Effect of Variable Guide Vanes on the Performance of a High-Bypass Turbofan Engine

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The ability of a part-span variable-inlet guide vane (VIGV) to modulate the thrust of a high-bypass turbofan engine was evaluated at altitude/Mach number conditions of 4572 m/0.6 and 9144 m/0.93. Fan tip, gas generator, and supercharger performance were also determined, both on operating lines and during fan duct throttling. The evaluation was repeated with the bypass splitter extended forward to near the fan blade trailing edge. Gross thrust attenuation of over 50% was achieved with 50 deg VIGV closure at 100% corrected fan speed. Gas generator supercharger performance fell off with VIGV closure, but this loss was reduced when a splitter extension was added. The effect of VIGV closure on gas generator performance was minimal.

Nomenclature

D	= duct diameter
$ETAFH2C$	= fan hub efficiency measured from engine inlet to core inlet
$ETAFT$	= fan tip efficiency
$FPRH2C$	= fan hub pressure ratio measured from engine inlet to core inlet
$FPRT$	= fan tip pressure ratio
$NF/\sqrt{\theta_2}$	= fan speed corrected to engine inlet temperature, percent of 7005 rpm
$NG/\sqrt{\theta_{2C}}$	= gas generator speed corrected to core inlet temperature, percent of 15,683 rpm
PS	= static pressure, kPa
PT	= total pressure, kPa
$PT2$	= engine inlet pressure, kPa
$PT2C$	= gas generator inlet pressure, kPa
S/G	= strain gage
TM	= metal temperature, K
TT	= total temperature, K
VIGV	= variable inlet guide vane
$WA1$	= total engine inlet airflow, kg/s
$WA2C$	= core inlet airflow, kg/s
WAT	= fan tip airflow, $WA1 - WA2C$, kg/s
WF	= fuel flow, kg/h
α	= VIGV angle, deg
δ	= ratio of total pressure to absolute pressure of NASA standard sea-level conditions
θ	= ratio of total temperature to absolute temperature of NASA standard sea-level conditions

Subscripts

BL	= boundary layer
2	= engine inlet
$2C$	= gas generator inlet

Introduction

THE propulsion system of a V/STOL aircraft must provide substantial and rapid thrust modulation to control attitude, especially during takeoff, landing, and hover. In a high-bypass turbofan, most thrust is developed in the fan tip; thus, variable-inlet guide vanes (VIGV), controlling the airflow into a fan, have been proposed as one means of achieving this modulation.

Performance of a variable inlet guide vaned fan has previously been demonstrated on rig tests,[1,2] and on a full-scale engine test.[3] However, in these tests the VIGV covered the entire annulus ahead of the fan, thus as fan tip performance decreased with VIGV closure, so did gas generator supercharging. In a two-engine VTOL aircraft, the gas generator size is determined by a one-engine inoperative vertical landing requirement where one core engine must drive both fans. Thus, decreased core supercharging due to full-span VIGVs would necessitate an increased core engine size. A part-span VIGV, the subject of this paper, would maintain core supercharging. In addition, a forward extension of the fan/core bypass splitter was tested to investigate its potential for further improving core supercharging.

The evaluation reported herein was conducted in the NASA Lewis Research Center PSL altitude chamber at simulated flight conditions of 4572 m (15,000 ft) altitude, 0.6 Mach number with 284 K (511°R) inlet temperature, and at 9144 m (30,000 ft) altitude, 0.93 Mach number with both 284 and 259 K (466°R) inlet temperatures.

Apparatus

Engine and Installation

A YTF34-F5 high-bypass turbofan, configured to closely resemble a TF34-100 engine, was used in this evaluation. At the design point, the fan pressure ratio was 1.5:1, the total airflow was 151 kg/s (333 lb/s), the bypass ratio was 6.2:1, and the core compressor pressure ratio was 14:1. Design point thrust was 40,000 N (9000 lb). A detailed description of the engine may be found in Ref. 4. The engine was installed in a conventional direct-connect manner with a labyrinth seal isolating the inlet ducting from the test chamber. A photograph of the installation is provided in Fig. 1. The engine was mounted on a thrust bed suspended from the test chamber by four long flexure rods. The outer fan cowling and convergent fan and core exhaust nozzles were extended to provide a nearly coplanar exhaust. The core nozzle exit area was 1258 cm² (195 in.²). The fan had two possible nozzles, a "nominal" nozzle with an exit area of 4640 cm² (719 in.²) and a large nozzle having an exit area of 5670 cm² (879 in.²).

A fan back-pressure system (Fig. 2) was installed for portions of the test when fan characteristic curves between a nominal operating line and a limit line were being determined.[5] When this large structure was mounted on the thrust bed, thrust data were not recorded.

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Variable Inlet Guide Vane and Extended Splitter

The part-span VIGV evaluated in this program is shown in Figs. 3 and 4. The assembly consisted of 30 fixed forward struts, cantilevered from an outer casing and mutually supported by a fixed inner ring, and 30 movable rear flaps. The undeflected VIGV was completely uncambered and was intended to produce nominal TF34 performance. A detailed description of the VIGV design was given in Ref. 3.

The extended splitter configuration is shown in Fig. 5. This splitter provided an aerodynamically shaped physical boundary between the fan hub and tip flows from immediately behind the fan trailing edge, rearward to the core inlet splitter. Its purpose was to reduce spillage of fan hub airflow over the splitter and thus maintain fan hub performance.

Instrumentation

The instrumentation used to acquire the data to be presented is shown in Fig. 6. As this figure indicates, the airflow measurement station, the fan inlet and exit, and the gas generator inlet and exit were heavily instrumented. Pressures were recorded on individual transducers and on scanivalves. The differential pressure scanivalve transducers were calibrated on each data scan. Temperatures were measured on either Chromel-Alumel or copper-constantan thermocouples referenced to 339 K (610°R).

Stress levels in the VIGV, fan blades, fan exit guide vanes, and compressor third-stage stators were monitored using strain gages. A photoelectric scan system[6] was also used to monitor fan blade vibrations.

Procedure

For this evaluation, the average engine inlet total pressure and total temperature, and the test chamber altitude pressure, were maintained at values corresponding to a simulated Mach number of 0.6 at 4572 m (15,000 ft) altitude with an inlet total temperature of 284 K (511°R) or at a simulated Mach number of 0.93 at 9144 m (30,000 ft) altitude with inlet total temperatures of 284 K (511°R) or 259 K (466°R). The low inlet pressures were chosen to reduce stress levels on the test hardware. The lower inlet temperature was selected to permit running at higher speeds while avoiding turbine temperature limits.

Tests were run in two phases. Performance data, with thrust measurement, were recorded on the nominal and low (large fan nozzle) operating lines at VIGV closures of 0, 15, 35, and 50 deg. Then, the fan back-pressure jets were installed and data were recorded along lines of constant fan speed from the operating line to an aeromechanical or aerodynamic limit. No thrust data were recorded during the fan mapping tests. These procedures were followed for the baseline TF34 with

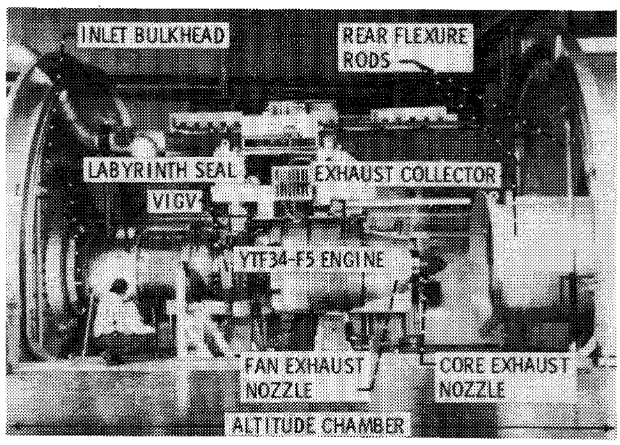

Fig. 1 TF-34 engine, with VIGV, installed in altitude facility.

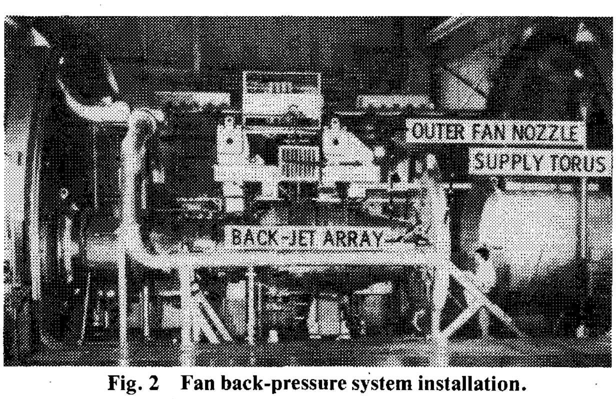

Fig. 2 Fan back-pressure system installation.

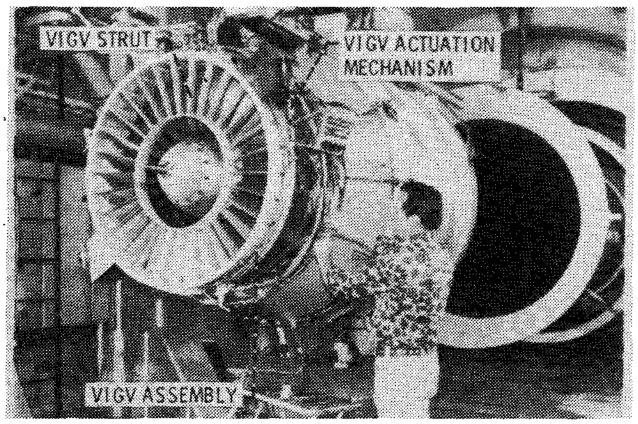

Fig. 3 Part-span VIGV installed on YTF34-F5 engine.

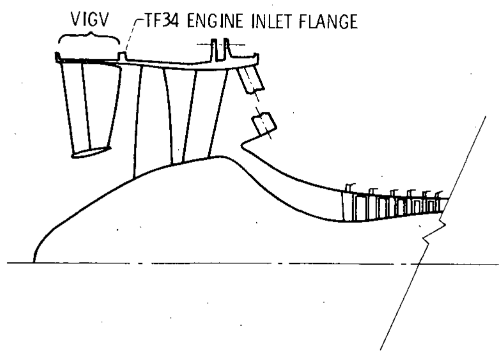

Fig. 4 Cross section of VIGV installed ahead of TF34 turbofan engine.

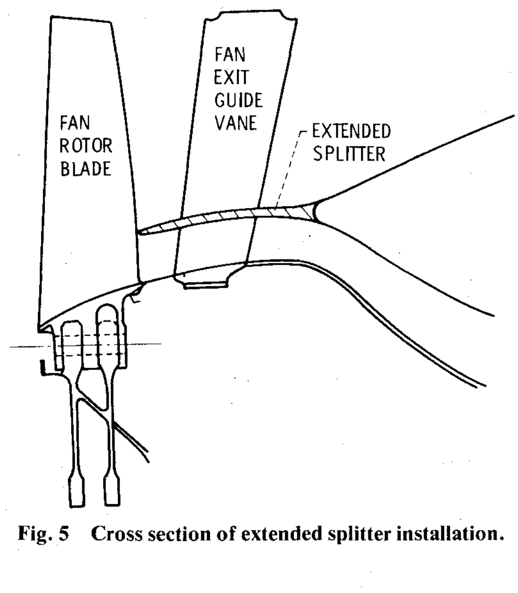

Fig. 5 Cross section of extended splitter installation.

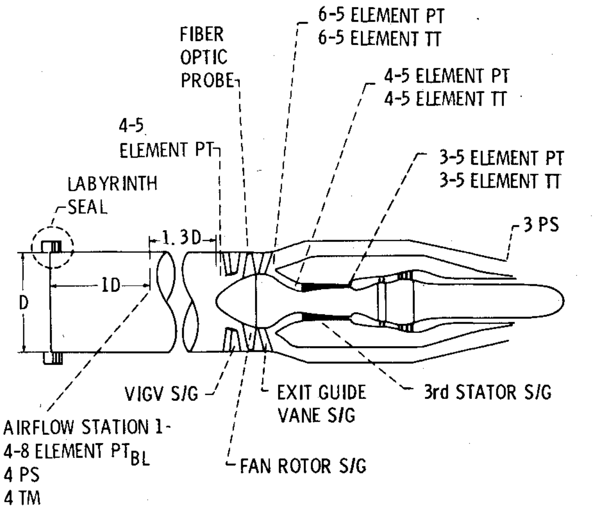

Fig. 6 Schematic of TF34 installation, instrumentation and VIGV.

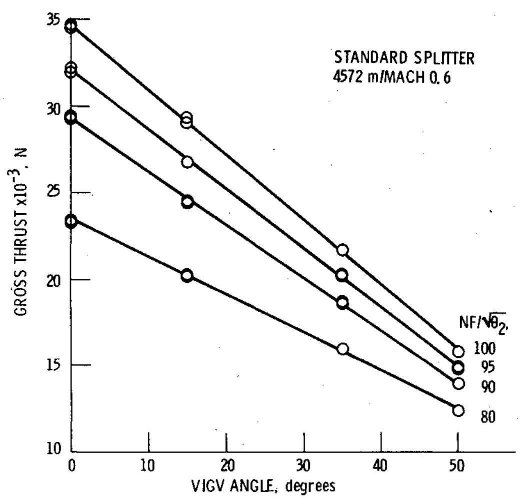

Fig. 7 VIGV attenuation of gross thrust.

VIGVs and also for the TF34 with VIGVs and the extended splitter.

It should be noted that excess fan turbine power, due to fan unloading with VIGV closure, was not extracted and so did not simulate many typical V/STOL load requirements. Therefore, to maintain a constant fan speed, it was expected that the core speed, and therefore the throttle position, would have to be reduced as the VIGV closed.

Results and Discussion

Effect of VIGV on Thrust and Fan Performance

The objective of installing variable inlet guide vanes ahead of a high-bypass turbofan engine was to investigate thrust modulation and engine performance changes due to the VIGVs. Figure 7 shows the measured attenuation of gross thrust with VIGV closure at 4572 m altitude, 0.6 Mach number. At 100% corrected fan speed, closing the VIGV from 0 to 50 deg decreased thrust from 34,700 to 15,790 N (7800 to 3550 lb), more than a 50% thrust drop. The part-span VIGV was designed to achieve this modulation by reducing the fan tip airflow, which comprised more than 85% of the total inlet flow, with minimal effect in the fan hub region.

The effect of the VIGV on fan performance at 95% corrected fan speed, $NF\sqrt{\theta_2}$, can be seen in Fig. 8. As the VIGV closed from 0 to 50 deg, the constant-speed line dropped, providing a reduced pressure ratio and airflow characteristic. Fan tip efficiency decreased as the VIGV closed beyond 15 deg with a dramatic loss between 35 and 50 deg.

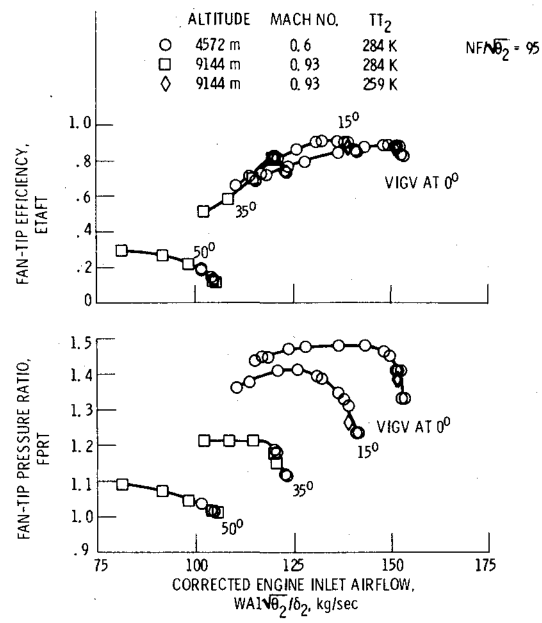

Fig. 8 Effect of VIGV closure on fan tip performance with standard bypass splitter.

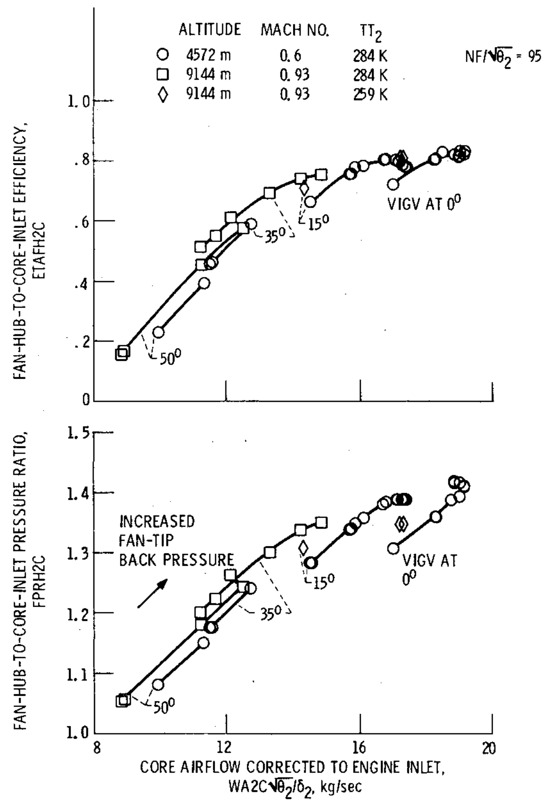

Fig. 9 Effect of VIGV closure on supercharger performance with standard bypass splitter.

In no case was a fan stall encountered. At 0 and 15 deg VIGV, fan flutter modes limited operation. At 35 and 50 deg, fan exit guide vane stresses due to EGV stall were limiting. These were also the limits encountered at other speeds with the standard bypass splitter. More information on these aeromechanical limits can be found in Ref. 7.

Gas generator supercharging by the fan hub and through the gooseneck is presented in Fig. 9 in terms of the ratio of core inlet pressure to engine inlet pressure, efficiency, and gas generator inlet airflow corrected to the engine inlet conditions. As the VIGV closed, the supercharger pressure ratio and efficiency curves shifted to lower airflow, pressure ratio, and efficiency, with a large performance loss between 35 and 50 deg. Note that on these data as the fan tip was back pressured, both the pressure ratio and corrected airflow increased for the supercharger, which was not throttled, helping to satisfy the increased power demand put on the core engine during fan duct throttling.

Fan tip performance with the extended splitter is shown in Fig. 10. Along lines of constant fan speed, the fan tip pressure ratio and airflow began at lower values than with the standard splitter. Even the curves for 0 deg VIGV are not colinear. This is believed to be due to the extended splitter imposing one fixed fan exit area split which is not optimal for all speeds and airflows. As the fan tip was throttled, the characteristic for 0 deg VIGV gradually merged with its standard splitter counterpart. At 15 deg and greater VIGV closures, the characteristics with the extended splitter crossed the standard splitter curves and encountered limits at higher fan tip pressure ratios. With the extended splitter, fan flutter modes generally determined the limit during fan back pressuring.

Fan tip efficiency curves for both splitters nearly coincided at 0 and 15 deg VIGV. At larger closures, the fan tip efficiency with the extended splitter was lower at high flows, but rose and stayed above the efficiency with the standard splitter, as fan flow was throttled.

Supercharging performance with the extended splitter (Fig. 11) was higher than with the standard splitter. At each VIGV angle, both pressure ratio and efficiency showed improvement which, while small at lesser VIGV angles, became considerable beyond 35 deg.

The improved fan hub supercharging performance can be seen in more detail in Fig. 12 and Table 1 which compare the pressure profiles at the core inlet for VIGV at 35 deg and several resulting performance parameters for both splitter cases. The data were recorded at the same speed, core airflow, and engine inlet conditions. However, several differences appear. The average core inlet pressure with the standard splitter, 63.0 kPa (9.13 psia), was significantly lower than with the extended splitter, 68.5 kPa (9.93 psia), with a resulting difference in supercharging pressure ratio of 1.201 against 1.295. Also, the total pressure profiles for the standard splitter case are steeper than those for the extended splitter, imposing a larger hub radial distortion on the core engine. Even the radial static pressure gradients are less severe with the extended splitter.

It is believed that in applications in which fan power is extracted as the VIGV closes, requiring that core speed be maintained, the supercharger losses would be lowered further. This is because maintaining core airflow should decrease those losses due to diffusion of a portion of the fan hub flow into the fan duct.

Effect of VIGV on Gas Generator Performance

As the VIGV closed and unloaded the fan, excess power became available from the fan turbine. In order to maintain a constant fan speed, the throttle position and, therefore the core speed, were reduced. This is seen in Fig. 13 where the corrected core speed/fan speed match is presented for operating lines at the 4572 m/0.6 Mach number condition. The drop in core speed at 100% corrected fan speed was 5% as the VIGV closed from 0 to 15 deg, 4% from 15 to 35 deg, and 1% from 35 to 50 deg. With the extended splitter, it was necessary to reduce core speed even lower than with the standard splitter, due to improved core supercharging.

The core compressor remained on its nominal operating line. The only effect of VIGV closure on compressor performance was to move the operating point lower along the operating line due to the speed reduction previously shown in Fig. 13. In Fig. 14, the compressor operating line for the extended splitter appears to fall slightly below that with the standard splitter.

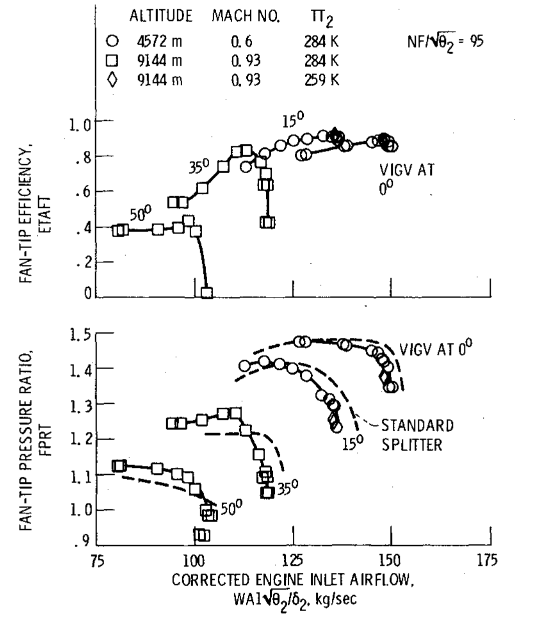

Fig. 10 Effect of VIGV closure on fan tip performance with extended bypass splitter.

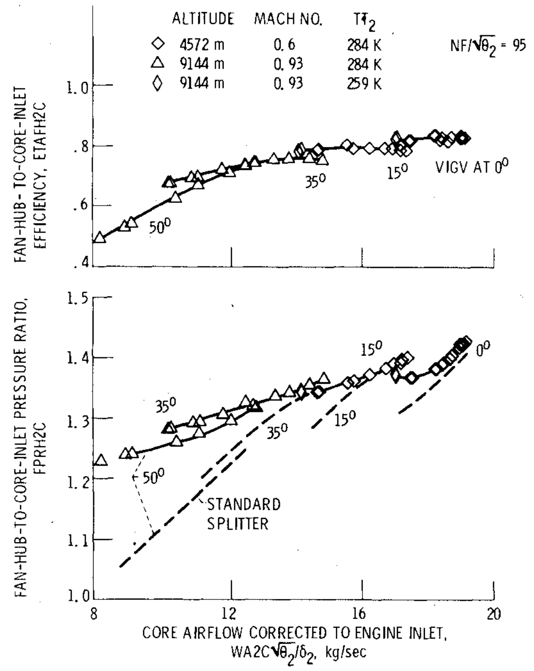

Fig. 11 Effect of VIGV closure on supercharger performance with extended bypass splitter.

Table 1 Effect of extended splitter on core supercharging

VIGV, deg Splitter	35 Standard	35 Extended
$PT2$, kPa	52.40	52.88
$NF/\sqrt{\theta_2}$,%	95.0	95.1
$WA1\sqrt{\theta_2}/\delta_2$, kg/s	120.4	118.0
$WAT\sqrt{\theta_2}/\delta_2$, kg/s	109.2	106.8
$WA2C\sqrt{\theta_2}/\delta_2$, kg/s	11.2	11.1
$PT2C$, kPa	63.0	68.5
$FPRT$	1.150	1.110
$ETAFT$	0.790	0.704
$FPRH2C$	1.201	1.295
$ETAFH2C$	0.513	0.697
$NG/\sqrt{\theta_{2C}}$	90.5	88.5

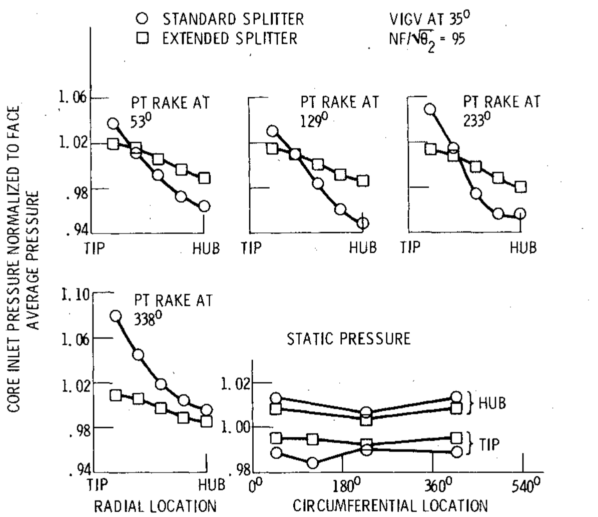

Fig. 12 Effect of extended splitter on core inlet pressure profiles at 9144 m/Mach 0.93.

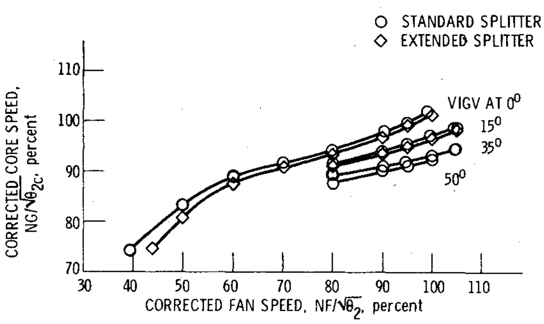

Fig. 13 Effect of VIGV and bypass splitter on engine speed match on nominal operating lines at 4572 m/Mach 0.6.

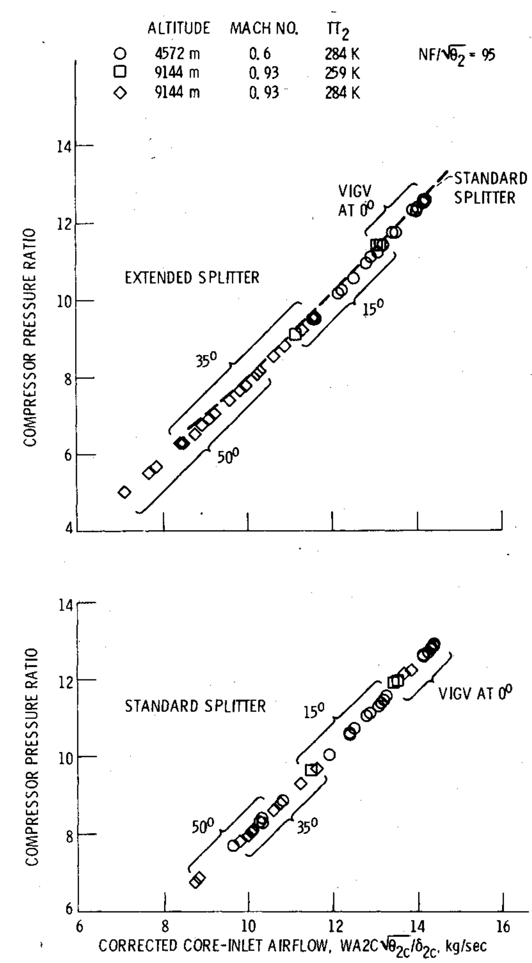

Fig. 14 Effect of VIGV and bypass splitter on compressor performance.

The effect of VIGV closure on fuel flow rate may be seen in Fig. 15. As the preceding would imply, less energy input was required to maintain a constant fan speed as the VIGV closed. The fan tip unloading and gas generator deceleration as the VIGVs closed at a fixed fan speed decreased the energy demands of the engine. With the extended splitter and its improved core supercharging and greater core speed drop, the fuel consumption was even lower.

Summary of Results

An experimental investigation was performed to evaluate the concept of using a part-span variable-inlet guide vane to modulate the thrust of a high-bypass turbofan engine with minimal effect on gas generator supercharging. Forward extension of the bypass splitter was also evaluated as a means of further eliminating supercharger losses. The major results of this investigation follow.

1) Deflecting part-span variable-inlet guide vanes provided a high degree of thrust modulation, largely through the modulation of fan tip performance. A reduction of gross thrust greater than 50% was demonstrated at a constant fan speed for a 6:1 bypass ratio engine.

2) The supercharger did suffer performance losses as the VIGV closed, especially at the larger VIGV angles. These larger losses were substantially reduced by extending the bypass splitter forward. Thus, the extended splitter becomes an important consideration when thrust modulation requires large VIGV closures.

3) The core compressor stayed on its operating line regardless of what was done to the fan. The core operating line was slightly lower with the extended splitter.

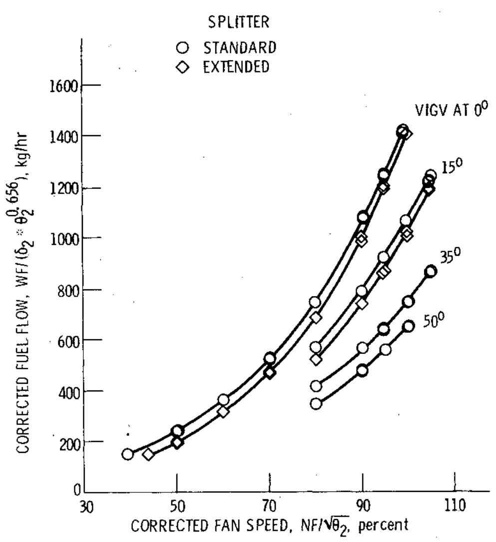

Fig. 15 Effect of VIGV and bypass splitter on corrected fuel flow on the operating line at 4572 m/Mach 0.6.

4) The gas generator supercharging was influenced by both the fan tip and the gas generator demands.

5) As the fan was unloaded with VIGV closure, excess power became available from the fan turbine. Therefore, to maintain a constant fan speed, the gas generator had to be decelerated by decreasing fuel flow.

In summary, the installation of a part-span variable-inlet guide vane system ahead of a high-bypass turbofan engine appears to be a feasible method of accomplishing the thrust modulation required for V/STOL attitude control.

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