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Performance Characteristics of Nonaxisymmetric Nozzles Installed on an F-18 Propulsion 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. The performance of a single-expansion ramp and a two-dimensional convergent-divergent nozzle were compared to the baseline axisymmetric nozzles. The effects of vectoring and reversing were also studied. The results of this investigation indicate that nonaxisymmetric nozzles can be installed on a twin-engine fighter airplane with equal or better performance than axisymmetric nozzles. The nonaxisymmetric nozzles also offer potential for innovative and improved aircraft maneuver through thrust vectoring and reversing.

Nomenclature

A/B	= afterburner
A_e/A_t	= nozzle expansion ratio, exit area divided by throat area
$C_{(F-D)}$	= thrust-minus-drag coefficient
$C_{L,\mathrm{aft}}$	= total afterbody lift coefficient
$C_{L,j}$	= jet lift coefficient
C_p	= pressure coefficient
ΔC_L	= $C_{L,\mathrm{aft}}$ jet-off lift coefficient
D	= afterbody drag
F_g	= gross or resultant thrust
F_i	= ideal thrust
FS	= fuselage station, in.
M	= Mach number
NPR	= Nozzle pressure ratio
α	= angle of attack, deg
δ	= measured effective static turning angle, deg
δ_N	= nozzle geometric turning angle, deg

Introduction

NONAXISYMMETRIC nozzles and their application to advanced tactical aircraft have received considerable attention in recent years.[1,2] The nonaxisymmetric nozzle concept offers the potential to reduce aft end drag through improved integration, improved maneuverability through thrust vectoring and reversing, and improved survivability through reduced infrared signature and radar cross section.

The Langley Research Center has conducted a variety of research programs aimed at providing an adequate data base necessary to evaluate the potential of nonaxisymmetric nozzles properly. These programs have included studies of thrust vectoring,[3,4] basic nozzle performance,[5-7] and configurations with nonaxisymmetric nozzles.[8,9] References 10-13 present results from studies conducted by other organizations.

This paper summarizes the results of a wind tunnel study of nonaxisymmetric nozzles installed on a 10% scale F-18 jet-effects model. The objective was to determine the performance of the nonaxisymmetric nozzles relative to the aircraft's baseline axisymmetric nozzle. Two generically different nonaxisymmetric nozzles, a single-expansion ramp and a two-dimensional convergent-divergent type were tested.

Model Description and Procedure

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 in Fig. 2. This model was wing-tip supported and only afterbody (including tails) forces and moments were measured with a six-component force balance. The outer wing panels were modified as shown in Fig. 1, in order to provide structural integrity of the wind tunnel model.

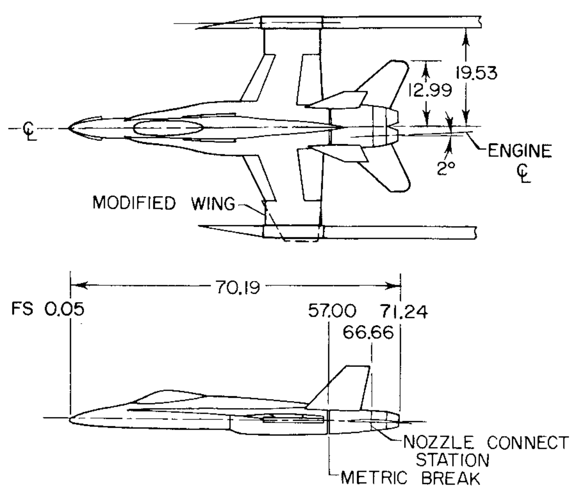

Fig. 1 Sketch of F-18 model, all dimensions in inches.

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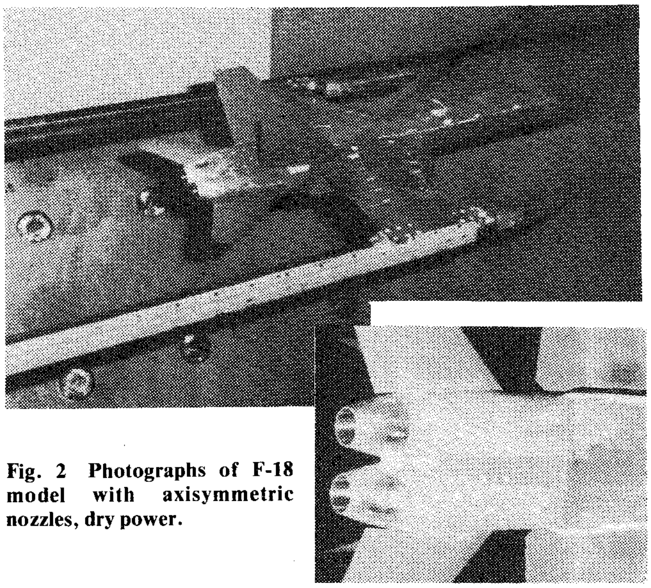

Fig. 2 Photographs of F-18 model with axisymmetric nozzles, dry power.

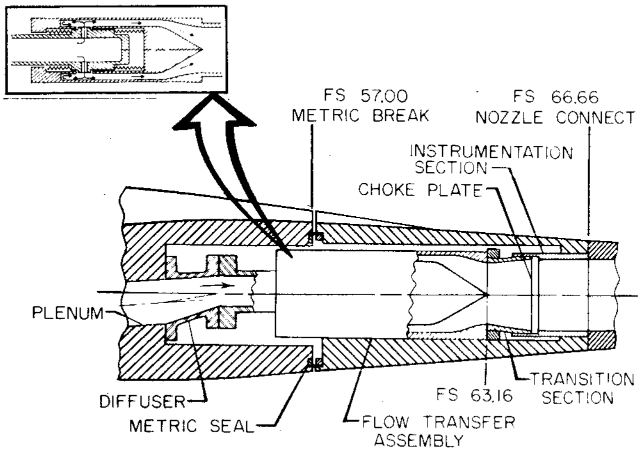

Fig. 3 Sketch of internal flow duct.

Modifications were made to the original model in order to convert it from an afterbody-drag model to one on which total afterbody thrust-minus-drag forces were measured including installation of both the horizontal and vertical tails. This was accomplished by replacing the original nonmetric internal flow ducts with flow transfer assemblies as indicated in Fig. 3. These flow transfer devices have been used in several previous investigations.[3,4,6,7,12,13]

An external high-pressure-air system provided a continuous flow of clean dry air at a controlled temperature of about 70°F at the nozzles. 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. Flexible metal bellows, shown in the insert of Fig. 3, are located in each end of the flow transfer assemblies and act to minimize pressurization tares and provide a leak-free assembly. Extensive calibrations with ASME nozzles were performed prior to the investigation with jets operating under known loading conditions to determine bellows and flow-transfer tare forces. Additional details concerning these procedures can be found in Refs. 4, 6, and 7.

Transition and instrumentation sections, including choke plates, were attached to each of the flow transfer assemblies and terminated at FS 66.66 which was the common nozzle connect section. Each instrumentation section contained six total pressure probes and one total temperature probe downstream of the choke plate. Thus, nozzle performance parameters calculated from these measurements are independent of effects due to the transition sections. Total pressure profiles were determined for the ASME calibration nozzle and for the two-dimensional, convergent-divergent nozzle at an afterburner power setting with the divergent flaps removed. Thus, total pressure profiles were measured at the throat of a convergent two-dimensional nozzle. Each total pressure probe was then corrected to the integrated value of jet total pressure at the nozzle throat.

This investigation was conducted in the Langley 16-Ft Transonic Tunnel at Mach numbers from 0.60 to 1.20. Nozzle pressure ratio was varied from jet-off up to 10.0. Horizontal tail incidence was 0 deg for all configurations. Reynolds number based on the wing mean geometric chord varied from about 3.4×10^6 to 4.8×10^6. All tests were conducted with boundary layer trip strips located at the nose and leading edge of all lifting surfaces of the model.

Nozzle Designs

The baseline F-18 axisymmetric nozzle and two nonaxisymmetric nozzle types were tested. The nonaxisymmetric nozzles represent two generically different types: 1) single-expansion ramp (SERN) with combined internal/external expansion, and 2) two-dimensional convergent-divergent (2-D C-D). Each nonaxisymmetric nozzle type was integrated into the F-18 such that realistic external lines were established which were also expected to minimize potential areas for external flow separation in the transonic speed range. Realistic external lines were necessary to maintain 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 aircraft afterbody. For the installation of the nonaxisymmetric nozzles, modifications were made to the fuselage starting at about FS 60. This modification essentially consisted of filling in the engine/nozzle interfairing that began at this fuselage station. Each of the three afterbody/nozzle combinations was tested in the Northrop water tunnel in order to determine potential regions of separated flow.

Two nozzle power settings were investigated and represented 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} Thrust vectoring was investigated for both nonaxisymmetric nozzle types and thrust reversing was investigated for the 2-D C-D nozzle only. Nozzle parameters are summarized in Table 1.

Existing nozzle designs were used in defining model lines for all three nozzle types. As indicated above, the F-18 nozzle lines were used for the axisymmetric nozzle. The augmented deflector exhaust nozzle (ADEN) provided the lines for the single ramp nozzle. Since this is a "plug" type nozzle, it has

Table 1 Nozzle Parameters Tested

Nozzle	A_e/A_t	Vector angles, deg	Reverser deployment, %
Axisymmetric			
Dry	1.28	0	0
A/B	1.56	0	0
ADEN			
Dry	1.15	−7, 0, 7, 20	0
A/B	1.19	−7, 0, 7, 20	0
2-D C-D			
Dry	1.15	−7, 0, 7, 20	0,100
A/B	1.15	−7, 0, 7, 20	0

both an internal and an external area ratio. The internal area ratios listed in Table 1 are based on the flow area at the end of the lower surface. The 2-D C-D nozzle flap schedule was set to provide area ratios the same as the ADEN internal value for the dry configuration and the external value for the high Mach A/B configuration. However, for a realistic application, all thrust vectoring, both dry and A/B, was judged to be employed at subsonic operating conditions where lower nozzle pressure ratios make lower area ratios a reasonable choice. Therefore, the 2-D C-D nozzle thrust vectoring studies were conducted using an area ratio of 1.15.

Baseline Axisymmetric Nozzle

The baseline axisymmetric nozzle installed on the F-18 model is shown in Figs. 1 and 2. A sketch of the nozzle showing both the dry and A/B power setting is given in Fig. 4. This axisymmetric exhaust nozzle is a hinged flap, variable position, convergent-divergent type nozzle. Both the convergent and divergent portions of the nozzle are conical. A single actuation system controls the nozzle area. The nozzle throat A_t has a range of full-scale areas from 220 in.^{2} to 500 in.^{2} The nozzle exit area A_e is controlled by an adjustable linkage rod and is a unique function of throat area. Thus, for a set linkage rod length/hinge location, the nozzle area ratio A_e/A_t is a unique function of A_t.

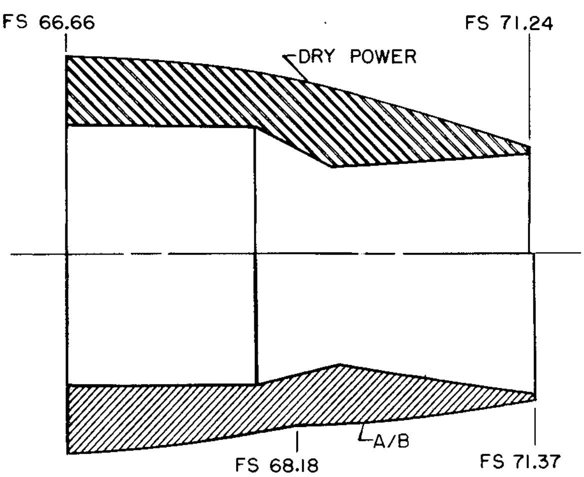

Fig. 4 Sketch of axisymmetric nozzle.

ADEN Nozzle

The ADEN nozzle installed on the F-18 model is shown in the photographs of Fig. 5. Figure 6 presents a sketch of the nozzle. The small insert sketch is provided to indicate basic mechanical features of the nozzle.

The ADEN nozzle[10,11] is a two-dimensional, variable area, external single-expansion exhaust system. Basic components consist of : 1) a transition casing from a round cross section at the tail pipe connect flange to a rectangular 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. The rotating thrust deflector utilized in V/STOL installations has been removed in the F-18 installation since 90 deg thrust vectoring is not required.

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. Capability of inflight thrust vector control is provided by utilizing a variable aft expansion ramp. Rotation of the expansion ramp provides an upward or downward vertical component as desired.

The two-dimensional nozzle shape blends well with airframe contours and the nozzle aspect ratio (dry cruise throat

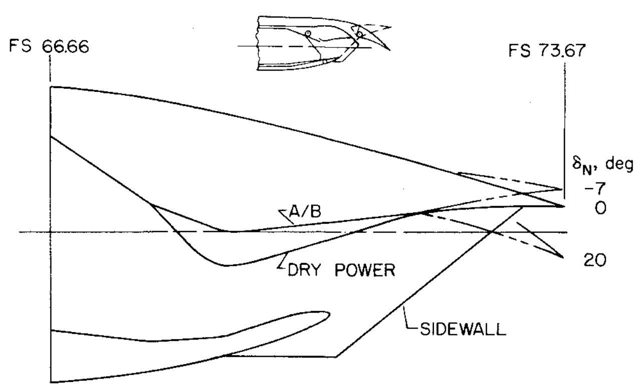

Fig. 6 Sketch of ADEN nozzle.

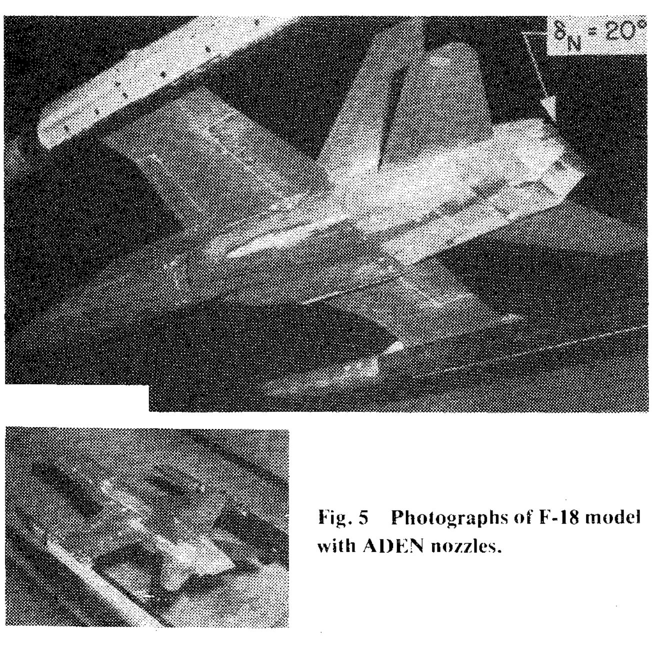

Fig. 5 Photographs of F-18 model with ADEN nozzles.

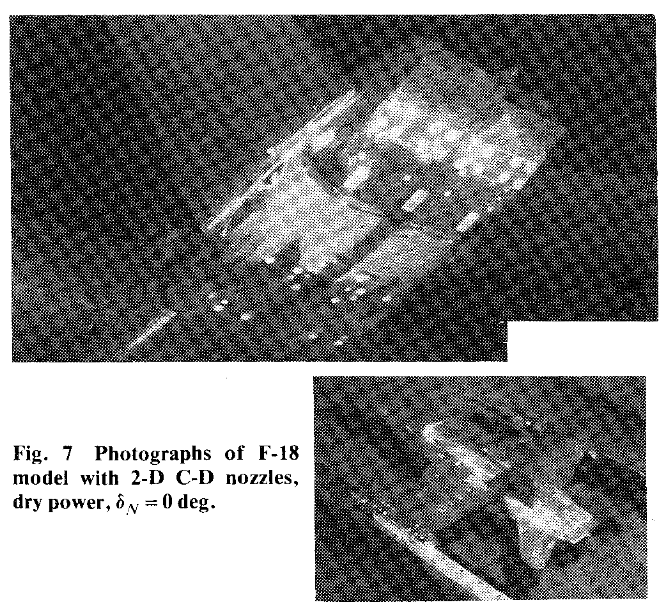

Fig. 7 Photographs of F-18 model with 2-D C-D nozzles, dry power, $\delta_N = 0$ deg.

width/height ratio) was selected to fill the area behind the engine. In addition, sidewall thickness has been minimized by locating actuation hardware in available areas 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.

Two-Dimensional Convergent-Divergent Nozzle

The two-dimensional convergent-divergent (2-D C-D) nozzle installed on the F-18 model is shown in the photographs of Fig. 7. Sketches of the nozzle in both dry and afterburner power at $\delta_N = 0$ deg and dry power at $\delta_N = 20$ deg are shown in Fig. 8 along with a sketch to indicate mechanical features.

The 2-D C-D nozzle is a variable-area internal-expansion exhaust system. It is a three-flap design between fixed sidewalls. The two-dimensional primary flap controls nozzle throat area. The two-dimensional variable position secondary flap and boattail flap assembly controls both nozzle exit area and thrust vector angle. Thrust vectoring is achieved by differential positioning of the upper and lower assemblies. Thrust reversing is provided by a two-dimensional clamshell blocker and outer door combination. The reverser is located immediately downstream of the transition section that changes the exhaust duct from round to rectangular cross section. As in the case of the ADEN design, the 2-D C-D nozzle aspect ratio and sidewall thickness were designed to provide an exhaust system that blends well with the aircraft afterbody contours and minimizes 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 exit aft 1.19 in.

F-18 Model Results

Unvectored Performance

A comparison of the static performance of each of the nozzles is presented in Fig. 9 for both dry and A/B power settings. The performance levels shown are typical for these type nozzles.[7] The lower static performance for the axisymmetric nozzle with A/B power is due to overexpansion losses that result from the high expansion ratio A_e/A_t of 1.56.

A comparison of afterbody performance between the axisymmetric and nonaxisymmetric nozzles installed on the F-18 model is shown in Fig. 10. The thrust-minus-drag term includes the drag of the horizontal and vertical tails. The results shown include the dry power nozzles at $M = 0.9$ and the A/B power nozzles at $M = 1.2$ and are typical for the other Mach numbers tested. Both the angle of attack and horizontal tail incidence angle are 0 deg.

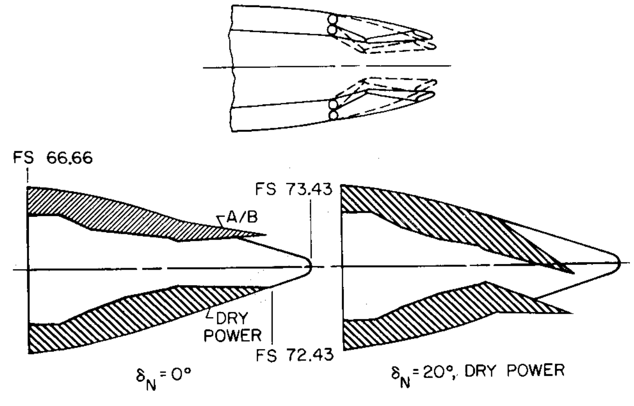

Fig. 8 Sketch of 2-D C-D nozzle.

For the dry-power nozzle, afterbody performance is higher for the 2-D C-D nozzle than for the axisymmetric nozzle. For nozzle pressure ratio NPR < 6.0, the ADEN dry-power performance is about the same as the axisymmetric nozzle; 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. This favorable external flow effect can increase the nozzle internal performance by some 3%.[12]

For the A/B power setting, the ADEN performance is lower than the axisymmetric nozzle at $M = 1.2$. This lower performance may result from adverse external flow effects resulting from the interaction of both the external and internal supersonic flows.

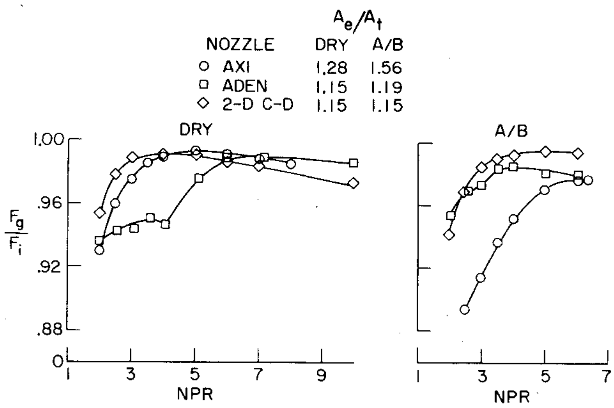

Fig. 9 Comparison of static nozzle performance.

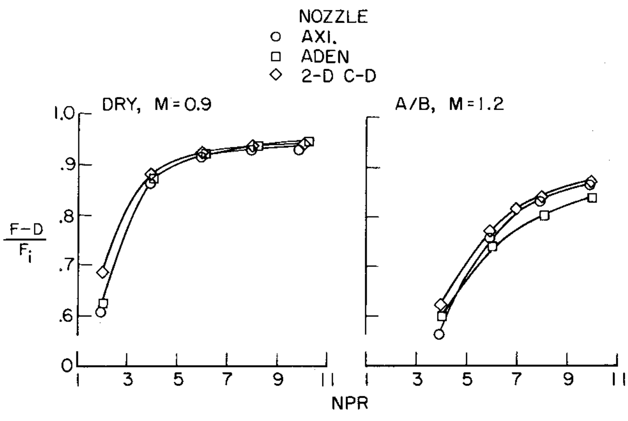

Fig. 10 Comparison of F-18 afterbody performance, tails metric, $\alpha = 0$ deg.

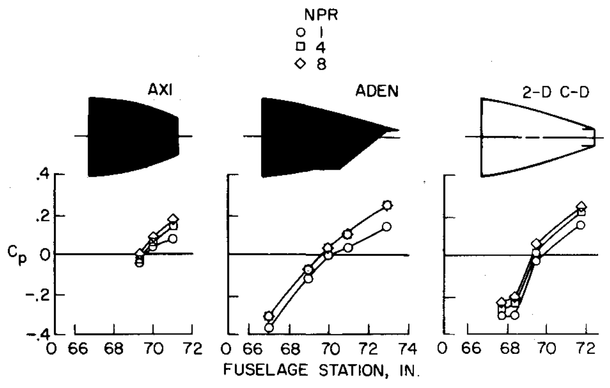

Fig. 11 Comparison of pressure distributions along the centerline of the nozzle upper surface, dry power, $M = 0.9$, $\alpha = 0$ deg.

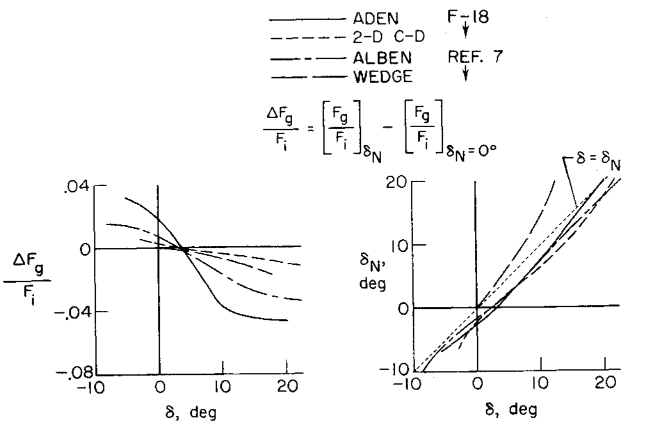

Fig. 12 Comparison of static vectoring performance, dry power, NPR = 4.0.

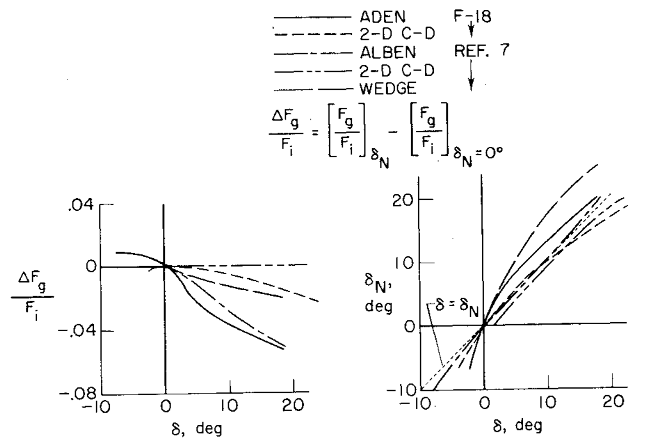

Fig. 13 Comparison of static vectoring performance, A/B, NPR = 4.0.

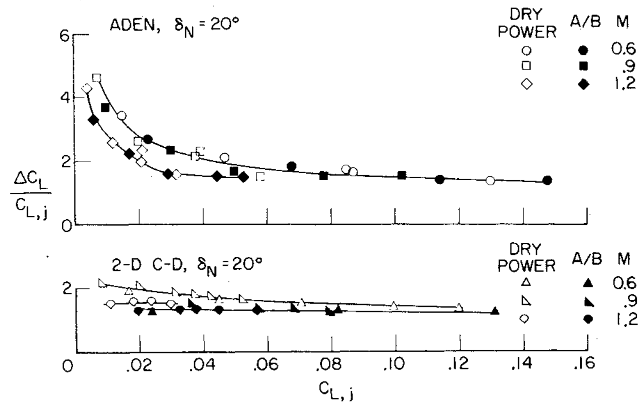

Fig. 14 Measured lift amplification due to vectoring, $\alpha = 0$ deg.

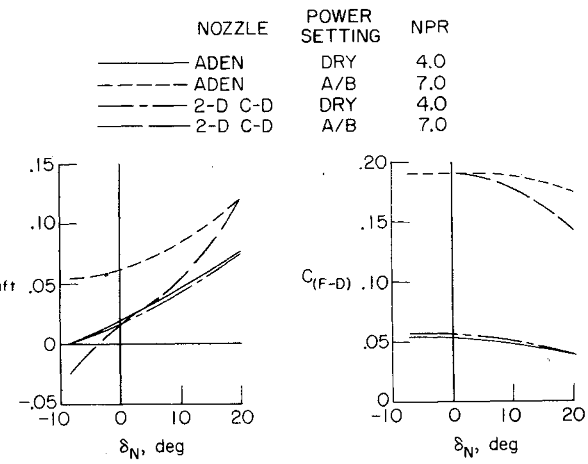

Fig. 15 Effect of vectoring on F-18 afterbody characteristics, $M = 0.9$, $\alpha = 0$ deg.

These results are significant in that the results of this investigation show that nonaxisymmetric nozzles can be installed on twin-engine fighter aircraft with higher installed thrust-minus-drag characteristics than the same aircraft with axisymmetric nozzles which have been refined through several experimental programs.

Limited external pressures were measured to aid in the analysis of the force data. Figure 11 shows pressure distributions along the center line of the nozzle upper surface for the three nozzles tested at $M = 0.9$ for selected pressure ratios. These data indicate excellent pressure recovery characteristics with no apparent flow separation indicated from initial tests conducted in the Northrop water tunnel.

Vectored Performance

One of the potential benefits identified for nonaxisymmetric nozzles in prior studies[1,3] was supercirculation lift due to thrust vectoring. However, this potential for improved maneuvering capabilities can be easily offset by losses in nozzle internal performance associated with thrust vectoring. The analytical study of Ref. 1 indicated that 15 deg vectoring may be optimum for subsonic maneuver and that losses in performance of more than 2% at 15 deg vectoring would substantially negate any supercirculation benefits.

A comparison between the vectoring performance for the two nonaxisymmetric nozzles of the current investigation (at both power settings) and the nozzles of Ref. 7 is given in Figs. 12 and 13 for wind-off conditions. In general, the relative merit of the two nonaxisymmetric nozzle concepts is strongly dependent upon the type of flow turning employed, and the results of the present investigation confirm the earlier data of Ref. 7. The 2-D C-D nozzle has the best overall static performance with the least turning losses because the flow is turned in the nozzles at essentially subsonic speeds. The ADEN nozzle employs supersonic-flow deflection at positive vector angles as its turning mechanism, and hence has larger losses due to shock-induced momentum losses. It should be noted for the ADEN type nozzle that external flow effects may change the magnitude of these losses at wind-on conditions.

As expected at forward speeds, vectoring increased the lift of the afterbody due to both the lift component of the deflected thrust and induced lift due to increased circulation. It was found that the induced lift effects at a given deflection angle and for a given nozzle correlate well when plotted as a function of the jet lift. This correlation is shown in Fig. 14 for both the ADEN and 2-D C-D nozzles at $\delta_N = 20$ deg. First, these results indicate that the ADEN nozzle has superior lift amplification characteristics, especially at low values of jet lift. However, it should be noted that jet lift is determined by using measured static turning angles. Second, the correlations for each nozzle are dissimilar. Figure 15 presents total afterbody lift and thrust-minus-drag characteristics as a function of nozzle geometric vector angle at $M = 0.9$, $\alpha = 0$ deg and at selected nozzle pressure ratios. For a particular power setting, the ADEN nozzle has either equal or better performance when compared to the 2-D C-D nozzle. This result probably indicates a beneficial effect of external flow on the ADEN turning losses shown in Figs. 12 and 13.

F-18 Thrust Reversing Performance

Significant potential for improved deceleration capabilities at all flight conditions was identified in the analytical study of Ref. 1 for an assumed in-flight reverse thrust of 30% of

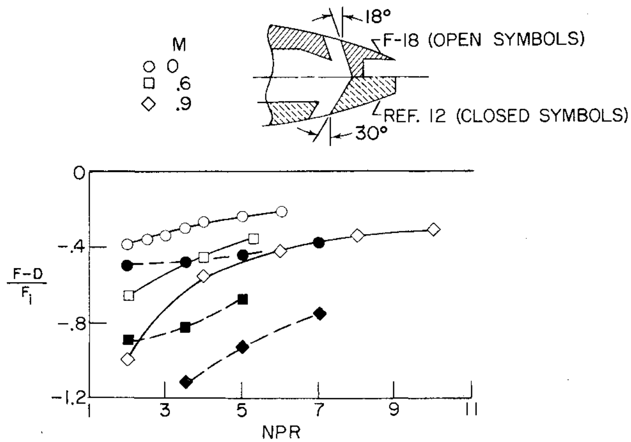

Fig. 16 Reverser thrust performance of the 2-D C-D nozzle, dry power, $\alpha = 0$ deg.

forward thrust. However, for landing operation, reverse-thrust levels of 50% of the forward thrust are desirable for effective ground-roll reduction.

Thrust reverser performance for the 2-D C-D nozzle installed on the F-18 is presented in Fig. 16. The upper half of the sketch shown on Fig. 16 shows a schematic of the reverser tested during the current study which was designed for 30% reverse dry-power thrust. The present results are compared to another General Electric designed 2-D C-D reverser.[7,12] This reverser was designed for 50% reverse dry-power thrust and is shown in the lower half of the sketch of Fig. 16. These results indicate that while each particular design achieved its static design goal, the reverser of Ref. 12 is a more effective reverser at forward speeds. However, the more realistic F-18 reverser probably has less base drag because of the open base of the configuration (as contrasted to the flat base of the reverser of Ref. 12). In general, open or ventilated bases have less base drag than closed or flat bases.

Concluding Remarks

An investigation to determine the performance characteristics of nonaxisymmetric nozzles installed on a F-18 jet-effects afterbody model has been conducted in the Langley 16-Ft Transonic Tunnel. The performance of a single-expansion ramp (ADEN) and two-dimensional convergent-divergent nozzle was compared to the baseline axisymmetric nozzles. The effects of vectoring and reversing were also studied.

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