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Effects of Wind on Turbofan Engines in Outdoor Static Test Stands

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Summary

Wind can affect measured thrust and can cause turbofan engine speed to fluctuate during outdoor testing. Techniques used at an outdoor test stand at NASA Lewis Research Center to make testing easier and faster and to improve data repeatability include using an inflow control device (ICD) to make fan speed steadier, taking many raw data samples for better averaging, and correcting thrust for wind direction and speed. Data from engine tests are presented to show that the techniques improve repeatability of thrust and airflow measurements under various wind conditions.

Introduction

During outdoor static testing of turbofan engines, the wind can cause significant erratic fluctuations in fan speed. In addition, wind speed and direction can affect both measured thrust and measured inlet airflow. Thus, the wind can influence the accuracy and repeatability of engine performance data and make its reliability as a predictor of flight results suspect.

Informal discussions with several outdoor test stand users disclosed that there is no common approach to dealing with wind effects. Each organization has established testing restrictions and criteria based on its own needs and experience. Typically, performance tests are conducted when the wind is blowing generally into the inlet (headwind) at an average speed less than 4.5 m/s (10 mph). Corrections to measured thrust, based on ram drag (inlet momentum) due to the axial component of the wind velocity, are sometimes made. Airflow corrections are not made.

A computerized search of public literature for the past several years found little documentation on wind effects during testing and no reference at all to thrust correction.

The purpose of this paper is to describe testing techniques favored at an outdoor test stand at NASA Lewis Research Center and to present some typical turbofan performance data to show how these techniques improve the data repeatability. The techniques include using an inflow control device (ICD) at the engine inlet to steady fan speed, taking many data samples to obtain good time-averaged performance, and correcting measured thrust with a simple term based principally on ram drag from wind. The design and construction features of some ICD's used successfully in various tests at Lewis are shown. The thrust correction method is evaluated with engine test data obtained with moderate head-, cross-, and tailwinds. Data taken during typical wind conditions with and without an ICD installed are examined to show how wind can affect inlet airflow measurement repeatability.

Apparatus

Engine and Test Stand

The engine used for the test data presented in this paper is the quiet, clean, general aviation turbofan (QCGAT) engine made by AiResearch Manufacturing Co. of Arizona (now Garrett Turbine Engine Co.). This engine is one of two distinctly different QCGAT engines designed and made for NASA to demonstrate that technology developed for large commercial and military engines could be adapted successfully to smaller engines. The other QCGAT engine was made by AVCO Lycoming Division. Each of the engines incorporates many modern design features such as a mixer exhaust system, low-emission combustors, geared fan, and noise-reduction techniques including acoustic suppression panels in the inlet and in the bypass duct.

The AiResearch QCGAT engine (Fig. 1) has a 4.2 bypass ratio and produces 18 000 N (4000 lb) thrust at sea-level-static conditions. The test stand at Lewis was equipped with a pivot that could be moved in the horizontal plane to change the direction of the engine inlet relative to the prevailing wind. However, for routine testing the engine position was fixed.

Inflow Control Device (ICD)

ICD's were developed to reduce tone noise from rotor-inflow distortion interaction in acoustic tests. The Federal Aviation Administration (FAA) recently has accepted acoustic certification data from tests using ICD's. During outdoor testing fan speed was observed to be much steadier when an ICD was installed, probably because large-scale inflow disturbances were reduced.

In general, an ICD is an inlet flow straightener mounted at the engine inlet. It must effectively filter out inflow nonuniformities, and it also may serve as a FOD (foreign object damage) screen to prevent the engine from ingesting debris. Fine-mesh screens, honeycomb, and perforated plates have been used to make ICD's. The principal differences in ICD's reported in acoustic literature have been in size (fan diameters) and construction methods.

Some of the ICD designs used for acoustic testing of a JT15D-1 (53-cm (21-in.) diam fan) business jet engine at Lewis are shown in Fig. 2. The largest device (Fig. 2(a)) consisted of 12 honeycomb panels supported by a stiff screen in a framework made of strong steel ribs. This ICD was large and heavy and required external support on the test stand. However, acoustic performance was excellent.[2] Similar designs, suitably scaled, have been used for acoustic testing of large commercial engines.[3,4]

A smaller ICD (Figs. 2(b) and (c)) was self-supporting, much lighter in weight than the previous design, and still had satisfactory acoustic characteristics.[5] It was about two fan diameters in size and was mounted from a machined area on the cowling surface. It was made from nine triangular shaped sections of flexible honeycomb. Design and construction details are described in Ref. 5.

The smallest ICD (Fig. 2(d)) was a flat sheet of stiff honeycomb mounted in the cylindrical part of a bellmouth inlet. This ICD has acoustic transmission losses.[6] It also has a higher aerodynamic pressure drop than the other ICD's, because of its high throughflow velocity. Pressure losses for the three designs are shown in Fig. 3. Because of the inlet system pressure loss, some of the engine performance parameters with the smallest ICD are changed significantly, particularly the measured thrust and airflow. When using an ICD of this type, compensation for inlet loss (larger exhaust nozzle areas and/or thrust allowance) may be needed for accurate comparison with no-ICD data.

The ICD shown in Fig. 2(a) was adapted for use with the QCGAT engine and was used during the tests reported herein. For QCGAT the ICD was 2.75 fan diameters in size and was mounted over a flight-like inlet having a throat-to-fan diameter ratio of 0.84.

Procedure

With the ICD installed, performance data were obtained at several relative-wind conditions and engine power settings in back-to-back tests on the same day. The engine was configured with a referee separate-flow exhaust nozzle system. Data readings were taken while the wind was reasonably steady in both speed and direction. All the thrust data were taken without shutting down or adjusting the measuring system. System tares read at various times during the day were 0±44 N (0±10 lb). At another time additional airflow data were obtained both with and without the ICD installed during a series of routine acoustic test sessions over a period of several weeks. For those tests, the engine had the design 12-lobe mixer exhaust system, which was larger in effective flow area than the referee nozzle system. Also for those tests the ICD was removed and replaced without disturbing the airflow measuring instrumentation.

Thrust, fan speed, and other important measurements were made many times during each data reading. Total data taking time for each reading was about 1 min. Based on our experience, it is believed that the large quantity of raw data thus obtained improves the accuracy of the final averages and, consequently, the repeatability of the test results. If the wind changed significantly during data acquision, the reading was repeated.

Thrust, airflow, and fan speed results have been referenced to sea-level-static standard-day conditions. For tests without the ICD the inlet pressure was assumed to be atmospheric pressure. For tests with the ICD installed the inlet pressure was assumed to be atmospheric pressure minus the ICD pressure loss.

Results and Discussion

All results indicate the repeatability, not the absolute accuracy, of the data obtained during the various tests. Accuracy depends on many factors, such as instrumentation, measurement method, test configuration, and the like, which are not within the scope of this study.

Use of ICD to Steady Fan Speed

The effectiveness of the ICD in steadying the QCGAT fan speed is illustrated in Fig. 4. (Similar results were observed for the other ICD's described in a previous section of this paper.) With the ICD the fan ran much steadier for all wind conditions, and measured thrust and many other performance parameters were likewise steadier. Steadier operation made testing easier and quicker, and improved the repeatability of the test results. Figure 4 also indicates that without an ICD the fan speed is most erratic for tailwind; this fact is well known and is partly the reason some test stand operators prefer to test with a headwind or no wind.

Thrust

Theory. To calculate the effect of wind, suppose that the engine is moving through still air with speed equal to the axial component of the wind velocity. Then the ram drag (inlet momentum, $m_1 V_0$) is easily calculated from measured airflow, wind speed V_w, and wind direction relative to the inlet axis α_w. Also, suppose that the same wind causes aerodynamic drag on the frontal area of test stand hardware attached to the thrust measuring system. Ram and test stand aerodynamic drag act in the same direction and are considered to be the only wind forces affecting measured engine thrust. In addition, by mechanical design the thrust system does not react to side loads. Then,

"No-wind" thrust = measured thrust
± (ram drag + test stand aerodynamic drag)

where the drags are added to measured thrust for headwind and subtracted from measured thrust for tailwind.

For the QCGAT engine setup the frontal area of test stand structure attached to the thrust measuring system was estimated to be 3 m^2 (32 ft^2), and the drag coefficient was assumed to be 1.2.

Test results. Thrust measured over a range of fan speeds up to maximum with the ICD installed is shown in Fig. 5 for several wind conditions. The curve fit is a high-order mathematical expression with least squares fit to the crosswind data. The crosswind data are considered to be the best measure of thrust because the thrust measuring system does not react to side loads and because the airflow is not affected by wind when the ICD is used (discussed in the next section of this report). In the figure some of the headwind data are below the curve-fit. The same data are displayed in Fig. 6(a) as deviations from the curve-fit expression. The crosswind data fall within a ±1/4 percent repeatability band, but the head and tailwind data generally fall outside this band.

The no-wind thrust (measured thrust corrected for ram drag and test stand aerodynamic drag as described previously) is shown in Fig. 6(b). The crosswind data tend to remain in the ±1/4-percent band because corrections were small. Most of the other data moved into the same band ±44 N (±10 lb). Corrections to the headwind data were most successful. The tailwind data as a whole appear to be as close to the curve-fit with or without the correction applied. In theory, there is no obvious reason to change the correction method for tailwind. However, the few data points from this test suggest that correction might be neglected for tailwind.

Although not shown in the figures, the test stand aerodynamic drag was much smaller than ram drag; therefore, the results of this test would not be changed substantially if stand drag were neglected.

Airflow

In the discussion of airflow measurement, two sets of results will be presented. The first shows the airflow data from the same tests which provided the thrust data shown in Fig. 5 and will be used to examine the effect of wind on flow measurement when an ICD is used. The second shows airflow data from a series of routine acoustic tests made over a period of several weeks, and will be used to compare airflow measurements made under various wind conditions with and without the ICD installed.

For all the tests airflow was computed from inlet throat area, average inlet total pressure (assumed to be atmospheric pressure minus ICD pressure loss), and average wall static pressure from eight taps spaced uniformly around the duct, which were converted (from previous experimental calibrations) to effective average stream static pressure.

Effect of wind with ICD installed. Inlet airflow measured in tests with an ICD for several wind conditions is shown in Fig. 7. The curve fit is a third-order mathematical expression with least-squares fit to the headwind data. The headwind measurements are considered to be the best representation of the engine airflow characteristic because the inflow is most nearly uniform. The same data are shown in Fig. 8 as deviations from the curve-fit expression. Most of the data scatter fairly evenly in a ±1/4-percent repeatability band. For this degree of repeatability there is negligible effect of wind on airflow measured by wall static pressure taps when the ICD is used. This conclusion is corroborated by the circumferential profiles of wall static pressure shown in Fig. 9 for two different wind conditions. There was no undue scatter in pressure at any of the eight wall taps during the four data scans (11 sec between scans) and no important difference in the two scan averaged profiles. This result seems reasonable because the crosswind-to-inlet throat velocity ratio should cause less than 1° of inflow angle. The pressure measured at taps 5 and 6 may be in error because of small undetected instrument plumbing leaks - steady leaks would change the absolute value of airflow, but not the repeatability of the airflow measurement.

The inlet velocity gradients, which could be implied by the circumferential pressure profile in Fig. 9, would also be affected by total pressure profiles or variations (no total pressure measurements were made in the inlet for these tests). Inlet total pressure is usually assumed to be steady, but in fact may vary in time and space because of local flow separation or other large-scale or unsteady inflow disturbances.

Comparison of airflow measured with and without ICD. Over a period of 8 weeks routine acoustic tests were made with and without the ICD installed. Airflow measurements from one of the tests were chosen as a base, and a third-order mathematical expression was fitted to these data in the manner described for Fig. 8. Comparison of all the other measurements with the base data is shown in Fig. 10. With the ICD (Fig. 10(a)) almost all the data fall within a ±(1/4 percent + 0.1 kg/sec) repeatability band. Without the ICD (Fig. 10(b)) more than half the data readings fall within the same band, and all but one are within 1 percent of the curve-fit expression. The data most discrepant from the curve fit are usually from tests with crosswind from the tail quarter, and the discrepancy is believed to be due mainly to unsteady fan speed and consequent errors in the true averaged fan speed and in the averaged wall pressure measurements. If this is the case better repeatability would come with longer data-taking time or improved averaging techniques.

These results indicate that an ICD may not be needed to get acceptably repeatable airflow measurements, especially if testing is not done with tailwind. With or without the ICD, still better repeatability may require use of more elaborate instrumentation, such as pitot-static rake arrays in the inlet duct.

Conclusions

Performance data from QCGAT turbofan engine tests conducted in light to moderate winds at an outdoor static test stand at NASA Lewis Research Center have shown the following:

1. Fan speed is much steadier during outdoor testing with an inflow control device (ICD) mounted at the engine inlet to reduce inflow disturbances. Steadier operation made testing easier and quicker, and improved repeatability of the test results.

2. Thrust measurements are more repeatable when data are corrected for ram drag based on wind speed and direction.

3. Inlet airflow measurement repeatability did not depend on wind conditions with an ICD installed; without the ICD repeatability worsens, expecially for tests with tail-quarter winds that cause unsteady fan speed.

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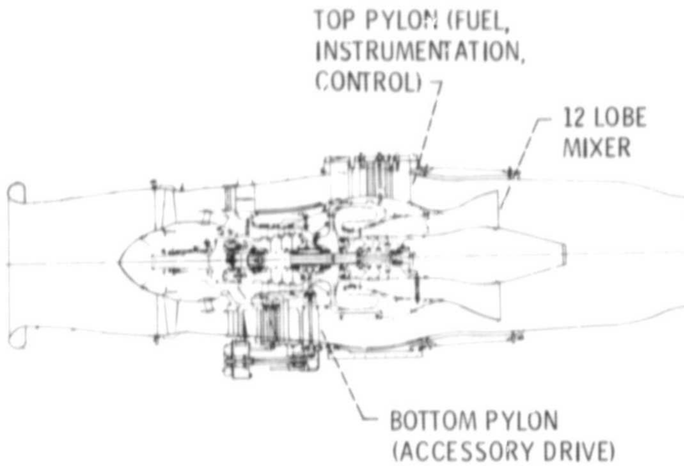
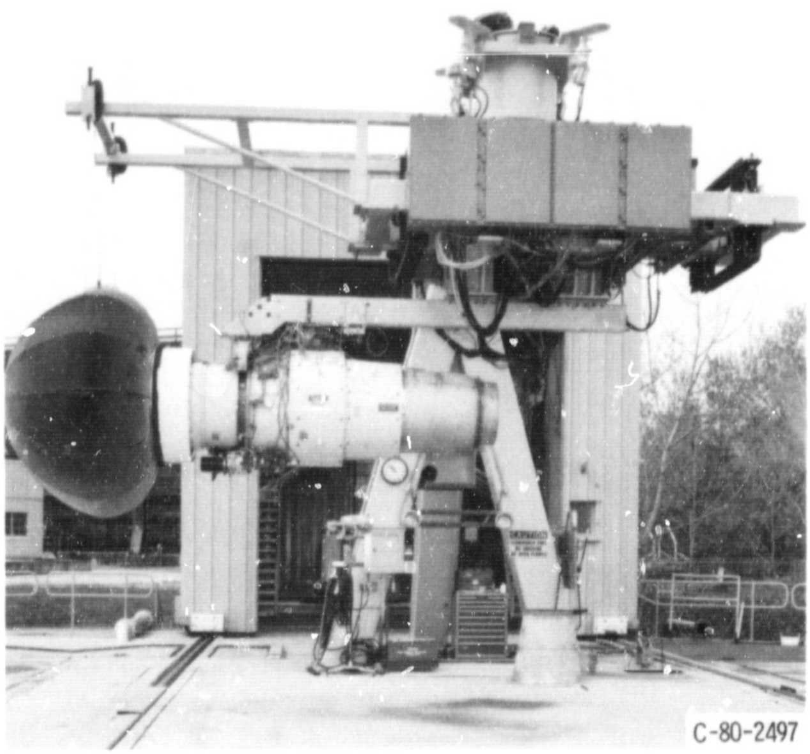
6. Jones, W. L., McArdle, J. G., and Homyak, L., "Evaluation of Two Inflow Control Devices for Flight Simulation of Fan Noise Using a JT15D Engine," AIAA Paper 79-0654, Mar., 1979.

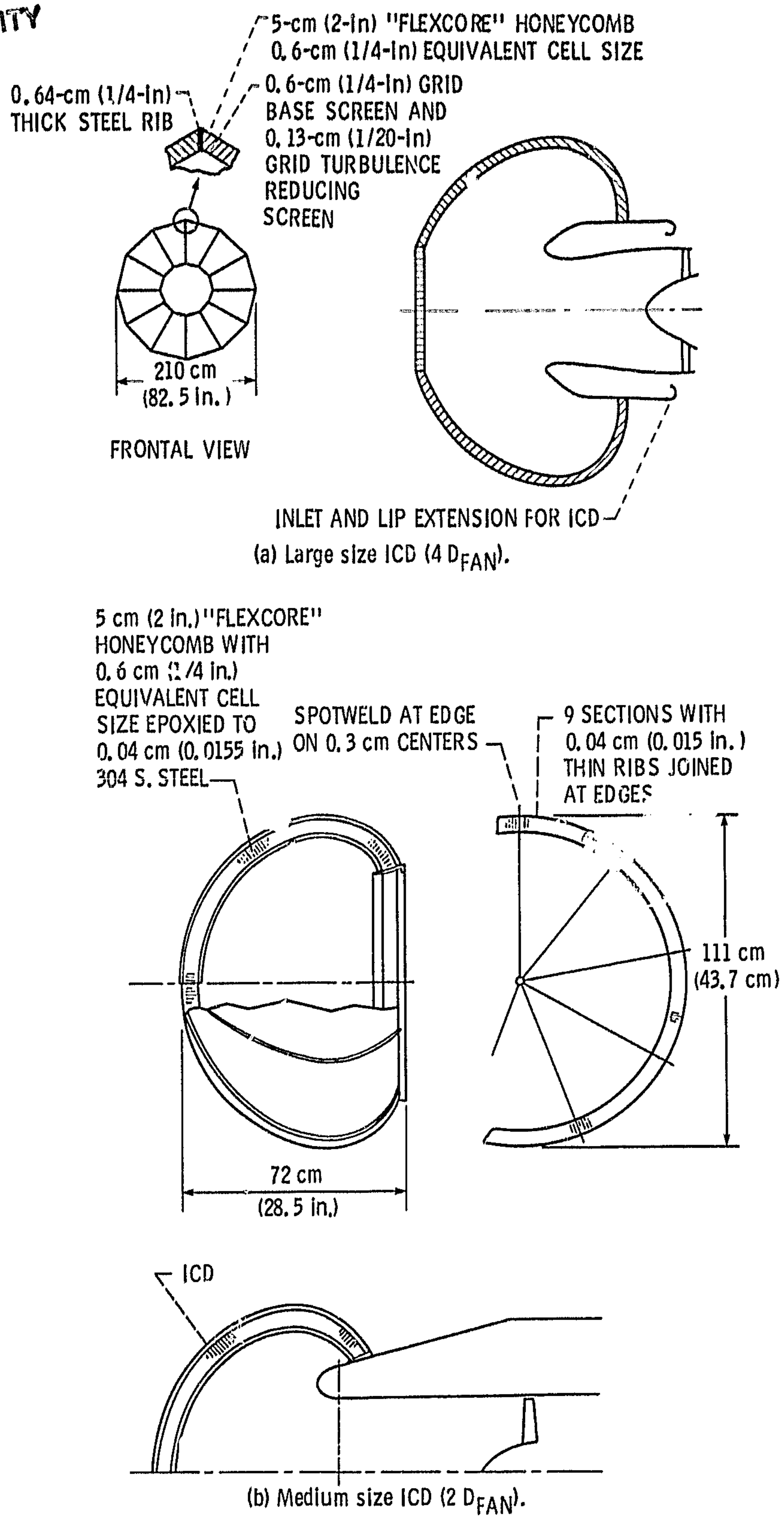


(a) Cross-section sketch.



(b) Engine on test stand with ICD installed.

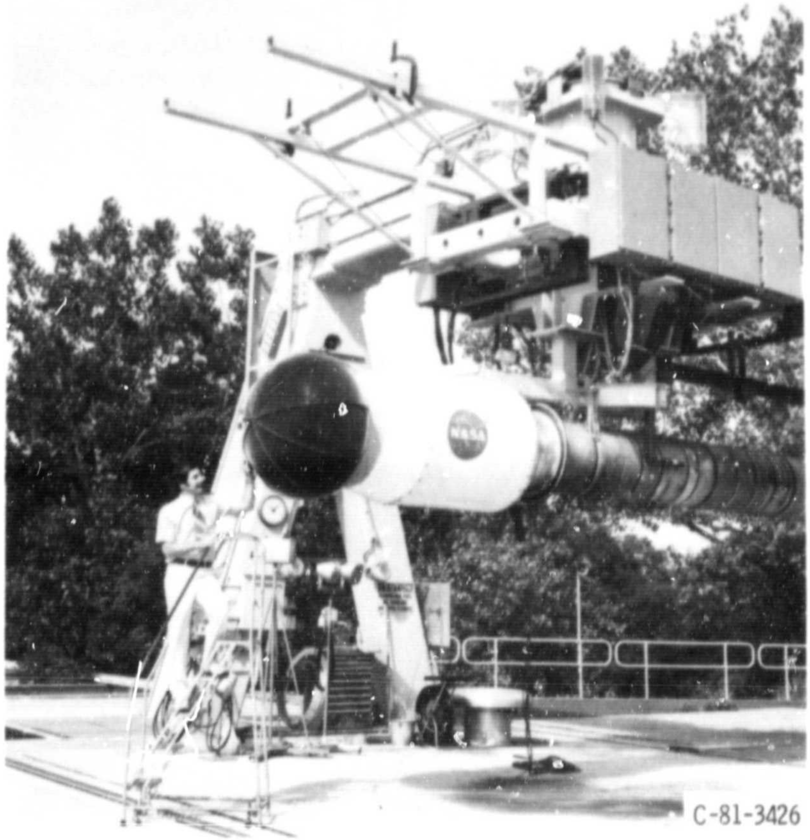
Fig. 1 AiResearch QCGAT turbofan engine.



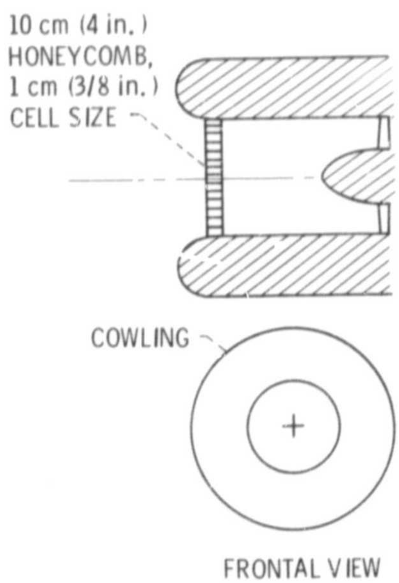
(a) Large size ICD (4 D_{FAN}).

(b) Medium size ICD (2 D_{FAN}).

Fig. 2 ICD designs tested on 9800-N (2200 lb) business-jet turbofan engine.



(c) Medium ICD on cowled engine for acoustic tests.



(d) Small size ICD (1 D_{FAN}).

Fig. 2 Concluded.

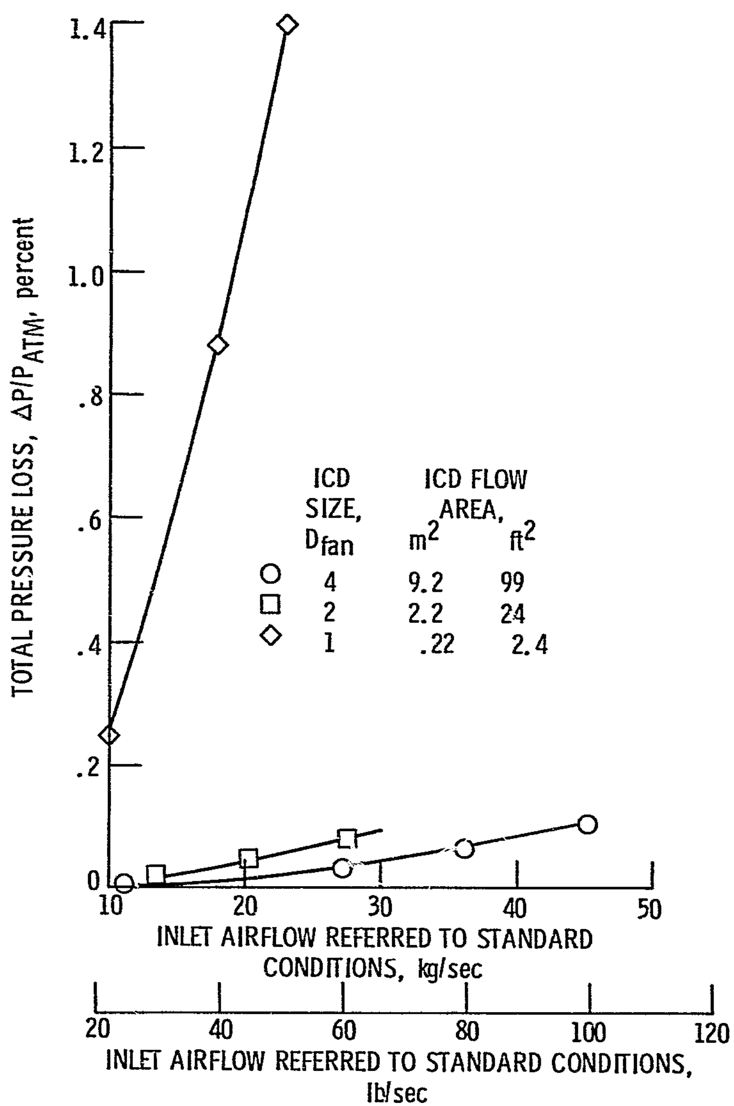


Fig. 3 Pressure loss through ICD's.

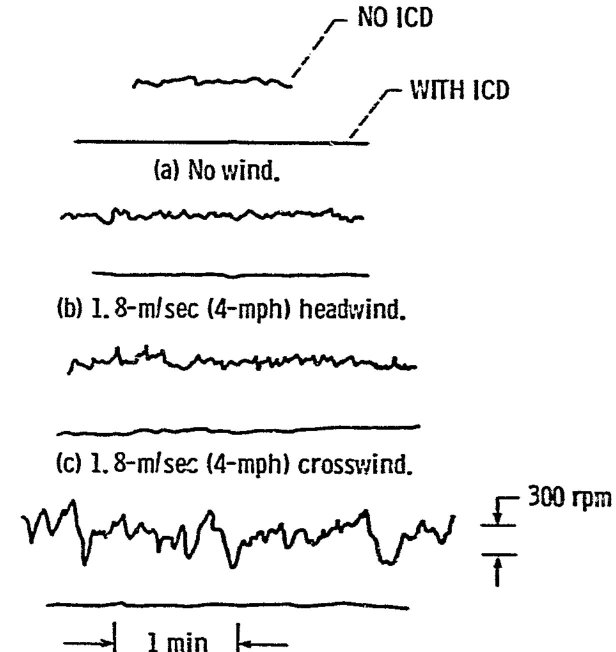


Fig. 4 Effect of ICD on QCGAT fan speed steadiness at takeoff power. Similar results obtained for other engines and ICD's tested outdoors at NASA Lewis.

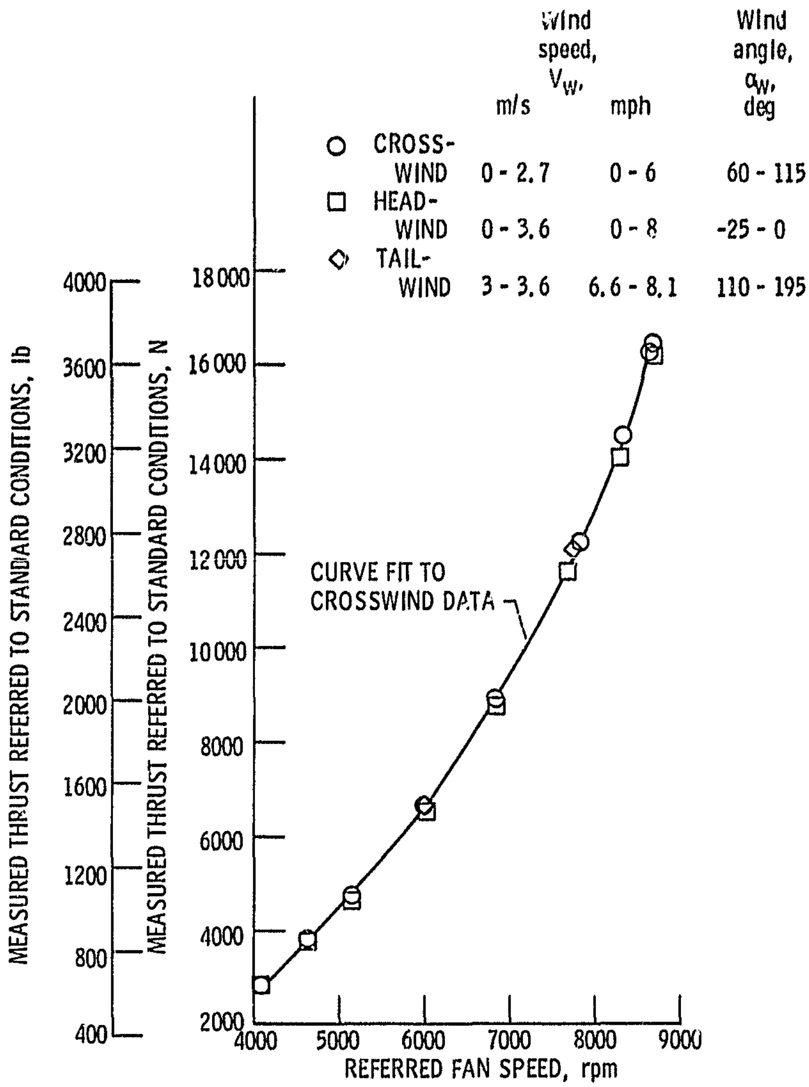
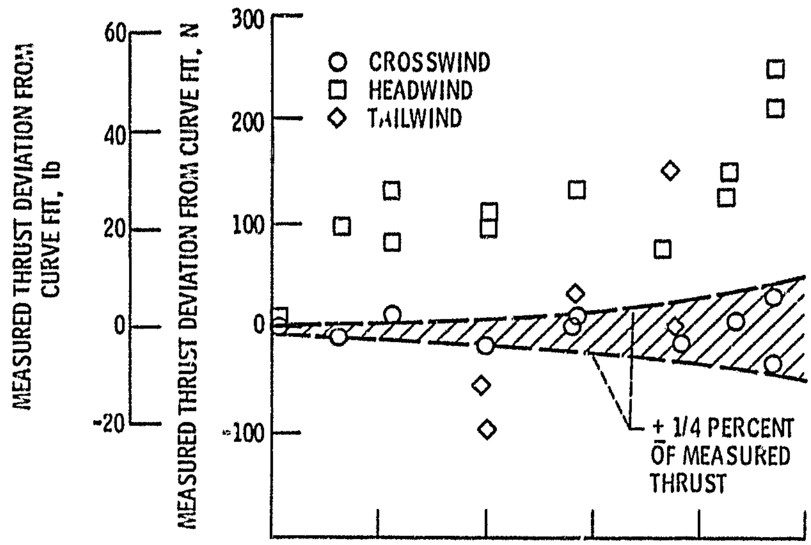
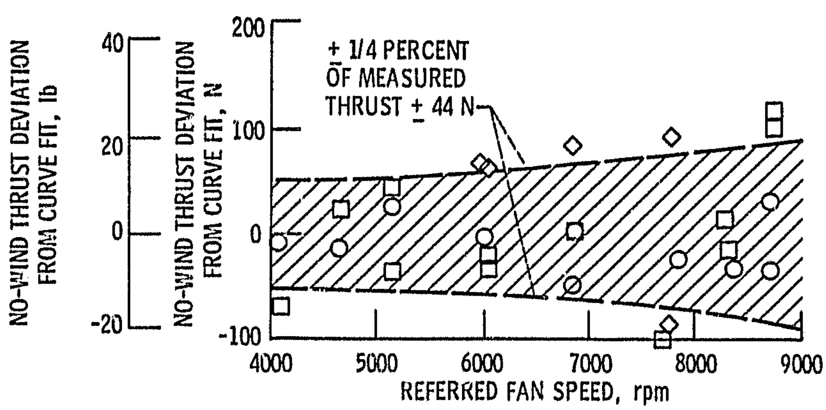


Fig. 5 Measured thrust data.



(a) Measured data.



(b) Measured data corrected for ram drag and test stand aerodynamic drag (no-wind thrust).

Fig. 6 Deviation of thrust measurements from curve fit through crosswind data, ICD installed.

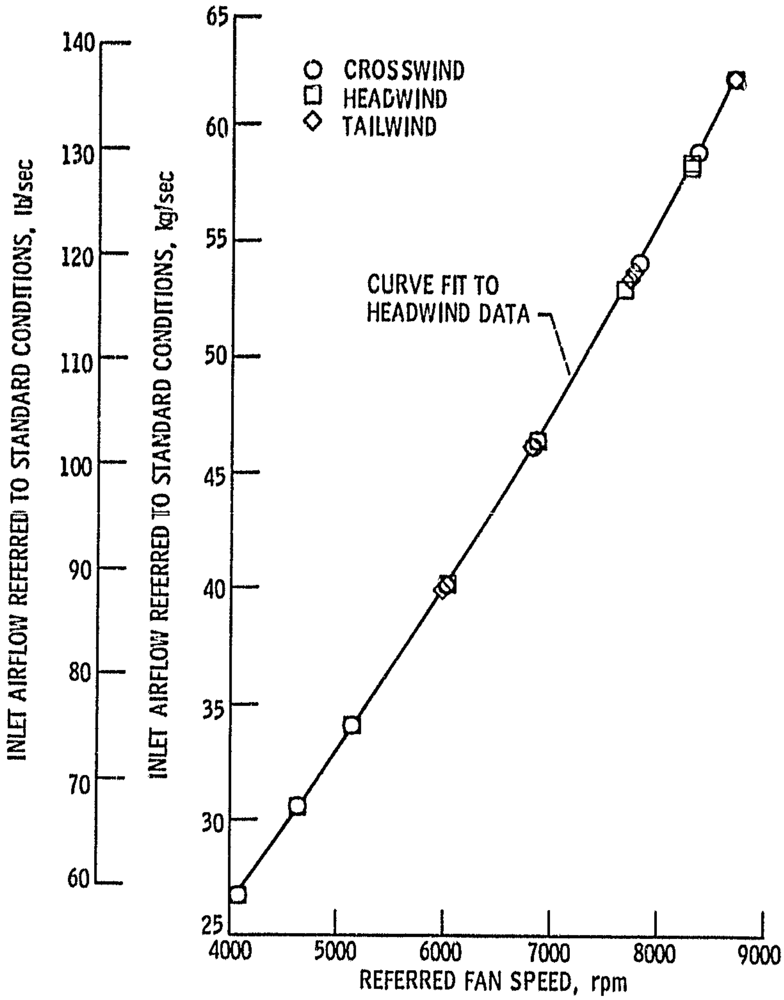


Fig. 7 Measured inlet airflow.

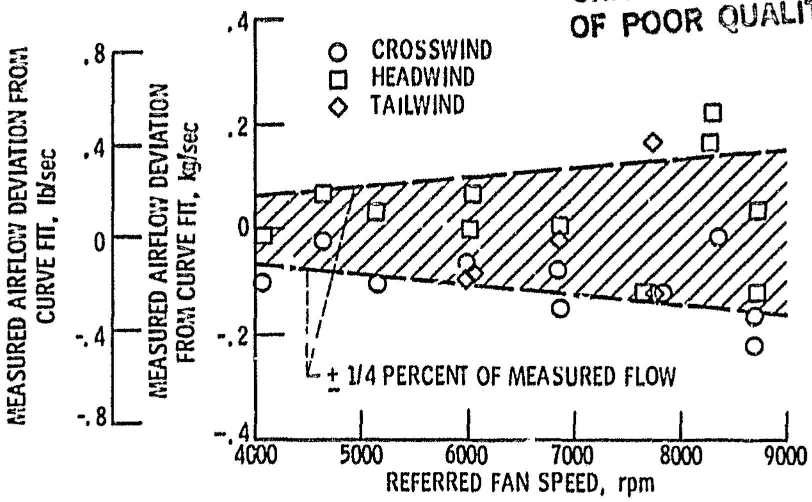


Fig. 8 Deviation of inlet airflow measurements from curve fit through headwind data. ICD installed.

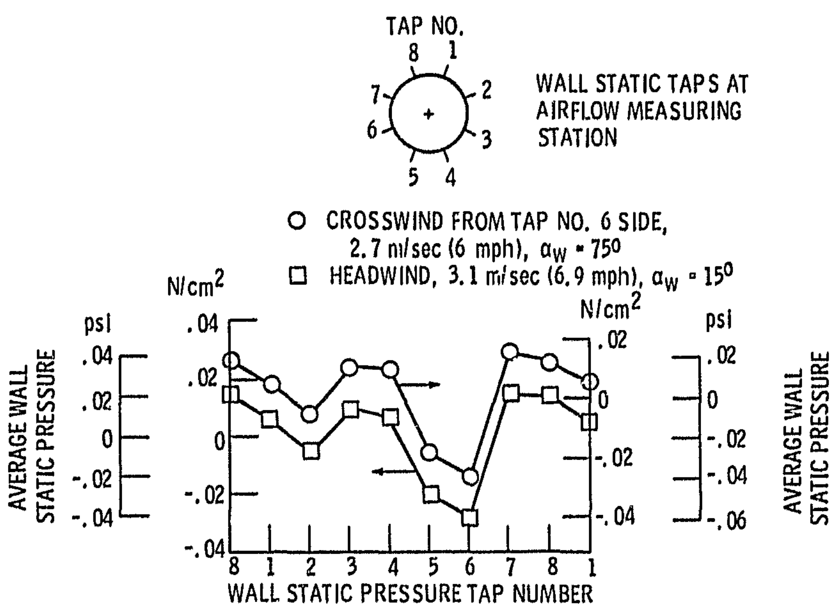


Fig. 9 Effect of wind on wall pressure at airflow measuring station. ICD installed.

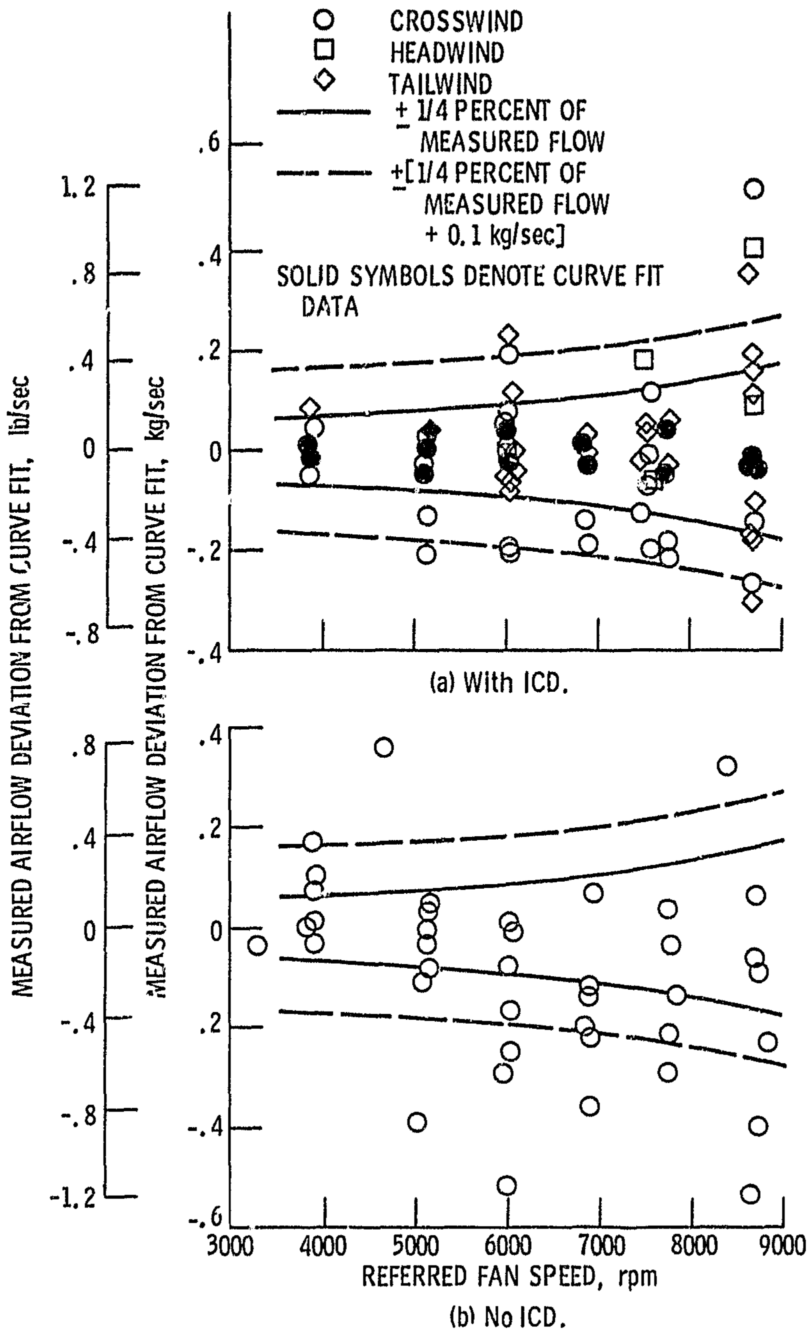


Fig. 10 Repeatability of airflow measurement with and without ICD installed. Wind speeds to 2.2 m/sec (5 mph).