

ward speeds are determined from measured static data and are a function of the freestream static and dynamic pressure. Because of this, any effects of the external flow on the internal performance of either the ADEN or wedge nozzle are reflected as a change in afterbody drag.

An examination of the basic data of Figs. 11 and 12 shows no consistent trends of afterbody drag variation for the F-18 with the nonaxisymmetric nozzles. Afterbody drag for the nonaxisymmetric nozzle configurations can be greater or less than the F-18 with the axisymmetric nozzle depending upon power setting, Mach number, and pressure ratio. Nonetheless, the nonaxisymmetric nozzle drag characteristics are generally quite favorable relative to those of the axisymmetric nozzles. Also, overall, the configuration with the wedge nozzle has the lowest afterbody drag. This is probably because of the low boattail angle of the wedge nozzle cowl.

This is further illustrated in the summary data of Figs. 13 and 14, where incremental afterbody drag is shown over the Mach number range at the scheduled nozzle pressure ratios shown in Figs. 7 and 8. For both the dry and A/B power settings, the wedge nozzle always has lower afterbody drag than the axisymmetric nozzle. The 2-D C-D configuration also has lower drag than the axisymmetric nozzle except in A/B power at subsonic and transonic speeds. The ADEN drag characteristics are generally similar to those of the 2-D C-D except that the axisymmetric nozzle drag values are also exceeded at $M=0.90$ and 1.60 in dry power (Fig. 13). However, the data shown on Fig. 13 indicate that the nonaxisymmetric nozzles have lower afterbody drag than the axisymmetric nozzle at dry power setting.

Concluding Remarks

An investigation to determine the aeropropulsive characteristics of nonaxisymmetric nozzles on an F-18 jet effects model has been conducted in the NASA Langley 16-Foot Transonic Tunnel and the AEDC 16-Foot Supersonic Tunnel. The performance of a two-dimensional convergent-divergent nozzle, a single expansion ramp nozzle, and a wedge nozzle was compared to the baseline axisymmetric nozzles. The results of these investigations demonstrate that two-dimensional convergent-divergent nozzles can be installed on close-spaced, twin-engine, fighter aircraft with equal or higher performance than axisymmetric nozzles. Under dry power conditions, the single expansion ramp and wedge nozzles also showed advantages.

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