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THEORETICAL FAN VELOCITY DISTORTIONS DUE TO INLETS AND NOZZLES

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ABSTRACT

Nonuniform velocity profiles imposed on the propulsion system fan can cause fan blade stresses and thrust losses. This paper presents a theoretical parametric study of the effects of inlets with 0^{o} and 90^{o} nozzle deflection on the velocity profile at a hypothetical fan. The parameters investigated are fan-to-nozzle spacing and inlet centerline offset. The interaction between the inlet and nozzle is also investigated. The study is made using a two-dimensional analysis.

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INTRODUCTION

Deflected thrust nacelles (fig. 1) are being considered for several VTOL type aircraft. While these nacelles are not subjected to as severe external flow conditions as their tilt-nacelle counterparts, they can experience severe internal flow conditions when the nozzles are deflected 90°. This is especially true when the nozzles are placed close to the exit plane of the fan. Such close-coupled nozzles produce distortions which are propagated upstream to the fan and can be severe enough to induce high fan blade stresses and cause fan performance (airflow and efficiency) degradation. One solution is to place the nozzle far enough downstream to eliminate the distortion. Another approach is to design the inlet and deflecting nozzle to minimize flow distortion at the fan. However the design to reduce this fan velocity distortion for a 90° deflection must also yield low distortion for operation in the cruise mode (i.e., zero deflection).

It is the purpose of this paper to present the effects of pertinent nozzle and inlet geometric variables on the velocity profiles at the fan for configurations applicable to VTOL deflected thrust nacelles. The geometric parameters investigated were fan-nozzle spacing and inlet centerline offset for both cruise (zero deflection), and takeoff and landing (90° deflection).

Calculations were performed at zero free stream velocity using the two dimensional analysis procedure described in reference 1.

SYMBOLS

A	area
a	lip ellipse semi-major axis
b	lip ellipse semi-minor axis
D	diameter
L	length
r	radius
V	velocity
x	axial length
y	vertical height
Δy	throat-to-fan centerline offset

Subscripts:

AVG	average
de	diffuser exit
f	fan

fe	fan exit
h_i	highlight
i	inner
in	inlet
MAX	maximum
MIN	minimum
N	nozzle displacement
o	outer
t	throat

RESULTS AND DISCUSSION

The discussion starts with the distortion generated by an isolated nozzle, and then adds the distortion effects of the inlet. In the present calculations, the fan is idealized to a pressure ratio of unity so no distinction exists between distortions at the fan generated upstream or downstream of the fan.

Isolated 90° Nozzle

The isolated effects of a 90° deflected nozzle were obtained by using the configuration shown in figure 2. Straight ducts of constant area were extended a large distance upstream and downstream of the 90° turn to eliminate termination effects. The turn itself was a constant area turn. The inner wall was a circular arc section with a radius (r_i/D_f) of 0.25 and the outer wall was also circular with a radius (r_o/D_f) of 1.25. The hypothetical fan was placed at various locations upstream of the nozzle entrance. This fan-to-nozzle spacing (L_N/D_f) was varied between 0 and 0.83. Due to the straight sections upstream and downstream of the turn, any velocity distortions measured at the fan locations are due entirely to the proximity of the 90° turn.

Figure 3 shows the effects of the fan-nozzle spacing on the duct velocity profile at the fan. The most severe distortion occurred at a L_N/D_f of 0 with the maximum and minimum velocities occurring on the inner and outer walls, respectively. This kind of distortion (i.e., asymmetric about inlet centerline) would appear as a circumferential distortion to a rotating fan and will be referred to subsequently as circumferential distortion. As the fan-nozzle spacing was increased, the velocity distortion decreased.

In an attempt to characterize the effect of fan-nozzle displacement by a single quantity, a velocity distortion parameter, defined as $(V_{max} - V_{min})/V_{avg}$, was used. The parameter is shown in figure 4 as a function of fan-nozzle spacing. As expected, the distortion is highest when the nozzle is nearest the fan. This distortion decreases to approximately 0.05 for the last nozzle location shown (L_N/D_f = 0.83), and it would approach zero if the fan were moved far enough upstream.

Nozzle With Straight Inlet

The interaction of the inlet and nozzle in both the zero deflection and 90° deflection modes was studied next. Figure 5 shows typical nacelle configurations for both 0° and 90° nozzle deflection for inlets with straight centerlines.

Both nacelles shown had the same inlet. The inlet had an elliptical internal lip with an a/b ratio of 2.0, a two-dimensional contraction ratio (D_{hl}/D_t) of 1.56 and a DAC-1 external forebody (ref. 2).

The diffuser had a conic section with a wall angle of 14°. The diffuser was mated to the lip with an elliptic section with a/b = 3 and to the fan with a circular arc. The diffuser-exit-to-throat area ratio was 1.25. This results in a one-dimensional design throat Mach number of 0.73 for a diffuser exit Mach number of 0.5. The inlet-length-to-fan exit diameter ratio was 1.0.

For the zero deflection configuration, a constant area was maintained downstream of the fan. For the 90° deflection configuration, the fan-nozzle spacing was varied from 0 to 0.83. The nozzle was also a constant area turn as described previously.

Figure 6 shows the velocity profile at the fan for the inlet with a 0° and a 90° nozzle deflection for an L_N/D_f of 0. The zero nozzle deflection velocity profile shows a small distortion symmetrical about the centerline. This kind of distortion (i.e., symmetric about the inlet centerline) would appear as a radial distortion to a rotating fan and will be referred to subsequently as radial distortion. This distortion is due to the internal geometry of the diffuser upstream of the fan. For L_N/D_f = 0, the deflected nozzle velocity profile is strongly affected by the nozzle. Although not shown, additional calculations were performed for other values of L_N/D_f. As would be expected when the fan nozzle spacing is increased, the profile for the inlet with a 90° deflection nozzle approaches that of the inlet with a 0° deflection nozzle.

Figure 7 shows the effect of fan-nozzle spacing on the velocity distortion parameter $(V_{max} - V_{min})/V_{avg}$ at the fan. The inlet with zero deflection is not a function of L_N/D_f since the passage downstream of the fan is a straight constant area passage. It is, however, shown as an asymptotic reference line. The velocity distortion for the inlet with a 90° deflection nozzle shows high distortion for small values of L_N/D_f. In this region of high distortion, the fan velocity profile is strongly influenced by the nozzle. While for larger values of L_N/D_f, the distortion for the inlet with the deflecting nozzle approaches that of the inlet with 0° deflection. In this region, the inlet and diffuser are the dominating factors determining distortion values. In the range between the two limits, the distortion is influenced by both the inlet and deflecting nozzle.

Nozzle With Offset Inlet

Some of the velocity distortions shown (fig. 7) may be excessive for safe, efficient operation of the fan. One method to reduce fan velocity distortion caused by the nozzle is to design the inlet to produce a fan velocity profile which will cancel part of the nozzle distortion. This can be accomplished by shaping the inlet centerline. Figure 8 shows nacelles with inlets offset by Δ_y/L_D for both the 0° and 90° deflection nozzles. A cubic centerline was fit between the inlet throat and the fan face. The diffuser walls, both inner and outer, were then shifted according to the local passage centerline offset. The passage area distribution as a function of axial distance for the offset inlets is the same as it was for the corresponding straight centerline inlets. The nozzle was also spaced at various distances from the fan in the same manner as it was for the straight centerline inlets.

Figure 9 shows the effect of centerline offset on the fan velocity profile for a fan-nozzle spacing of 0.16. (The curve for the zero offset inlet and 90° deflection nozzle is, of course, the same as that shown previously for the straight centerline nacelle.) For the 90° deflecting nozzle the velocity distortion has been markedly reduced by offsetting the centerline by 0.25. However, for the zero deflection nozzle (cruise mode) configuration, the velocity distortion is now high. Therefore, a compromise offset is required so that the nacelle can operate safely and efficiently at both 0° and 90° nozzle deflection.

The resulting velocity distortion parameter as a function of throat-to-fan centerline offset for a fan-nozzle displacement of 0.16 is shown in figure 10. For the nacelle with zero deflection, the distortion is a minimum at zero offset when the distortion is radial in nature. The distortion then increases with increasing inlet centerline offset due to circumferential distortion. For the nacelle with 90° deflection the distortion reaches a minimum where the circumferential distortion due to the inlet centerline offset cancels most of the circumferential distortion due to nozzle deflection. The minimum, however, cannot be less than the inlet radial distortion.

If the distortion at cruise (0° deflection) and takeoff and landing (90° deflection) are of equal importance, then the minimum distortion, considering both 0° and 90° deflection, occurs at the intersection of the dashed and solid curves, point A. In general, combinations of inlet offset and fan-nozzle spacing can be used to achieve the most compact nacelle possible constrained by the allowable velocity distortion at the fan.

SUMMARY OF RESULTS

The effect of close coupled inlets and nozzles on fan velocity profiles and distortions was investigated using two-dimensional potential flow analysis. Some of the specific results are:

1. As the distance from the fan to the nozzle entrance increases, the velocity profile distortion at the fan for a deflecting nozzle decreases.

2. Offsetting the inlet centerline reduces the distortion due to a 90° deflected nozzle but the offset increases the distortion for the 0° nozzle deflection. A value of offset exists which minimizes the distortion for operation over the range of nozzle deflections from zero to 90°.

REFERENCES

1. Hawk, J. Dennis; and Stockman, N. O.: Computer Programs for Calculating Two-Dimensional Potential Flow Through Deflected Nozzles. NASA TM (to be published).

2. Albers, James A.; Stockman, N. O.; and Hirn, John J.: Aerodynamic Analysis of Several High Throat Mach Number Inlets for the Quiet Clean Short-Haul Experimental Engine. NASA TM X-3183, 1975.

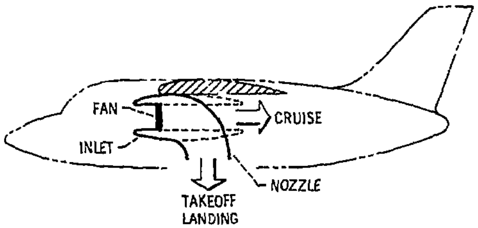


Figure 1. - Idealized VTOL aircraft with deflecting nozzle.

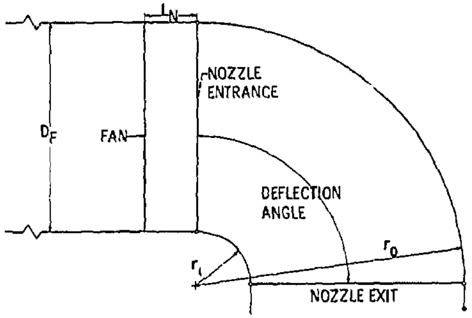


Figure 2. - Isolated nozzle: 90° deflection.

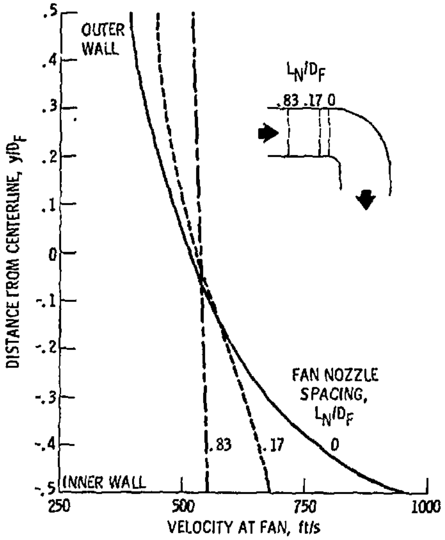


Figure 3. - Effect of fan-nozzle spacing on velocity profile at the fan: straight duct upstream of fan; 90° deflection.

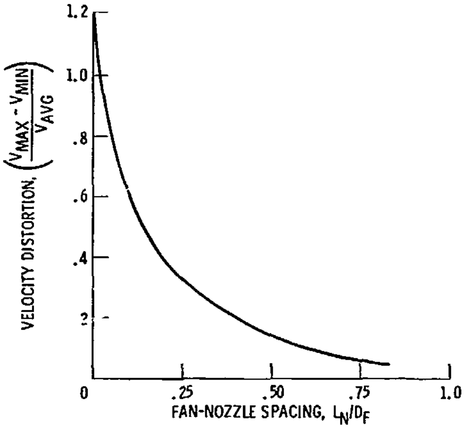
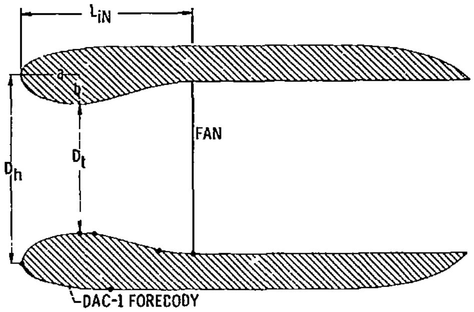
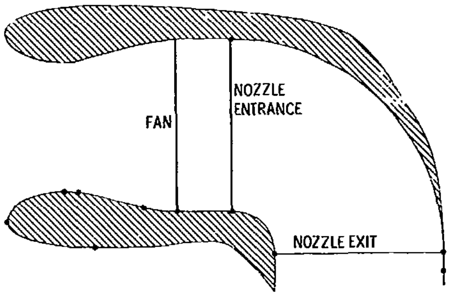


Figure 4. - Theoretical effect of fan-nozzle spacing on velocity distortion at the fan: 90° deflection.



(a) 0° NOZZLE DEFLECTION.



(b) 90° NOZZLE.

Figure 5. - Nacelles with straight inlets.

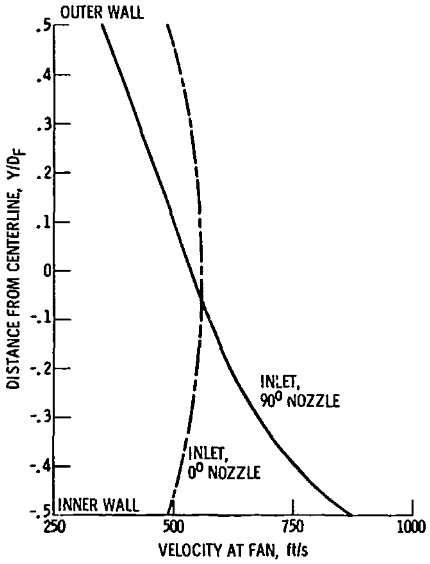


Figure 6. - Effect of nozzle deflection on velocity profile at the fan: straight inlet; $L_N/D_F = 0$.

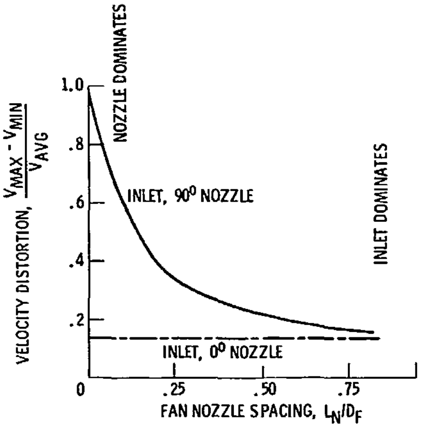
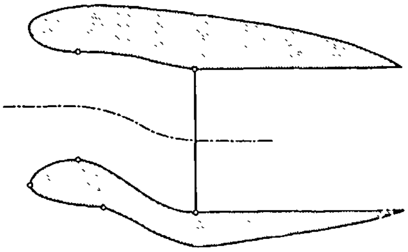
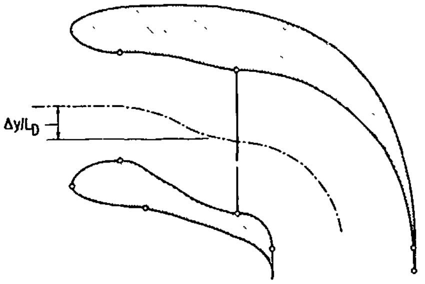


Figure 7. - Effect of fan-nozzle spacing on velocity distortion at the fan: straight inlet.



(a) 0° NOZZLE DEFLECTION.



(b) 90° NOZZLE DEFLECTION.

Figure 8. - Nacelles with offset inlets.

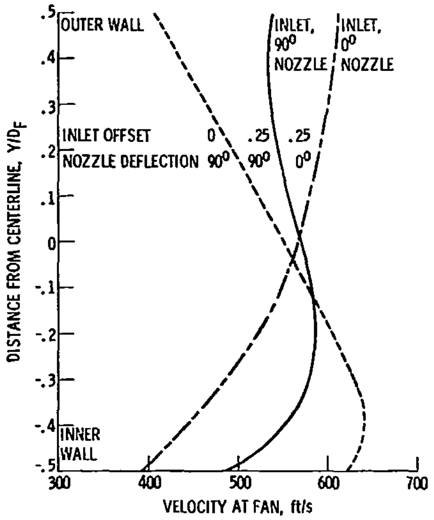


Figure 9. - Effect of inlet centerline offset and nozzle deflection on velocity profile at the fan: L_N/D_F = 0.16.

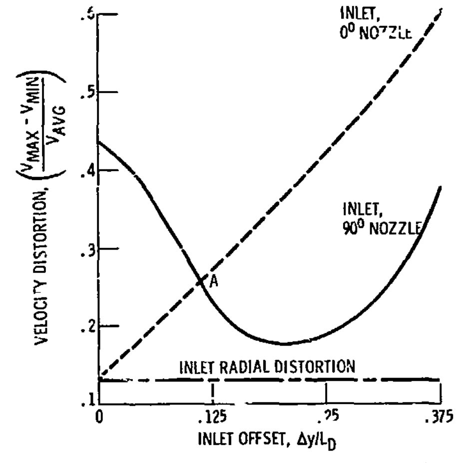


Figure 10. - Effect of inlet centerline offset and nozzle deflection on velocity distortion at the fan: L_N/D_F = 0.16.

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