Performance of a Cascade Thrust Reverser for Short-Haul Applications

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Aerodynamic and acoustic characteristics are presented for a cowl-mounted, model cascade thrust reverser suitable for short-haul aircraft. Thrust reverser efficiency was determined from isolated fan-driven models under static and forward velocity conditions. Cascade reverser noise characteristics were determined statically in an isolated pipe-flow test, whereas aerodynamic installation effects were determined with a wind-tunnel, fan-powered airplane model. Application of test results to short-haul aircraft calculations demonstrates that such a cascade thrust reverser may be able to meet both the performance and noise requirements for short-haul aircraft operation. However, aircraft installation effects can be quite significant.

Nomenclature

a/g	= aircraft deceleration as a fraction of the acceleration due to gravity
b_c	= cascade length (distance from the leading edge of the initial cascade blade to the blocker door), m
b_s	= stator-reverser spacing distance (distance from stator exit to cascade inlet), m
C_D	= aerodynamic drag coefficient, aerodynamic drag$/qS$
C'_D	= airplane-model-measured drag coefficient, drag (including reverse thrust)$/qS$
C_L	= aerodynamic lift coefficient, aerodynamic lift$/qS$
C'_L	= airplane-mode-measured lift coefficient, lift (including effect due to reverse thrust)$/qs$
d	= fan duct diam, 15.2 cm
d_t	= fan tip diam, 14.0 cm
f_c	= ⅓ octave band center frequency, Hz
g	= acceleration due to gravity, 9.8 m/sec^2
N	= model fan rotational speed
N_d	= model fan design rotational speed, 35,800 rpm
N/N_d	= fraction of design rotational speed, %
P	= total pressure, N/m^2
PNL	= perceived noise level, PNdB
PWL	= sound power level for each ⅓ octave band, dB re 10^{-13} W
p_a	= ambient pressure (static tests), N/m^2
p_s	= static pressure, N/m^2
q	= freestream dynamic pressure, $\frac{1}{2}\rho_0 V_0^2$
S	= wing area, m^2
T	= thrust, N
T_{to}	= static ($V_0 = 0$) thrust for engine at takeoff power setting
T/W	= thrust to weight ratio
V_0	= aircraft forward velocity during ground roll (freestream velocity), m/sec
V_{rc}	= reverser flow recirculation velocity (freestream velocity at which the onset of recirculation occurs), m/sec
V_t	= reverser termination velocity (freestream velocity at which the reversing operation is terminated), m/sec

Introduction

THE application of thrust reversing to short-haul aircraft operation differs from the case of conventional aircraft because of the shorter field length, higher thrust-to-weight ratio, and lower landing speeds of short-haul aircraft. The thrust reverser for these applications should be similar to those on present conventional aircraft in that it must generate sufficient reverse thrust to stop the airplane after touchdown, minimize the additional required weight, eliminate reingestion of hot exhaust flow, and avoid jet impingement on the ground. During the period of reversing, neither the engine operating point nor the internal flow quality should be affected adversely, since this may result in reduced stall margin, reduced thrust, increased fan noise, and increased blade vibrational stress.

High thrust reversing efficiencies in conjunction with the higher installed thrust-to-weight ratio of short-haul aircraft can be used to advantage in reducing reverser-related noise; however, the general application of a high-efficiency reverser to an aircraft in terms of both performance and noise has not been considered previously. Previous studies[1,2] have considered the aerodynamic performance of cascade thrust reversers applied to current high bypass ratio engines, but neither reference includes a discussion of the acoustic characteristics of an engine during the reversing operation. However, the acoustic characteristics of some model cascade thrust reversers have been determined, and the results indicate that reverser noise levels can be very significant. It has been shown[3] that reverser noise is a function of exhaust flow pressure ratio, cascade geometry, and reverser efficiency, and that high-efficiency reversers produce less noise than low-efficiency reversers.

One way in which the reverser noise may be reduced is to reduce the engine power setting, which reduces the engine noise, but this procedure requires a highly efficient thrust reverser so that the aircraft deceleration is sufficient for all stopping operations. In brief, a balance is required between thrust reverser efficiency, thrust reverser noise, and engine power setting in order to meet both the performance and noise goals.

The approach of this paper is first to consider a representative short-haul aircraft in terms of ground deceleration performance and reverser requirements. From this analysis, the range of interest of reverser power settings is determined. By use of an example reverser, data are shown to illustrate isolated fan/reverser thrust performance, the performance of four fan/reverser systems installed on a model airplane, and isolated reverser noise characteristics.

The material presented in this paper was obtained from three different test programs. All of the tests used the same small-scale cascade thrust reverser, which had a geometric circumferential emission angle of 241.2° and a design turning angle of 135°. All of the tests except the measurement of noise characteristics used a model fan, which was 14.0 cm in diam and operated at a design pressure ratio of 1.25. The noise

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measurements were made by exhausting a supply of unheated air through the reverser. The installed reverser characteristics were determined by use of an airplane model that had four similar fan/reverser systems. Tests were conducted under static conditions and in a wind tunnel with freestream velocities ranging up to 41 m/sec. The model fan rotational speed was varied from 60 to 100% of the fan design speed.

Reverser Operating Requirements

The first consideration of the reverser operating requirements is the deceleration performance of a short-haul aircraft, which is determined for assumed aerodynamic characteristics and runway conditions. The aircraft reversing effectiveness ϵ is defined as the increase per unit thrust-to-weight ratio in aircraft deceleration with the reversers operating and without the reverser operating, i.e.,

$$\epsilon \equiv \frac{(a/g)_r - (a/g)_{nr}}{(T/W)_{to}} \tag{1}$$

Solving the force balance equation for the aircraft reversing effectiveness yields

$$\epsilon = \frac{1}{(T/W)_{to}} \left\{ \left[\frac{a}{g} \right]_r - \frac{C_D \rho_0 V_0^2}{2(W/S)} - \left[1 - \frac{C_L \rho_0 V_0^2}{2(W/S)} \right] \mu \right\} \tag{2}$$

Figure 1 shows the required aircraft thrust reversing effectiveness ϵ as a function of the airplane deceleration $(a/g)_r$ for values of the parameters described in Table 1. As shown in Fig. 1, for a fixed aircraft deceleration, decreasing the forward velocity significantly increases the required reversing effectiveness because of the reduced aerodynamic drag force. However, an opposing trend is introduced because a high thrust-to-weight ratio significantly reduces the required reversing effectiveness. Thus, short-haul aircraft with low landing speec and high installed thrust present a design challenge for thrust reversing systems.

The thrust reverser efficiency η_r, which is a measure of the internal flow performance and discharge angle of the cascade vanes, is defined as the ratio of the reverse thrust to the static ($V_0 = 0$) forward thrust with the engine at the same power setting. Assuming no interactions between the thrust reverser and the other retarding forces, the reversing effectiveness

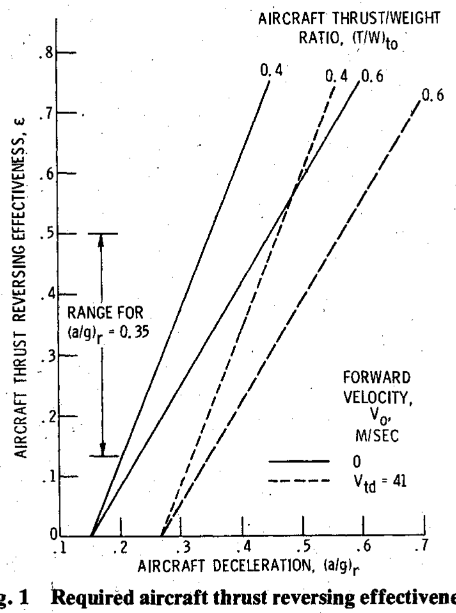

Fig. 1 Required aircraft thrust reversing effectiveness.

Table 1 Assumed aircraft characteristics during thrust reversing

Symbol	Value	Remarks
C_D	0.5	Typical values
C_L	0	Typical values
W/S	100	Typical values
μ	0.15	Wet/icy runway or partial braking
$(T/W)_{to}$	0.4, 0.6	Range for short haul aircraft
V_0	0, 41 m/sec	Static and touchdown (landing) conditions

Table 2 Reverser geometry and fan operating parameters

Reverser geometric parameters		Fan operating parameters		
Spacing ratio, b_s/d	Cascade length, b_c/d	Thrust setting, T/T_d	Percent-design speed, N/N_d	Total pressure ratio, P_2/P_a
0.10	0.58	0.4	60	1.08
...	...	0.6	75	1.14
...	...	1.0	100	1.25

ϵ also can be expressed as

$$\epsilon = T_r / T_{to} \tag{3}$$

Then, from Eq. (3), the relationship between the engine thrust setting and the reverser efficiency becomes

$$\text{engine thrust setting} = T_{f,a} / T_{to} = \epsilon / \eta_r \tag{4}$$

Equation (4) is plotted in Fig. 2 for constant values of reversing effectiveness. The area between the curves shown on Fig. 2 encloses the range of reverser effectiveness derived from Fig. 1 for a deceleration $(a/g)_r$ of 0.35. Figure 2 illustrates that reducing the engine thrust setting for the purpose of reducing noise, or for other reasons, requires increased reverser efficiency to maintain the same aircraft deceleration.

A representative case, $\epsilon = 0.3$, is shown on Fig. 2 as the median of the values in order to simplify the analysis. For the representative case, engine thrust settings for reversing of 1.0, 0.6, and 0.4 correspond to approximate reverser efficiencies of 0.30, 0.50, and 0.75, respectively, and are indicated by the solid symbols on Fig. 2. This range of reverser efficiency ($0.3 \leq \eta_r \leq 0.75$) specifies the range of interest in this paper. The values of the engine thrust setting (1.0, 0.6, and 0.4) will be used throughout this paper to illustrate the aerodynamic and acoustic characteristic of the model reverser/fan system.

Apparatus

The data presented in this paper were obtained from three test programs: wind-tunnel isolated fan/reverser thrust tests, installation effects on a four-fan airplane model in a wind tunnel, and single reverser acoustic tests. All of the tests used the same thrust reverser, and all except the acoustic tests used the same model fan.

Thrust Reverser

The thrust reverser (Fig. 3) consisted of eight replaceable cascade sectors and two axial support rails located 180° apart. Each cascade sector subtended a circumferential flow angle of 40.5° and was replaceable by a solid sector, which provided circumferential blockage of the flow. The data in this paper were limited to a single geometry, where the total emission was through six cascade sectors. The reverser configuration had two solid (nonflow) sectors located at the bottom of the nacelle as shown in Fig. 3a, and a total flow emission angle of 241.2°. The flow was turned into the cascade reverser by a blocker door which had a forward sloping surface of 45° and

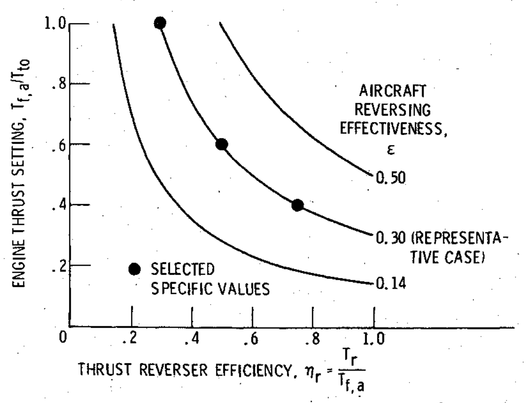

Fig.2 Relationship between engine thrust setting and thrust reverser efficiency.

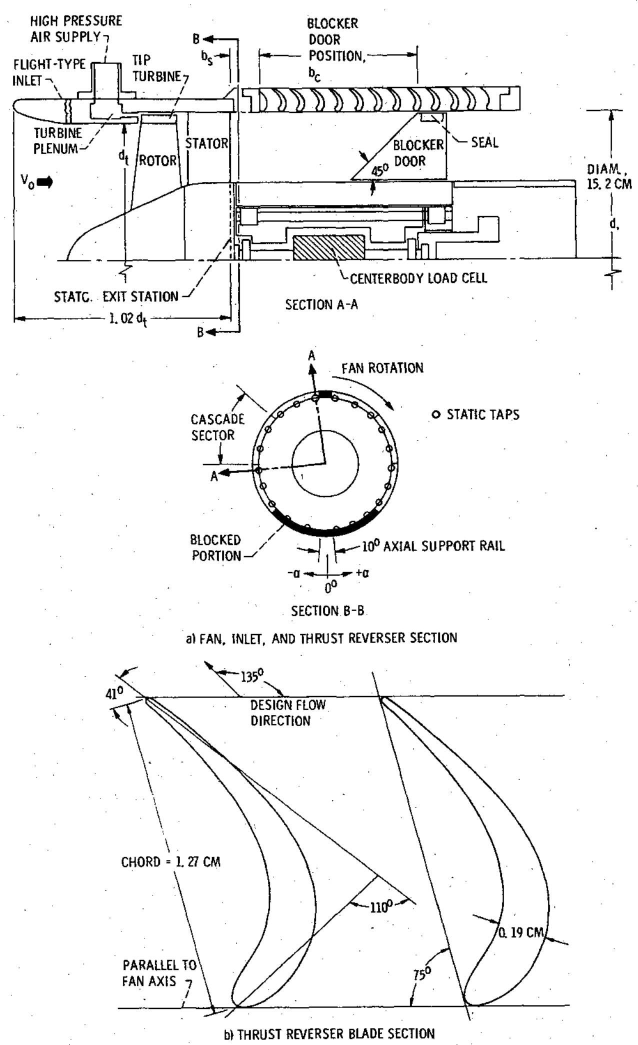

Fig. 3 Fan/reverser model.

seals to prevent flow leakage axially (Fig. 3a). The blocker door was axially translatable to provide a variation of the cascade length b_c and the open (exit) flow area of the thrust reverser.

The design of the cascade reverser blades was reported[4] previously, and is reviewed briefly here. The impulse-type cascade blades (Fig. 3b) had an airfoil shape with a maximum thickness of 15% of the blade chord. The blade chord length and solidity were 1.27 cm and 1.3, respectively. The chord length is assumed to be about half that which would be expected on a full-size engine installation. The design turning angle for the flow was 135°, which required a camber of 110° and mean line slope at the trailing edge of 41° (Fig. 3b). For an outlet flow angle of 135°, the reversing efficiency η_r would be expected to be about 0.7, and would be representative of the reverser required for low-thrust setting ($T_{f,a}/T_{to}=0.4$) operation described previously.

The shortest possible spacing distance b_s (Fig. 3a) represented the most severe coupling between fan and reverser, and that spacing ($b_s/d=0.10$) was selected for the configuration used in the test programs. A value of the blocker door position b_c/d of 0.58 was chosen for the tests as the best value to match the forward- and reverse-thrust fan characteristics over the entire range of percent design rotational speed. A summary of the reverser geometry and the fan operating parameters is given in Table 2.

Model Fan and Inlets

The fan had a rotor tip diameter of 14.0 cm, and at the design rotational speed of 35,800 rpm passed a mass flow of 2.49 kg/sec at a pressure ratio of 1.25. The fan was driven by a tip turbine which, at the fan design speed, required a mass flow of 0.47 kg/sec of unheated air at a pressure of 2590 kN/m^2 in the turbine plenum. Further information on the basic fan was reported elsewhere.[5,6]

Two inlet arrangements were used during the aerodynamic performance test series: an extended bellmouth inlet plus recirculation barrier for static tests and a flight-type inlet without a recirculation barrier (Fig. 3a) for both static and wind-tunnel tests. The bellmouth inlet was used only when the recirculation barrier was installed and located 4.3 fan tip diameters forward of the fan stator exit plane. The flight-type inlet (Fig. 3a) had a symmetrical lip made up of quadrants of two 2.1 ellipses and an inlet contraction ratio (highlight-to-throat area ratio) of 1.29. With the flight-type inlet, the cowl from inlet highlight to stator exit had a length of 1.02 fan tip diameters (Fig. 3).

Airplane Model

A three-view drawing of the airplane model with dimensional characteristics is presented in Fig. 4. The model had a high wing and no tail. The airfoil section of the wing was NACA 4415, and a double slotted flap with the last flap deflected 60° was used throughout the tests. The wing had a 0.3505 m mean aerodynamic chord, a 35° quarter-chord sweep angle, a 2.54-m span, a 0.8903 m^2 planform area, and a 7.25 aspect ratio. Four under-the-wing fan/reverser assemblies with the geometry previously described were installed on the airplane model. The centerline of each fan was located two fan tip diameters above a stationary flow splitter plate to simulate the relative location of the airplane with respect to the ground during a landing gound roll.

Results and Discussion

In the following sections, the results of the test programs to determine the thrust performance of the isolated and installed fan/reverser systems are considered, together with calculations of aircraft performance based on these data. The presentation of reverser acoustic data concludes the discussion.

Isolated Thrust Reverser Efficiency

The thrust reverser efficiency for a single-isolated fan/reverser system was determined from tests in a low-speed wind tunnel.[7] Figure 5 presents the results in the form of thrust reverser efficiency η_r as a function of the ratio of freestream velocity V_0 to the average fan outlet flow velocity V_j. Ideally, the denominator of the velocity ratio should be the cascade discharge velocity. However, the average fan outlet flow velocity was assumed to be representative of the reverser outlet velocity (i.e., perfect impulse flow across cascade), and a correlation between the calculated V_j values and the measured fan rotational speed was used to determine the average fan outlet flow velocity used in Fig. 5. The use of

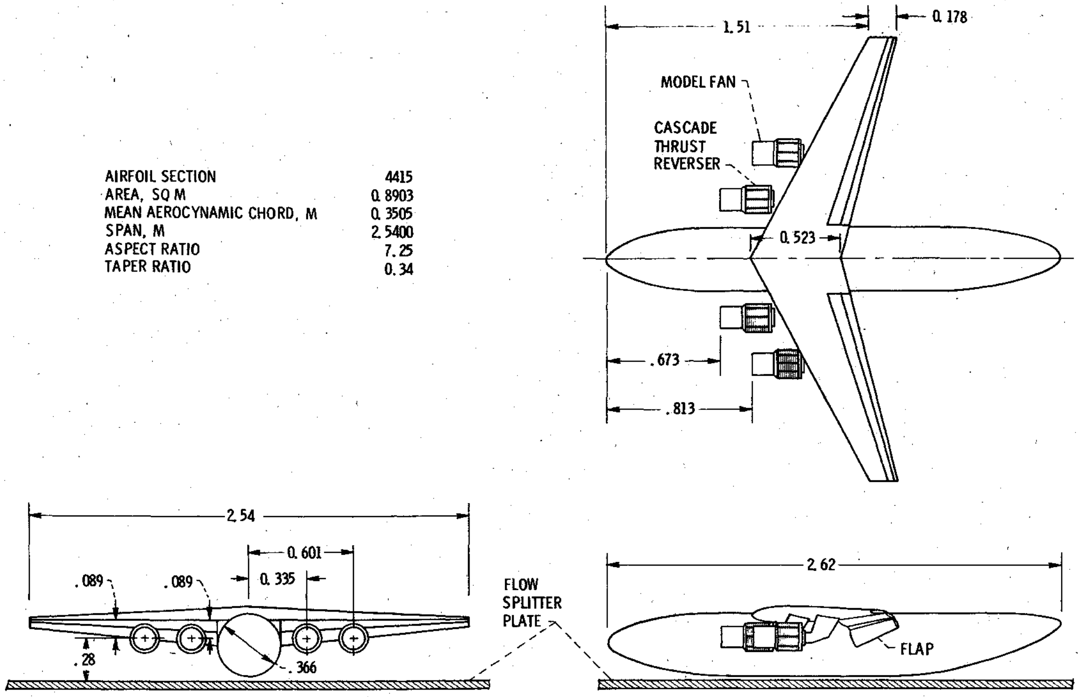

Fig. 4 Airplane model including four fan/reverser systems (all dimensions in meters).

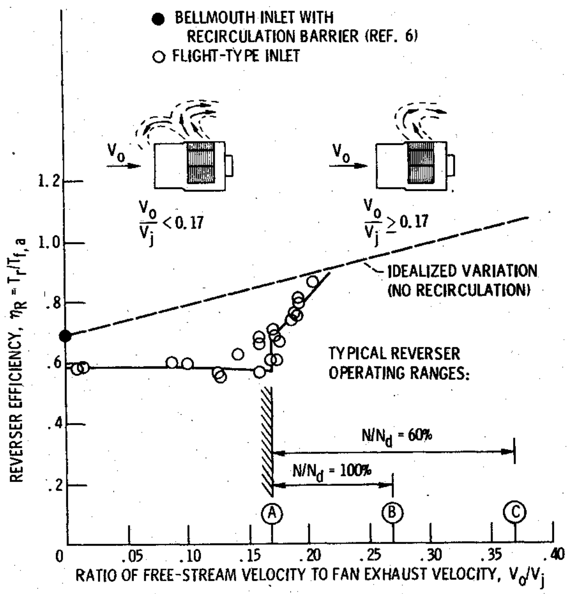

Fig. 5 Isolated thrust reverser efficiency.

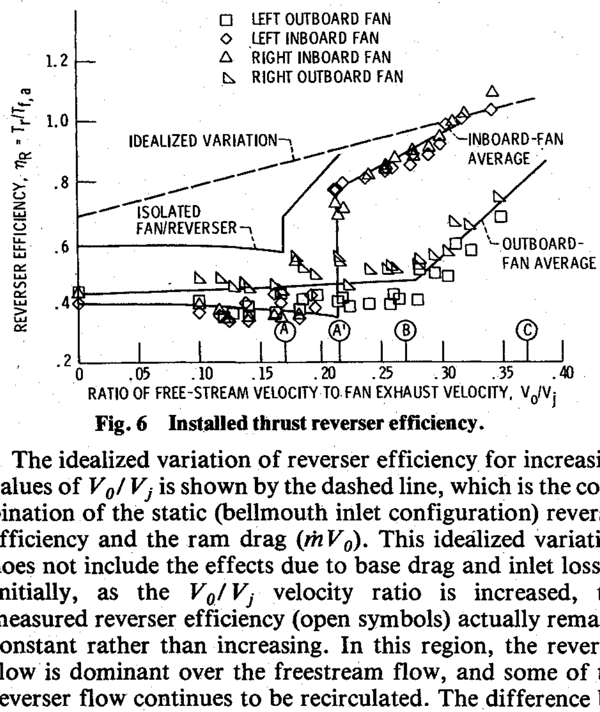

Fig. 6 Installed thrust reverser efficiency.

the V_0/V_j velocity ratio nondimensionalizes the data and permits a comprehensive analysis of the results to be made. The thrust reverser efficiency η_r was determined as the ratio of the measured fan/reverser system thrust to the measured static ($V_0=0$) forward thrust of the forward thrust configuration (no reverser) at the same fan rotational speed. The fan thrust measurement was made using a single component load cell aligned with the fan axis.

The interaction of the reverser flow and the freestream flow is a very complex process that involves several distinct regimes. The solid symbol on Fig. 5 represents the value for the static ($V_0=0$) reverser efficiency[6] using a bellmouth inlet and recirculation barrier, which was used to prevent recirculation of the reversed flow. At the static condition, a significant reduction of the reverser efficiency from 0.69 to 0.58 occurs when the barrier is removed and bellmouth inlet is replaced by the flight-type inlet. This reduction in reverser efficiency is attributed to the recirculation of some of the exhaust flow.[4]

The idealized variation of reverser efficiency for increasing values of V_0/V_j is shown by the dashed line, which is the combination of the static (bellmouth inlet configuration) reverser efficiency and the ram drag ($\dot{m}V_0$). This idealized variation does not include the effects due to base drag and inlet losses. Initially, as the V_0/V_j velocity ratio is increased, the measured reverser efficiency (open symbols) actually remains constant rather than increasing. In this region, the reverser flow is dominant over the freestream flow, and some of the reverser flow continues to be recirculated. The difference between the idealized variation and the data implies that the percentage of the exhaust flow being recirculated has increased with increased V_0/V_j in this region.

At a V_0/V_j ratio of approximately 0.17 (point A on Fig. 5), the freestream flow deflects the reversed exhaust flow sufficiently so that recirculation is eliminated. Once the recirculation of the exhaust flow is eliminated, the reverser efficiency becomes approximately 0.7 and increases with increasing freestream velocity due to the increase in ram drag and base drag with forward speed. A similar result for a cascade thrust reverser is discussed elsewhere.[8]

The effect of low fan rotational speed (or low thrust setting) operation on the thrust reverser efficiency during reversing also is illustrated by Fig. 5. During the reverser operation on an aircraft, the V_0/V_j ratio decreases from a relatively high value to a low value because of the deceleration of the aircraft. By operating the fan at a reduced rotational speed, the value of V_j is correspondingly decreased. For example, for a fixed landing speed, say 41 m/sec, the values of V_0/V_j are 0.27 and 0.37 for 100 and 60% design rotational speeds, respectively. These two values are denoted by the letters B and C. Hence, reduced rotational speed operation has an initial reverser efficiency (when $V_0=41$ m/sec) that is higher than the initial value for the high rotational speed operation. However, there are few data from the test in the recirculation-free region.

The lower limit of the reverser operating range, as shown on Fig. 5, may be determined to be the value of V_0/V_j at which recirculation occurs with a significant reduction of reverser efficiency. The velocity at which recirculation occurs approaching from high values of V_0 is defined as the recirculation velocity V_{rc}. For the V_j values corresponding to percent design rotational speeds of 100, 75, and 60, the values of the recirculation velocity (V_{rc}) are determined to be 27, 22, and 20 m/sec, respectively. Therefore, reducing the fan thrust setting (percent design speed) also reduces the lower limit of the freestream velocity at which recirculation occurs.

As shown on Fig. 5, the experimental data for reverser efficiency for the selected configuration fall within or above the range of desired values developed earlier (Fig. 2). The minimum value of η_r achieved in the tests is 0.55, which exceeds the minimum required value of 0.3 by a comfortable margin. Values of η_r in excess of 0.7 are achieved for $V_0/V_j \geq 0.17$. This is consistent with the requirements for high reverser efficiency specified in the section on reverser operating requirements.

Installed Thrust Reverser Efficiency

This section presents and discusses the results of experiments conducted with the airplane model with four fan/reverser systems installed. The installed thrust reverser efficiencies are examined and compared to the results obtained with the isolated fan/reverser (Fig. 5). The comparison between the installed and isolated thrust reverser efficiency determines the aircraft installation effect and can provide an early indication of the actual aircraft performance.

Figure 6 presents the installed thrust reverser efficiency as a function of the ratio of the freestream velocity to the fan outlet velocity. Data are presented for each of the four fan/reverser systems on the airplane model. The thrust reverser efficiency η_r and the V_0/V_j velocity ratio were determined in the same manner as previously described in connection with Fig. 5. The relationships representing both the idealized thrust reverser efficiency and the results of the isolated reverser tests (Fig. 5) also are shown.

The average static reverser efficiency ($V_0=0$) for all four fans of the airplane model was reduced to $\eta_r=0.42$, as compared to $\eta_r=0.58$ for the isolated configuration. This further reduction below that of the isolated configuration is caused by an increased amount of recirculated exhaust flow, which is due to the close proximity of adjacent fans to one another and of the inboard fans to the fuselage (Fig. 7a). Some loss in efficiency also may be because of the addition of the simulated ground plane to the model (splitter plate, Fig. 4). The data for the airplane model have the same trends, however, as the data for the isolated reverser, as shown. The reverser efficiency for both inboard and outboard fans remains at a uniform level for values of V_0/V_j below 0.22. For the values of $V_0/V_j<0.20$, the reverser efficiencies of the inboard fans are below those of the outboard fans, as shown by the curves representing the average inboard and average outboard efficiencies on Fig. 6. The lower efficiencies of the inboard fans in this region are due to the fuselage deflection of the exhaust flow (Fig. 7a.).

Figure 6 shows that, above a value of approximately 0.22 (point A', Fig. 6), the inboard and outboard fans display individual characteristics. At point A', the inboard fans show an abrupt increase in reverser efficiency similar to the isolated configuration, whereas the values of η_r for the outboard fans remain unchanged. The value of V_0/V_j of 0.22 is then the recirculation velocity ratio (V_{rc}) for the inboard fans of the airplane model, and is greater than the corresponding value for the isolated fan/reverser (point A). Similar to the consideration of the isolated fan/reverser, the airplane model recirculation velocities are 35, 29, and 25 m/sec for percent design rotational speeds of 100, 75, and 60%, respectively.

For $V_0/V_j>0.22$ for the inboard fans and $V_0/V_j>0.28$ for the outboard fans, the reverser efficiencies increase with increasing V_0/V_j ratio. For the inboard fans, the efficiency ap-

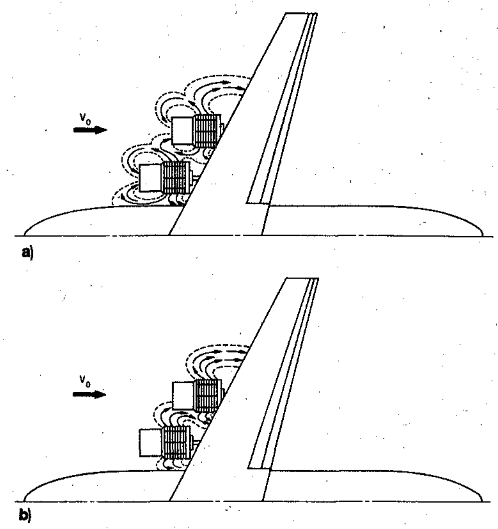

Fig. 7 Reverser exhaust flow patterns for the airplane model: a) $V_0/V_j<0.22$; b) $V_0/V_j \geq 0.22$.

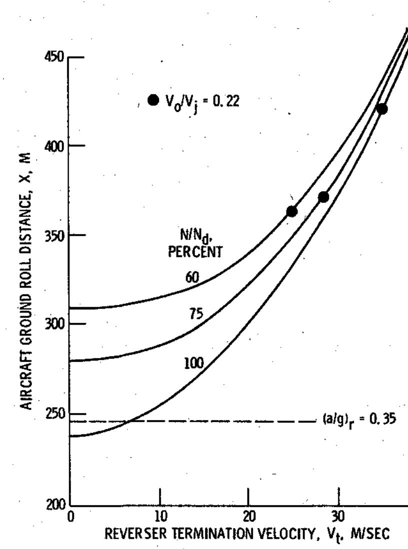

Fig. 8 Variation of calculated ground roll distance.

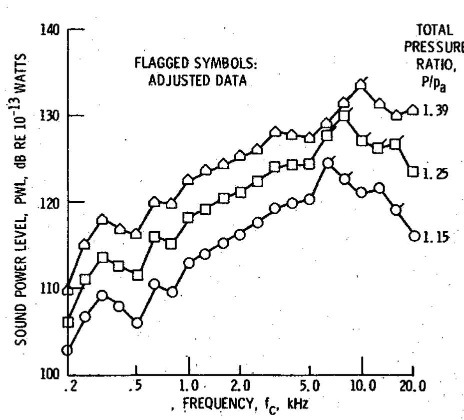

Fig. 9 Thrust reverser adjusted sound power level spectra.

proaches the idealized variation at high values of V_0/V_j. The increase in efficiency is due to the same causes as discussed in the case of the isolated fan/reverser. However, the reverser efficiencies of the outboard fans remain below the values of the inboard fans because of the ingestion of the inboard fan exhaust by the outboard fan inlet (Fig. 7b). The ingestion between adjacent fans is caused by the relative location of the fan nacelles and wing sweep.

The data of Fig. 6 illustrate that the installation of reverser systems on an airplane can promote ingestion effects, which result in sizeable losses in reverser efficiency. However, the values of the average reverser efficiency for the selected configuration still fall within or above the range of values ($0.3 \leq \eta_r \leq 0.75$) determined in the section on reverser operating requirements.

Calculated Aircraft Performance

The predicted aircraft deceleration is determined by use of the equation

$$(a/g)_r = [C_D' q/(W/S)] + \mu\{1 - [C_L' q/W/S)]\} \qquad (5)$$

where C_D' and C_L' are obtained from balance measurements made with the airplane model. The coefficients C_D' and C_L' are different from the aerodynamic force coefficients C_D and C_L, which were used in the section on reverser operating requirements, since C_D' and C_L' are based on the total forces, including the effects of the thrust reversers. The $(a/g)_r$ values are determined by assuming that C_L' and C_D' measured on the airplane model apply directly to a full-scale aircraft having a wing loading W/S of 100.

For moderate to high values of the runway friction coefficient μ,[9] the deceleration values for all fan rotational speeds and freestream velocities are very high, with a minimum value of $(a/g)_r = 0.45$. Therefore, for moderate to high values of μ, the values of the aircraft deceleration exceed the previously selected range of interest $[0.3 \leq (a/g)_r \leq 0.4]$. Therefore, the aircraft can be decelerated with reduced fan rotational speed operation, which also implies reduced noise. Furthermore, partial braking combined with low rotational speed operation of the reversers can be used to obtain $(a/g)_r$ values between 0.3 and 0.4. The results of these calculations indicate that under normal operating conditions an aircraft using the selected reverser can adequately decelerate and also reduce brake wear.

The results of these calculations are much different, however, for a low friction coefficient. For an example case of $\mu = 0.15$, some of the deceleration values are less than 0.30 for a 60% fan design rotational speed. In this case, it is not clear that the aircraft can meet the previously determined requirements. Therefore, calculations of the ground roll distance for the case when $\mu = 0.15$ are required to determine the suitability to short-haul applications.

Calculated ground roll distances for a low runway friction factor ($\mu = 0.15$) are shown in Fig. 8. The results are plotted against the reverser termination velocity V_t, which is defined as the lower limit of the freestream velocity to which the reversers are used. The ground roll distance is determined by use of the equation

$$X = \frac{1}{g}\int_{V_{td}}^{V_t} \frac{V\,dV}{(a/g)_r} + \frac{1}{g}\int_{V_t}^{0} \frac{V\,dV}{(a/g)_{nr}} \qquad (6)$$

where $(a/g)_r$ and $(a/g)_{nr}$ are determined from model balance measurements with the reversers operating and without the reversers operating, respectively. The deceleration values without the reversers operating $(a/g)_{nr}$ were determined by performing a wind-tunnel test with the cascade reverser removed from the model airplane and the model fans unpowered.

The results of Eq. (6) are shown in Fig. 8 for three fan percent design speeds and an assumed aircraft touchdown (reverser initiation) velocity of 41 m/sec. The ground roll distance increases as the reverser termination velocity increases. As expected, the effect of percent fan design rotational speed becomes less significant as the reverser termination velocity increases.

For the assumed representative deceleraton rate of 0.35, the ground roll required to stop the aircraft initially at 41 m/sec is 245 m. This value of 245 m is representative of the goal that would be derived from the discussion of the reverser operating requirements (Figs. 1 and 2) and is shown in Fig. 8 by the dashed line. As shown on the figure, this goal can be met by operating the fan reversers at the design rotational speed down to a reverser termination velocity of about 8 m/sec. This procedure, however, would require operating the aircraft in the region of reverser exhaust recirculation, and at a high noise level.

If either fan operation during recirculation or reverser noise level (due to high fan rotational speed and high total pressure ratio) cannot be accepted, the ground roll distance exceeds the distance goal. The solid symbols on each line of constant rotational speed represent the point at which recirculation occurs for the inboard fan of the airplane model ($V_0/V_j = 0.22$, Fig. 6). If the reverser termination velocity is selected (as in the case of conventional aircraft) to be the same value as the recirculation velocity, then it is clear from the figure that the required ground roll distance is greater than the desired value of 245 m in all cases. For the selected reverser, it is interesting that, for the case when $V_t = V_{rc}$, the shortest ground roll distance is obtained by using the lowest value of the fan percent design speed ($N/N_d = 60\%$). This effect of the use of low percent design speed operation is opposite that which would be expected. In this case, the ground roll distance is 365 m, or about a 50% increase over the goal value of 245m. Since the example being considered ($\mu = 0.15$) is such an extreme or infrequent case, this result may well be acceptable to short-haul aircraft operation.

Reverser Acoustic Results

The material previously presented asserted that the combination of a high efficiency thrust reverser and low thrust setting operation of the engine would meet both the performance and noise goals for a short-haul aircraft. Previous sections have dealt with the aerodynamic performance of the reverser. This section is devoted to the noise generated by the same thrust reverser. Even though the model fan is not included in the acoustic test results, the thrust reverser is identical to that of the previous sections. A more detailed acoustic study of this reverser along with other configurations is presented in another report.[3]

A notable feature of the results for the selected thrust reverser is the presence of high frequency narrow band noise in the sound power level spectra in the 5 to 8 kHz region. The natural mechanical frequency of the reverser cascade blades was measured as 8.4 KHz. Hence, it is highly probable that the narrow band noise is caused primarily by a mechanical

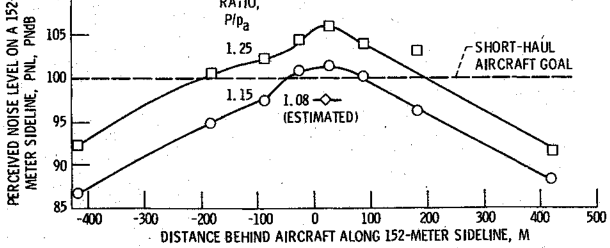

Fig. 10 Sideline perceived noise level.

resonance of the cascade blades.[3] However, it is suspected that the origin of noise may be complicated by sources in addition to mechanical resonance, and that further analysis is needed to verify the preliminary conclusion of mechanical resonance.

Since these mechanical vibratory tones most likely would not be present in an actual installed configuration, the narrow band acoustic spectra (sound pressure level values, which also were recorded) were modified by smoothing the data in the region of concern. The modified narrow band spectra were then used to generate adjusted ⅓-octave sound power level spectra. Figure 9 presents the adjusted sound power level spectra for the selected reverser for total pressure ratios across the cascade reverser (P/p_a) of 1.39, 1.25, and 1.15. The data points that were modified by the smoothing techniques are shown on Fig. 9 as flagged symbols. The reverser total pressure ratio P/p_a is based on a measurement well upstream of the reverser, but essentially is the same as the stator exit average total pressure ratio P_2/p_a of the model fan tests. As shown in Table 2, the latter two pressure ratios (1.25 and 1.15) correspond approximately to 100 and 75% fan design speeds, respectively, for the fan/reverser configuration.

The data of Fig. 9 indicate that the sound power level decreases with decreasing total pressure ratio. This is a beneficial trend in the data, since it indicates that noise levels of reversers can be reduced by reducing the pressure ratio of the engine (e.g., power setting or fan rotational speed). It also can be seen that the peak power is shifted toward higher frequencies as the total pressure ratio is increased.

The adjusted acoustic data of the selected reverser configuration were used to predict full-scale aircraft sideline noise. The PNdB values were calculated by use of a standard method[3] with the sound intensity levels obtained for the model tests scaled directly with area to a fan having a diameter of 1.96 m, as compared to 0.18 m for the model. In order to scale the frequencies, it was assumed that the frequency varies inversely with the spacing distance between cascade blades, and that a full-scale cascade reverser would have blades twice the size (and spacing) of the model.

Figure 10 presents the estimated reverser sideline perceived noise level in PNdB for a single full-scale engine as a function of the distance in meters behind the aircraft along a 152 m sideline. The curves include the data for nozzle pressure ratios of 1.25 and 1.15, which correspond to 100 and 75% fan design speeds, respectively, for the fan/reverser configuration.

Also shown is the target value of 100 PNdB, which represents the sideline noise goal during reverser operation for a short-haul aircraft. The maximum values of the sideline noise are 106.0 and 101.3 PNdB for total pressure ratios of 1.25 and 1.15, respectively. The peak sideline noise for a 1.08 total pressure ratio is estimated at between 97 and 98 PNdB.

The results of Fig. 10, which were calculated from the isolated model reverser data, indicate that lower noise levels can be achieved by reducing the reverser total pressure ratio, i.e., by reducing the thrust setting. However, the entire aircraft must meet the 100 PNdB sideline noise goal. If it is assumed that the fuselage completely shields the sideline noise from two of the four engines, then approximately 3 dB should be added to the value of Fig. 10 to be representative of the aircraft sideline noise. The full-scale aircraft noise goal is approached only for the low pressure ratio case ($P/p_a = 1.08$, $N/N_d = 60\%$, or $T/T_d = 0.4$). This result implies that both the performance and noise goals can be met under normal conditions by use of the selected reverser and low thrust setting operation. For the extreme case of the low runway friction coefficient, the results indicate that either the noise goal or the nominal ground roll distance would be exceeded in stopping the aircraft.

The preceding results assume that the acoustic characteristics are not changed by airplane installation effects, contrary to the case of the aerodynamic performance results. This may not be the case, and additional acoustic tests of the airplane model are required. However, if the sideline noise is adversely effected by installation effects, additional acoustic suppression gains also may be possible by selecting the chord or spacing of the reverser cascade such that the frequencies of the maximum sound pressure level fall in a frequency range that contributes less to the PNdB value. In addition, further reductions in the reverser noise may be achieved by improving the internal aerodynamics of the flow in the fan/reverser system, reducing the cascade length (i.e., reducing the reverser exit area), and using noise-shielding panels.[3]

Conclusions

Experimental investigations of the performance of a cowl-mounted cascade thrust reverser suitable for short-haul aircraft were conducted. The tests were performed to determine the isolated fan/reverser thrust performance, installed reverser performance on a powered airplane model, and acoustic characteristics without a model fan. This paper considered only one cascade thrust reverser, which included highly cambered, contoured blades and a partial circumferential emission pattern of 241°. The main results of these investigations may be summarized as follows:

1. The tests of the isolated fan/reverser indicate that recirculation of the reverser exhaust flow by the fan significantly reduces the thrust reverser efficiency.
2. High reverser efficiencies (greater than 0.7) can be achieved at low fan thrust settings (engine power settings).
3. Installing the thrust reversers on a model four-fan airplane produces further reductions in reverser efficiency. These installation losses were attributed to the recirculation of the exhaust flow and the ingestion of the inboard fan exhaust by the outboard fan. However, the reversers installed on the model airplane display trends with forward velocity similar to that of the isolated reverser.
4. Acceptable full-scale aircraft deceleration and ground roll performance can be attained with the cowl-mounted cascade reverser when operated at low thrust settings under normal operating conditions.
5. Decreasing the thrust or power setting reduces the noise output of the reverser. It is estimated that for the subject reverser a full-scale aircraft operating at a 40% thrust setting can achieve a 152 m perceived sideline noise goal of 100 PNdB.
6. For the case of a very low runway friction factor ($\mu = 0.15$), either the nominal ground roll distance or the aircraft noise goal would be exceeded in stopping the aircraft.

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