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8. SUMMARY OF LARGE-SCALE TESTS OF DUCTED FANS

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SUMMARY

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Several research areas which have been investigated by the NASA on large scale isolated ducted fan models are discussed. Research concerned with performance has indicated that: (1) ducted fan inlet design does not appear to be a major problem, (2) ducted fan nacelles must be very carefully designed, otherwise the drag becomes excessive, and (3) increasing fan tip clearance reduces the shroud thrust and reduces the capability of the fan for absorbing power. Research concerned with the occurrence of duct lip stall due to angle of attack indicates that neither inner nor outer duct lip stall for reasonably sized ducted fans is the problem that it was once considered to be.

Author

INTRODUCTION

Ducted fans have been proposed for many applications, from lifting, thrusting units for VTOL airplanes to propulsive units replacing jet engines for STOL airplanes. In this paper the term ducted fan will be used for all configurations which have a fan or propeller surrounded by a shroud or fairing. Hence configurations which range from ducted propellers (having pressure ratios of 1.03) to high bypass ratio turbofan engines (having pressure ratios of 1.30) will be called ducted fans. In this paper several research areas which have been investigated by the NASA on isolated ducted fan models will be considered. Figure 1 outlines the subjects to be covered. First the ideal performance of ducted fans will be discussed to review the basic performance characteristics of ducted fans. Then several research areas pertinent to performance will be discussed: namely, inlet losses, nacelle drag, and fan tip clearance. Next duct lip stall due to angle of attack will be considered. Both inner and outer lip stall will be covered.

NOTATION

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A_j duct exit flow area (see fig. 3)

A_f fan flow area (see fig. 3)

A_o upstream flow area (see fig. 3)

c_D external nacelle section drag coefficient, $\frac{\text{section drag}}{q(\text{overall frontal area})}$

C_D overall external nacelle drag coefficient, $\frac{\text{drag}}{q(\text{overall frontal area})}$

C_P power coefficient, $\frac{\text{power}}{\rho n^3 d^5}$

C_{ST} shroud thrust coefficient, $\frac{\text{shroud thrust}}{\rho n^2 d^4}$

C_T total thrust coefficient, $\frac{\text{total thrust}}{\rho n^2 d^4}$

d fan diameter, ft

M free-stream Mach number

n fan rotational speed, rps

P_L local static pressure, psf

P_S free-stream static pressure, psf

P_{T_i} total pressure at fan, psf

P_T free-stream total pressure, psf

q_i dynamic pressure at fan, psf

q free-stream dynamic pressure, psf

T_c total thrust coefficient, $\frac{\text{total thrust at } 0^\circ\ \alpha}{q\left(\frac{\pi d^2}{4}\right)}$

V forward velocity, fps

V_∞ forward velocity, knots

α angle of attack, deg

ρ mass density of air, slugs/cu ft

RESULTS AND DISCUSSION

Theoretical Considerations

To review the basic reason for studying ducted fans, theoretical ducted fan performance is compared with the actual performance of a turbojet engine.

The results are shown in figure 2. The ratio of ideal thrust-to-static-thrust (computed using compressible, isentropic flow tables assuming a perfect gas) is presented as a function of forward velocity for pressure ratios of 1.03, 1.1, and 1.3. The 1.03 pressure ratio is the approximate value for the ducted fans employed on the X-22A flight vehicle; 1.1 is the value for the models for which experimental results will be discussed later, and 1.3 is a representative value proposed for current V/STOL aircraft designs.

To illustrate the potential of ducted fans, the thrust required curve for a representative VTOL airplane is shown. It is apparent the thrust available curves for the ducted fans generally match the thrust required curve of the VTOL airplane much better than does the curve for the turbojet. For example at the point indicated, the thrust available for the 1.03 pressure ratio matches the thrust required. At this velocity the turbojet has much more thrust available than is required and would have to be operated at partial power to achieve a thrust-drag balance. This is, of course, an inefficient operating condition.

The theoretical curves presented in figure 2 were computed allowing the duct exit area to decrease with forward velocity to maintain a constant fan pressure ratio and flow velocity. The area ratios required will now be discussed briefly to illustrate the effect of pressure ratio. This will be done to allow a broader interpretation of the experimental results which were obtained at only one pressure ratio (1.1).

Figure 3 shows the theoretical inlet flow area variation and the exit area variation required to maintain fan pressure ratio and velocity. The left hand part of figure 3 shows the ratio of upstream-to-fan-flow area as a function of free-stream Mach number. The right hand part of figure 3 shows the ratio of exit-to-fan flow area as a function of free-stream Mach number. As can be seen, the variation in upstream-flow area with Mach number is greater as pressure ratio is reduced. It is also apparent that the variation in exit-flow area with Mach number is greater as pressure ratio is reduced.

This indicates that the problem of designing inlets and nozzles becomes greater as pressure ratio is reduced. Low pressure ratio ducted fans would probably require more inlet diffusion and hence longer inlets. In addition they would probably require longer exhaust nozzles to keep the exhaust flow angularity to an acceptable value.

This analysis has assumed a fixed blade angle fan. If a variable blade angle fan were employed, the large changes in inlet and exhaust area with Mach number would not be required. This is because the variable blade angle fan can tolerate variations in flow velocity and maintain reasonable efficiency as does a free propeller.

Inlet Studies

In practice inlet designs usually involve a compromise between static requirements and cruise requirements to avoid variable inlet geometry. Hence, there is the possibility of large inlet losses at either cruise or static conditions. In view of this, a summary of recent experimental inlet studies will now be examined. These studies involved testing the two ducted fans shown in figures 4 and 5. Both of these models had pressure ratios of about 1.1 and were quite similar to each other in arrangement. A gas generator was mounted directly to the top of the fan nacelle. The gas generator exhaust was distributed to turbine blades at the tip of the fan blades.

The primary physical differences between the two models were in the method of mounting and size. The model shown in figure 4 was supported by struts and had a 5-foot-diameter fan, while the model shown in figure 5 was sting mounted and had a 3-foot-diameter fan.

The test velocity ranged from 0 to 0.8 Mach number for the 3-foot model and from 0 to 0.2 Mach number for the 5-foot model.

The inlet studies performed on these models are summarized in figure 6. The loss in total pressure divided by the dynamic pressure at the fan is shown as a function of the ratio of free-stream to fan dynamic pressure. Shown at the top of the figure are half section views of the inlets. The 3-foot model was tested with three different inlets.

As can be seen from this figure the 5-foot model had a rather large inlet loss precisely at static conditions.[1] However, at very slight free-stream dynamic pressures, corresponding to about 10 to 20 feet per second, it dropped to below 0.05. As the inlet length was reduced, the inlet loss was reduced, and that of the shortest inlet was negligible.

At static conditions the inlet loss corresponds precisely to the reduction in static thrust. As free-stream dynamic pressure is increased, the loss in thrust becomes a smaller part of the inlet loss divided by dynamic pressure at the fan. In view of this, and because the inlet losses decrease with free-stream dynamic pressure, the magnitude of the inlet losses is not considered serious.

It may be inferred from the theoretical discussion earlier that ducted fans with higher pressure ratios would probably have lower inlet losses than these fans because fewer inlet design compromises are required. (At least for Mach numbers ranging from 0 to 0.8.)

Nacelle Drag

The external nacelle drag of ducted fans is a potential major problem. Figure 7 summarizes the low-speed nacelle drag results obtained from investigations performed on the 5-foot-diameter ducted fan shown before. A sketch of the front view of the ducted fan is shown on the left of the figure. A summary of the drag results obtained at windmill conditions is given on the right. Section drag based on frontal area is shown as a function of azimuth angle. These drag values were obtained from flow momentum surveys at the nacelle trailing edge.

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[1]See references 1 and 2 for a more detailed discussion of the aerodynamic characteristics of this model.

At 0° azimuth the drag coefficient is about 0.1, at 90° azimuth it reaches a maximum of about 0.5, and at 180°, a minimum of about 0.04. This minimum value is considered representative of the value which could be obtained on an isolated fan nacelle, that is, without the gas generator on top of the nacelle and without support struts. The value of 0.04 is reasonably low, more than half of which can be attributed to friction drag.

Near the 90° azimuth location the drag coefficient is shown as a dashed line because of the influence of the horizontal support struts and the resulting uncertainty of the nacelle drag. It is evident that the strut adversely affects the drag of a considerable area of the nacelle. This suggests that interference drag should be carefully considered on aircraft having strut mounted ducted fans.

At 0° azimuth the drag coefficient is significantly higher than the value at 180° because the flow on the engine fairing was separated.

In figure 8 the nacelle drag obtained from high-speed windmill tests of the 3-foot-diameter ducted fan is summarized. This drag was obtained from balance data and is the overall external nacelle drag. Drag coefficient based on frontal area is shown as a function of Mach numbers for the three inlet configurations. In addition, the minimum section drag coefficient for the 5-foot model is shown along with the estimated friction drag. The friction drag is shown as a band because of the variation in wetted surface area for the different configurations.

Comparison of the low-speed drag coefficients of the 3-foot model with the friction drag and minimum section drag of the 5-foot model suggests that the overall drag of the 3-foot model is high. This is probably because of flow separation on the nacelle fairing around the gas generator.

As shown, the primary difference in drag characteristics between the three inlets is in the value of the drag divergence Mach number. The lowest drag divergence Mach number was only about 0.4, while the highest was 0.6. Both values are about 0.2 lower than the design value. Pressure surveys indicated that this was probably due to the nacelle fairing around the engine.

This is suggested by the results shown in figure 9 for the long inlet. The minimum surface static pressure coefficient is presented as a function of Mach number. The results for three azimuth positions are shown. The divergence Mach number for the 180° station was 0.8. (This is the design value and would be comparable to that for an isolated fan.) For the 30° azimuth station the divergence Mach number is 0.7. No pressure coefficient data were available for the 0° azimuth station. However, the divergence Mach number is probably near 0.6 where the drag divergence shown in figure 8 occurred.

These results suggest that isolated nacelles for low pressure ratio fans can probably be designed with high drag divergence Mach numbers. However, considerable care must be exercised when designing nacelles for configurations which have the engine mounted directly to the fan nacelle.

The significance of the drag coefficient values which have been shown are illustrated in figure 10. Thrust divided by static thrust is shown as a function of forward velocity for 1.1 and 1.3 pressure ratios. The ideal thrust is shown along with the ideal thrust less the external nacelle drag. This drag was computed for drag coefficients of 0.04 and 0.066. (As previously discussed, 0.04 was the minimum section drag coefficient for the 5-foot model and 0.066 was the minimum overall drag coefficient for the 3-foot model.) The drag was computed assuming a ratio of nacelle frontal area-to-fan area of 1.5. As can be seen, increasing the drag coefficient from 0.04 to 0.066 reduces the thrust a significant amount. In addition, the ducted fan with the lower pressure ratio is more sensitive to variations in drag coefficient; that is, the incremental reduction in thrust is much larger for the low pressure ratio fan than it is for the high pressure ratio fan.

Fan Tip Clearance

For shaft-driven ducted fans the minimization of the fan tip clearance is essential for achieving maximum performance. However, this is not compatible with the usual structural requirements, which dictate a reasonable magnitude of tip clearance to prevent fan-shroud interference. Hence it is necessary to precisely define the reduction in performance due to increased tip clearance. In view of this, studies were performed on a 7-foot-diameter, shaft-driven ducted fan. This model is shown in figure 11. It employed a three-bladed propeller with variable pitch and had a static pressure ratio of about 1.03. This ducted fan was a full-scale model of that employed on the X-22A VTOL airplane.

Figure 12 shows representative tip clearance effects on thrust and power coefficient at constant blade angle. Thrust and power coefficients based on fan rotational velocity are presented as functions of advance ratio for two values of tip clearance. Both shroud thrust and total thrust coefficient are shown. As might be expected, the incremental thrust loss due to tip clearance decreased with advance ratio.

The effects of tip clearance on static performance are examined in more detail in figure 13. On the left in figure 13 thrust and power coefficients are presented as functions of the ratio of tip clearance to diameter. Results are shown for the 7-foot-diameter model and for the 4-foot-diameter model of reference 3. Comparison of the shroud thrust with total thrust indicates that, for ratios of tip clearance to diameter up to 0.02, the loss in thrust is primarily due to shroud thrust loss. Hence, the fan thrust, which is the difference between the total and shroud thrust, is essentially unaffected by the increase in tip clearance.

The power results presented on this figure indicate that, not only is the thrust reduced with increased tip clearance, but the power is reduced as well. Hence, increasing the tip clearance reduces the ability of the fan to absorb power.

Comparison of the results for the 7-foot model with the 4-foot model indicates large differences in the power and thrust coefficient variations with tip clearance. The power coefficient variation for the 4-foot model is much flatter than that for the 7-foot model. The shroud thrust is also flatter, although it is not as obvious in the figure. The net effect of the differences are shown in the right hand part of the figure. Here shroud thrust coefficient divided by power coefficient is shown as a function of the tip clearance ratio. The reduction in performance of the 7-foot model as tip clearance is increased is much less than that for the 4-foot model, indicating that the 7-foot model was much less sensitive to increasing tip clearance.

The significance of the results obtained from the 7-foot model may be interpreted in terms of the X-22A flight vehicle. If the power is maintained constant at the maximum of 1250 hp per duct, an increase in tip clearance from 1/4 to 1-1/2 inches would result in a static thrust loss of about 10 percent.

Duct Lip Stall

Ducted fans which are tilted with respect to the airstream during low speed lifting conditions may encounter stall of either the inner or outer duct lip. Previous small scale investigations have indicated this to be a potential major problem area. Stall of the inner lip is of primary concern because it is more heavily loaded and would result in a larger reduction in lift when stalled. In addition, stall of this lip affects the fan loading asymmetrically.

In figure 14 the inner lip stall boundaries are summarized for several ducted fan models. The small sketch shows what is meant by inner lip stall. The angle of attack at which complete stall occurs is shown as a function of the reciprocal of the thrust coefficient based on free-stream dynamic pressure. For angles of attack above these curves the flow is completely separated. For angles less, the flow is either not separated or only partially separated.

The configurations investigated are shown by scale drawings with the respective leading-edge radii indicated. The upper surface is the inside surface of the shroud. As can be seen from the drawings, the two X-22A models and the VZ-4 model are very similar and differ primarily only in scale. Comparison of the lip stall boundaries for the VZ-4[2] and the small scale X-22A model indicates a sizable scale effect. However, the VZ-4 boundary and the full scale X-22A boundary were identical. These results suggest the for a given shape of shroud or duct there is a certain minimum value of lip radius required to achieve the stall angle indicated by the upper boundary. The boundary for the 5-foot model was lower than the boundaries for the other full scale ducts. This was probably because of the lip camber used on the 5-foot model.

Outer lip stall has also been a problem for small scale ducted fan models. In view of this, the outer lip stall boundary for the small scale and full scale X-22A model was examined. The results are shown in figure 15. The sketch shows what is meant by outer lip stall. The angle of attack at which complete

[2]See reference 4 for a more detailed discussion of the inner lip stall boundary for this model.

stall occurs is shown as a function of the reciprocal of the thrust coefficient. These results are similar to those for inner lip stall in that there is a large effect of scale.

As discussed in paper number 9 by Mr. Maki, outer duct lip stall would probably not be encountered by a flight vehicle such as the X-22A. Inner lip stall would only be encountered during flight at high descent rates. The X-22A employs ducted fans having a pressure ratio of 1.03. To investigate the significance of pressure ratio on the lip stall boundaries for flight vehicles, the lip stall boundaries for the vehicle described by Mr. Hickey in the preceding paper were determined.[3] These boundaries were determined assuming the use of 1.3 pressure ratio ducted fans. The results are shown in figure 16.

The level unaccelerated trim curve is shown along with the inner lip stall boundary. The outer lip stall boundary was too far away from the trim curve to appear on this figure. Hence it is not considered to be a problem. In addition, it is apparent from these results that inner lip stall would not be a problem either for this vehicle because of the large duct angle margin between the trim curve and the stall curve. Inner lip stall would not be encountered even at very high rates of descent.

In view of this discussion it is apparent that neither inner nor outer duct lip stall for reasonably sized ducted fans is the problem that it was once considered to be.

CONCLUDING REMARKS

From the discussion contained in this paper the following conclusions can be made.

1. Inlet design does not appear to be a major problem on 1.1 pressure ratio ducted fans as far as inlet losses are concerned. In view of this it would probably not be a problem on higher pressure ratio ducted fans. Hence variable inlet geometry probably would not be required.

2. Nacelle fairings must be carefully designed for ducted fans, especially those for low pressure ratio ducted fans. Otherwise the losses due to drag become excessive. The results also suggest that for isolated nacelles, high drag divergence Mach numbers can be achieved. However, if the engine is mounted on the nacelle, then considerable care is required to achieve high drag divergence Mach numbers.

3. Thrust continues to decrease with increasing fan tip clearance. Hence, the desirability in minimizing fan tip clearance is apparent. In addition, the capability for absorbing power is reduced as fan tip clearance is increased.

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[3]The boundaries were determined using the results shown in figures 14 and 15 for the full scale X-22A model.

4. For flight vehicles which employ tilting ducted fans, duct lip stall due to angle of attack does not appear to be a major problem. Inner lip stall would only be encountered during high descent rates. This becomes even less of a problem if high pressure ratio ducted fans are employed. Outer lip stall would probably never be encountered during flight.

REFERENCES

1. Giulianett, Demo J.; Biggers, James C.; and Corsiglia, Victor R.: Wind Tunnel Test of a Full-Scale, 1.1 Pressure Ratio, Ducted Lift-Cruise Fan. NASA TN D-2498, 1964.

2. Przedpelski, Z. J.; Heikkinen, A. H.; and Vacek, L.: Aerodynamic Investigation of Low Speed VTOL Transition Characteristics of X353-5B Cruise Fan. General Electric Report Number R63FPD426, Dec. 1963.

3. Hubbard, Harvey H.: Sound Measurements for Five Shrouded Propellers at Static Conditions. NACA TN 2024, 1950.

4. Mort, Kenneth W.; and Yaggy, Paul F.: Aerodynamic Characteristics of a 4-Foot-Diameter Ducted Fan Mounted on the Tip of a Semispan Wing. NASA TN D-1301, 1962.

SUBJECTS TO BE COVERED

- IDEAL PERFORMANCE OF DUCTED FANS
- PERFORMANCE RESEARCH AREAS
  - INLET LOSSES
  - NACELLE DRAG
  - FAN TIP CLEARANCE
- ANGLE-OF-ATTACK RESEARCH AREAS
  - INNER LIP STALL
  - OUTER LIP STALL

Figure 1

COMPARISON OF IDEAL THRUST OF DUCTED FANS WITH TURBOJET THRUST

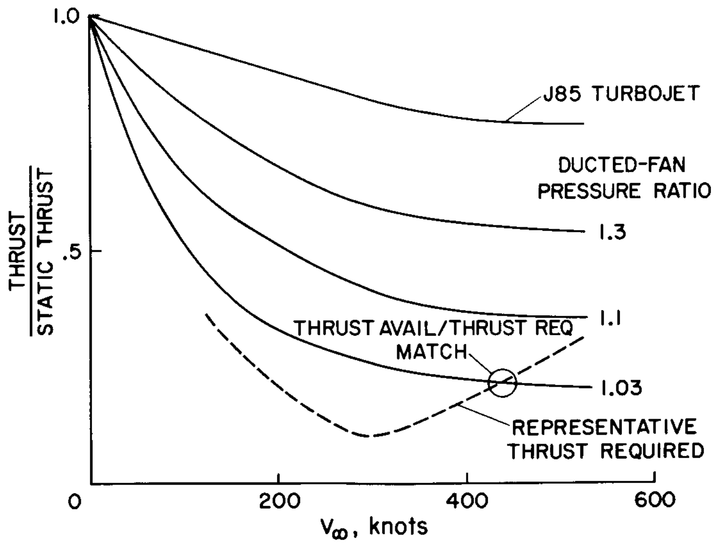

Figure 2

IDEAL FLOW AREA RATIOS OF DUCTED FANS

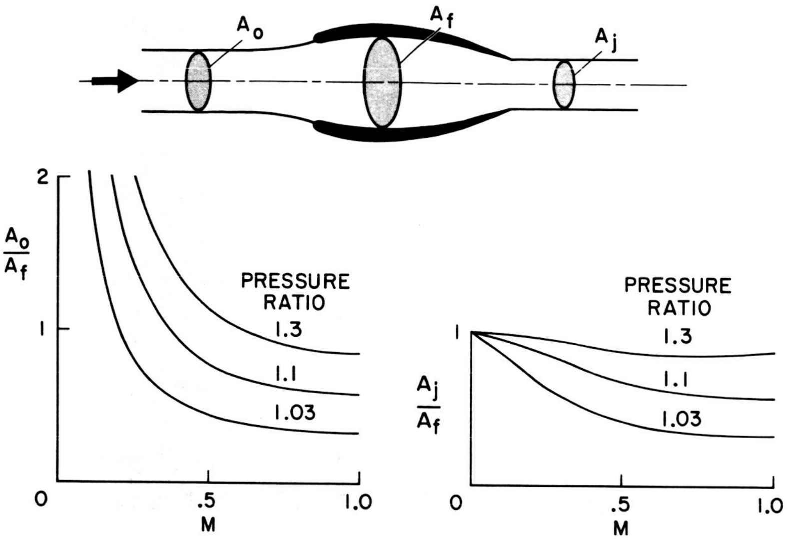

Figure 3

5-FOOT-DIAMETER, 1.1 PRESSURE RATIO DUCTED FAN

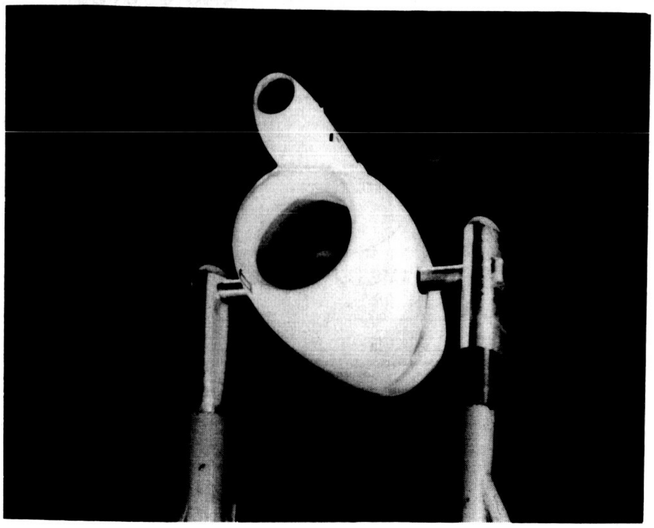

Figure 4 A-31081

3-FOOT-DIAMETER, 1.1 PRESSURE RATIO DUCTED FAN

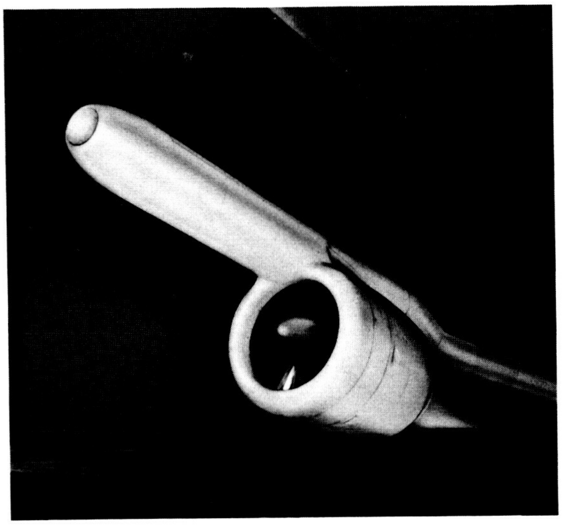

Figure 5 L-65-4553

EFFECT OF INLET GEOMETRY ON INLET TOTAL PRESSURE LOSSES, 1.1 PRESSURE RATIO DUCTED FANS

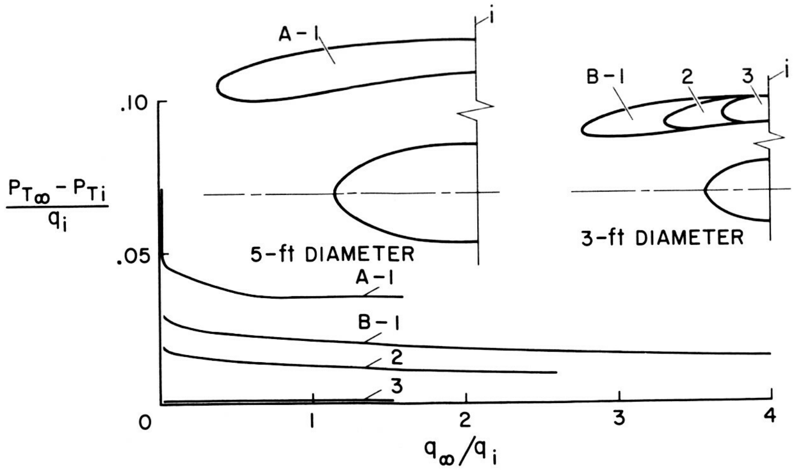

Figure 6

NACELLE DRAG OF 5-FOOT-DIAMETER,
1.1 PRESSURE RATIO DUCTED FAN

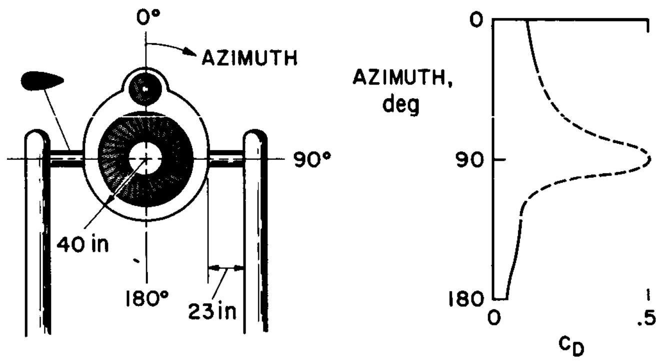

Figure 7

NACELLE DRAG OF 3-FOOT-DIAMETER,
1.1 PRESSURE RATIO DUCTED FAN

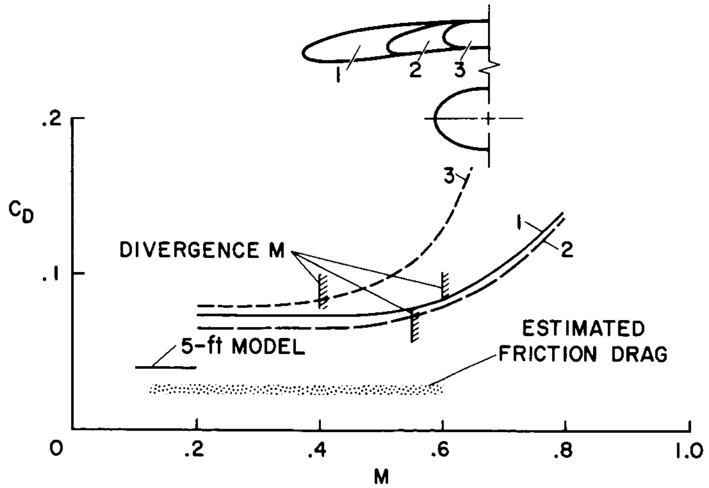

Figure 8

PEAK PRESSURE COEFFICIENT FOR 1.1 PRESSURE RATIO, 3-FOOT-DIAMETER DUCTED FANS

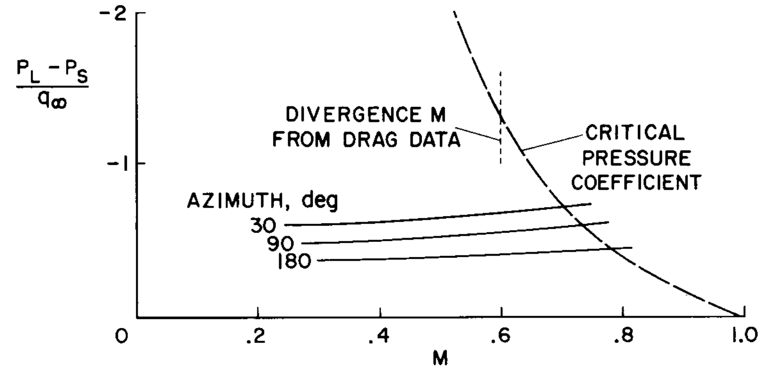

Figure 9

EFFECT OF NACELLE DRAG ON THRUST
FRONTAL AREA/FAN AREA = 1.5

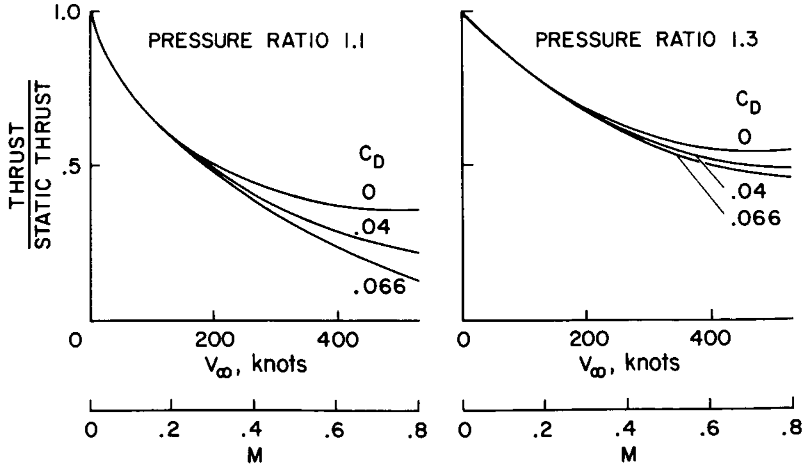

Figure 10

X-22A FULL-SCALE DUCTED FAN, 7-FOOT DIAMETER

Figure 11 A-33770.1

THRUST AND POWER COEFFICIENTS FOR TWO TIP CLEARANCES

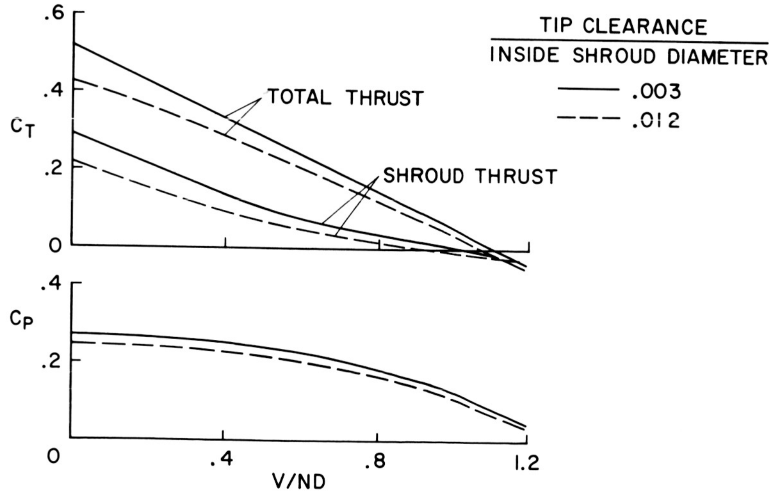

Figure 12

EFFECTS OF TIP CLEARANCE ON STATIC PERFORMANCE

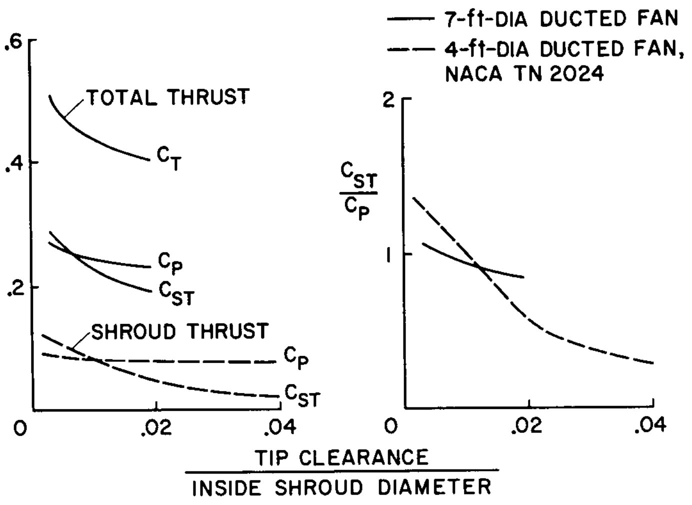

Figure 13

DUCT ANGLE OF ATTACK AT WHICH INNER LIP STALL OCCURS

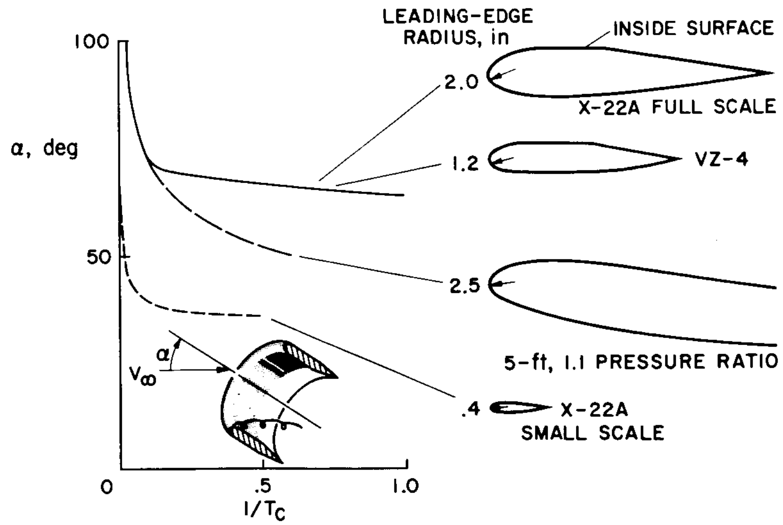

Figure 14

DUCT ANGLE OF ATTACK AT WHICH OUTER LIP STALL OCCURS

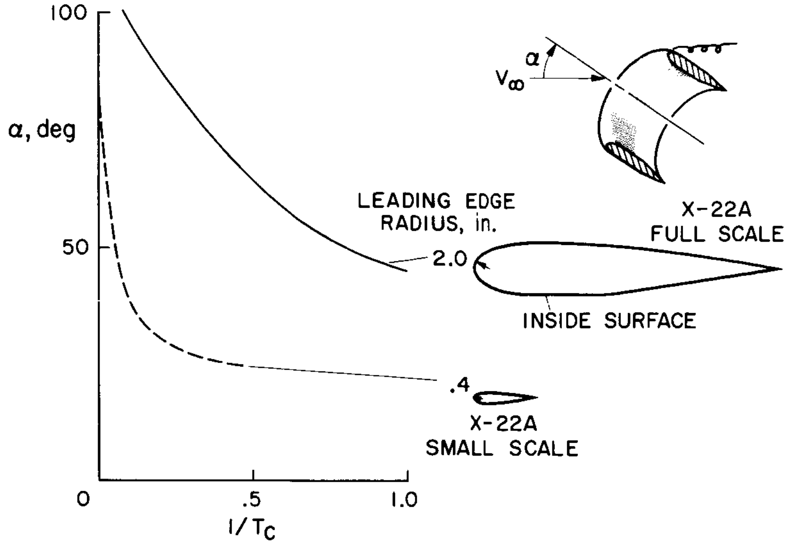

Figure 15

PREDICTED INNER LIP STALL BOUNDARY FOR VEHICLE EMPLOYING 1.3 PRESSURE RATIO DUCTED FANS

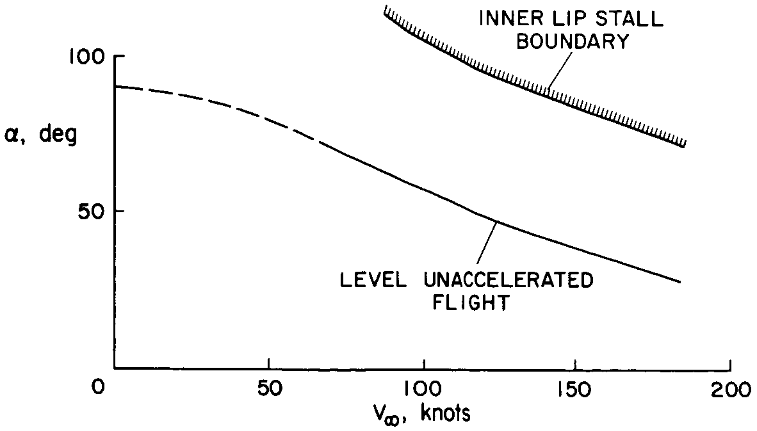

Figure 16