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INSTALLATION EFFECTS ON PERFORMANCE OF MULTIPLE MODEL V/STOL LIFT FANS

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Abstract

The location and appendages of a lift fan on a V/STOL aircraft are expected to have a measurable effect on fan performance. 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 (static case) and during the transition to fully-wingborne flight (crossflow case).

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.) diameter tip-turbine driven model VTOL lift fans mounted chordwise in a two-dimensional wing to simulate a pod-type array.

The performance data provided significant insight into possible thrust variations and losses caused by the presence of cover doors, adjacent fuselage panels, and adjacent fans. The effect of a partial loss of drive air supply (simulated gas generator failure) on fan performance was also investigated. 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

High-bypass-ratio fans are currently considered as an appropriate device for providing direct vertical lift for STOL and VTOL transport aircraft (e.g., ref 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).

To study such installation effects, 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.) diameter tip-turbine driven model lift fans mounted chordwise in a two-dimensional wing to simulate a pod-type array. The installation of the three fans was conducted as an expedient follow-on experiment to a previous investigation of a 15-in. diameter lift fan installed in the same wing (refs. 2 and 3).

Tests were performed over a range of velocities from 0 to 274 km/hr (o 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. Further data were obtained for a simulated gas generator failure to a single fan (partial loss in turbine drive air supply). Fan performance was measured in terms of exit total and static pressures, speed, and gross thrust for each fan. Overall 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. 4. 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 percent 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. 1(a). 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. Figure 1(b) 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 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

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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. 1(b). Because of this arrangement, pressure forces acting on the plates were included in the fan balance measurement.

The base performance of a similar fan with identical instrumentation was independently made (ref. 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. The various topics are: fan interaction effects, partial admission tests, and static and crossflow cover door effects. 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:

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

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 (ref 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. 1(b). No inlet or exit cover doors were installed. 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 $N/\sqrt{\theta}$. The data are presented in ratio form to facilitate comparison between the fans.

As indicated in Fig. 3, 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. The increase in thrust with crossflow velocity exhibited by the downstream fan is due to a partial recovery of the momentum of the inlet air stream.

The curve also shows the variation of the algebraic sum of the thrust for all three fans. The level decreased only about 4 percent over the test range of crossflow velocity. Most likely, this reduction would represent no problem to the aircraft in terms of total thrust loss. However, the difference in thrust between the upstream and downstream fans is about 5 percent at 30 m/sec crossflow velocity and increases to about 12 percent at 67 m/sec. Differences such as these cause adverse 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 (ref. 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.

Simulated Gas Generator Failure

As mentioned previously, the turbine plenums on each fan were divided into two 180° segments. The two segments were connected to separate air supply lines. A failure of a gas generator for a remote lift fan system (e.g., ref. 1) could then be simulated by shutting off the air supply to one of the turbine plenum segments.

Typical data from this series of tests are presented in Fig. 5 in which the ratio of thrust at partial admission to thrust at full admission is plotted as a function of crossflow velocity. Data are presented for 100 percent and 70 percent fan design speed. Two test conditions are represented in the figure: (1) forward and aft fans operating normally at a given speed and the center fan receiving half of its required drive air (partial admission)(fig. 5(a)); and (2) center fan operating alone at partial admission (fig. 5(b)). Figure 5 shows that approximately 55 to 60 percent of the fan thrust was retained if the fan was originally operating at 100 percent or 70 percent corrected design apeed at the time of supply power failure for both configurations. There was a slight increase in the ratio over the range of crossflow velocity tested for both speeds and configurations. The value of the ratio computed from load cell measurements for the center fan operating alone under static conditions agreed well with the calculated data.

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 Figs. 6(a) through 6(d) The inlet configurations included: rectangular side doors (fig. 6(a)); side mounted butterfly doors (fig. 6(b)); and center mounted butterfly door (fig. 6(c)). The exit door was the side mounted rectangular configuration (fig. 6(d)). 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. 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. 7 and 8. 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. 7 and 8 show that static thrust losses introduced by the use of inlet and exit cover doors can be significant. For the configurations tested, thrust loss varied from around 7 percent to 15 percent. 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 percent blockage of the fan inlet flow area and the thrust loss was approximately 8 percent.

Crossflow tests: total thrust. - The results of the crossflow tests for the various inlet and exit cover door configurations tested are given in Figs. 9 and 10. In the figures, the ratio of the fractional change in thrust for the sum of all three fans to a reference thrust value is 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 and only the faired curves shown. The data are for wing angle of attack $\alpha = 0^\circ$ and for each fan operating at 100 percent corrected design speed. The test results showed that total fan thrust increased with increasing crossflow velocity by 1 to 5 percent 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 butterfly doors - 135° open was the only configuration that performed slightly better than the clean fan configuration at velocities above 60 m/sec.

Other data, not shown, indicated the effect of wing angle of attack on the thrust trends for the cases with doors attached was about the same as for the clean fans (i.e., positive angle of attack caused a reduction in thrust, whereas negative angle of attack caused an increase in thrust compared to the zero angle of attack case).

The effect of the doors on the overall pitching moment as measured by the wing load cells is shown in Fig. 11. Plotted on the figure is a dimensionless ratio of the change in moment measured about the wing 0.25 chord position $(\Delta M)_{0.25\,C}$ against crossflow velocity for several inlet and exit door configurations. The ratio is formed by the change in wing moment using the moment caused by the clean fans in static operation as a reference value. It is nondimensionalized by the product of the wing chord c and the corrected static thrust F/δ of all three fans running at 100 percent corrected rotational speed $N/\sqrt{\theta}$. As can be seen, the doors create some changes in pitching moment compared to the clean fans case. In all cases, a tendency toward an overall positive "nose-up" pitching moment is introduced by fan operation in crossflow, despite the fact that a relative "nose-down" pitching moment is produced by the relative thrust variations of the upstream and downstream fans (fig. 3). The overall positive moment occurs because of the predominant effect of the induced lift on the wing created by the interactions between the fan throughflow and the free-stream flow.

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 12, 13, and 14 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 percent to 12 percent, depending on the configuration. These differences in thrust between upstream and downstream fans generated the force changes that resulted in the variations in pitching moment shown in Fig. 11.

Results with the rectangular exit doors attached are shown in Fig. 15. 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 percent between upstream and downstream fans.

Figure 16 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 percent.

The overall 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 overall effects of individual fan thrust variations.

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 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. 17. 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. 17, 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. 18. The effect of proximity of the fuselage simulator panel to the fan on static thrust was significant. The thrust loss was around 8 percent when the fuselage simulator panel was closest to the fan (position A), and around 12 percent 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. 19 as referenced to the clean fans case. A slight increase in thrust with crossflow velocity was observed in all cases.

Concluding Remarks

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.

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3. Yuska, J. A., and Diedrich, J. H., "Fan and Wing Force Data from Wind-Tunnel Investigation of a 0.38 Meter (15-in.) Diameter VTOL Model Lift Fan Installed in a Two-Dimensional Wing," TN D-6654, 1972, NASA, Cleveland, Ohio.

4. Yuska, J. A., Diedrich, J. H., and Clough, N., "Lewis 9'x15' V/STOL Wind Tunnel," TM X-2305, NASA, Cleveland, Ohio.

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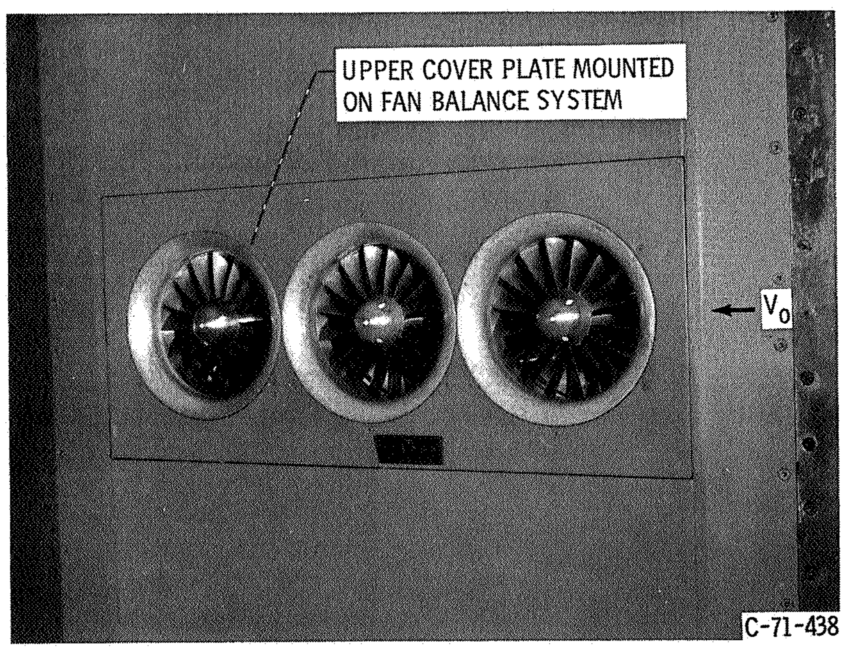
(a) Overall view of wing and fans in LeRC 9'x15' V/STOL propulsion tunnel.



(b) Closeup view of 3 fans.

Figure 1. - Multiple fan-in-wing apparatus.

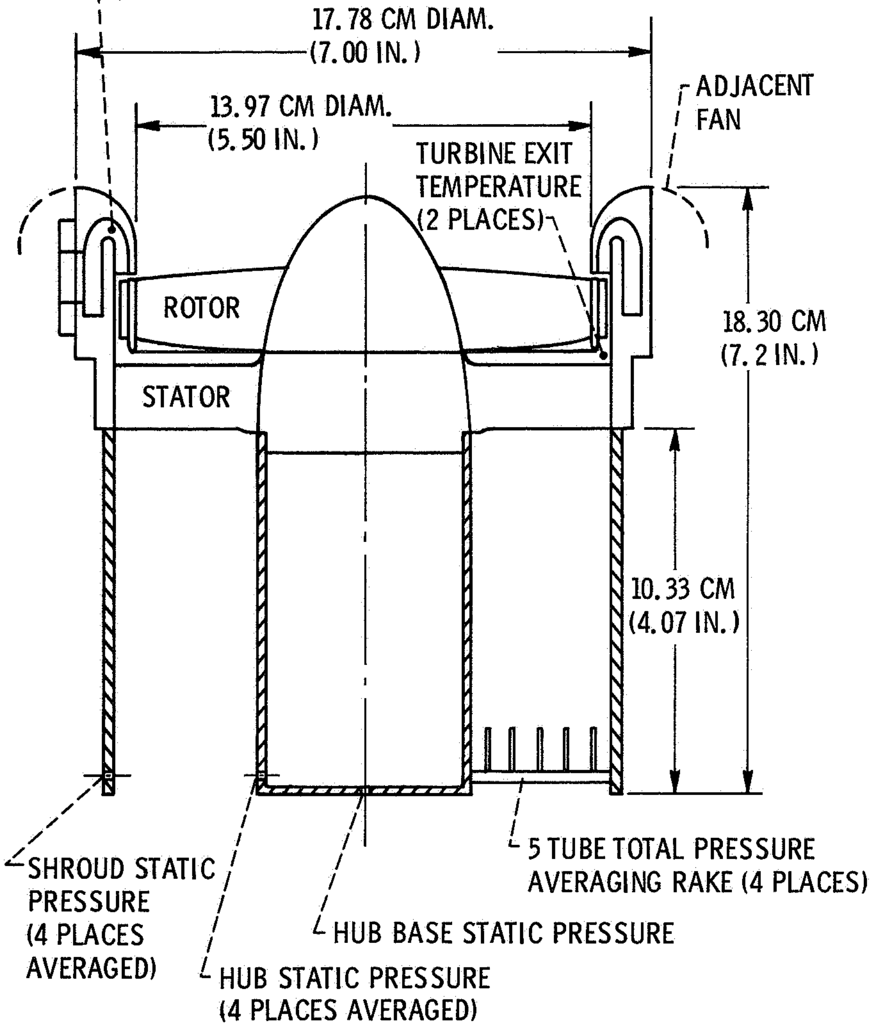


Figure 2. - Section view of model lift fan showing instrumentation types and location.

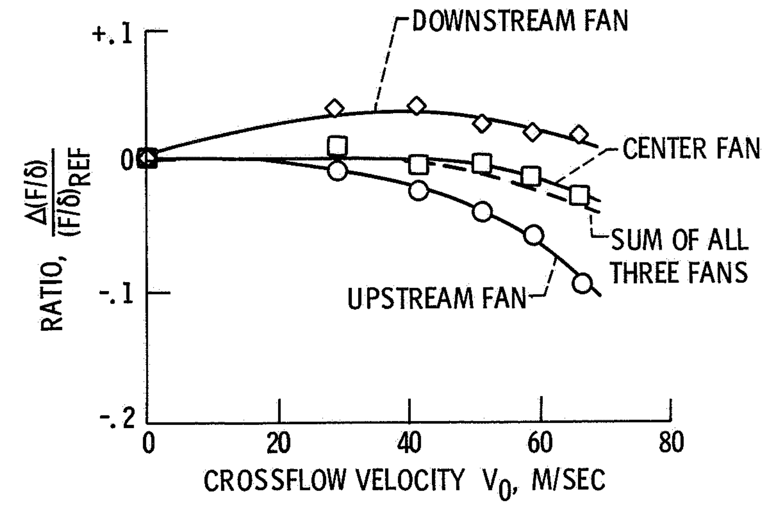


Figure 3. - No inlet or exit doors. Variation in thrust for each fan with crossflow velocity. All three fans running at 100 percent $N/\sqrt{\theta}$; $\alpha = 0^0$.

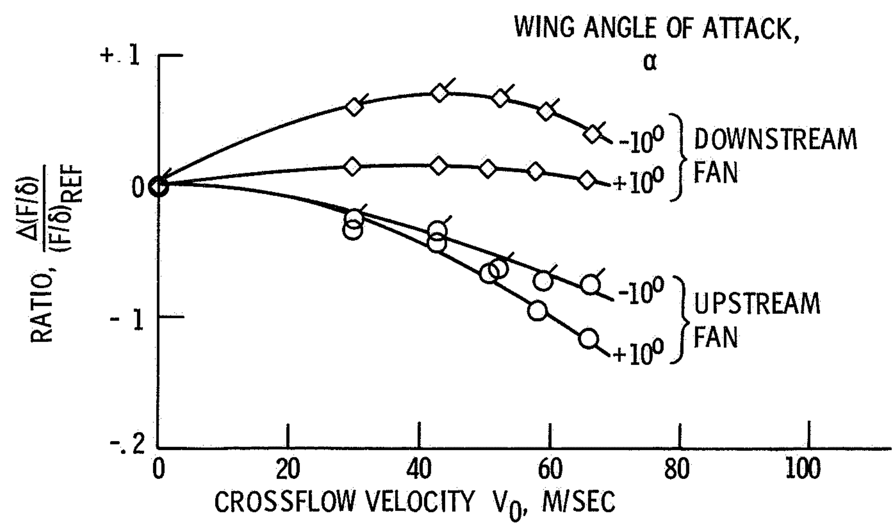


Figure 4. - No inlet or exit doors, range of angle of attack. Variation in thrust for each fan with crossflow velocity. All three fans running at 100 percent $N/\sqrt{\theta}$.

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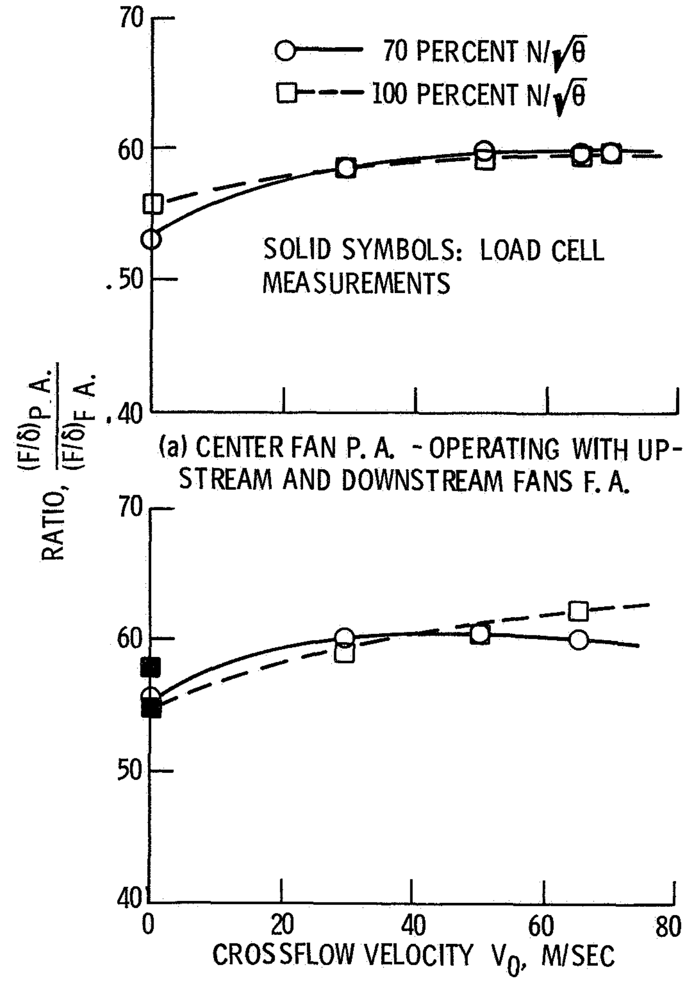
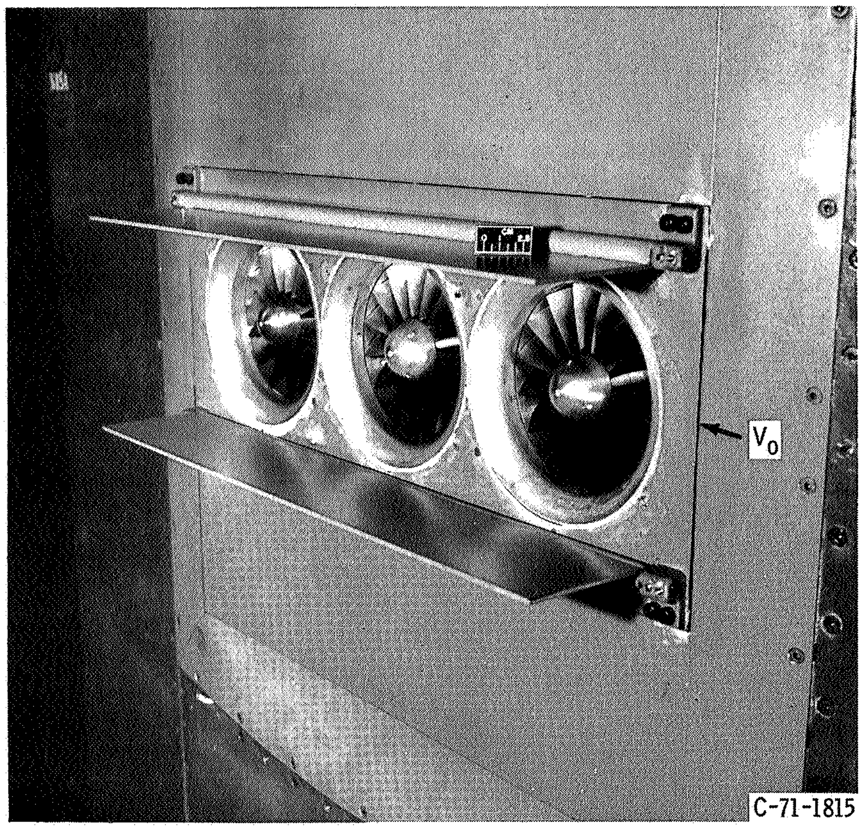
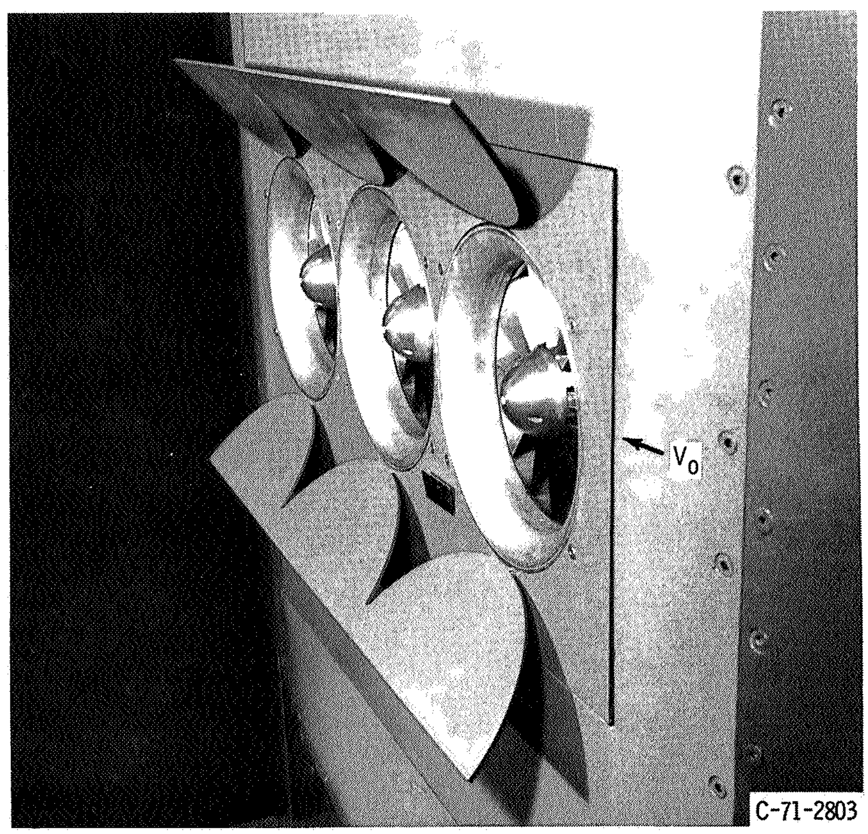


(b) CENTER FAN P. A. - OPERATING ALONE.

Figure 5. - Ratio of thrust with partial admission to thrust with full admission in crossflow for 180^{0} partial admission in center fan. No inlet or exit doors; $\alpha = 0^{0}$.



(a) Rectangular side doors, 90° open position.



(b) Side mount butterfly doors, 135° open position.

Figure 6. - General types of cover door configurations.

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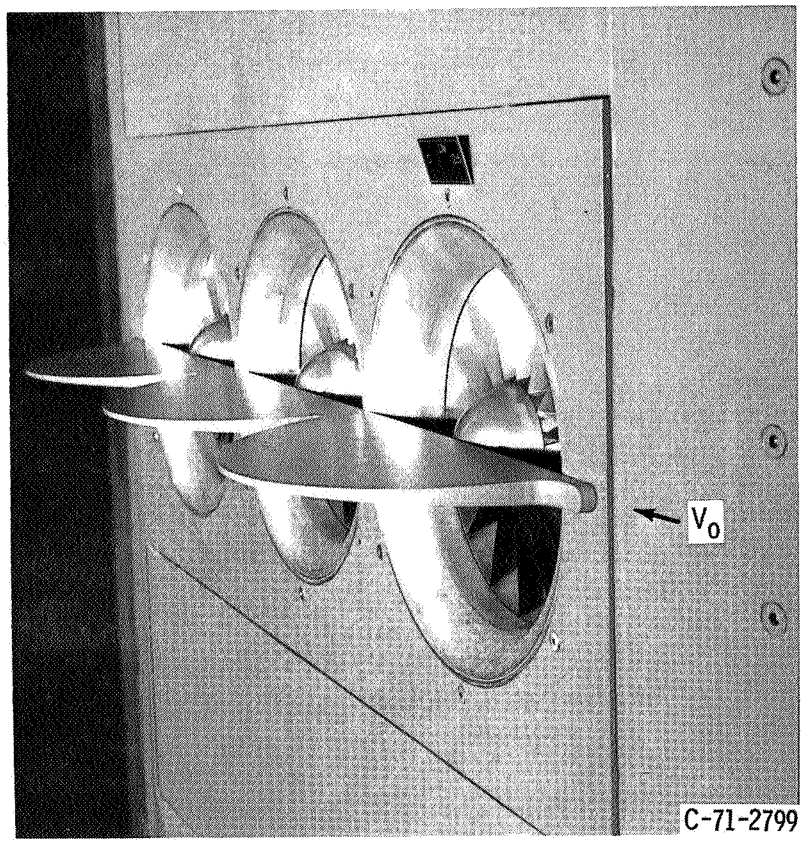
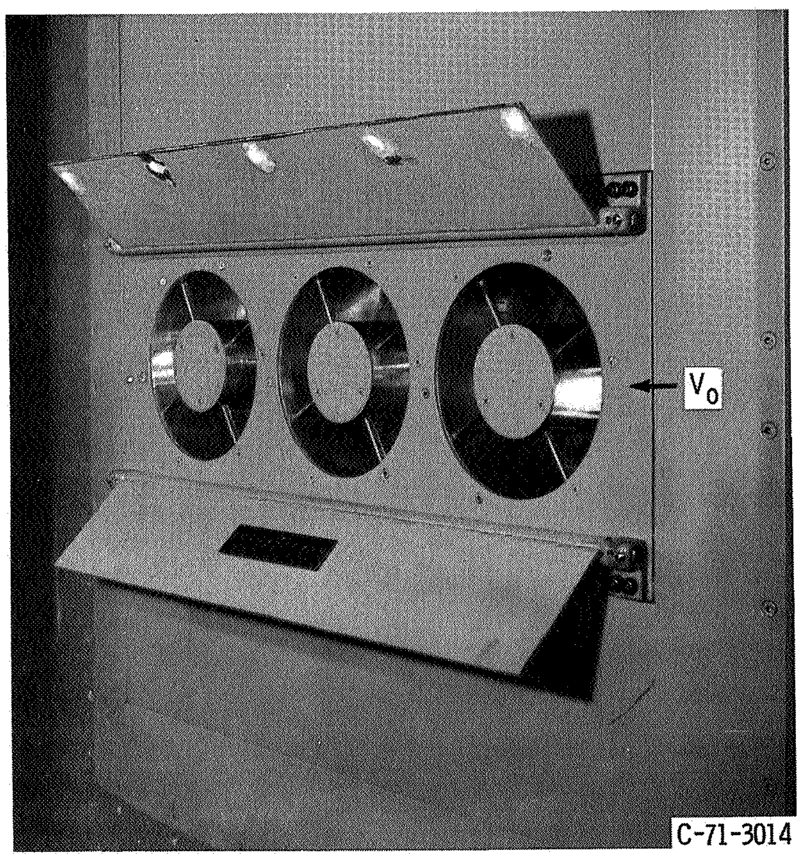


(c) Center mount butterfly doors.



(d) Exit rectangular doors, 135^0 open position.

Figure 6. - Concluded.

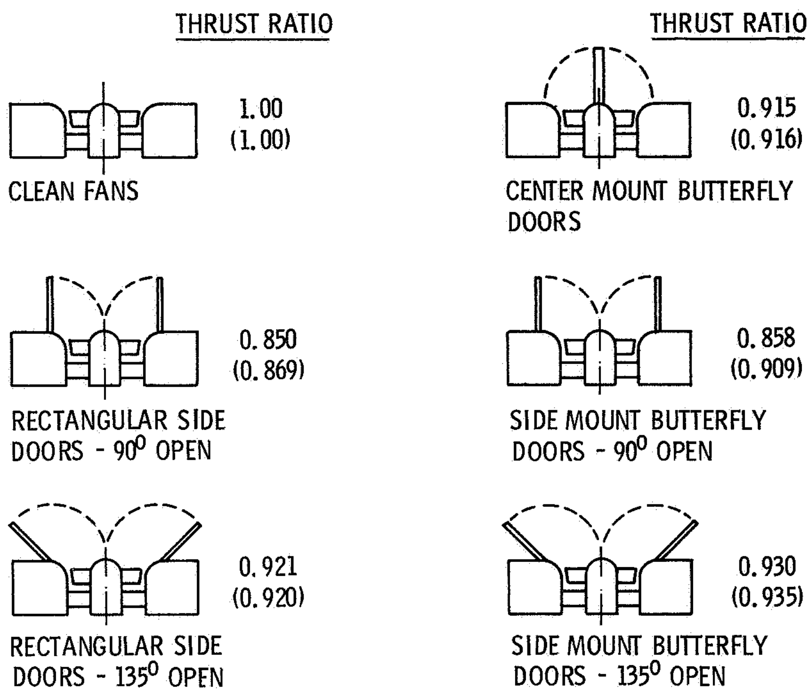


Figure 7 - Static thrust ratio for the various inlet doors tested. Upper value obtained from calculated expansion thrust, lower value from load cell measurements.

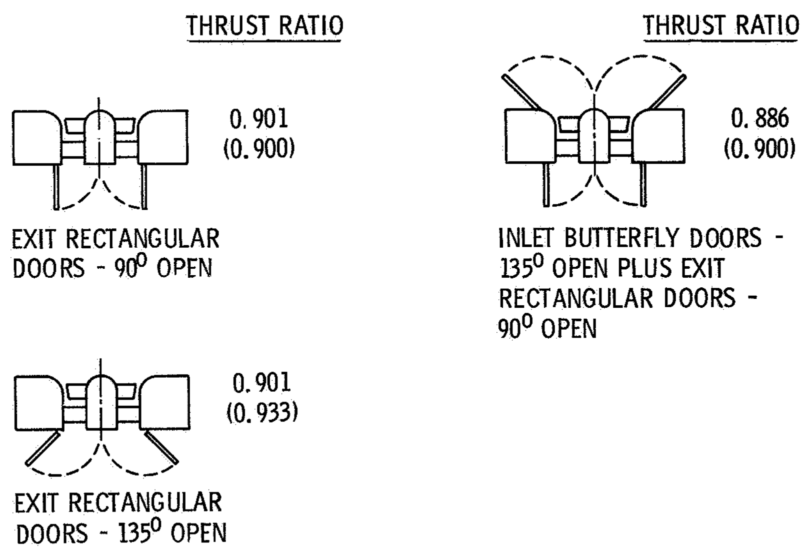


Figure 8. - Static thrust ratio for the various exit door configurations tested. Upper value obtained from calculated expansion thrust, lower value from load cell measurements.

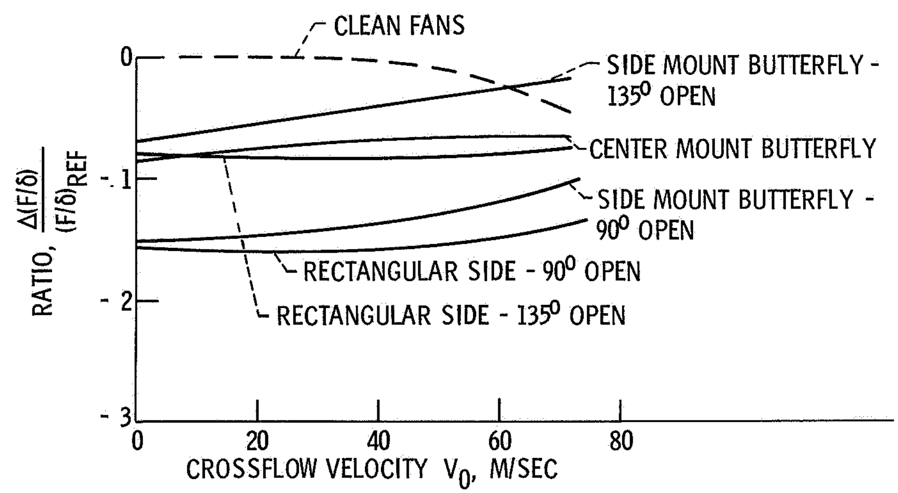


Figure 9. - Variation in thrust with crossflow velocity for various inlet door configurations. All three fans running at 100 percent $N/\sqrt{\theta}$; $\alpha = 0^0$

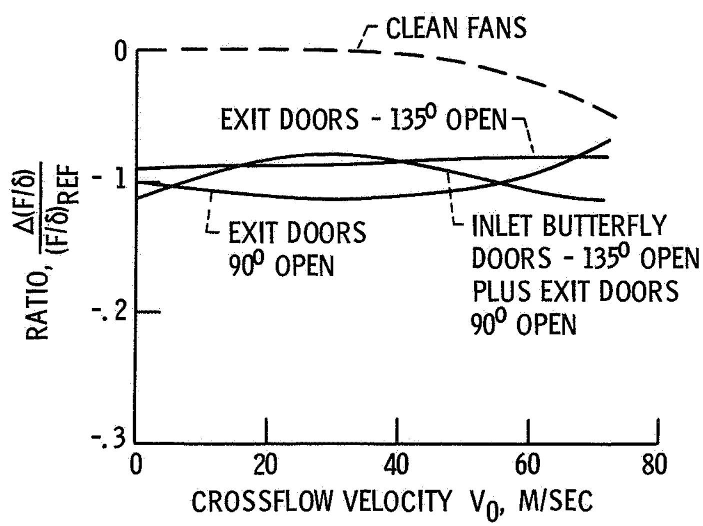


Figure 10. - Variation in thrust with crossflow velocity for various rectangular exit door configurations. All three fans running at 100 percent $N/\sqrt{\theta}$; $\alpha = 0^0$.

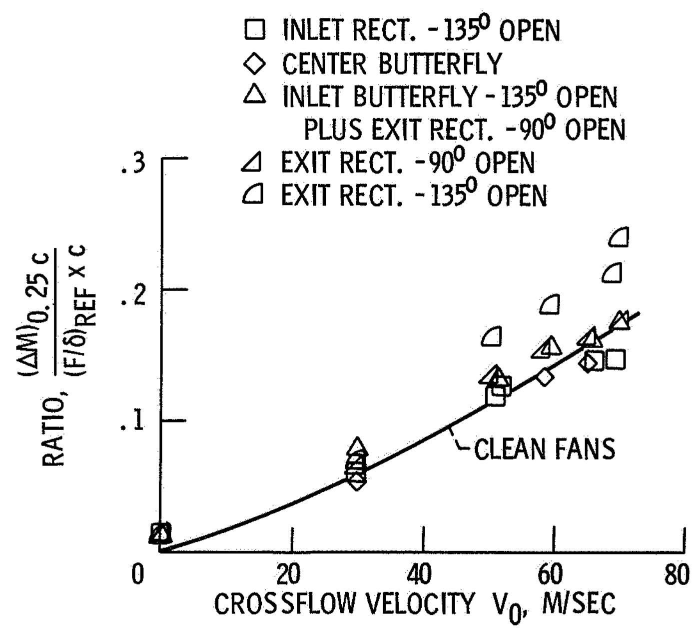


Figure 11. - Variation of moment with crossflow velocity for several door configurations. All three fans running at 100 percent $N/\sqrt{\theta}$; $\alpha = 0^0$.

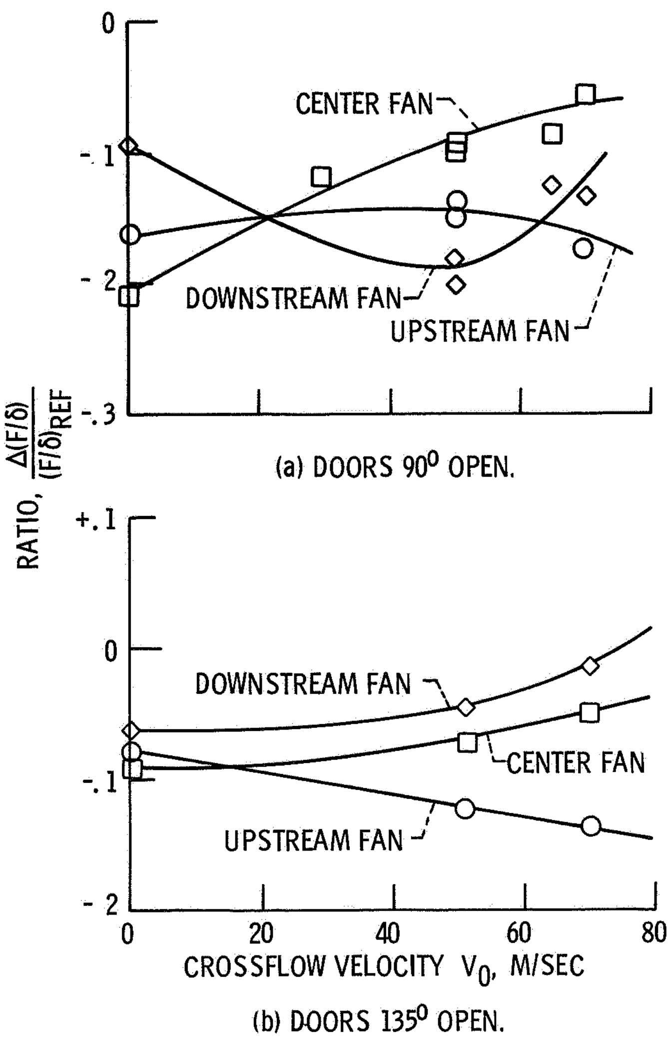


Figure 12. - Inlet rectangular doors. Variation in thrust of each fan with crossflow velocity. All three fans running at 100 percent $N/\sqrt{\theta}$; $\alpha = 0^0$

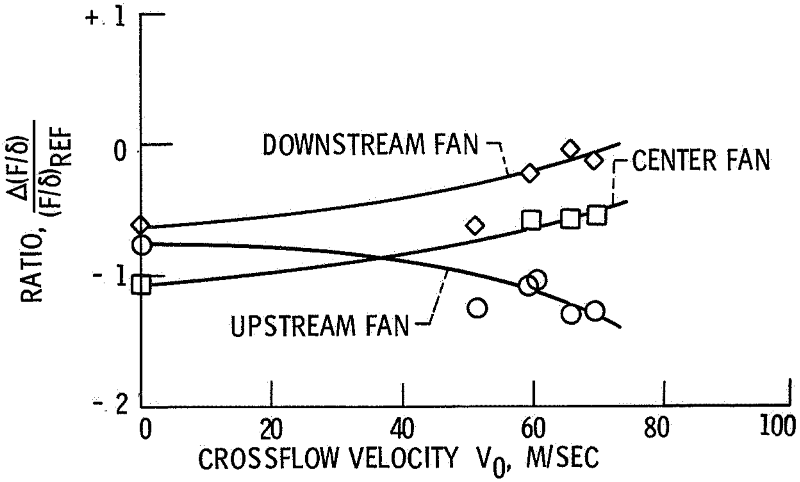


Figure 13. - Center-mount butterfly doors. Variation in thrust of each fan with crossflow velocity. All three fans running at 100 percent $N/\sqrt{\theta}$; $\alpha = 0^0$

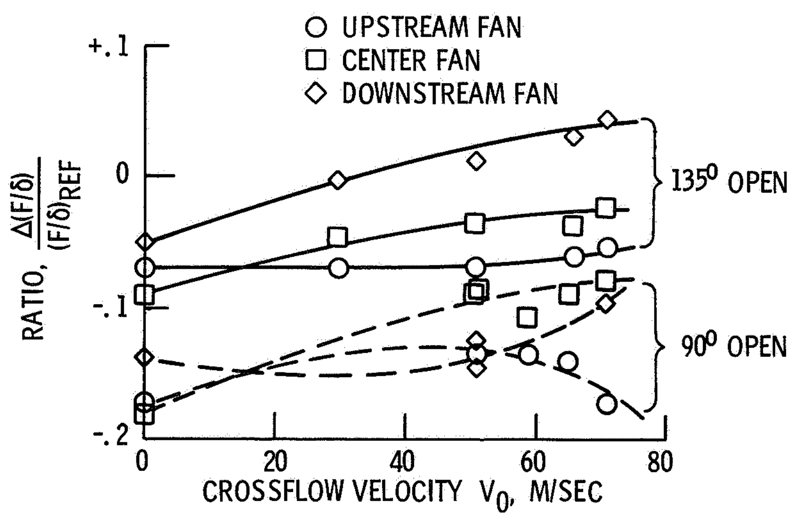


Figure 14. - Side-mounted butterfly doors at various openings. Variation in thrust of each fan with crossflow velocity. All three fans running at 100 percent $N/\sqrt{\theta}$; $\alpha = 0^0$.

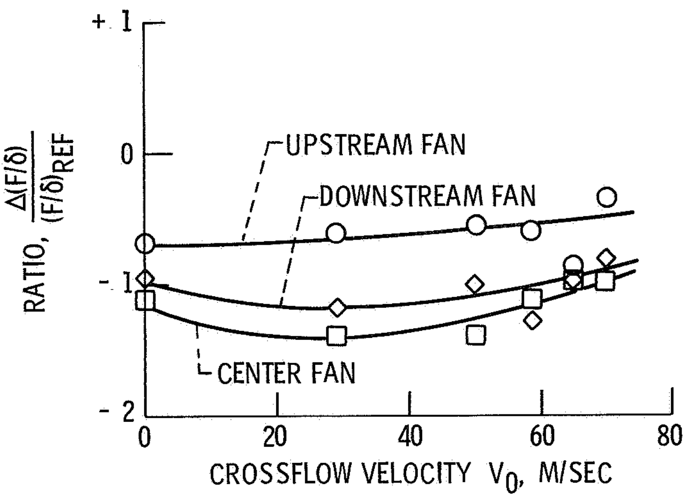


Figure 15. - Exit rectangular doors - 90° open. Variation in thrust of each fan with crossflow velocity. All three fans running at 100 percent $N/\sqrt{\theta}$; $\alpha = 0^0$

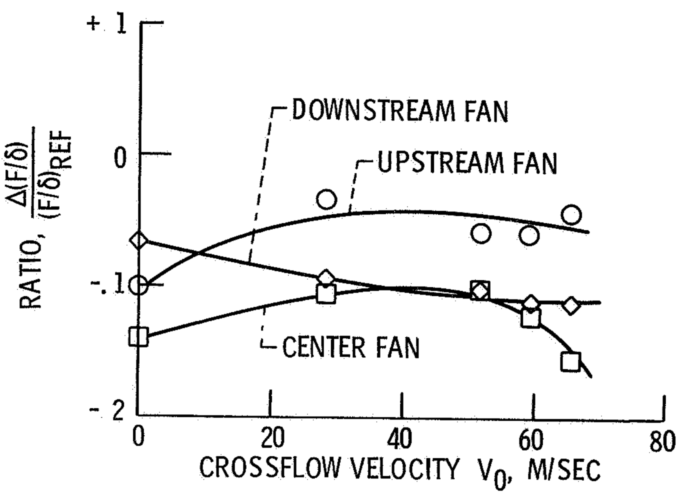


Figure 16. - Inlet butterfly doors - 135° open; exit rectangular doors - 90° open. Variation in thrust of each fan with crossflow velocity. All three fans running at 100 percent $N/\sqrt{\theta}$; $\alpha = 0^0$

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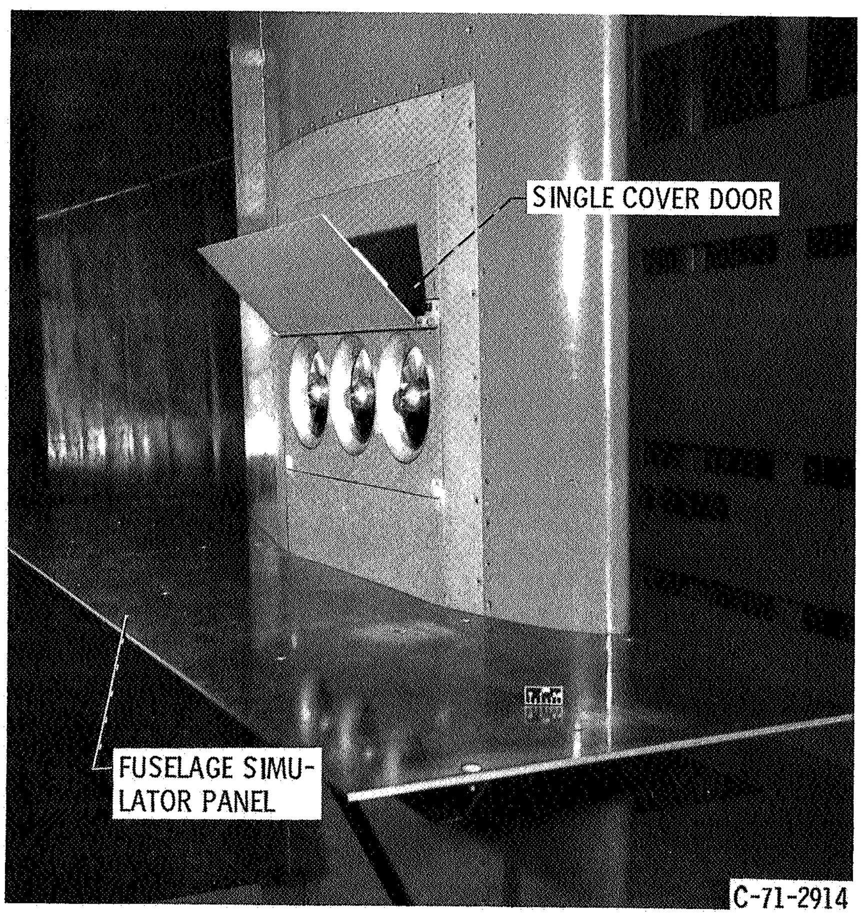

Figure 17. - Installation of fuselage simulator panel on multiple lift fan model.

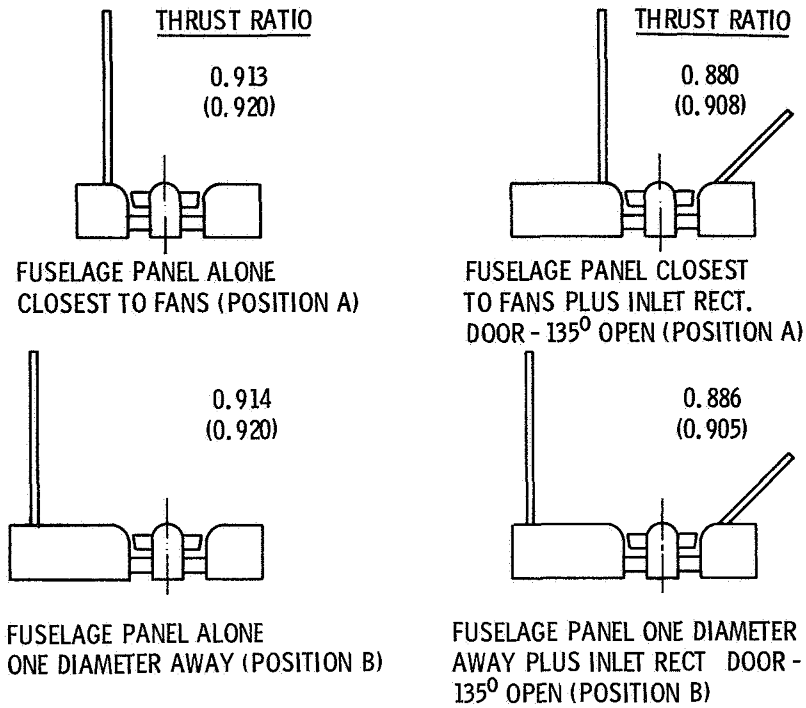

Figure 18. - Static thrust ratio for the various fuselage panel configurations. Upper value obtained from calculated expansion thrust; lower value obtained from load cell force measurement.

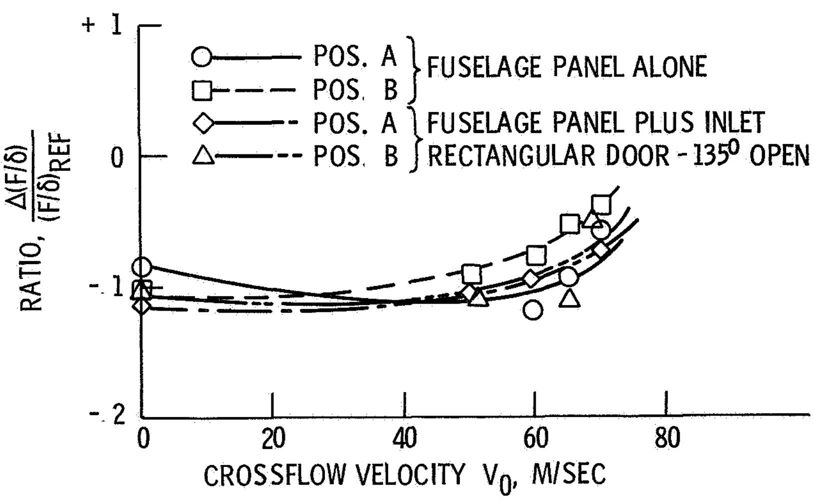

Figure 19. - Variation in thrust with crossflow velocity for various fuselage panel configurations. All three fans running at 100 percent $N/\sqrt{\theta}$; $\alpha = 0^{0}$.