Performance of Jet V/STOL Tactical Aircraft Nozzles

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V/STOL aircraft impose stringent requirements on exhaust nozzles. In many cases, this type nozzle must provide a high level of thrust for liftoff and maintain it while vectoring. Grumman ran a test program to optimize V/STOL nozzle designs and obtain a basic understanding of the complicated exhaust nozzle flow process. The program made use of fiberglass models which were 1/6.5 scale of representative fighter designs. Tests were run statically with cold air. The configurations examined were cut-off plug, single bearing swivel-tee plenum, single bearing swivel-scroll plenum, and flap nozzle. The effects of number of vanes, Mach number, and distortion were examined. The performance of the nozzles was broken down into plenum and nozzle, where applicable.
INTRODUCTION

The Navy is currently developing the Sea Control Ship on which V/STOL aircraft of various types will be used. The concept of jet V/STOL aircraft has been successfully demonstrated with the development of the subsonic Harrier, but now there is a need to develop a supersonic V/STOL fighter/interceptor. Development of such high-performance aircraft necessitates optimization of the exhaust system.

V/STOL propulsion systems often require rotating the exhaust nozzle. This might be accomplished with lift engines if they were to provide horizontal thrust in case of loss of lift/cruise engine thrust, or with the lift/cruise engine to provide additional lift. A supersonic configuration (Fig. 1) employing such concepts contains a hybrid propulsion system of two lift turbojets.
NOTE. SWIVEL PLANE CANTED INWARD

Fig. 3 Cutoff plug nozzle

Fig. 4 Single-bearing swivel-tee plenum nozzle

and one lift/cruise turbofan, with all engines utilizing pairs of vectorable nozzles. The nozzle swivel planes are canted inward to have the nozzles splayed outward as they rotate rearward, thus avoiding impinging on the fuselage. The requirement of thrust rotation, therefore, presents the problem of minimizing thrust loss in systems where loss mechanisms, such as separation and shocks, are likely to occur as the exhaust gases transit from an annulus to a circle and rotate up to 90 deg.

Together with these requirements, certain unique problems occur with V/STOL aircraft. These include the suckdown effect and downwash problems.
due to the high-temperature (1900 F) exhaust of lift turbojets.

Possible candidates for V/STOL vectorable nozzles include the triple bearing swivel, cascades, flap, and bifurcated single-bearing swivel (Fig. 2). The triple bearing swivel nozzle encounters ground clearance problems. The cascade nozzle is unattractive because of unwanted loss of thrust due to resulting side forces. The bifurcated swivel nozzle presents an attractive configuration in its ability to produce the fountain effect (1), i.e., buoyancy which can effectively counteract suckdown. Multiple jet patterns reduce lift loss for both in-ground and out-of-ground effect. The inherent high performance and simplicity of the flap nozzle make it attractive for V/STOL application. However, this configuration has drawbacks, such as heating the underside of the aircraft as the exhaust gases are vectored.

1 Numbers in parentheses designate References at end of paper.
An experimental program was conducted to obtain both performance figures and basic insight into a number of promising nozzle configurations. The configurations were basically designed for lift engine technology, but lift/cruise engine applications are possible with some of the designs.

NOZZLE MODELS

The test program examined four basic nozzle configurations (Figs. 3 through 6):

1. Cutoff plug
2. Single-bearing swivel-tee plenum
3. Single-bearing swivel-scroll plenum
4. Flap.

All but the cutoff plug were made of fiberglass. The nozzle models were 1/6.5 scale of representative fighter designs. Wooden patterns were used to form the fiberglass layups (Fig. 7). The nozzle models were built in such a fashion as to enable splitting them after a test, permitting inspection of oil and lampblack patterns. A typical oil drop study is seen in Fig. 8, depicting areas of separation and recirculation. (Vanes were later added to attach the flow to the nozzle wall.) The single-bearing swivel configurations had nozzles which rotated in the swivel plane. They had grooves molded into the contour to enable accommodation of zero, one, two, three, or five vanes, providing equal areas, Fig. 8(d). Total-pressure rings were located at the entrance to the rotating nozzles, enabling a performance estimate of the losses in the plenum and nozzles separately: Calculation of Cv could be based on engine total pressure or $C_{Vn}$ based on total pressure to the rotating nozzle. The nozzles also had extensions to vary the flow enclosure, Fig. 8(a).
FACILITY DESCRIPTION

The test program was conducted at the Grumman test facility complex (Fig. 9). The tests were run statically, i.e., with a free-stream Mach number of zero. The V/STOL thrust stand (Fig. 10) is composed of a three-component balance system — one self-contained force link flexure (x direction) and two flexures on a separate beam to measure vertical force (z direction) and moment (Mz). Therefore, the thrust vector's magnitude, direction, and location is measured. Air flows into the rig from a high-pressure bottle bank (2400 psia) and is throttled down to less than 50 psia (NPR = 1.4 - 3.0). The air then goes through a turbine flowmeter to measure weight flow. The flow meter provides a discharge coefficient accuracy of ± 0.3 percent.

The flow enters the model by flex hosing perpendicular to the plenum, thereby removing the x (axial) momentum component of the incoming flow, and then proceeds through a choke plate section composed of a screen and backup straightening vanes. In the next section, the flow accelerates
Fig. 8(d) Close-up of airflow patterns

1. HYPERSONIC WIND TUNNEL
2. PEBBLE BED AIR STORAGE HEATER
   70 LB/SEC AT 3000°F AND 2800 PSI
3. 65,000 CU FT VACUUM SPHERE
4. SUPersonic WIND TUNNEL: MACH 1.5 TO 4
   MAXIMUM STAGNATION PRESSURE 500 PSI
   TEST SECTION SIZE 225 SQ IN.
5. TRANSONIC WIND TUNNEL: MACH 0.6 TO 1.3
   MAXIMUM STAGNATION PRESSURE 75 PSI
   TEST SECTION SIZE 576 SQ IN.
6. CONTROL ROOM (COMPLETELY AUTOMATIC
   CONTROL SYSTEM)
7. SILENCERS
8. COMPRESSOR: 850 CFM, 3000 PSI
9. TEST AIR STORAGE TANKS
   1200 CU FT/3000 PSI
10. COMPRESSOR: WATER COOLING TOWER
11. VECTORED THRUST RIG
12. 2ND STAGE CONTROL VALVE
13. TURBINE FLOW METER
14. 1ST STAGE CONTROL VALVE
15. HIGH PRESSURE LINE

Fig. 9 Wind tunnel facilities

The balance system was calibrated in the instrumentation laboratory using weights; the same procedure was repeated on the thrust stand. The entire system was then pressure-checked. A reference convergent nozzle was used to obtain rig corrections which were applied after the rig.
DATA ACQUISITION AND REDUCTION

Pressure measurements were recorded by differential transducers and then filtered through a 5-cps passive filter. The signals were then applied to a SEL 810A digital computer, which performed both data acquisition and data reduction. An analog plotter provided completely reduced and plotted data within minutes of a run.

Actual weight flow is obtained by measuring static pressure upstream of the flowmeter, temperature downstream of the flowmeter, and rotor cps.

Force measurements are read from strain gages in the x-component force link and z-component flexures.

Weight flow measurements were converted to discharge coefficient \( C_d \), and force measurements were converted to thrust coefficient \( C_v \).

TEST RESULTS

Cutoff Plug

The cutoff plug was established as a reference goal because of its inherent high performance. Fig. 11 shows the cutoff plug with no outer nozzle, i.e., an annular nozzle and an outer nozzle with a wall angle of 27 deg and an L/D of 0.15. A performance increase of 3.73 percent is obtained by addition of the outer nozzle. Similar results were obtained (2) with the optimum length-to-diameter ratio between 0.11 and 0.18 and the optimum angle between 20 and 40 deg. The thrust performance \( C_v \) results are high. However, it must be noted that the exhaust gases are not vectored in this configuration.

Single-Bearing Swivel-Tee Plenum

Performance of the single-bearing swivel-type plenum nozzle is shown in Fig. 12 and can be
\[
\frac{\Delta F_O/F_G}{\Delta P_T/P_T} = \left[ \frac{P_{\infty}/P_T}{\sqrt{\frac{\gamma}{2}} \left(1 + \gamma \frac{\gamma}{2} \right) \left[ \frac{\gamma}{2} \right]^\gamma} \right] \frac{W \sqrt{T}}{\text{const}}
\]

For example, at an NPR of 2.0, \( \frac{\Delta F_O/F_G}{\Delta P_T/P_T} = 0.65 \).
For configuration two of Fig. 12, it is seen
that at an NPR of 2, \( C_v \) equals 0.922. From Fig.
13, with an inlet Mach number of 0.6, the plenum
total pressure loss is 6.9 percent. This con-
verts into a \( C_v \) loss of 4.48 percent. The loss
of the rotating nozzle itself at an NPR of 2 is
4.40 percent. (\( C_v \) adds up to more than 1.00 when
the losses are added due to the inaccuracy of
the measurements.) One major reason for the
nozzle loss is the nonuniformity of the flow en-
tering the nozzle due to the flow transition from
an annulus to a circle. The total pressure dis-
tribution across the flow area at the plenum in-
let and exit is seen in Fig. 14. A more uniform
distribution was obtained by channeling the flow
to the nozzle by the addition of an insert (Fig.
15). A study of performance change with number
of vanes is seen in Fig. 16 for the single-bearing
swivel-tee plenum nozzle without a boot extension.
Without vanes, the flow separates completely from
the nozzle wall and performance is poor, Fig.
8(d). Addition of one vane results in a \( C_v \) of
0.825 at NPR = 3.0. There is another substantial
increase in \( C_v \) with three vanes (\( C_v = 0.895 \)), but
performance only increases to \( C_v = 0.905 \) with five
vanes.

The effect of rotating the nozzle is seen
in Fig. 17. A loss of 2 percent in \( C_v \) occurred
for a 90-deg rotation at an NPR of 2.2.

**Single-Bearing Swivel-Scroll Plenum**

The scroll pattern was formed to guide the
exhaust flow from the turbine annulus to the noz-
kle opening. Performance of this configuration
with the boot extension and Mach 0.3 nozzle is
shown in Fig. 18. However, plenum oil flows in-
dicated large areas of separation and recircula-
tion (Fig. 19). Performance levels in \( C_v \) were
2.85 percent below that of the tee plenum at an
NPR of 3.0. It is believed that the scroll per-
formance was low because the flow into the scroll
had zero swirl; i.e., it was assumed that the
lift engine turbine exit guide vanes would remove
the swirl. However, if the incoming flow was to
swirl, it would more easily follow the contour of
the transition from the turbine annulus to the
nozzle opening. Previous studies (2,3) alluded
to two possibilities of loss in thrust coefficient
due to swirl: (a) loss of energy resulting from
tangential velocity, and (b) low base pressures
(on the turbine base) resulting from free vortex
motion. However, they were not applicable to
this configuration. In the first case, the scroll
would guide the flow into the rotating nozzle
making use of the tangential velocity; the second
case is not possible since the base would be en-
closed by the scroll contour. Thus, if the engine had modified or omitted exit guide vanes, performance would have been improved with this configuration. Lack of engine guide vanes would also result in engine weight reduction, elimination of vane component pressure drop, and shortening of engine length.

Flap Nozzle
The flap nozzle provided high-level thrust coefficient performance (Fig. 20) as it was vectored from 0 through 45 deg. A higher $C_v$ level was reported (4), but that data was only taken for one isolated flap. The present configuration included the transition from the turbine exit and four flaps emanating from two slots (Fig. 6). There was no discernible difference in $C_v$ as the flap was vectored from 0 to 15 deg. A 1 percent drop in $C_v$ at a NPR of 3.0 was experienced when the flap was vectored from 15 to 30 deg. The actual thrust angle varied as a function of NPR (Fig. 21). The correction was linear for 15, 30, and 45, but, for some reason, as yet unexplainable, it was nonlinear at 0 deg.

CONCLUSIONS
The test results demonstrated that good thrust performance can be achieved for a fully developed, bifurcated single-bearing swivel nozzle and a partially vectored flap configuration. For maximum thrust performance, these V/STOL nozzle designs:

1. Must maintain a uniform Mach number distribution entering the rotating nozzle

2. Must diffuse the turbine exhaust fully, i.e., lower the Mach number prior to vectoring the exhaust gas.

Follow-on work will focus on limiting the lift engine's exhaust thermal footprint. Work has been initiated in this area (5) using non-vectored, high-aspect-ratio nozzles, but the effort to develop a vectorable, high-aspect-ratio nozzle must be continued. Design, manufacture, and $C_v$ testing of initial configurations have been completed and thermal footprint testing is currently underway.

REFERENCES