Installation Effects on Performance of Multiple Model V/STOL Lift Fans

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The location and appendages of a lift fan on a V/STOL aircraft are expected to have a measurable effect on fan performance. To study such installation effects, an experimental program was performed in which the individual performance of multiple VTOL model lift fans was measured. The model tested consisted of three 13.97 cm (5.5 in.) diam tip-turbine driven model VTOL lift fans mounted chordwise in a two-dimensional wing to simulate a pod-type array. Several inlet and exit cover door configurations and an adjacent fuselage panel was tested. The results of the tests demonstrated that lift fan installation variables and hardware can have a significant effect on the thrust of the individual fans. Hence, for valid results, fan test models should provide a close scaling or simulation of the complete real installation.

Introduction

THE high-bypass-ratio fan is an appropriate device for providing direct vertical lift for STOL and VTOL transport aircraft.[1] The location of a lift fan on a V/STOL aircraft is expected to have a significant effect on fan performance. Furthermore, such installation variables as inlet and exit cover door design and location, fan proximity to the fuselage, and the proximity of other fans or engines are all likely to affect the thrust of individual fans during takeoff and landing and during the transition to fully-wingborne flight (crossflow case).

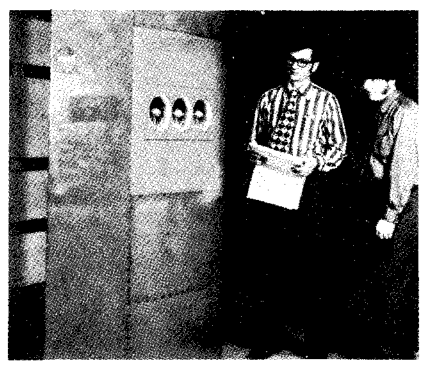
Accordingly, an experimental program was performed in which the individual performance of multiple model lift fans was measured. The model tested consisted of three 13.97 cm (5.5 in.) diam tip-turbine driven model lift fans mounted chordwise in a two-dimensional wing to simulate a pod-type array.

Tests were performed over a range of velocities from 0 to 274 km/hr (0 to 170 mph) at the NASA-Lewis 9- by 15-foot V/STOL Propulsion Tunnel. Individual fan thrust performance was measured under static and crossflow conditions with inlet and exit cover doors of various designs installed on the basic model. Tests were also performed with a large panel simulating an airplane fuselage mounted next to the fans at two lateral positions. Fan performance was measured in terms of exit total and static pressures, speed, and gross thrust for each fan. The three-fan assembly was mounted on a load cell balance within the wing to provide a measurement of fan static thrust. Over-all model lift, drag, and moment coefficients were also determined.

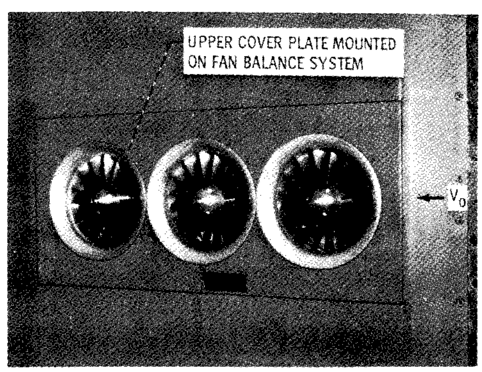
Apparatus and Test Procedure

The multiple-fan model was tested in the NASA Lewis 9- by 15-foot V/STOL Propulsion Tunnel which is fully described in Ref. 2. The tunnel has a test section 2.74 m high by 4.57 m wide and provides for flow velocities from about 80 to 274 km/hr (50 to 170 mph). The test section has longitudinal slots with approximately an 11% open area and is housed in the return leg of the Lewis 8- by 6-foot Transonic Wind Tunnel.

A photograph of the model in the test section is shown in Fig. 1a. A full-span airfoil 2.74 m high with a 1.37 m chord was used as a carrier for the longitudinal array of three fans. Details of the wing system are given in Refs. 3 and 4. Figure 1b shows a close view of the three model lift-fans. The model lift fans used were manufactured by Tech Development: model TD-457 with modified inlets and duct exit extensions. The fans had a rotor tip diameter of 13.97 cm (5.5 in.) and were driven by a tip turbine supplied with high-pressure, ambient-temperature air. The turbine plenum on each fan was divided into two 180° segments. Each segment of the turbine plenum was fed from a separate air supply line.



a) Over-all view of wing and fans in LeRC 9′ × 15′ V/STOL propulsion tunnel.



b) Closeup view of three fans.

Fig. 1 Multiple fan-in-wing apparatus.

Received November 27, 1972; also presented as Paper 72-1175 at the AIAA/SAE 8th Joint Propulsion Specialist Conference, New Orleans, La., November 29–December 1, 1972; revision received March 14, 1973.

Index categories: VTOL Propulsion; VTOL Aircraft Design; VTOL Testing.

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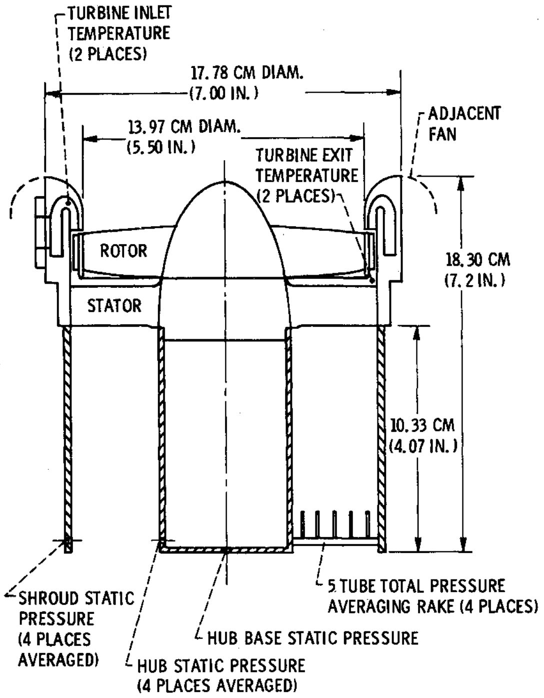


Fig. 2 Section view of model lift fan showing instrumentation types and location.

A cross section of one of the fans is shown in Fig. 2. The three fans were identically instrumented. The fan duct exit was instrumented with four total pressure rakes, each having five probes manifolded together. The probes were located radially at centers of equal areas. Four manifolded static pressure taps in the shroud and four manifolded static pressure taps in the centerbody or hub were located at the duct exit. The static taps were 90° apart located circumferentially between the total pressure rakes. The hub base had a single static pressure tap on the fan centerline. Turbine inlet and exit temperature was measured, each with two thermocouples. The total air flow rate supplied to the tip-turbines was measured by means of a calibrated orifice plate installed in the turbine air supply line. Fan speed was measured with a magnetic pickup installed in the centerbody.

The fans were attached to a plate hinged on one end and supported by two load cells on the other end. This system allowed for a direct measurement of the axial force of the fan array. An upper and a lower cover plate was attached to the model fan assembly and balance plate, thus forming the upper and lower surfaces of the wing adjacent to the fan. The upper cover plate is shown in Fig. 1b. Because of this arrangement, pressure forces acting on the plates were included in the fan balance measurement.

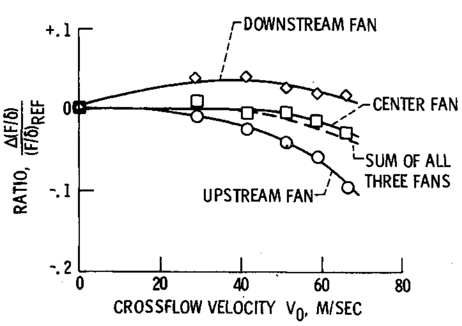


Fig. 3 No inlet or exit doors. Variation in thrust for each fan with crossflow velocity. All three fans running at 100% $N/(\theta)^{1/2}$; $\alpha = 0°$.

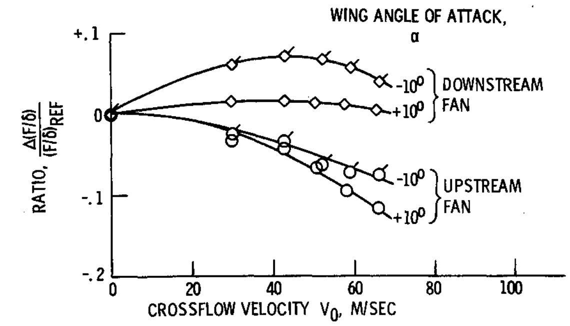


Fig. 4 No inlet or exit doors, range of angle of attack. Variation in thrust for each fan with crossflow velocity. All three fans running at 100% $N/(\theta)^{1/2}$.

The base performance of a similar fan with identical instrumentation was independently made.[5] The base performance included direct fan thrust and weight flow measurements and a conventional fan operating map.

Results and Discussion

The following section presents the principal results from the program. Included are fan interaction effects and effects of cover doors and an adjacent fuselage panel in static and crossflow. In most cases the data are presented in terms of the change in fan corrected thrust (F/δ) that occurs over the range of the test variable compared to the reference condition of zero crossflow (static case) with the clean inlet configuration as follows:

$$\frac{\Delta(F/\delta)}{(F/\delta)_{\mathrm{REF}}} = \frac{(F/\delta) - (F/\delta)_{\mathrm{REF}}}{(F/\delta)_{\mathrm{REF}}}$$

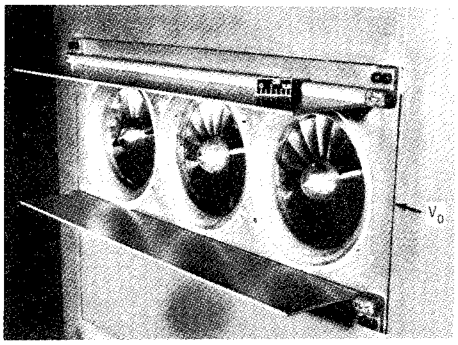
The data are presented in ratio form to facilitate comparison.

Fan thrust was determined as the expansion thrust computed from an effective velocity obtained by allowing the total fan discharge flow to expand to ambient static pressure. Discharge total temperature was determined from an iterative procedure based on measured temperatures and pressures. Appropriate flow and velocity coefficients obtained from calibration tests of a similar fan assembly[5] were included in the computation. Fan thrust was also determined for the static cases from the fan plate load cells.

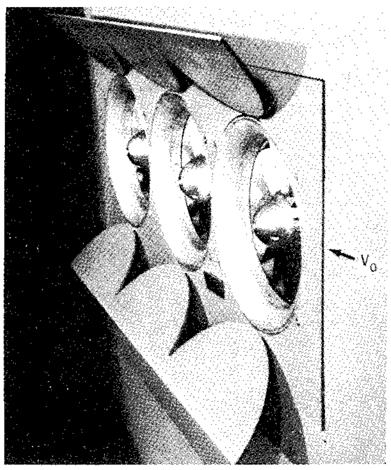
Interaction Effects

The first series of tests performed were the fans in a "clean" configuration as shown in Fig. 1b. Figure 3 presents the results of these tests over the crossflow velocity range at zero wing angle of attack with all three fans operating at constant design corrected rotational speed $N/(\theta)^{1/2}$. As indicated in the figure, the thrust of the upstream fan decreased significantly more than the two downstream fans, while the thrust of the downstream fan increased slightly over the entire range of crossflow velocities tested. The upstream fan had the greatest thrust loss because the entering air is forced to turn more abruptly than in the case of the two downstream fans. There was less inlet flow distortion and an increase in fan weight flow for the successive fan locations in the downstream direction. This increase was due to a partial recovery of the momentum of the inlet air stream.

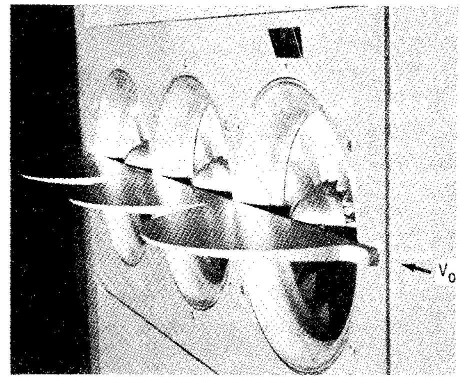
Figure 3 also shows the variation of the algebraic sum of the thrust for all three fans. The level decreased only about 4% over the test range of crossflow velocity. Most likely, this reduction would represent no problem to the



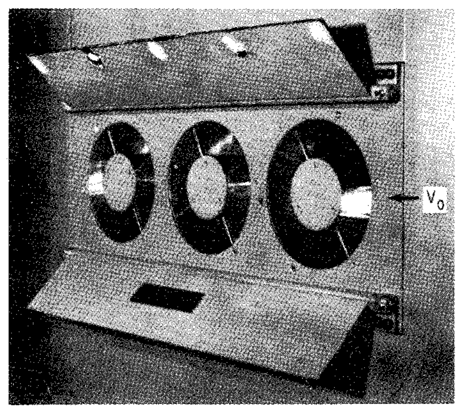
a) Rectangular side doors, 90° open position.



b) Side mount butterfly dors, 135° open position.



c) Center mount butterfly doors.



d) Exit rectangular doors, 135° open position.

Fig. 5 General types of cover door configurations.

aircraft in terms of total thrust loss. However, the difference in thrust between the upstream and downstream fans is about 5% at 30 m/sec crossflow velocity and increases to about 12% at 67 m/sec. Differences such as these can cause pitching moments which will require a counteracting control moment to keep the aircraft in level flight.

Changing wing angle of attack resulted in a relative increase in thrust level for each fan at negative angles of attack, and a relative decrease in thrust at positive angles of attack, as shown in Fig. 4. This effect was observed previously in single fan-in-wing tests.[4] The figure indicates that angle of attack affected the thrust of both the upstream fan and the downstream fan over the complete range of crossflow velocities tested. The effect of changes in angle of attack for the center fan was similar to the trends shown for the downstream fan.

Cover Door Effects

The next series of tests investigated the effect on static and crossflow thrust variations of various inlet and exit cover door configurations. The general types of cover doors tested are shown in Fig. 5a–d. The inlet configurations included: rectangular side doors (Fig. 5a); side mounted butterfly doors (Fig. 5b); and center mounted butterfly door (Fig. 5c). The exit door was the side mounted rectangular configuration (Fig. 5d). The inlet doors were sized to cover the bellmouth of each fan. For the inlet rectangular and side-mount butterfly doors, door open angle positions of 90° and 135° were tested. For the center-mount butterfly door, a single fixed position of 90° open was tested.

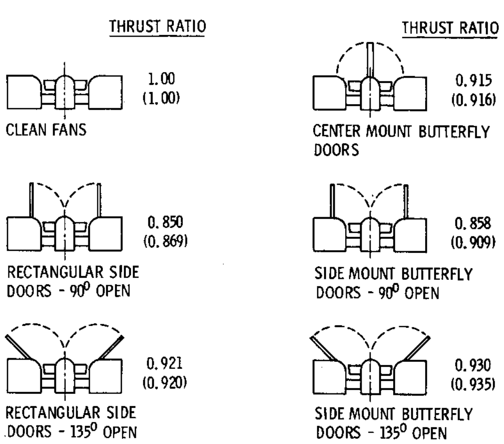


Fig. 6 Static thrust ratio for the various inlet doors tested. Upper value obtained from calculated expansion thrust, lower value from load cell measurements.

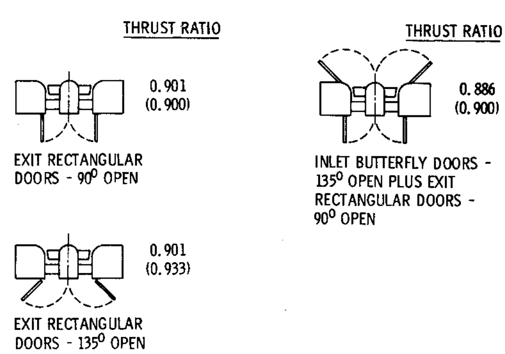


Fig. 7 Static thrust ratio for the various exit door configurations tested. Upper value obtained from calculated expansion thrust, lower value from load cell measurements.

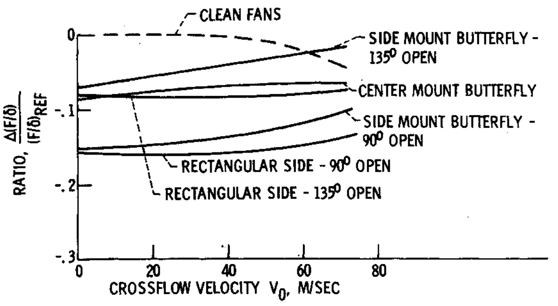


Fig. 8 Variation in thrust with crossflow velocity for various inlet door configurations. All three fans running at 100% $N/(\theta)^{1/2}$; $\alpha = 0°$.

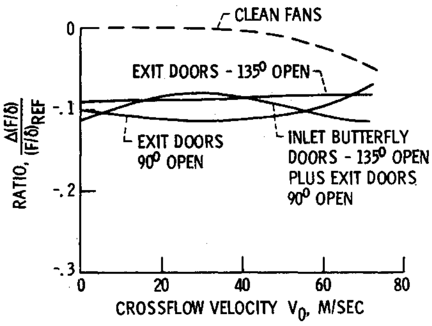


Fig. 9 Variation in thrust with crossflow velocity for various rectangular exit door configurations. All three fans running at 100% $N/(\theta)^{1/2}$; $\alpha = 0°$.

The exit rectangular doors were tested in the 90° and 135° open positions as shown. A combination of the side mount butterfly doors at both 90° and 135° open and the exit rectangular doors at 90° open was also tested. The side inlet doors were attached to the model at the edge of the inlet bellmouths of the fans. The exit doors were attached about 1.27 cm (0.5 in.) from the edge of the fan duct.

Static Tests

The results of the static (no crossflow) tests for the various door configurations tested are given in Figs. 6 and 7.

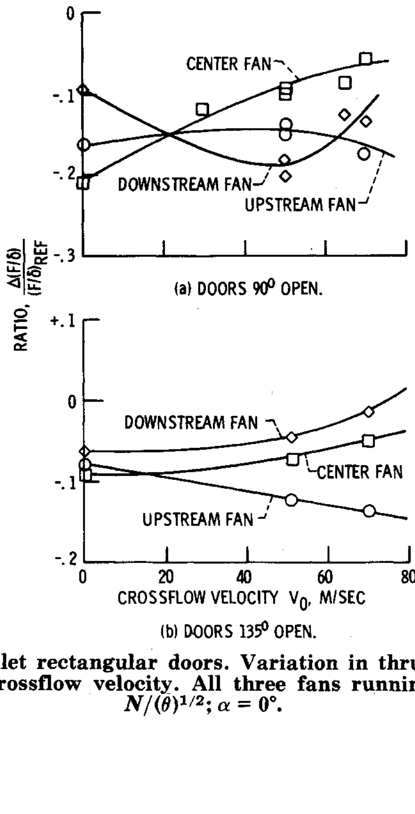


Fig. 10 Inlet rectangular doors. Variation in thrust of each fan with crossflow velocity. All three fans running at 100% $N/(\theta)^{1/2}$; $\alpha = 0°$.

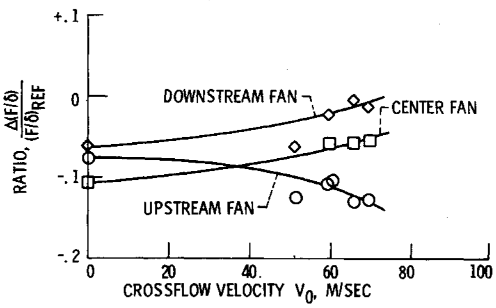


Fig. 11 Centermount butterfly doors. Variation in thrust of each fan with crossflow velocity. All three fans running at 100% $N/(\theta)^{1/2}$; $\alpha = 0°$.

For these tests all three fans were operating at design speed. The thrust ratio, defined as the fan thrust with the door attached divided by the fan thrust with no inlet or exit cover doors (clean inlet), is listed for each inlet door configuration. Two values are given for each case: the upper value was obtained from the calculated expansion thrust; the lower value in parentheses was obtained from the load cell force measurement.

The results of Figs. 6 and 7 show that, for the configurations tested, thrust loss varied from around 7–15%. For both inlet and exit cover doors, static thrust losses can be reduced if the door opening angle can be made as wide as possible. There appears to be some advantage at high opening angles in using an inlet side door with flow openings (side-mounted butterfly door) compared to a solid rectangular door. Also, the thrust loss of the center-mount butterfly door case may be directly attributable to the blocked flow area in the inlet caused by the thickness of the door. For the particular configuration tested, the door thickness created an 8% blockage of the fan inlet flow area and the thrust loss was approximately 8%.

Crossflow Tests: Total Thrust

Figures 8 and 9 show the ratio of the fractional change in thrust for the sum of all three fans to a reference thrust value plotted against crossflow velocity. The reference thrust value chosen was the sum of the thrust of all three fans in the clean configuration (no inlet or exit doors) at zero crossflow velocity. Individual data points are omitted from these figures for clarity. The data are for wing angle of attack $\alpha = 0°$ and for each fan operating at 100% corrected design speed.

The test results showed that total fan thrust increased with increasing crossflow velocity by 1–5% in every case but one (the inlet butterfly door, 135° open plus exit rectangular, 90° open). However, in general, the thrust increase was not sufficient to overcome the loss in thrust caused by the presence of the doors. The side-mounted

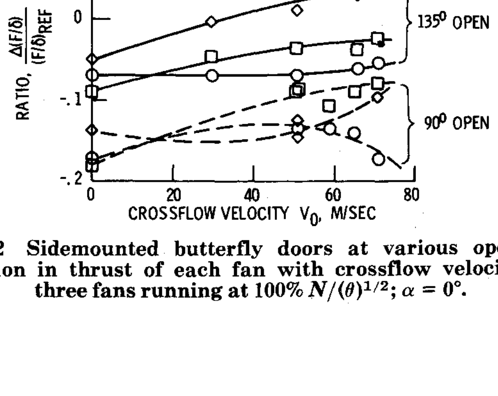


Fig. 12 Sidemounted butterfly doors at various openings. Variation in thrust of each fan with crossflow velocity. All three fans running at 100% $N/(\theta)^{1/2}$; $\alpha = 0°$.

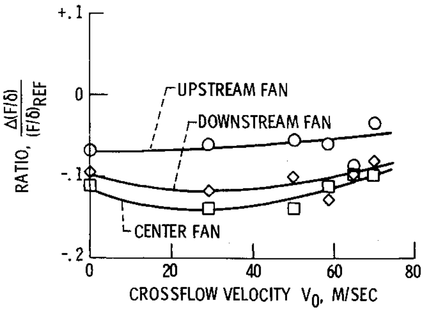


Fig. 13 Exit rectangular doors 90° open. Variation in thrust of each fan with crossflow velocity. All three fans running at 100° $N/(\theta)^{1/2}$; $\alpha = 0°$.

butterfly doors–135° open was the only configuration that performed slightly better than the clean fan configuration at velocities above 60 m/sec. Thrust trends for varying angle of attack were about the same as for the clean fan case.

Crossflow Tests: Individual Fan Thrust

The discussion up to now has been primarily concerned with the sum or total performance of all three fans together under various operating conditions. In the discussion that follows, the individual performance of each fan under the same operating conditions will be investigated. Figures 10–12 show the individual fan performance for three inlet door configurations. As shown in the figures, as the crossflow velocity increased the upstream fan in most cases lost thrust while the center fan and the downstream fan generally gained thrust as in the case of the clean inlet fans (Fig. 3). The maximum difference in thrust level between the upstream and downstream fans at V_0 = 70 m/sec ranged from around 5–12%, depending on the configuration.

Results with the rectangular exit doors attached are shown in Fig. 13. Here the results differed significantly from the inlet door cases, because the thrust level of the upstream fan increased with increasing crossflow velocity and was at a higher level than both of the other two fans. For this configuration there was a maximum difference in thrust level of only 5% between upstream and downstream fans.

Figure 14 shows the results of tests with both inlet and exit doors installed. Apparently, the exit doors had the predominant effect because the thrust variations with crossflow velocity were reversed compared to the inlet doors only case. The maximum observed difference in thrust level for the inlet and exit door installation was about 8%.

The over-all effects of variations in individual fan thrust in crossflow on control thrust requirements in an actual aircraft may be more pronounced than indicated in this model test. The test model had a ratio of wing planform area to total fan flow area far in excess of that for a real aircraft configuration. This size imbalance tended to minimize the over-all effects of individual fan thrust variations.

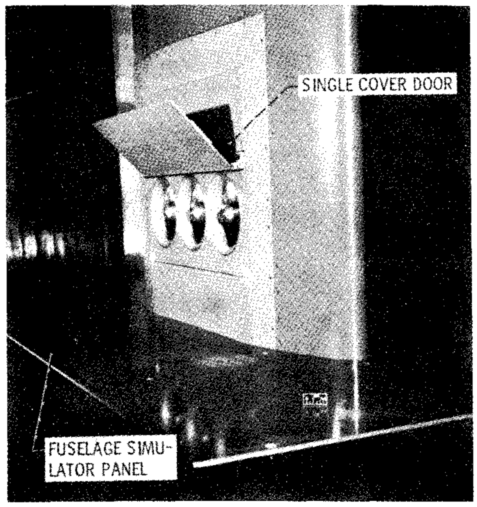


Fig. 15 Installation of fuselage simulator panel on multiple lift fan model.

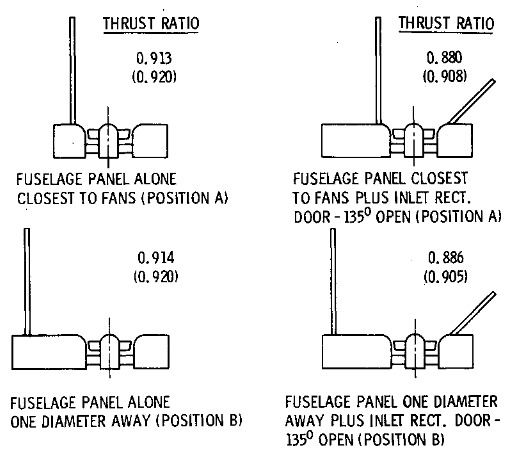


Fig. 16 Static thrust ratio for the various fuselage panel configurations. Upper value obtained from calculated expansion thrust; lower value obtained from load cell force measurement.

Effect of Proximity to Fuselage

In some V/STOL aircraft configurations, the lift fans might be installed in the wings or in pods adjacent to the fuselage. To obtain a measure of the effect of an adjacent fuselage on fan performance, a large panel was installed in

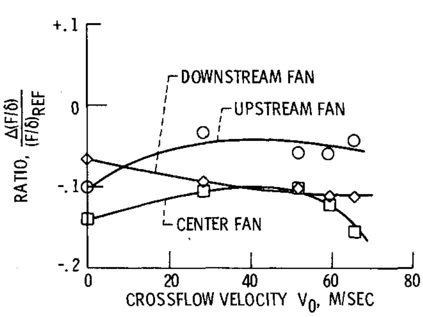


Fig. 14 Inlet butterfly doors 135° open; exit rectangular doors 90° open. Variation in thrust of each fan with crossflow velocity. All three fans running at 100% $N/(\theta)^{1/2}$; $\alpha = 0°$.

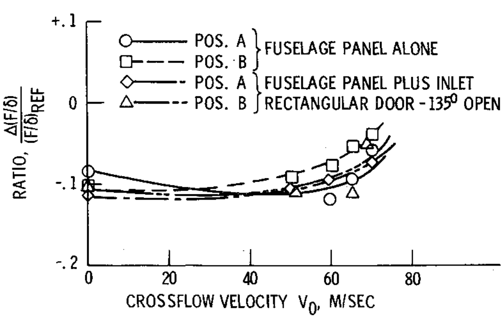


Fig. 17 Variation in thrust with crossflow velocity for various fuselage panel configurations. All three fans running at 100% $N/(\theta)^{1/2}$; $\alpha = 0°$.

close proximity to the fans. The fuselage simulator panel extended well out in front of and behind the fans, as well as slightly below the lower surface of the wing, as shown in Fig. 15. The height of the panel was about three fan bellmouth diameters above the upper surface of the wing carrier. Static tests were run with and without an inlet cover door. The cover door, shown attached in Fig. 15, was a single rectangular panel one fan bellmouth diameter in height at an opening angle of 135° from the horizontal.

Data from static tests are presented in Fig. 16. The effect of proximity of the fuselage simulator panel to the fan on static thrust was significant. The thrust loss was around 8% when the fuselage simulator panel was closest to the fan (position A), and around 12% when the rectangular inlet cover door was added. Lateral movement of the fuselage simulator panel to position B for both configurations had little effect on the static thrust ratio.

The thrust variations in crossflow for the four panel configurations tested is shown in Fig. 17 as referenced to the clean fans case. A slight increase in thrust at high crossflow velocity was observed in all cases.

Conclusions

The performance data presented herein have provided a significant insight into possible thrust losses and thrust distributions in a multiple lift fan array caused by the presence of adjacent fans, inlet and exit cover doors, and adjacent fuselage panels. The measured thrust variations due to these installation effects were of a sufficient magnitude to warrant consideration in the determination of installed thrust for takeoff and for individual fan thrust control during transition. The experiments also indicated that for valid results, lift fan test models should provide a close scaling or simulation of the complete real installation.

References

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