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# F-15 Forebody Vortex Flow Control Using Jet Nozzle Blowing

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**A low-speed wind-tunnel test was conducted to determine the lateral–directional control effectiveness of a forebody jet nozzle blowing on a 10% scale F-15E model. This investigation of pneumatic forebody vortex flow control was the first of its kind performed on an F-15 configuration. The test acquired six-component force balance data in the NASA Langley 30- by 60-Foot Tunnel at a freestream dynamic pressure of 8 psf at an equivalent Reynolds number per foot of approximately 5.08 × $10^5$. Asymmetric forebody jet blowing was effective in generating yawing moments through an angle of attack (AOA) range that extends beyond the limit of rudder control power. The optimum nozzle configurations were pointed outward, and yawing moments generated within the maneuver range of AOA ($\alpha$ < 40 deg) increased with increases in both blowing rate and AOA. Above 10-deg AOA, blowing rates of $C_\mu$ = 0.010 and greater resulted in yawing moments that approached or exceeded that developed by full rudder deflection.**

## Nomenclature

| | |
|---|---|
| AOA, $\alpha$ | = angle of attack, deg |
| $C_L$ | = lift coefficient |
| $C_l$ | = rolling moment coefficient, body axis |
| $C_m$ | = pitching moment coefficient, body axis |
| $C_n$ | = yawing moment coefficient, body axis |
| $C_\mu$ | = blowing coefficient, $\dot{m}V_{jet}/qS_w$ |
| $\bar{c}$ | = mean aerodynamic chord, in. |
| $D$ | = forebody base diameter, 5.0 in. |
| $d$ | = jet nozzle i.d., in. |
| $\dot{m}$ | = nozzle mass flow rate, slug/s |
| $q$ | = dynamic pressure, psf |
| SCFM | = nozzle mass flow rate, $60\dot{m}/\rho_{S.L.}$, standard ft$^3$/min |
| $S_w$ | = wing reference area, 6.08 ft$^2$ |
| $V_{jet}$ | = sonic jet exit velocity, ft/s |
| $X/D$ | = nondimensional axial location |
| $\beta$ | = sideslip angle, deg |
| $\Delta$ | = incremental change |
| $\theta$ | = nozzle pointing direction, deg |
| $\rho_{S.L.}$ | = air density at sea level |
| $\phi$ | = forebody circumferential position, deg |

## Introduction

EXISTING fighter aircraft possess limited directional control authority at moderate to high angles of attack, because of the loss of effectiveness of the empennage surfaces as they become immersed in the wake flow. However, the forebody vortices strengthen with increasing angle of attack (AOA) and have been found, by proper manipulation, to be a successful means of gaining control authority. Specifically, pneumatic forebody vortex flow control (VFC) techniques such as jet nozzle blowing and slot blowing have been proven to yield yaw power that is greater than conventional rudder performance at the same AOA.[1,2]

Past experimental studies performed on existing aircraft configurations that possess forebodies with an elliptical cross section have found that the jet nozzle blowing technique is not necessarily forebody geometry dependent, but may be configuration dependent because of downstream vortex interactions.[1,3,5] However, parameters such as jet location, blowing direction, and the amount of blowing need to be varied to establish the optimal blowing configuration.

Earlier forebody VFC investigations have discovered that the developed side force and resulting yawing moment direction will vary with the pointing direction of the jet nozzle. Guyton and Maerki[1] found that on the X-29, tangential aft blowing produced a nose-right moment with blowing on the right-hand side (RHS). However, when the jets were pointed outward, a force was generated in the direction opposite the side of blowing. In addition, it was found that the magnitude of the resulting force increased with increasing blowing rate. LeMay et al.[3] discovered that while blowing aft, the jet positioned closer to the nose of the F-16C was more effective in developing a yawing moment in a direction opposite the side of blowing. The circumferential position of the jet nozzles in that case was 45 deg up from horizontal. Mosbarger's[4] isolated F-16 forebody investigation discovered that with the jets positioned 60 deg up from the horizontal, canting them inward or outward 60 deg, generated an equivalent level of yawing moment. Kramer et al.[5] discovered that jets located 60 deg above the horizontal on the F/A-18, and canted inboard, resulted in the optimum configuration. It was found that the resulting yawing moment was positive when blowing on the RHS. In general, it appears that the further upstream the jet nozzle is located, the more effective the blowing is in developing a yawing moment.

The objective of this wind-tunnel investigation was to quantify the effectiveness of forebody jet nozzle blowing on the F-15E configuration as a means for developing additional yaw power. The parameters of concern for this test included nozzle location (axial and circumferential), nozzle pointing direction, and blowing rates.

## Experimental Details

### Wind-Tunnel Facility and Test Conditions

The wind-tunnel test was conducted in the NASA Langley 30- by 60-ft tunnel. This facility consists of an open-jet

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test section 30 ft high, 60 ft wide, and 56 ft long. It is a closed-loop, dual-return passage design. For subscale model testing, the angle of attack and sideslip angle can be varied continuously when incorporating the small model support system. For the current test the freestream velocity was set at 82 ft/s ($q$ = 8 psf), resulting in a Reynolds number per foot of $5.08 \times 10^5$. The angle of attack was varied from −4 through 80 deg, whereas the sideslip angle varied between ±20 deg. The nondimensional $C_\mu$ was varied between 0.0–0.020. All of the aerodynamic force balance data are referenced about the center of gravity [c.g. = 25.65% $\bar{c}$, fuselage station FS = 557.1]. The accuracy of the force balance data is ±0.5% of the full-scale output for each channel. The model positioned in the NASA Langley wind tunnel is shown in Fig. 1.

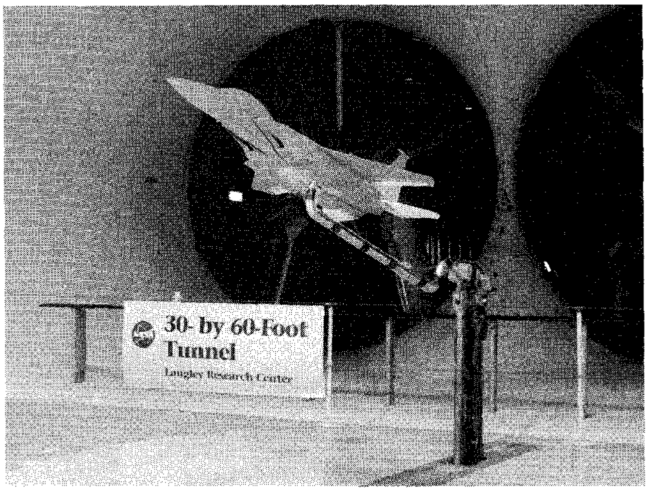


**Fig. 1 10% scale F-15E model in NASA Langley wind tunnel.**

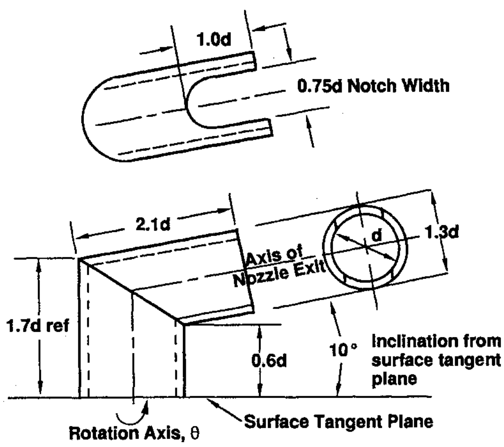


**Fig. 2 Forebody jet nozzle design[1]: *d* selected from supply pressure and mass flow requirements. All other dimensions as fractions of *d*.**

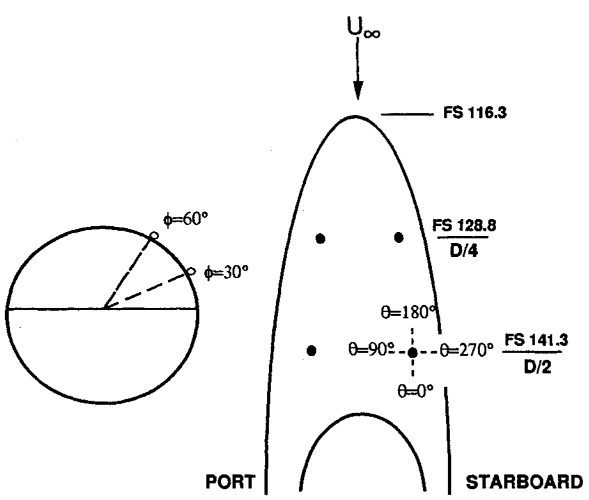


**Fig. 3 Forebody jet blowing convention.**

## Model

A 10% scale F-15E model was used for this investigation. New forebodies, capable of supporting jet nozzle blowing, were designed and fabricated to mate with the existing full-configuration model. The forebody model was designed to allow for a pair of nozzles to be placed symmetrically about the centerline. The nozzle design (Fig. 2) was modeled after the slotted nozzle developed and used in the X-29 forebody blowing experiments by Guyton and Maerki.[1] This slotted nozzle design has proven to be more effective than a circular nozzle.

Inner nozzle diameters $d$ of 0.125 and 0.0625 in. were used to determine nozzle size effects, while this also allowed for a wider range of blowing rates. The nozzles were supplied by a common plenum within the forebody. This arrangement al-

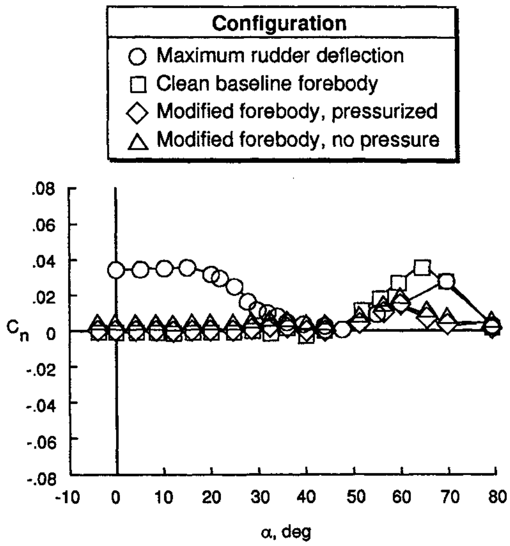


**Fig. 4 Forebody baseline yawing moment comparisons.**

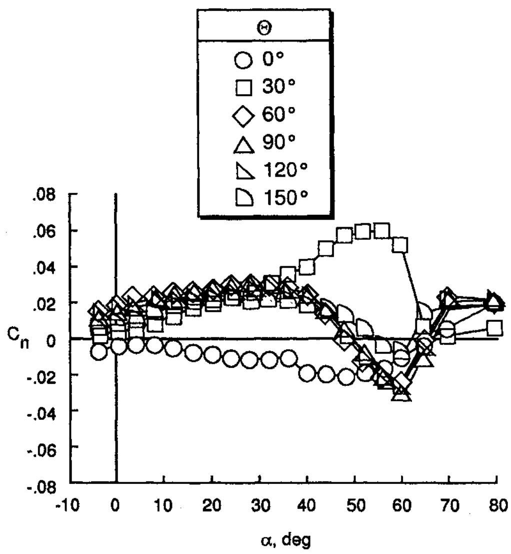


**Fig. 5 Yawing moment vs AOA as a function of inboard jet pointing direction: $\phi$ = 60 deg, $X/D$ = 0.25, starboard $C_\mu$ = 0.020, and $d$ = 0.125 in.**

lowed for symmetric blowing using a single supply source, or individual blowing on either side. The plenum was instrumented with a total pressure probe and thermocouple. Plenum conditions were set to ensure a sonic nozzle exit velocity. To minimize any bridging effects between the high-pressure air lines supplying the plenum and the internal force balance, a trombone piping system internal to the model and a lightweight, flexible free-flight hose were used.

The jet nozzle could be varied between two axial locations: $X/D$ = 0.25 (FS 128.8), and $X/D$ = 0.5 (FS 141.3), where $D$ is the reference forebody base diameter (FS 165.1). The circumferential position around the forebody could be either 30 or 60 deg up from the horizontal. As a result, four jet locations were investigated. The jet nozzles were capable of rotating 360 deg. The pointing direction of 0 deg represents blowing straight aft, whereas 90 deg represents blowing inboard directly across the forebody (Fig. 3).

## Results

Initially, baseline runs were made to ensure that the new modified forebody models compared well with the previous clean forebody configuration. In addition, the effects of the high-pressure air lines were investigated. As seen in Fig. 4, there is an asymmetry in $C_n$, starting at approximately 50-deg AOA with the clean configuration. Most importantly, any bridging effects of the high-pressure air are not discernible.

### Pointing Direction

Jet nozzle parameter investigations began with a predetermined maximum blowing level of $C_\mu = 0.020$ to optimize the nozzle location and pointing direction. This was performed on the starboard side with the pointing direction varied in 30-deg increments. In all cases blowing was performed on the starboard side while a dummy nozzle was located on the port side in the same axial location and pointing direction. In addition, the blowing was with a slotted nozzle having an i.d. of 0.125 in. The optimized pointing direction, in the maneuver range AOA ($\alpha < 40$ deg), was considered that which yielded a maximum yawing moment for each of the four forebody jet locations considered (two axial stations for each of the two circumferential positions). The optimized pointing direction in the maneuver range AOA was not necessarily the same as that for the high AOA range ($\alpha > 40$ deg). (Symmetry of the fore-

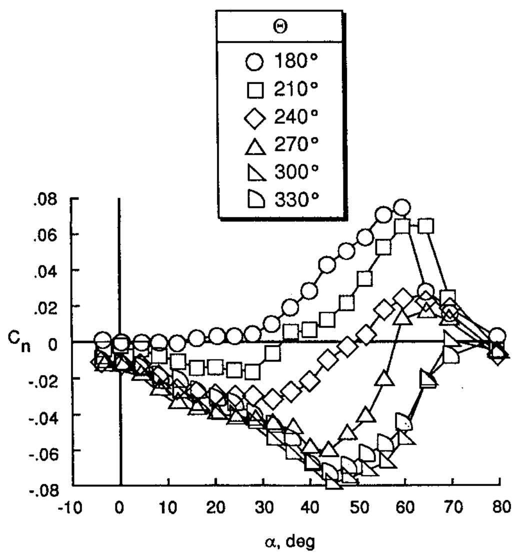


**Fig. 6 Yawing moment vs AOA as a function of outboard jet pointing direction: $\phi$ = 60 deg, $X/D$ = 0.25, starboard $C_\mu$ = 0.020, and $d$ = 0.125 in.**

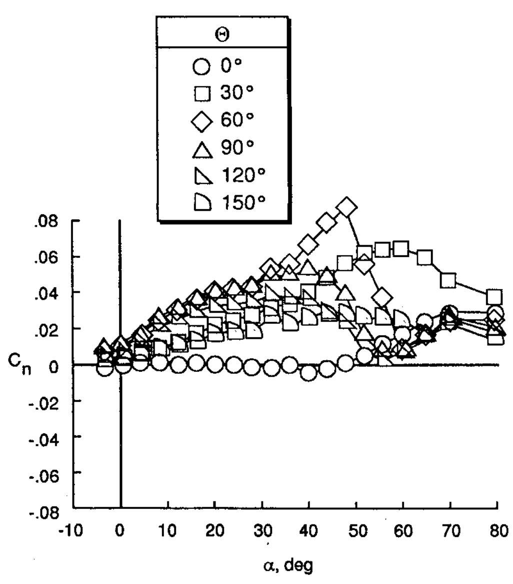


**Fig. 7 Yawing moment vs AOA as a function of inboard jet pointing direction: $\phi$ = 60 deg, $X/D$ = 0.50, starboard $C_\mu$ = 0.020, and $d$ = 0.125 in.**

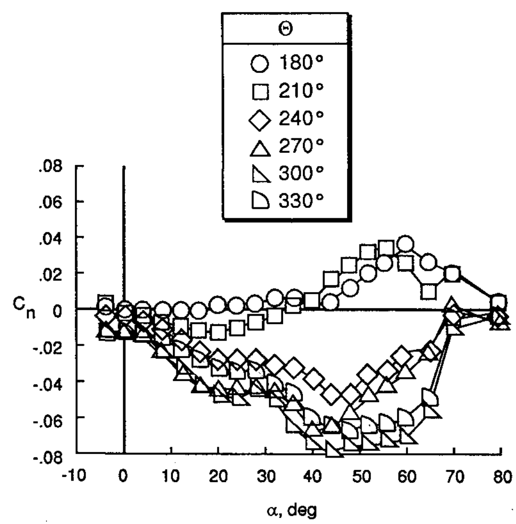


**Fig. 8 Yawing moment vs AOA as a function of outboard jet pointing direction: $\phi$ = 60 deg, $X/D$ = 0.50, starboard $C_\mu$ = 0.020, and $d$ = 0.125 in.**

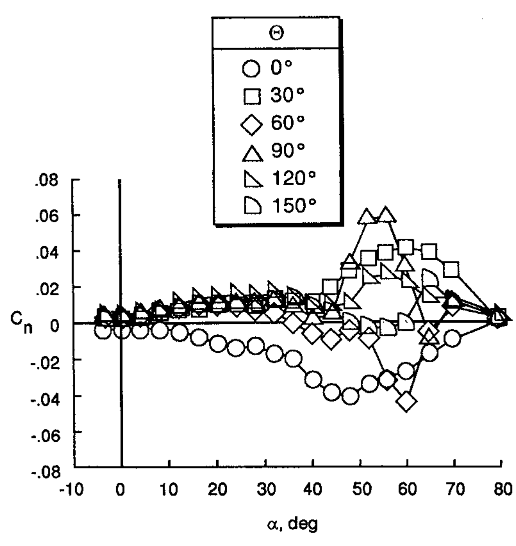


**Fig. 9 Yawing moment vs AOA as a function of inboard jet pointing direction: $\phi$ = 30 deg, $X/D$ = 0.25, starboard $C_\mu$ = 0.020, and $d$ = 0.125 in.**

body jet blowing was also investigated and confirmed by blowing on the port side.)

Figures 5 and 6 show yawing moment coefficient vs AOA with the jet nozzle located in the 60-deg circumferential position and in the forward location ($X/D = 0.25$). In Fig. 5 the starboard blowing inboard (across the forebody) results in an initial positive yawing moment, or with a resulting side force in the direction to the side of the blowing. However, with the exception of $\theta = 0$ and 30 deg, the blowing effect is reduced after $\alpha > 35$ deg, and the resulting yawing moment/side force eventually reverses direction. In Fig. 6 a similar trend of direction reversal occurs with the outboard blowing, with the exception of $\theta = 300$ and 330 deg, but the direction of the yawing moment/side force is in the direction opposite the side of jet blowing.

In Figs. 7 and 8 the jet blowing is in the 60-deg circumferential position and in the aft position ($X/D = 0.5$). As in the forward position, blowing inboard across the forebody produces a positive yawing moment, and blowing outboard produces a negative moment. However, the direction reversal is not evident except for two pointing directions, $\theta = 180$ and 210 deg. Additionally, the maximum yawing moment coefficient of $C_n \approx 0.08$ is produced with a pointing direction of $\theta = 300$ deg for both forward and aft jet locations. (A maximum yawing moment coefficient of 0.08 is developed for $\theta = 60$ deg at $X/D = 0.5$, but $C_n$ falls off drastically above 50-deg AOA.)

In Figs. 9 and 10 the jet blowing is in the 30-deg circumferential position and in the forward position ($X/D = 0.25$). The resulting yawing moment directions are similar to those for the 60-deg circumferential position, blowing inboard on the starboard side produces an initial positive moment, whereas blowing outboard yields a negative moment. The inboard jet blowing is not as effective as blowing outboard for $\phi = 30$ deg. Blowing in a direction of $\theta = 240-330$ deg results in maximum yawing moment coefficients of 0.04 to about 0.08. As seen in Figs. 11 and 12, blowing in the aft position at the 30-deg circumferential location yields results similar in trend to that for the aft position of the 60-deg circumferential

**Table 1 Optimized nozzle pointing directions**

| Circumferential position, deg | $X/D$ | Pointing direction, deg |
|---|---|---|
| $\phi = 60$ | 0.25 | $\theta = 300$ |
| $\phi = 60$ | 0.50 | $\theta = 300$ |
| $\phi = 30$ | 0.25 | $\theta = 330$ |
| $\phi = 30$ | 0.50 | $\theta = 300$ |

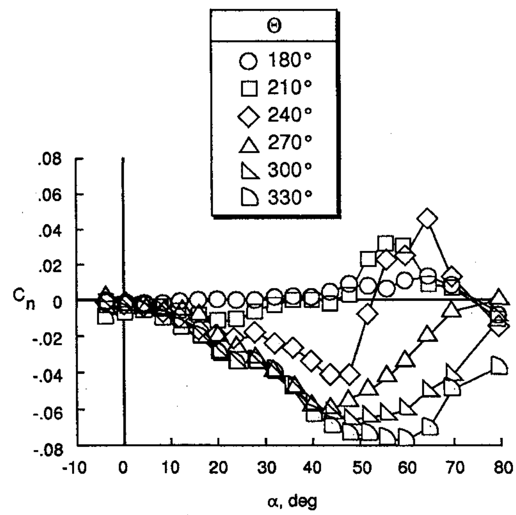


**Fig. 10 Yawing moment vs AOA as a function of outboard jet pointing direction: $\phi = 30$ deg, $X/D = 0.25$, starboard $C_\mu = 0.020$, and $d = 0.125$ in.**

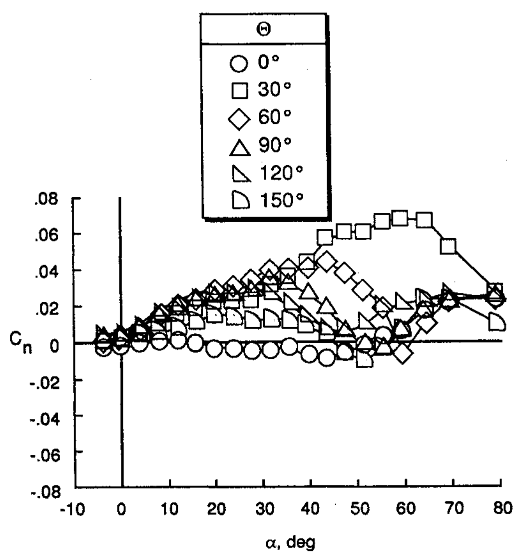


**Fig. 11 Yawing moment vs AOA as a function of inboard jet pointing direction: $\phi = 30$ deg, $X/D = 0.50$, starboard $C_\mu = 0.020$, and $d = 0.125$ in.**

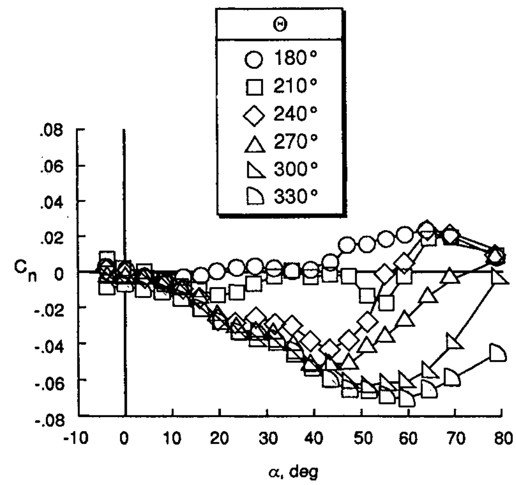


**Fig. 12 Yawing moment vs AOA as a function of outboard jet pointing direction: $\phi = 30$ deg, $X/D = 0.50$, starboard $C_\mu = 0.020$, and $d = 0.125$ in.**

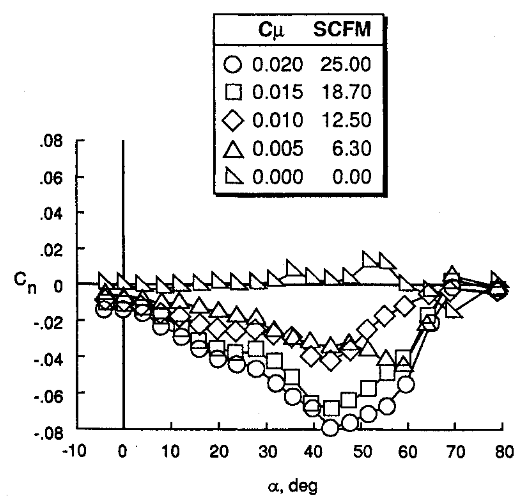


**Fig. 13 Yawing moment vs AOA as a function of starboard jet blowing: $\phi = 60$ deg, $X/D = 0.25$, $\theta = 300$ deg, and $d = 0.125$ in.**

location. For the aft blowing position, a pointing direction of $\theta$ = 30, 300, or 330 deg yields the highest level of yawing moment.

No flow visualization was performed in this investigation; however, it is postulated, based upon other research efforts, that the jet blowing outboard displaces the jet-side vortex away from the surface, while blowing inboard across the forebody delays the onset of separation and creates additional suction of the jet-side vortex. (Note in Figs. 5–12 that the presence of a nonzero yawing moment/side force at $\alpha$ = 0 deg is attributed to the jet blowing reaction force and a possible coanda effect from the nozzle blowing.)

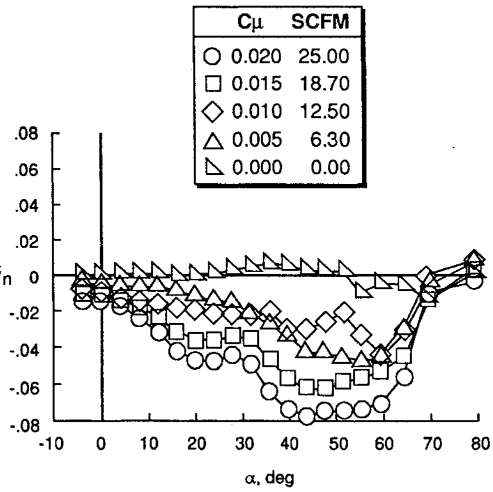


**Fig. 14 Yawing moment vs AOA as a function of starboard jet blowing: $\phi$ = 60 deg, $X/D$ = 0.50, $\theta$ = 300 deg, and $d$ = 0.125 in.**

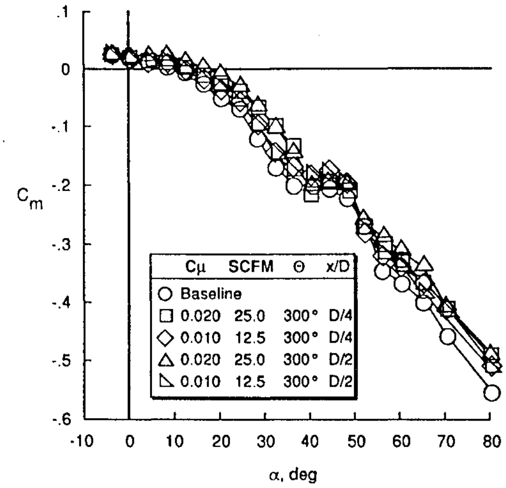


**Fig. 17 Pitching moment vs AOA: starboard jet blowing, $\phi$ = 60 deg, and $d$ = 0.125 in.**

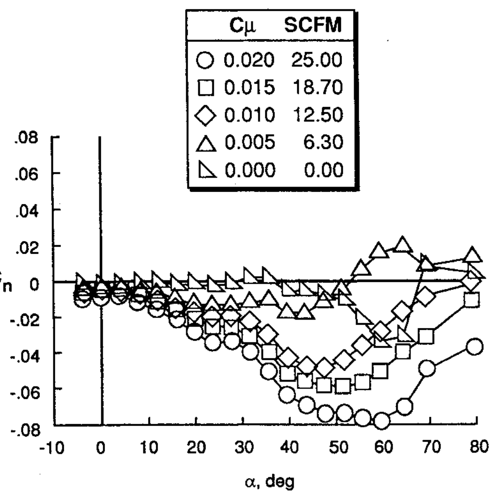


**Fig. 15 Yawing moment vs AOA as a function of starboard jet blowing: $\phi$ = 30 deg, $X/D$ = 0.25, $\theta$ = 330 deg, and $d$ = 0.125 in.**

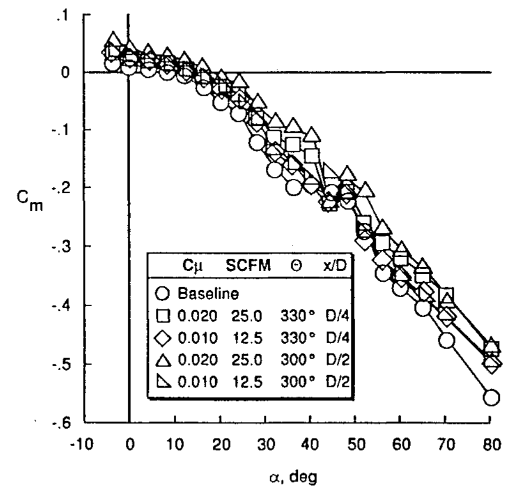


**Fig. 18 Pitching moment vs AOA: starboard jet blowing, $\phi$ = 30 deg, and $d$ = 0.125 in.**

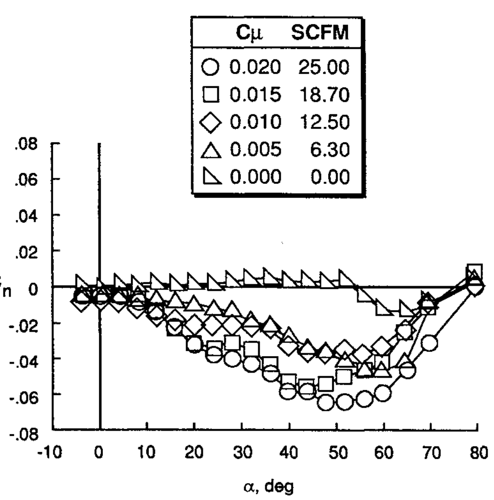


**Fig. 16 Yawing moment vs AOA as a function of starboard jet blowing: $\phi$ = 30 deg, $X/D$ = 0.50, $\theta$ = 300 deg, and $d$ = 0.125 in.**

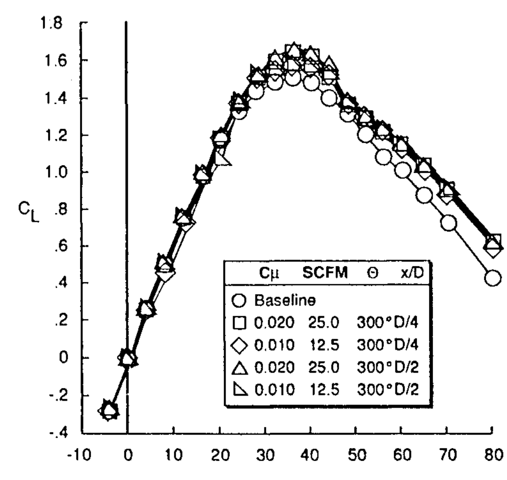


**Fig. 19 Lift vs AOA: starboard jet blowing, $\phi$ = 60 deg, and $d$ = 0.125 in.**

For each of the four nozzle locations an optimized pointing direction was chosen (Table 1). Based upon the yawing moment data, no significant differences are apparent to suggest that the forward ($X/D = 0.25$) or aft location ($X/D = 0.5$) would be the preferred, as is also the case between the two circumferential positions, $\phi = 30$ or 60 deg.

**Blowing Rates**

The four optimized cases listed in Table 1 were investigated for a range of blowing rates (Figs. 13–16). For the cases considered, the optimal pointing direction is the 60-deg outboard position ($\theta = 300$ deg), or the 30-deg outboard ($\theta = 330$ deg) for the forward position ($X/D = 0.25$) on the $\phi = 30$-deg nose. For the $\phi = 30$ deg, $\theta = 330$-deg position, the blowing effectiveness was maintained to higher AOA, although the lowest blowing rate yielded direction-reversal above 50-deg AOA. The outward blowing direction differs from previous tests on the X-29, F-16, and F-18 configurations, where it was found that inboard blowing provided optimum control effectiveness.[1,3–5] In the maneuver range AOA, the increment of yawing moment coefficient behaves rather linearly with increasing blowing rate (an incremental change in blowing yields a constant incremental change in $C_n$ vs AOA). The existence of the symmetrically placed nozzles without blowing has minimized the baseline asymmetry on the $\phi = 60$-deg nose (Figs. 13 and 14), whereas an asymmetry in a direction opposite to that of the baseline exists for the $\phi = 30$-deg nose (Figs. 15 and 16). Blowing rates corresponding to $C_\mu = 0.010$ generate yawing moment coefficients from 0.020 to 0.050 from 20- to 40-deg AOA. In comparison, full-rudder deflection produces a constant yawing moment coefficient of 0.035 through 20-deg AOA, and drops off to 0.0 at 40-deg AOA.

The forebody jet blowing had a destabilizing effect on pitching moment. The largest positive increment in pitching moment coefficient that was realized was $\Delta C_m \approx 0.1$ (Figs. 17

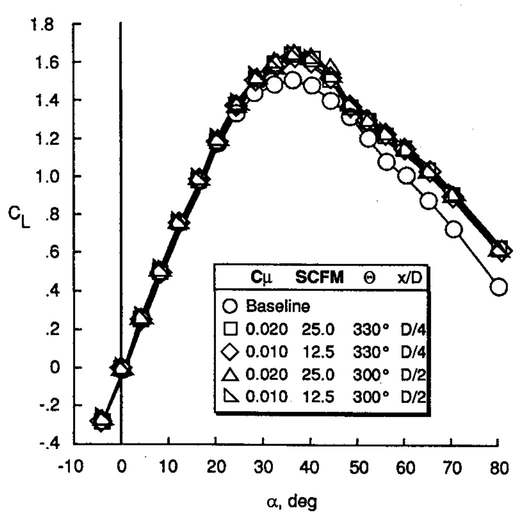


**Fig. 20 Lift vs AOA: starboard jet blowing, $\phi = 30$ deg, and $d = 0.125$ in.**

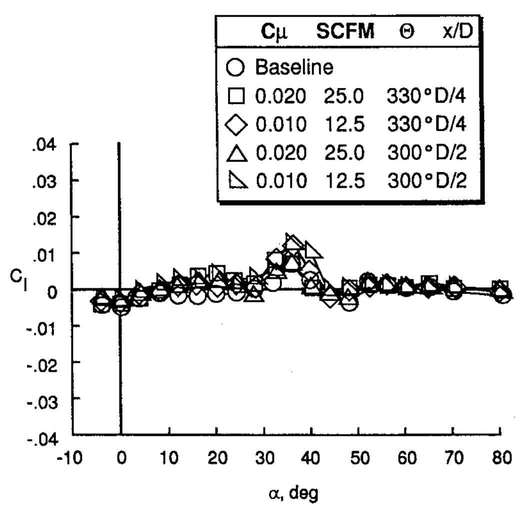


**Fig. 21 Rolling moment vs AOA: starboard jet blowing, $\phi = 60$ deg, and $d = 0.125$ in.**

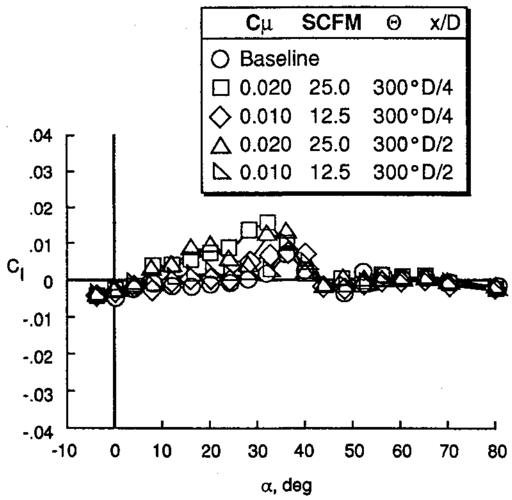


**Fig. 22 Rolling moment vs AOA: starboard jet blowing, $\phi = 30$ deg, and $d = 0.125$ in.**

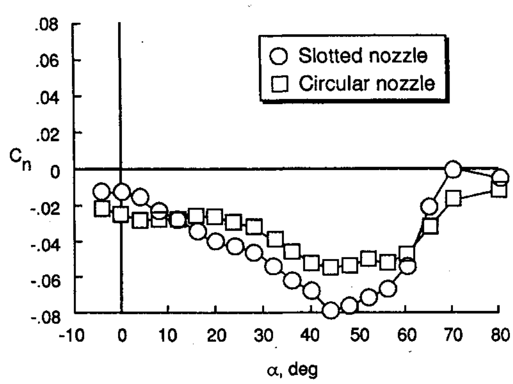


**Fig. 23 Yawing moment vs AOA: $\phi = 60$ deg, $X/D = 0.25$, $\theta = 300$ deg, starboard $C_\mu = 0.020$, and $d = 0.125$ in.**

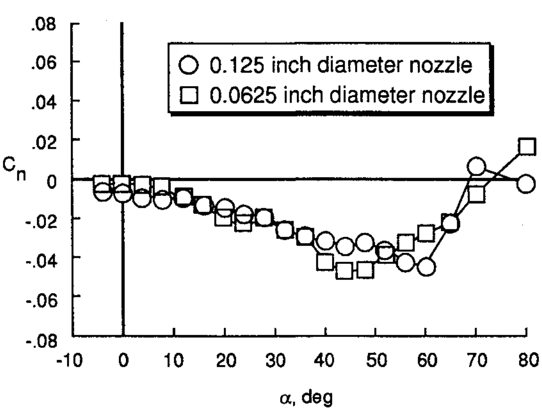


**Fig. 24 Yawing moment vs AOA: $\phi = 60$ deg, $X/D = 0.25$, $\theta = 300$ deg, starboard $C_\mu = 0.005$, and $d = 0.125$ in.**

and 18). As expected, there was an accompanying increase in lift coefficient through $C_{L_{max}}$ (Figs. 19 and 20). (The increase in lift above $C_{L_{max}}$ was found to be related to minimal axial stiffness added by the trombone.)

The rolling moment was influenced with increased blowing, but only in the AOA range up to maximum lift (Figs. 21 and 22). A positive rolling moment is developed along with the negative yawing moment with starboard jet blowing. The largest increment in rolling moment coefficient was obtained for the $\phi$ = 30-deg position ($\Delta C_l \approx 0.015$). This would support the postulation that the blowing-side vortex is being displaced away from the surface, and also influences the lift on the jet-side wing.

### Nozzles

A circular nozzle of the same diameter as that of the slotted nozzle was used to verify that the slotted nozzle design was more effective at influencing the forebody flowfield. Figure 23 is a comparison of generated yawing moment coefficients for the two nozzles at a blowing rate corresponding to $C_\mu = 0.020$ with an i.d. of 0.125 in. The data show that the slotted nozzle is more effective from 10- to 60-deg AOA. Figure 24 presents a comparison of the effect of nozzle diameter using slotted nozzle diameters of 0.125 and 0.0625 in. at an identical $C_\mu$ value of 0.005. This lower value of $C_\mu$ was the highest setting obtainable with the smaller diameter nozzle. The data show that there is no substantial difference in the generated yawing moments between these two nozzle sizes below 40-deg AOA. This result would indicate that $C_\mu$ would be the pertinent factor when scaling, and not the geometric nozzle size. This is in agreement with the high-$q$ wind-tunnel test on the F-16 by Mosbarger,[4] who also found no difference in yawing moment between two different size nozzles for the same $C_\mu$ level. Additionally, Kramer et al.[5] saw equivalent levels of generated yawing moment developed on the F-18 for a constant $C_\mu$ for various tunnel dynamic pressures.

### Sideslip

From earlier test runs in this investigation, the F-15 aircraft becomes directionally statically unstable, $C_{n_\beta} < 0$, at AOA over 20 deg. Implementing the forebody jet blowing above 20-deg AOA increases the directional control power available, as seen

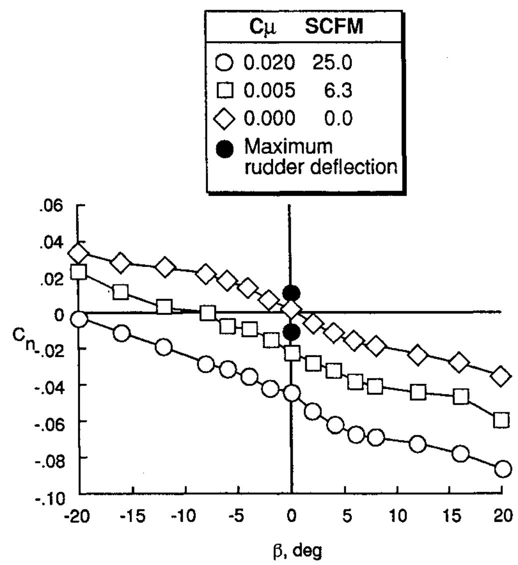


**Fig. 25 Yawing moment vs sideslip: starboard jet blowing, $\phi$ = 60 deg, $X/D$ = 0.25, $\theta$ = 300 deg, $d$ = 0.125 in., and $\alpha$ = 30 deg.**

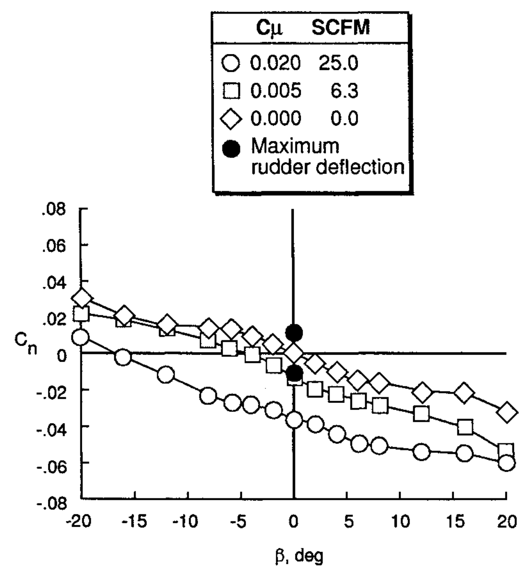


**Fig. 27 Yawing moment vs sideslip: starboard jet blowing, $\phi$ = 30 deg, $X/D$ = 0.25, $\theta$ = 330 deg, $d$ = 0.125 in., and $\alpha$ = 30 deg.**

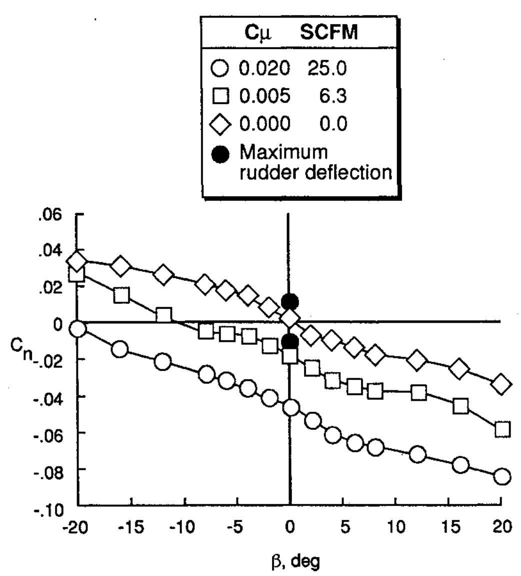


**Fig. 26 Yawing moment vs sideslip: starboard jet blowing, $\phi$ = 60 deg, $X/D$ = 0.50, $\theta$ = 300 deg, $d$ = 0.125 in., and $\alpha$ = 30 deg.**

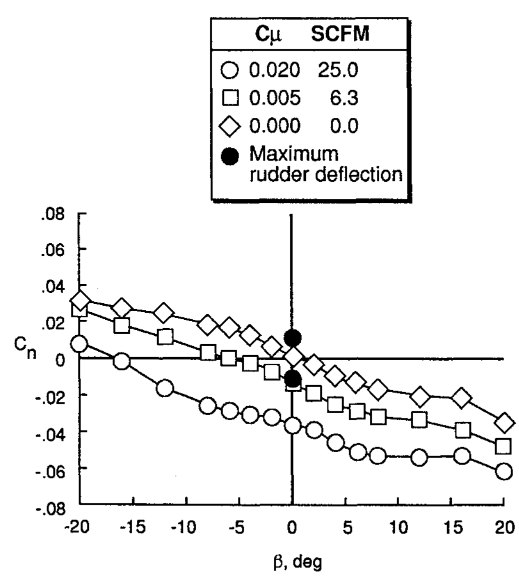


**Fig. 28 Yawing moment vs sideslip: starboard jet blowing, $\phi$ = 30 deg, $X/D$ = 0.50, $\theta$ = 330 deg, $d$ = 0.125 in., and $\alpha$ = 30 deg.**

in Figs. 25–28. (Note that in Fig. 28 the pointing direction is not at the more effective $\theta = 300$ deg.) Through the range of sideslip $-15 \leq \beta \leq 15$ deg, the jet blowing effect behaves linearly (a constant offset in yawing moment) at an AOA of 30 deg. For the two most effective blowing cases in sideslip at $C_\mu = 0.005$ ($X/D = 0.25$ and 0.50, $\phi = 60$ deg), an additional yawing moment increment of $\Delta C_n \approx -0.02$, from baseline or $\Delta C_n \approx -0.01$ from full rudder control is generated (Figs. 25 and 26). At $C_\mu \approx 0.020$, an increment of $\Delta C_n \approx -0.045$ and $-0.035$ is generated, respectively. However, above $\alpha = 60$ deg, the behavior becomes more erratic. This is expected, since the linear effectiveness of VFC at $\beta = 0$ deg at this AOA has been lost. Based upon the increments of yawing moment at sideslip, the preferred location of the jet would appear to be $\phi = 60$ deg rather than $\phi = 30$ deg.

## Concluding Remarks

The F-15 forebody jet blowing test demonstrated that the pneumatic VFC technology has generated sufficient levels of control power (yawing moment) to augment the conventional control authority over a wide range of AOA. From this investigation, the optimum nozzle pointing direction for each of the four locations considered was pointed outward. For an AOA above 10 deg, these nozzle configurations at blowing rates of $C_\mu = 0.010$ and greater provided levels of yawing moments that approached or exceeded that developed by full rudder deflection. In addition, the yawing moments generated at AOA approaching 65 deg exceeded the level of conventional control power in the low AOA range. The additional yawing moment generated with the forebody jet nozzle blowing increases with increasing AOA up to 45–60 deg. Beyond this AOA range, the jet blowing effectiveness begins to fall off with increasing AOA. From this data analysis, implementing the VFC technology on the F-15 has proven to be a viable option for increasing the aircraft's maneuverability. Since this investigation was the first experimental pneumatic VFC test performed on the F-15, wind-tunnel testing at higher dynamic pressures and larger Reynolds numbers need to be performed. Further refinement of the jet blowing locations $\phi$ and positions $\theta$ may possibly lead to even greater levels of VFC power.

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