Reynolds Number and Fan/Inlet Coupling Effects on Subsonic Transport Inlet Distortion

D. L. Motycka*
Pratt & Whitney Aircraft Group, East Hartford, Connecticut

The paper shows that the common practice of using scale model inlet distortion to evaluate high angle-of-attack engine/inlet compatibility on subsonic commercial aircraft is conservative, especially when the inlet lower lip is separated. The angle of attack at separation is shown to be Reynolds number sensitive; the higher Reynolds number full-scale configuration separates at a higher angle. The magnitude of distortion with a separated inlet is reduced by the favorable coupling effect of the fan and inlet.

Nomenclature

A_{TH} = inlet throat area, ft^2
M_n = freestream Mach number
P_{tL} = local total pressure at fan inlet
P_{to} = freestream total pressure
Re = Reynolds number (based on fan diameter)
W_{C2} = inlet airflow corrected to fan inlet condition, lb-m/s
α_i = inlet angle of attack (relative to the inlet centerline)
α_i vane = inlet angle of attack based on aircraft vane angle
α_i CL = inlet angle of attack based on α_i vane corrected for vertical acceleration

Introduction

THE engine inlet of a commercial transport is designed to provide optimum cruise drag and pressure recovery without any sacrifice of operational safety. The aircraft must operate trouble-free over a range of flight conditions (takeoff, climb, cruise, etc.), including emergency avoidance maneuvers. The inlet must allow satisfactory engine performance throughout these operational requirements; and during the development and certification process, tests are conducted to determine the acceptability of the design. Experience has shown that the most adverse case of total pressure distortion, which can cause engine surge or relatively high fan stresses, occurs when the inlet entrance conditions are severe enough to cause flow separation.

During the development of the engine, tests are conducted which evaluate the tolerance of the engine to severe inlet distortion. The distortion selected for the test is based on wind tunnel model tests designed to investigate the aircraft operating envelope for normal and emergency operation and is simulated in engine ground tests through the use of screens (see Fig. 1) or a cross-wind generator (see Fig. 2). It has been known for some time that at a given condition, the model tests can produce higher distortions than are normally experienced in flight, resulting in conservative engine evaluations. This report will identify the magnitude of these differences and show that the major reasons for these differences can be attributed to scale effects and engine/inlet coupling.

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*Project Engineer.

Reynolds Number (Scale Effects)

Recent model tests to evaluate external cowl separation boundaries at windmilling (engine out) airflow have revealed a strong sensitivity to Reynolds number (see Fig. 3). Two different inlets were tested by Pratt & Whitney in the CALSPAN variable density tunnel, both exhibiting similar trends. Data reported by Younghans et al.,[1] which was acquired in LeFauga facility in France, also had the same trend. Because the critical inlet distortion occurs when the internal lower lip is separated and because the flow properties are similar to those on the external upper lip at windmilling airflow, the sensitivity of the lower lip separation to Reynolds number was investigated.

A test of a 1/6 scale JT9D size inlet was conducted so that the angle of attack at separation for a given Mach number and inlet airflow could be determined within 1 deg angle of attack. (Throughout this report, internal inlet separation is determined by observing that the total pressure profile near the wall is constant and at or below the local wall static pressure.) The matrix of data is shown in Fig. 4 with the accuracy band indicated. An analytical prediction of separation was made at $M_n = 0.265$ and for a range of airflow. The computation utilizes a transonic three-dimensional potential flow model[2] with a separate three-dimensional boundary-layer calculation.[3] Angle of attack was varied in 1 deg increments and the

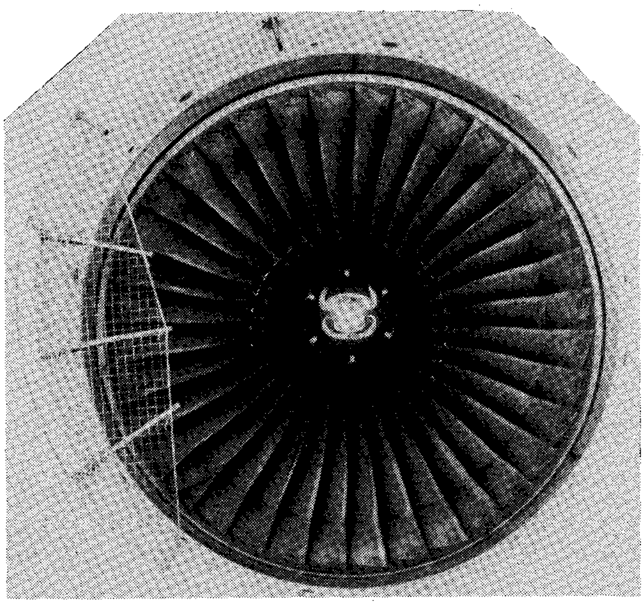


Fig. 1 Inlet distortion screen.

boundary layer separation point was determined by observing the point of vanishing skin-friction coefficient. The theoretical results at model Reynolds numbers are shown superimposed on the data in Fig. 4 with excellent agreement. The same computation was conducted at full-scale Reynolds numbers and the model vs full scale comparison is shown in Fig. 5 indicating approximately constant difference over the flow range.

The separation characteristics of an inlet with essentially the same geometry were evaluated in 0.469 scale in the NASA Ames 40 × 80 ft wind tunnel.[4] The results are shown in Fig. 6 as a function of Mach number and airflow. Because of the hot ambient wind tunnel temperatures, the maximum engine power limited the airflow rate W_{C2}/A_{TH} to 41.2 lb/s ft^2. The lowest available full-scale flow rate was 44.5 lb/s ft^2. In order to allow a comparison between the 1/6 scale, full scale, and 0.469 scale data at equal airflows, the data (Fig. 6) have been extrapolated from $W_{C2}/A_{TH} = 41.2$ lb/s ft^2 to the higher flows (dashed) by applying the analytical shape (Fig. 5) to the test data. Cross plots of the 1/6 scale, and 0.469 scale data at $W_{C2}/A_{TH} = 44.5$ lb/s ft^2 and 46 lb/s ft^2 are shown in Figs. 7 and 8 along with the data taken during a flight test of a full-scale inlet. The flight test inlet angles of attack are determined from a steady-state correlation, α_i vane, plus a lift related vertical acceleration correction resulting in a corrected angle, α_i CL. At the high angles of attack, the acceleration correction tends to over- or undercompensate due to the heavy vertical acceleration (buffet) and the true value of αi falls somewhere between α_i vane and α_i CL; therefore, both values are shown on the full scale curves. An analysis of the data points indicates that the scatter is caused by difficulty in determining the point of separation as well as some variation in inlet airflow rate. The line drawn through the data takes into consideration the accuracy of the individual data points but also gives significant weight to the analytical prediction. The theoretical analysis was only done for the full-scale and 1/6 scale configurations.

Figure 9 shows similar results for a second inlet. For this configuration 1/8 scale, 1/6 scale and full-scale tests were used and the model data was much more limited in scope than that

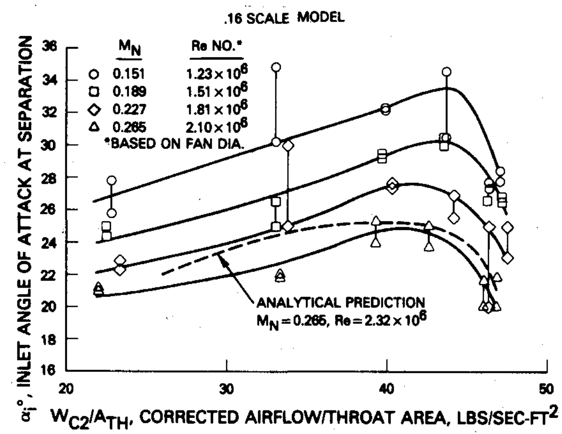


Fig. 4 Lower lip separation angle of attack vs corrected airflow.

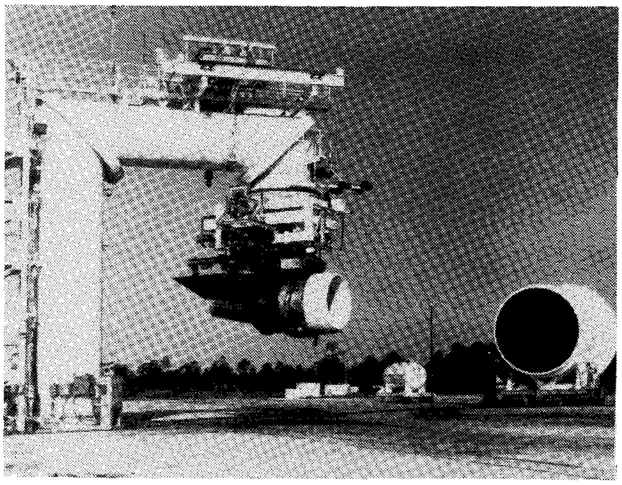


Fig. 2 Inlet cross wind distortion test.

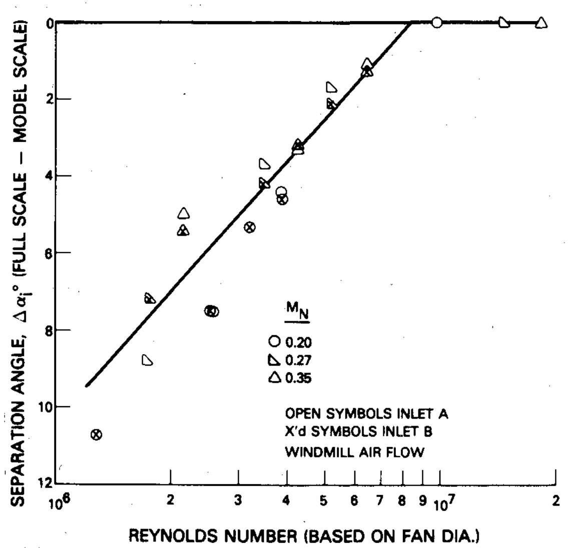


Fig. 3 Reynolds number vs angle of attack at separation during second segment climb.

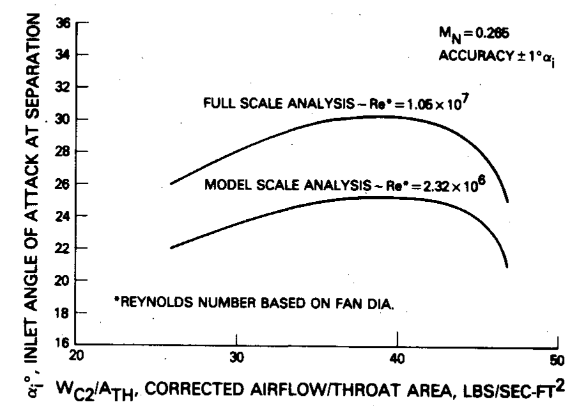


Fig. 5 Analytical prediction of separation angle of attack.

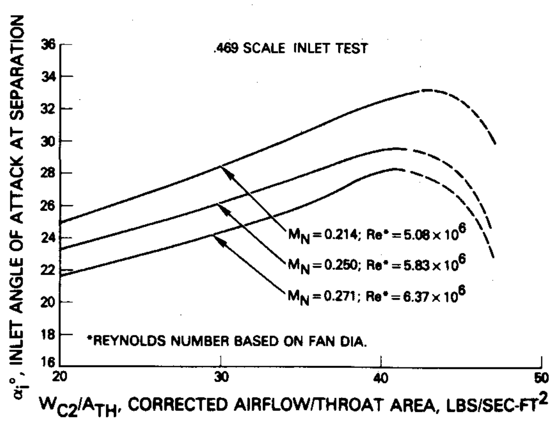


Fig. 6 Lower lip separation angle of attack vs corrected airflow/throat area.

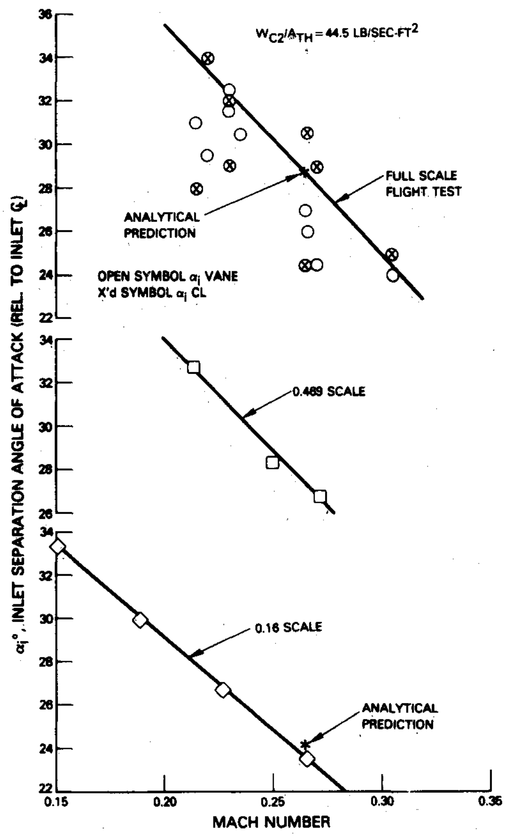


Fig. 7 Separation angle of attack vs Mach number.

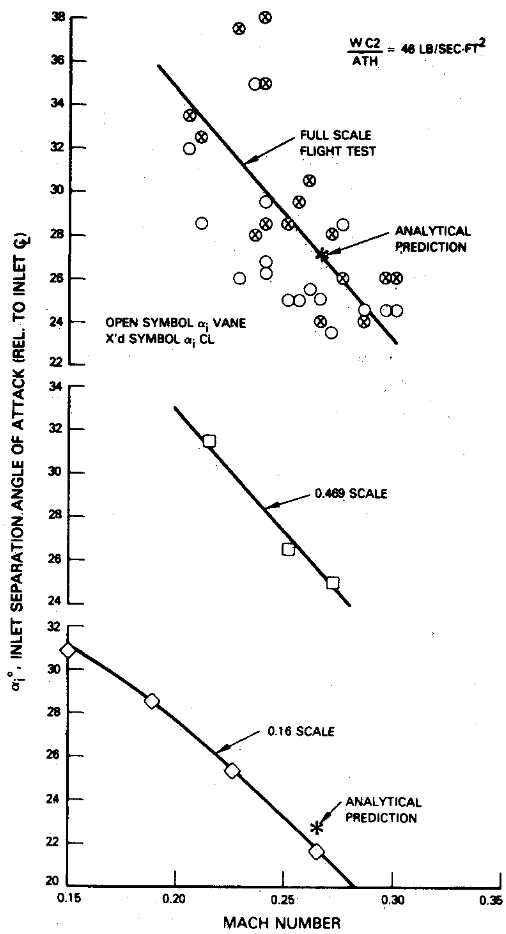


Fig. 8 Separation angle of attack vs Mach number.

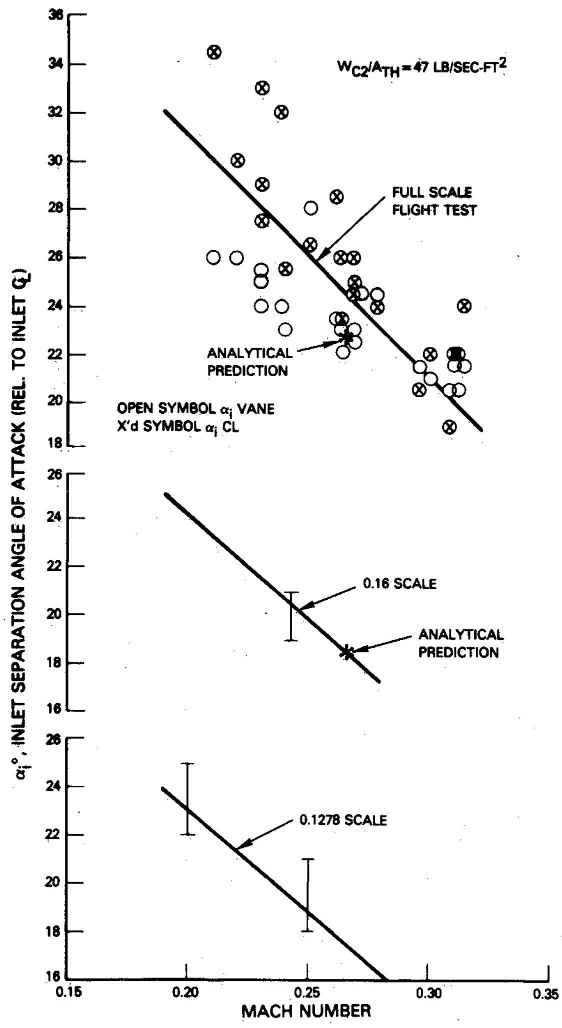


Fig. 9 Separation angle of attack vs Mach number.

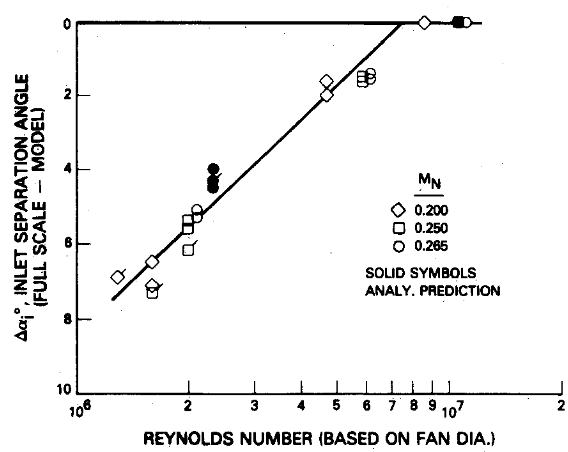


Fig. 10 Influence of Reynolds number vs inlet lower lip separation angle of attack.

for the first inlet. Figure 10 combines the data from Figs. 7-9 vs Reynold number. The trend observed agrees well with the analytical calculation and is similar to that for the Windmilling Case (see Fig. 3) showing that models tested at low Reynolds numbers can be expected to separate several degrees in angle of attack lower than the full-scale configuration.

Fan/Inlet Coupling

It has been observed that engines in flight have been more tolerant to inlet distortion than those ground tested behind

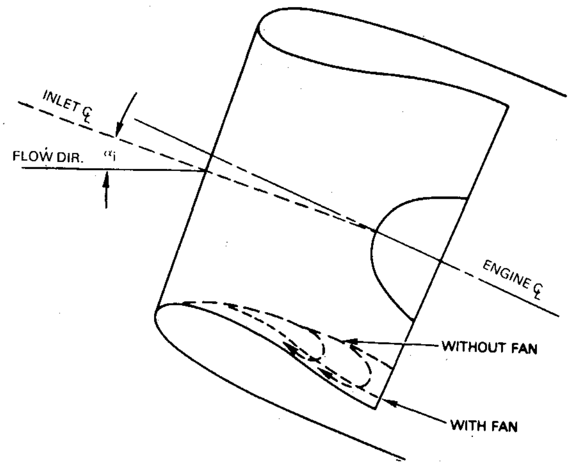


Fig. 11 Angle-of-attack distortion with and without fan coupling.

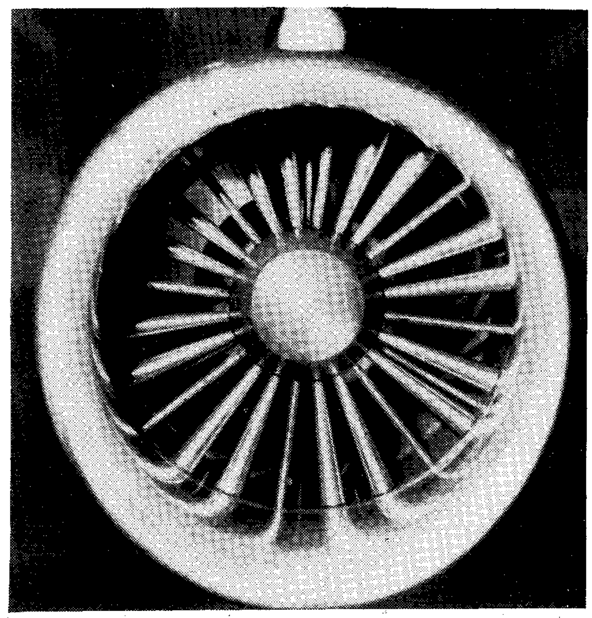
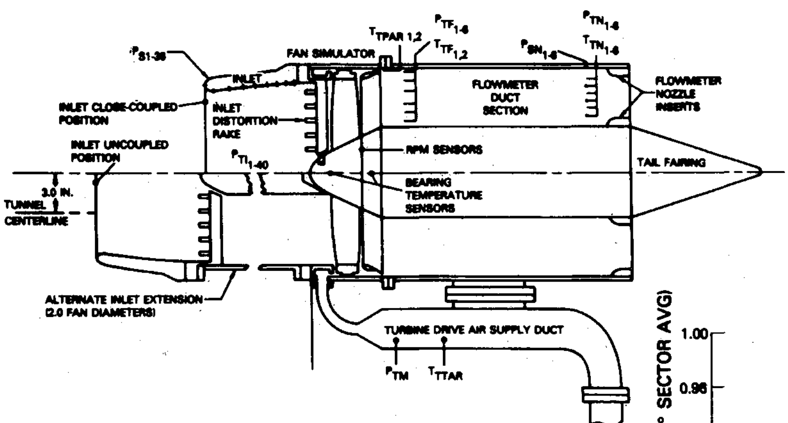


Fig. 12 Inlet wind tunnel model with radial blockage rods.



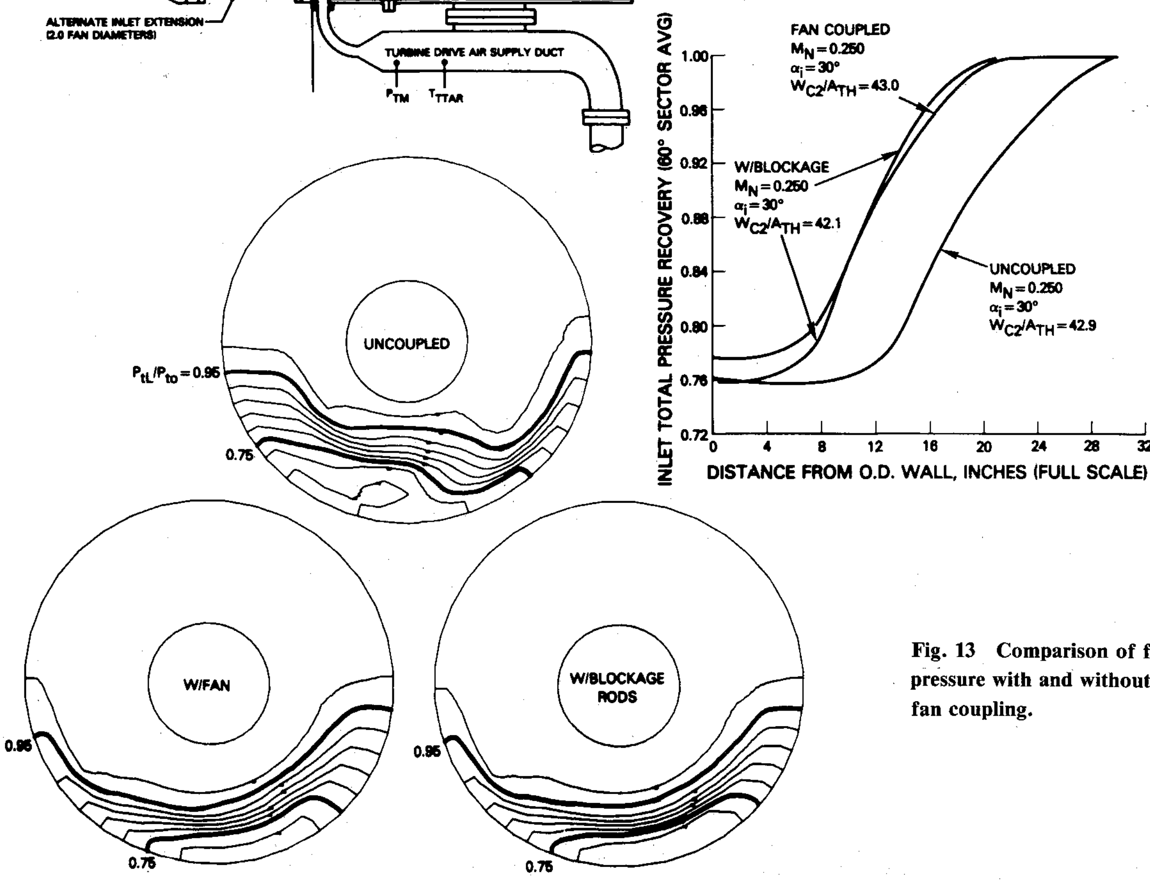


Fig. 13 Comparison of fan face total pressure with and without simulated fan coupling.

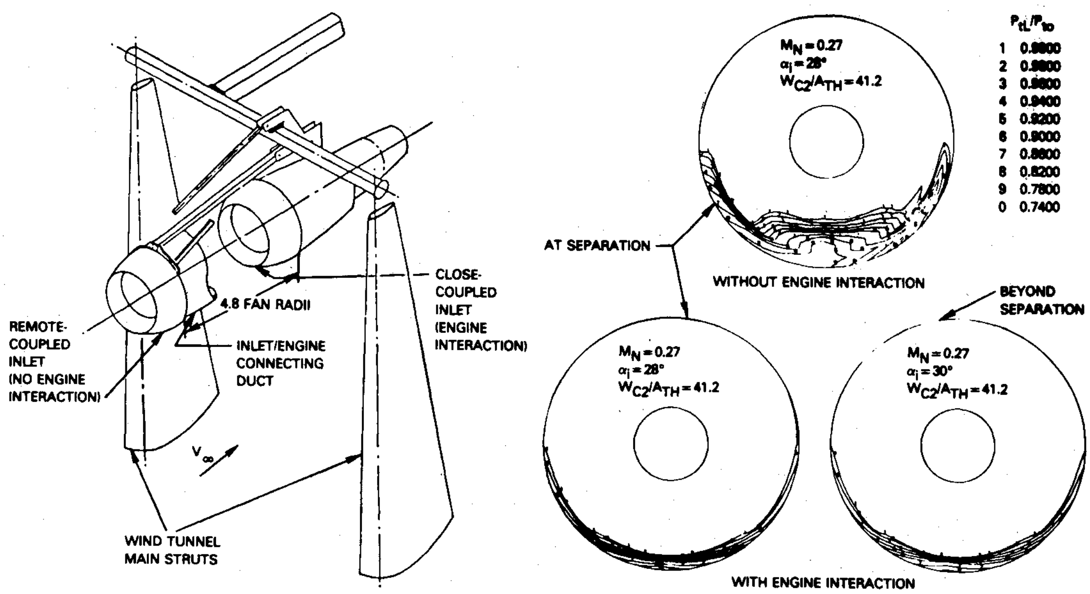


Fig. 14 Comparison of fan face total pressure with and without engine interaction.

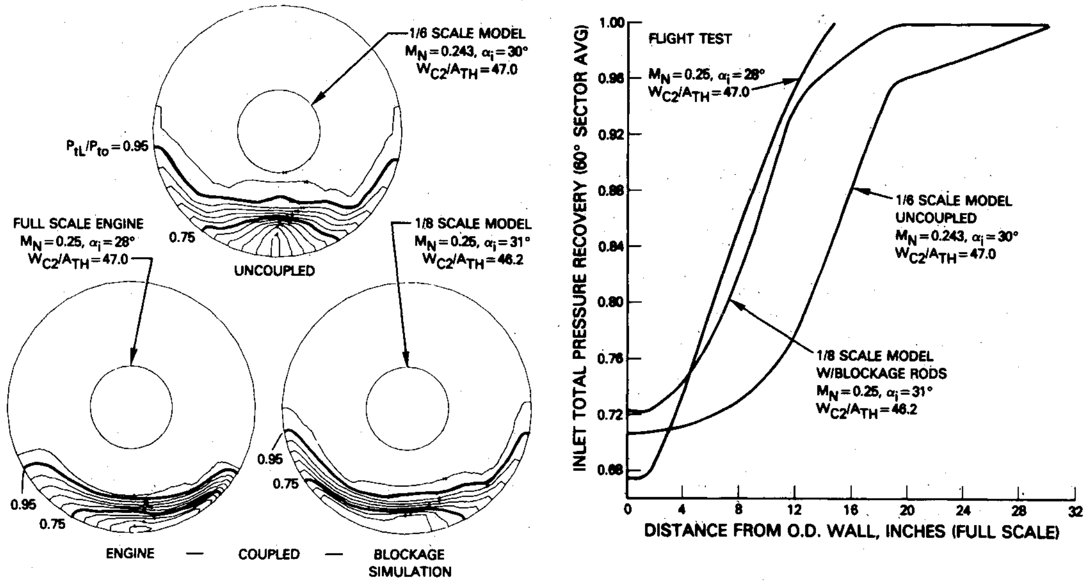


Fig. 15 Full scale vs model inlet distortion with and without fan/inlet coupling.

screens designed from model test distortion patterns at similar test conditions, especially when both the model and full-scale conditions are beyond flow separation. The differences have been attributed to a multitude of causes, including scale effects and engine/inlet coupling. Rarely has the full-scale and model distortion data been available for comparison at equivalent angle of attack, flow and Mach number. However, several tests have been conducted in recent years aimed at explaining these differences.

In 1978, Pratt & Whitney conducted a model test of a 1/8 scale JT9D/size inlet using a close coupled and remotely coupled powered fan. The lower angle-of-attack unseparated inlet distortion differences between close coupled and remotely coupled configurations were negligible. The separated conditions exhibited significant differences in distortion extent even though the minimum total pressure values were essentially the same. Apparently the influence of the fan was to pull flow into the separated wake and reduce its size (see Fig. 11). It was theorized that the fan acted to maintain the flow distribution across the duct and prevent any flow reversal resulting from the inlet separation. Also, the transonic velocities through it decouple the inlet from the downstream ducting. To verify this theory, tapered rods were inserted into the remotely spaced inlet at the normal plane of the fan (see Fig. 12). The rods were designed to choke the flow, cutting off any communication to the downstream ducting.

The effect of the choked blockage was to reduce the distortion to that equivalent to the fan-coupled configuration. Figure 13 compares the distortion patterns and also 60 deg sector circumferentially averaged distortion factors. It was also found that to adequately simulate the fan coupling at lower flows, the blockage area must be increased to maintain the choked condition. But at higher flows, the total pressure rakes themselves were sufficient blockage.

In the approximately 1/2 scale, 1980 Boeing/NASA Ames test,[4] the scale effects question was answered. The same close coupled and remotely spaced type test was conducted and again demonstrated the strong effects of fan coupling (see Fig.

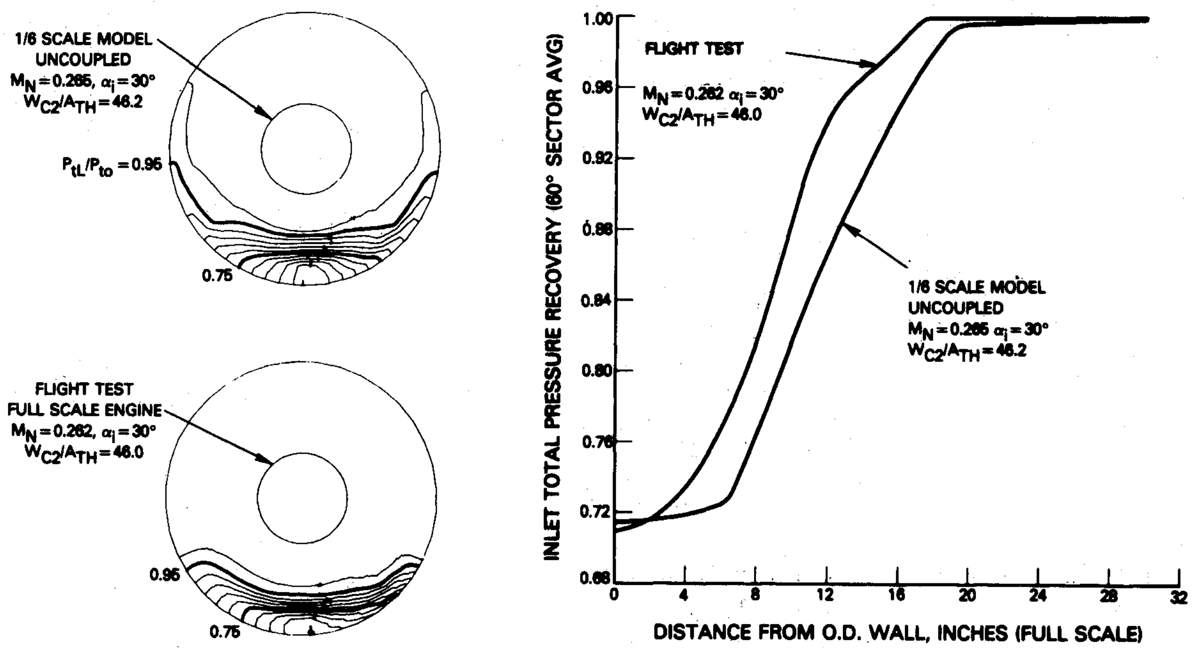


Fig. 16 Full scale vs model inlet distortion without fan inlet coupling.

14). In both the Pratt & Whitney and Boeing/NASA tests the coupling effect was shown to persist well beyond the point of inlet separation. It was also observed in both tests that the angle of attack at separation was essentially independent of the coupling.

In 1983, we were afforded the opportunity to compare model scale and full scale distortion patterns for two different inlets. The full-scale inlets were instrumented with two part span rakes located 40 deg apart and circumferentially in the region which produced the most adverse distortion. Using expected pattern shape, augmented by limited pressure measurements behind the fan, a technique was developed for creating full face patterns from these two rakes. Comparisons were made then between model and full scale data. Figure 15 compares a 1/6 scale model, a 1/8 scale model which utilized radial blockage rods, and a full scale flight test distortion. The influence of engine/inlet coupling is evident and the model with blockage agrees well with the full scale, especially when considering the full-scale accuracy. Figure 16 compares a 1/6 scale model with full-scale flight test distortion. In this case the model has fan face instrumentation which choked at approximately $W_{C2}/A_{TH} = 47$ lb/s ft^2. The model test condition was less than 2% airflow away from choking the rakes and therefore, includes some degree of simulated coupling. The model vs full scale comparison is close and within test tolerance.

Conclusion

Using inlet distortion patterns derived from scale model tests for evaluation of engine/inlet compatibility is conservative when the critical condition is beyond the point of inlet flow separation. The angle of attack at separation is sensitive to Reynolds number or model scale and can occur several degrees lower for the model vs full-scale inlet. The magnitude of this Reynolds number sensitivity is probably configuration dependent and care should be taken when using the data in this paper. It is recommended that further studies be made to determine the geometric sensitivity. Once separation has occurred, the effect of the full scale engine (fan) is to reduce the extent of the distortion through a coupled interaction. This coupling effect can be simulated in inlet model tests by creating a choked condition at the fan location.

Acknowledgments

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