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Part-Span Variable Inlet Guide Vanes for V/STOL Fan Thrust Modulation

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Part-span, variable inlet guide vanes (VIGV's) have been proposed as a means of modulating thrust for attitude control of V/STOL aircraft systems. The utilization of these part-span VIGV's in subsonic aircraft system studies have shown significant payoffs in reducing weight and increasing performance of the engine core when used in conjunction with a means of power transfer from one fan to the other. The part-span VIGV's were tested on a TF34 engine at NASA Lewis under a joint NASA-Navy sponsorship to demonstrate the feasibility and performance of these proposed thrust modulating devices on an operational engine system. The results of the tests showed the VIGV's to be an effective thrust modulating device while maintaining core supercharging. The fan was mapped to stall for a range of speeds and VIGV settings. Fan tip performance (modulated by part-span VIGV's) and hub performance (unmodulated) are presented. Testing was repeated with a splitter extended between the core and bypass streams. The effects of distortion were reduced and less stall sensitivity was experienced with the inlet guide vanes (IGV's). At 0-deg IGV closure little effect was seen on fan or core compressor efficiency and measured specific fuel consumption (sfc). Test data indicate that thrust modulation of ±20% can readily be achieved by using part-span VIGV's.

Introduction

THE development of a V/STOL aircraft is highly dependent upon the mission constraints, propulsion system(s), and control type and response necessary for maintaining aircraft attitude during hover and vertical operation. The integrated blending of the propulsion system and flight controls to achieve aircraft attitude control are more critical to the successful operation of the fixed wing V/STOL aircraft than any of the more conventional designs. As such, the propulsion system becomes the focal point for obtaining the necessary control power through use of vectoring nozzles, variable inlet guide vanes, variable pitch fans, bleed air reaction control systems, and other devices/systems.

In the last V/STOL A concepts development cycle, the mission constraints also became a driving design consideration owing to the imposition of a one-engine-inoperative (OEI) requirement upon the aircraft which created the need for a means of power transfer from the operable engine core to the inoperable core engine fan. Several methods of solving this requirement were suggested by the various aircraft manufacturers, one of which was the use of a cross shaft which linked the two fans through a power transfer gear set. The cross shafted propulsion system concept was utilized on several aircraft designs to achieve power transfer from one core to the other during normal hover and vertical operation as well as when one core was inoperative. A typical arrangement is shown in Fig. 1.

A method of rapidly modulating thrust while maintaining core and fan speeds was needed to achieve the rapid thrust response (as much as ±27%) for attitude control of the aircraft. The concept of variable inlet guide vanes (VIGV's) was proposed (Fig. 2) as a method which could rapidly modulate thrust (airflow) of the fan (as shown in Fig. 3) without disturbing the speed of the machine, provided that some means of transferring core energy (cross shaft) could be

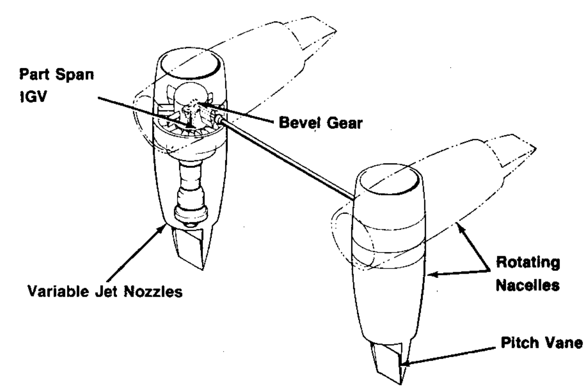

Fig. 1 Rotating nacelles—V/STOL A propulsion system.

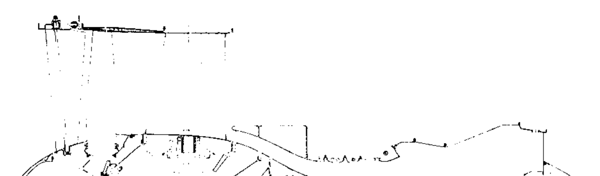

Fig. 2 Typical arrangement of variable inlet guide vane direct drive turbofan.

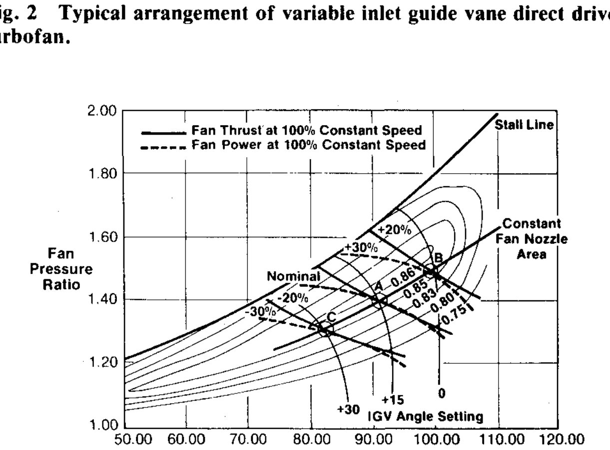

Fig. 3 Typical thrust modulation with variable inlet guide vanes.

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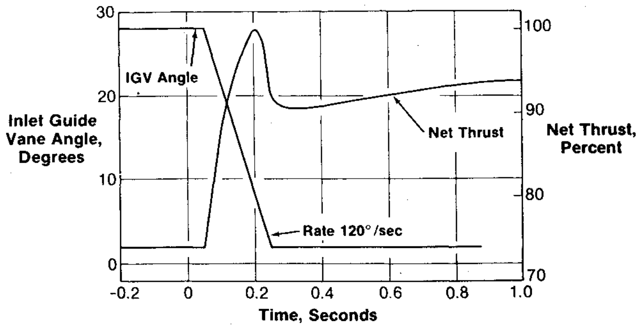


Fig. 4 Preliminary transient response capability with variable inlet guide vanes.

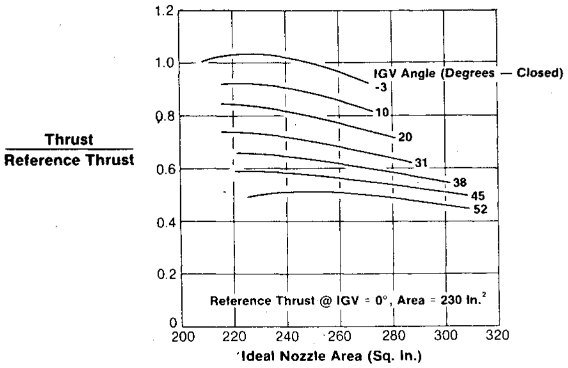


Fig. 5 YJ101-VIGV thrust characteristics based on test data.

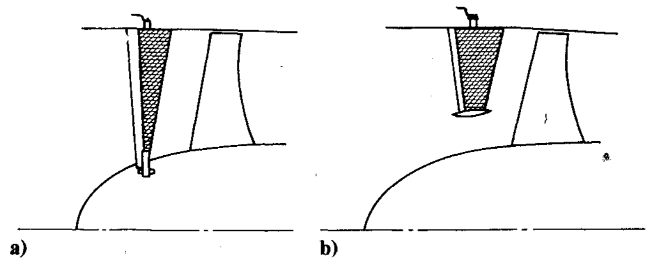


Fig. 6 Comparison of a) full-span and b) partial-span VIGV's.

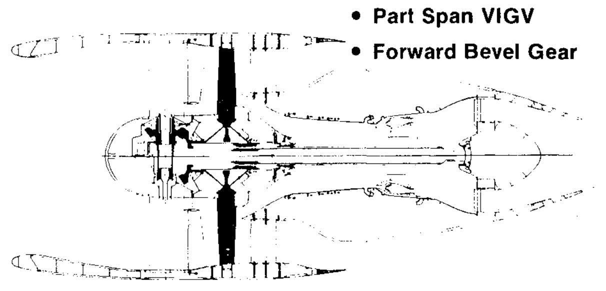


Fig. 7 Type A V/STOL direct drive VIGV turbofan.

utilized. In Fig. 3 movement along the operating line from some point A to B represents an increase in thrust/airflow as the VIGV is opened from 15 deg closed to 0 deg closed. Conversely, a movement along the operating line from point A to C represents modulating the thrust downward by closing the VIGV's. Since horsepower transfer is the key to interengine power transfer, the dotted line is shown to illustrate this effect as the VIGV's are moved from A to B or A to C. Figure 4 shows a typical transient response of a turbofan engine when modulated by VIGV's. The rapid thrust response characteristics shown in Fig. 4 more than meet the requirements imposed by the aircraft demands. (Time constants of 0.4-0.5 s are generally sufficient to provide the thrust modulation desired).

Variable inlet guide vanes have been used throughout the jet propulsion industry since they were introduced on the General Electric J79 engine some 25 years ago. Variable inlet guide vane and stator angles have generally been scheduled as a function of corrected rotor speed to provide for off-design engine matching. The utilization of VIGV's to achieve rapid thrust modulation with small changes in corrected rotor speed is, therefore, an extension of a proven concept. On a test of the YJ101 engine with variable inlet guide vanes in 1976 (unpublished, classified report), a range of inlet guide vane angles from 3 deg open to 52 deg closed was used at various fan speed-power conditions. Figure 5 shows the variations in thrust that were obtained on the YJ101. Thus utilization of VIGV's to achieve rapid thrust modulation for attitude control over a range of thrust modulation from 100 to 50% was demonstrated at a very early stage.

The development of the propulsion system for V/STOL A was strongly influenced by the need to transfer power from one fan to the other at very rapid rates with both cores operating and with one core inoperative. During an emergency vertical landing (OEI), the operating core and low-pressure turbine had to be capable of driving all fans to produce the required landing thrust plus enough excess power to develop the necessary control margin. (This extreme operating condition was the sizing point for the core.) Thus, to achieve a balanced thrust condition, the fan(s) on the operating core side was "low-flowed" by closing the VIGV's to reduce the fan thrust of this engine while the fan(s) on the inoperative core side was "high-flowed" by opening the VIGV's to increase the fan thrust. In addition, a ±20-27% control margin was required to produce the necessary attitude control of the aircraft. Variable inlet guide vanes provided the rapid modulation of thrust required for attitude control, but the full-span VIGV's also modulated the fan hub flow into the core. During most operating conditions, the VIGV's were partially closed owing to the need to have ±20-27% control margin available. At the emergency landing condition, the fan(s) on the operating core side had its VIGV's in a partially closed position while the fan(s) on the other side had its VIGV's almost fully open. This greatly modulated the pressure rise into the operating core, which led to the oversizing of the cores to accomplish the vertical landing. The full-span, partially closed, VIGV's desupercharged the core flow pressure rise at most operating conditions, which, in effect, oversized the core. This penalty was reflected in increased aircraft size and weight and greater fuel burned at cruise owing to the larger sfc. The part-span VIGV was conceived to maintain core supercharging by maintaining hub pressure ratio while permitting the fan bypass flow to be fully modulated. The attendant reduction in core size (12%), cruise sfc, and engine weight, which was brought about by the incorporation of part-span rather than full-span VIGV's, resulted in significantly large reductions in aircraft size and weight and cruise sfc. Figure 6 shows the full-span and part-span VIGV's. Based on the initial evaluation of the part-span concept, engine preliminary designs were developed, such as the one shown in Fig. 7.

Figure 7 shows an application of part-span VIGV's to a General Electric GE28 V/STOL A engine concept. The part-span VIGV permits the rapid modulation of thrust while maintaining core supercharging throughout the full variation range of the vanes. Power is transferred through the bevel gear set to a cross shaft which interconnects the other engine. Thrust can be modulated at constant speed through the use of the cross shaft so that attitude control (up to ±20% for this configuration) can be maintained during a hover or balanced thrust condition. During OEI conditions, power is transferred through the cross shaft to the dead core engine's fan to achieve a balanced thrust condition while maintaining the ±20% control margin.

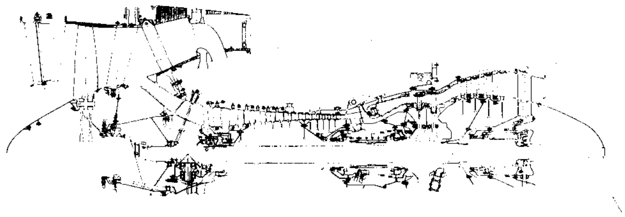
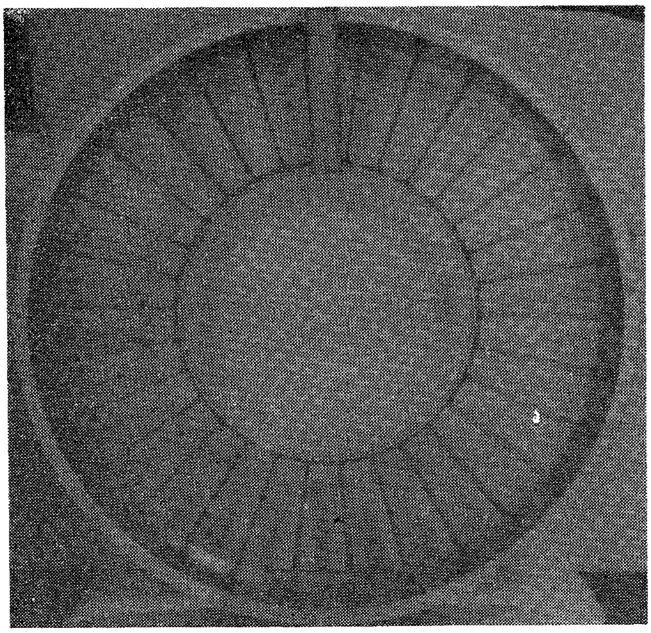
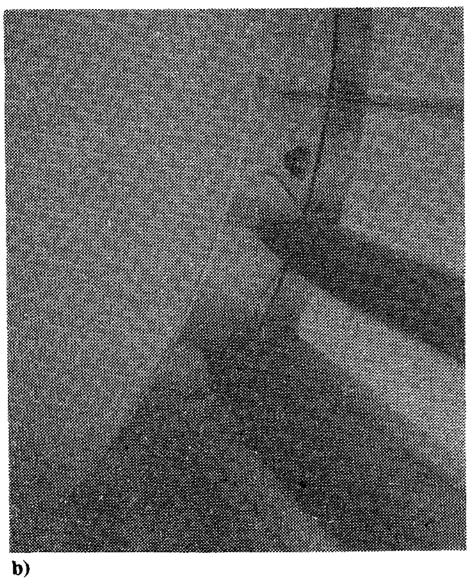


Fig. 8 TF34 PET part-span VIGV cross section.



a)



b)

Fig. 9 TF34 PET VIGV assembly. a) Forward looking aft. b) Inner diameter detail—aft looking forward.

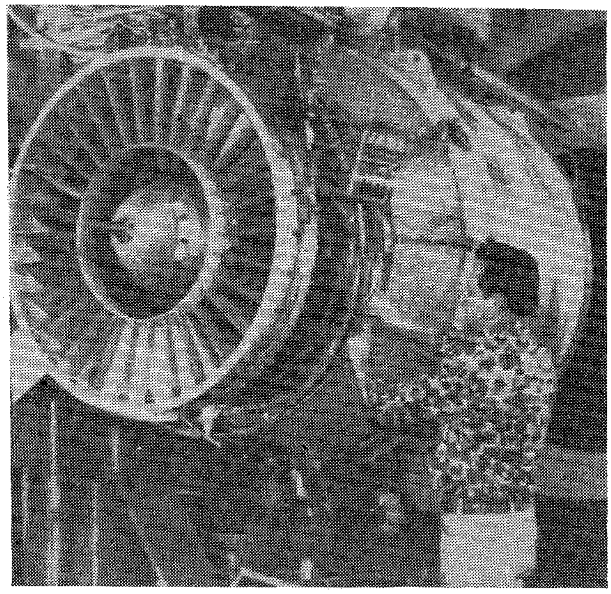


Fig. 10 TF34 VIGV assembly.

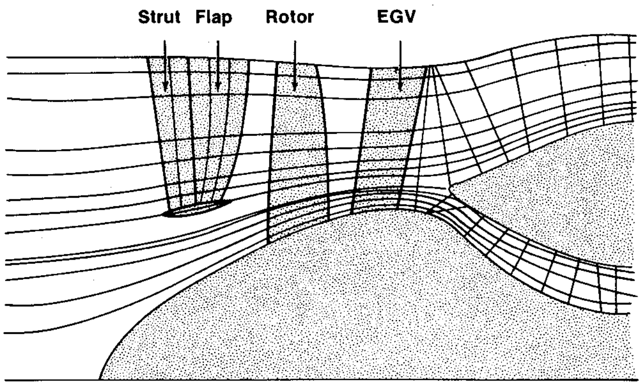


Fig. 11 TF34—part-span VIGV design streamline flow evaluation.

The significant payoffs identified for the part-span VIGV's led to the investigation of the feasibility and the demonstration of the capability of part-span VIGV's to modulate thrust while maintaining core supercharging through use of the part-span VIGV's. A joint NASA Lewis, U.S. Navy, and General Electric program, the TF34 Propulsion Engine Technology (PET) program was undertaken to test the part-span VIGV at NASA Lewis on a current engine configuration. VIGV hardware and designs were provided by General Electric under contract to NASA Lewis with funds supplied by the Navy. A description of the configurations tested and a summary of the results from those tests are presented.

TF34 Engine VIGV Design and Test

The Propulsion Engine Technology (PET) program at NASA Lewis utilizes a YTF34-F5 engine as a test bed demonstrator. A series of tests were planned, in conjunction with the U.S. Navy, to demonstrate the feasibility and performance of part-span VIGV's on an existing high bypass ratio turbofan engine. The VIGV's were designed to utilize as much of the existing hardware as possible with only minimal impact upon the engine configuration to help reduce costs and achieve an early demonstration of the objectives.

The installation of the part-span VIGV design in front of the fan rotor of a TF34 engine for testing at NASA Lewis is shown in Fig. 8. The TF34 fan normally does not have an IGV. The completed assembly of the VIGV's is shown in Figs. 9 and 10.

Figure 11 is a streamline flow plot of the VIGV/TF34 design. The streamline plot was generated analytically to depict the expected flow split of the configuration to aid in the design and cycle analysis of the part-span VIGV's. From this figure it can be seen that all the tip flow modulated by the strut-flap passes out the fan duct. The flow passing under the annular ring is, therefore, unmodulated by the inlet guide vane, as can be seen in Fig. 11, and enters the core engine duct with some excess flow passing out the fan duct to avoid core ingestion of wakes and secondary flow from the IGV's and annular ring. The flap chord is shortened near the inner ring to reduce discontinuities between modulated and unmodulated flow entering the fan rotor when the VIGV's are closed.

Figure 12 describes the instrumentation used in the tests. Fan aerodynamic performance is defined by full-span instrumentation at the fan stator discharge. Fan tip performance is defined by the outer instrumentation elements measuring the pressure and temperature of air passing out the fan duct; fan hub discharge performance is also measured by the inner instrumentation elements. The primary fan hub performance data used is defined by pressure and temperature instrumentation at the core compressor inlet and includes core inlet duct loss as part of the fan hub performance definition.

An extended splitter design (Fig. 13) was utilized to further examine the effects of hub supercharging on the engine core. Table 1 illustrates the significant payoffs in core size reduction that could be realized by using a part-span VIGV with an extended splitter in a V/STOL A engine system. This configuration was tested during a second series of tests at NASA Lewis over the same test matrix.

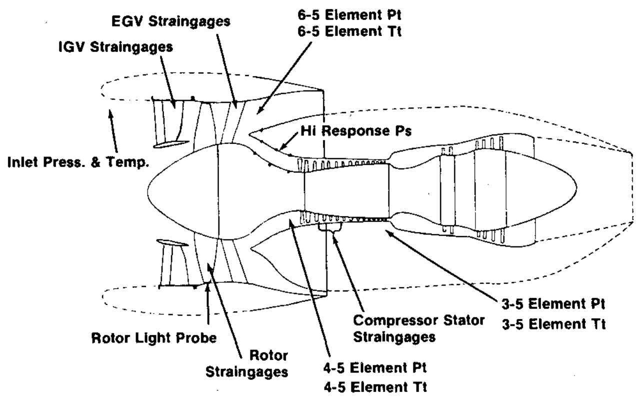


Fig. 12 Instrumentation arrangement.

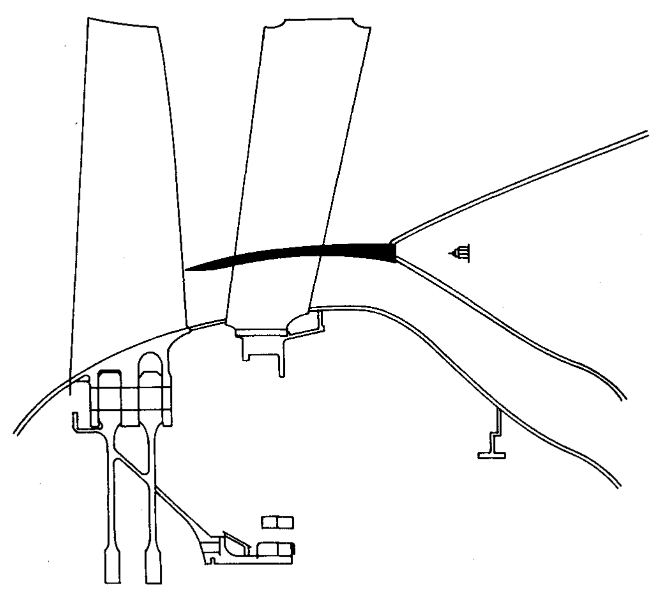


Fig. 13 TF34 extended splitter study configuration.

Since the demonstrator engine did not have a means of energy extraction such as a cross shaft, it was anticipated that the closing of the VIGV's would result in a core speed "drop-off" and diffusion/spillage of the excess core flow into the fan bypass duct. Within the constraints of the costs and schedules, it was not feasible to attempt to extract low-pressure turbine power in order to more accurately simulate the V/STOL A cross shafted system. The testing of both splitter types was expected to provide some insight into the effects of core supercharging and to determine to what extent the additional, physical restraining of the hub flow would have on the core speed.

The predicted thrust modulation for the TF34 VIGV tests is shown in Fig. 14. Modulations of ±20% of nominal thrust for normal vertical takeoff and for one-engine-inoperative (OEI) landing conditions are represented. These data represent a two-fan-two-core configuration such as that shown in Fig. 1. The test plan matrix centered about these operating conditions and was extended to include other fan speeds and IGV angles to represent anticipated fan operating conditions with complete definition of fan component mapping to stall. For these conditions, both fan tip and hub

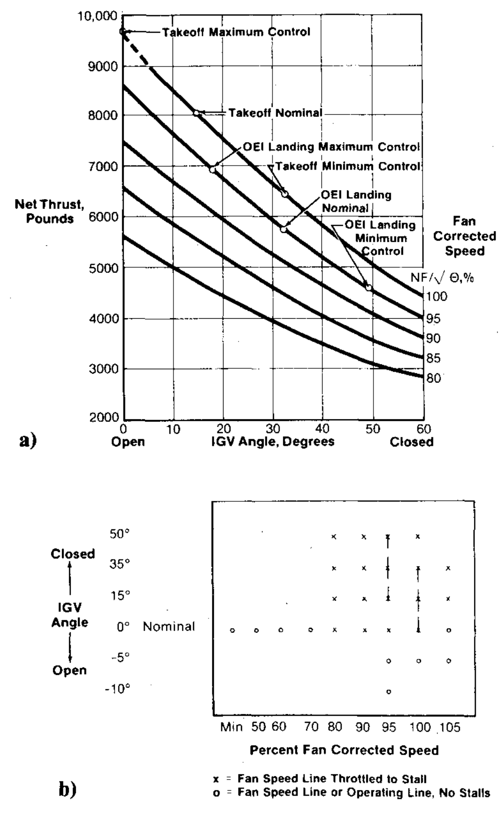


Fig. 14 TF34—PET VIGV test program. a) TF34 part-span, estimated performance. b) TF34 PET test matrix.

Table 1 Effect of TF34 VIGV configuration on core compressor sizing at closed IGV sizing point

Configuration	Nominal IGV	Full-span IGV	Part-span IGV	Part-span IGV with extended splitter
IGV angle	0 deg open	45 deg closed	45 deg closed	45 deg closed
Fan corrected speed	100%	100%	100%	100%
Fan hub pressure ratio (to core inlet)	1.425	1.164	1.295	1.320
Approximate relative core size required	base	+22%	+10%	+8%

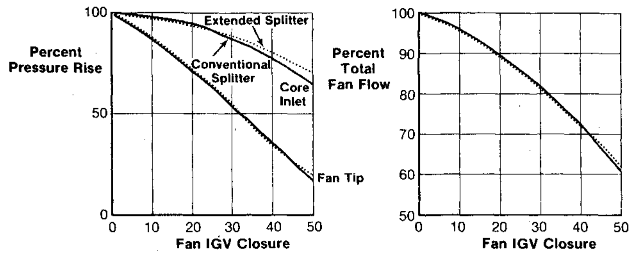


Fig. 15 TF34 partial-span VIGV fan 100% speed.

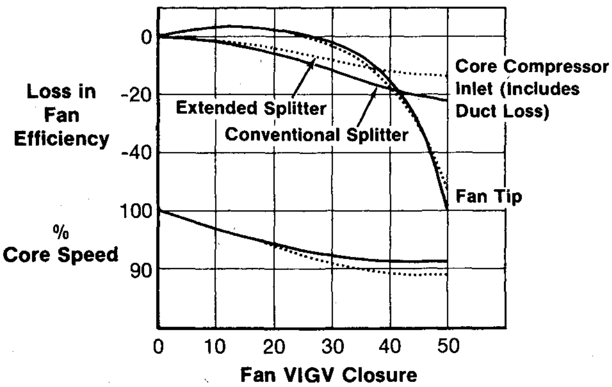


Fig. 16 TF34 part-span VIGV 100% speed.

map performance were defined. This test matrix was repeated with the fan bypass splitter extended forward through the stator up to the rotor trailing edge. Fan inlet distortion testing to stall was also completed at high rotor speeds for the conventional splitter configurations. Test data were taken along fan operating lines and at constant fan speeds for mapping of the fan to stall. Throttling the fan to stall was accomplished by the use of fan backpressure jets in the fan bypass nozzle.

Test Results

The data presented represent the online preliminary test data plotted by General Electric from recorded information. The finalized data tapes and reduced parameters are being processed. The data shown provide a good summary of the test results. Some of the more specific details of fan and core performance will necessarily have to await the completed data reduction by NASA Lewis.

Figure 15 shows data taken along an operating line with VIGV variation at 100% fan speed. These data describe fan airflow and pressure rise modulation as a function of VIGV closure angle. (0 deg is full open.) For this engine, variations of fan airflow represent variations in total thrust in lieu of the processed thrust data. The modulation experienced represented a 40% variation in fan airflow along with a relatively large reduction in fan tip pressure rise. This modulation is more than sufficient to provide the $\pm 20\%$ variation in thrust required for attitude control of the aircraft.

As was predicted, the core supercharging was maintained during VIGV operation. The maintenance of core inlet pressure rise relative to the fan tip is demonstrated at the top of Fig. 15. The relatively smaller drop-off in core pressure rise with VIGV closure demonstrates the advantage of a part-span vs a full-span VIGV system. The addition of the extended splitter further increased the core inlet pressure rise/core supercharging as shown. As expected, fan tip pressure rise and total flow modulation did not differ between splitter configurations.

Figure 16 shows the loss in fan tip efficiency, core inlet efficiency, and core speed as a function of VIGV closure angle. The fan tip efficiency was maintained throughout the normal 20-30 deg range of VIGV modulation. The drop-off in fan efficiency at VIGV closures beyond 35 deg results primarily from increased incidence on the fixed geometry fan stator and IGV turning loss.

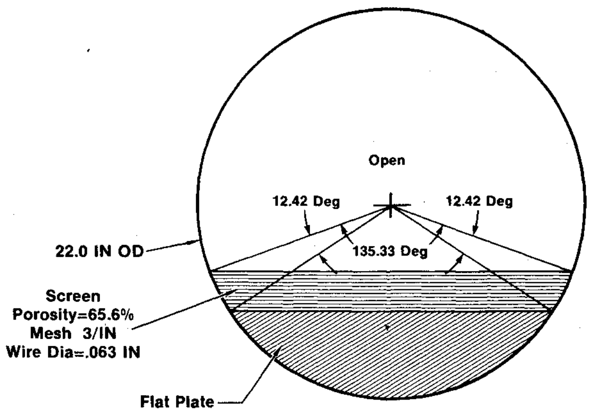


Fig. 17 S3A/TF34 fan crosswind distortion screen.

The large variation in fan tip efficiency beyond 35-deg closure angle is partially attributable to the fact that no extraction of energy from the core was incorporated in the system. Reduced core speed with VIGV closure was observed at constant fan speed as expected in the demonstrator in the absence of low spool power extraction. Power extraction in the demonstrator engine would have resulted in maintaining core speed and flow which, in turn, would have reduced the core inlet duct streamtube diffusion losses upstream of the conventional splitters. In the tests of the extended splitter, a combination of improved hub supercharging and reduced duct efficiency losses occurred which resulted in improved core supercharging. This effect is illustrated by the larger droop of the core speed during VIGV closure in Fig. 16. The core inlet efficiency of both splitter configurations could be further improved by maintaining core speed.

Stall test data were taken with a clean inlet and with a distortion screen. The distortion screen tested is shown in Fig. 17. Adequate stall margin was experienced for the range of VIGV closure angles and speeds tested for both the conventional and extended splitter configurations. At near stall conditions, above the normal operating line, with VIGV closures in excess of 35 deg, the fan stator stresses increased owing to the high flow incidence angles on the fixed (nonvariable) stators of the TF34 (PET) fan demonstrator engine. Optimized or variable fan stators are, therefore, a consideration in a product design.

Distorted flow conditions were significantly improved with the addition of VIGV's to the engine system. An S3A crosswind distortion screen was tested (Fig. 17) and the resultant data compared to earlier data obtained on the production TF34. Preliminary data indicate that the stall margin was improved by approximately 4 points using the VIGV's. The loss due to distortion was less than 2% for the VIGV configuration, compared to more than 6% for the conventional TF34 engine. Distortion transfer from fan to core was not affected by the VIGV's.

Conclusions

The following conclusions represent the final results of the program. During the time between presentation of the paper and final completion of this manuscript the data analysis was completed. All of the results were amplified by the final data.

1) The utilization of part-span VIGV's for flow and thrust modulation on a TF34 engine has been demonstrated and proven.

2) Test data indicate that a 30% airflow reduction and a 45% thrust reduction were achieved at a 40-deg IGV closure.

3) Test data indicate that at a 0-deg IGV closure no effect on the TF34's sfc was observed.

4) The extended splitter data show an improvement in core inlet pressure and fan efficiency (over 95% speed) over that of the conventional splitter.

5) VIGV's reduce stall sensitivity during testing with crosswind distortion screen.

6) Distortion transfer from fan inlet to core is significantly reduced with VIGV closure.

7) The data base for future V/STOL applications has been achieved.

Based on the test data, all objectives of the test program were met. The variable inlet guide vanes proved to be an effective, feasible thrust modulating device. The part-span VIGV's permitted the maintenance of the core supercharging during VIGV variations. No adverse affects of stall line or operating conditions were experienced. The use of part-span variable inlet guide vanes is a viable, functional method of modulating thrust with beneficial effects upon the engine system.