NASA/GE Quiet Engine "A"

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NASA and the General Electric Co. are jointly developing two low noise propulsion technology demonstrators (Engine "A" and "C" incorporating, respectively, a low tip speed and high tip speed fan) under the Experimental Quiet Engine Program. The acoustic and Aerodynamic performance characteristics of Engine "C" which is currently on test will be reported at a later date. The present paper describes the design, component development and engine evaluation of the "A" demonstrator. The aerodynamic and acoustic performance obtained on the fan component are discussed. The demonstrator engine acoustic test program is outlined. The effect of inlet geometry and duct acoustic treatment are presented. The static acoustic data are extrapolated to flight and compared with the FAA noise regulations.

Introduction

IN the last ten years, noise around airports has increased steadily with increasing airplane traffic resulting in large annoyance to the surrounding communities. While the aircraft operation noise abatement procedures and land zoning will provide some relief to this growing problem, it is felt that a generally adequate solution will be provided only by the introduction of Quiet Propulsion Technology.

NASA and the General Electric Company are developing in a joint effort two low noise propulsion technology demonstrators in the 22,000 lb thrust class under the Experimental Quiet Engine Program: 1) Engine "A" with an 1160 fps tip speed fan, and 2) Engine "C" which incorporates a fan with a higher rotational speed (1550 fps). The goals for the Quiet Engine Program call for an engine 15–20 PNdb quieter than currently available engines in that thrust class. Engine "A" has completed an extensive test program at General Electric during the summer and fall of 1971. Engine "C" acoustic investigation is currently getting underway and will continue into the spring of 1973. The acoustic and aerodynamic performance characteristics of Engine "C" will be reported in the spring of 1973. This paper will address itself to the design, component development and engine evaluation of the "A" propulsion demonstrator.

In general, there are three approaches to noise reduction applicable to engine technology. They include; thermodynamic cycle selection, design features that reduce source noise, and suppression of the generated noise. These three approaches were taken concurrently in the design of Quiet Engine "A." Concerning the thermodynamic cycle, selection of a high bypass ratio permitted thrust generation by means of a low specific thrust—that is, a high mass flow with a low exhaust velocity. Further, a high extraction of turbine energy resulted in a reduction in exhaust velocity of the core engine with additional attendant reductions in jet noise. Reduction of fan source noise involved the judicious selection of design parameters, such as spacing of rotating and stationary parts, blade/vane ratios, and elimination of inlet guide vanes. Sound suppression materials were also added in the fan inlet and exhaust ducts.

Figure 1 shows a cutaway drawing of the Quiet Engine "A" with the low noise design features indicated. Since the engine's bypass ratio is 5.6, the core and fan exhaust jet velocities (1176 and 780 fps, respectively) are relatively low reducing jet noise substantially below the suppressed fan noise levels. The fan inlet guide vanes were eliminated to reduce wake interaction noise. The axial spacing between the fan rotor blades and the downstream outlet guide vanes was selected as two aerodynamic chord lengths (approximately 4 projected chords) to minimize rotor wake interaction noise. The ratio of the number of vanes to number of blades, which is 90–40 or 2.25, was chosen to reduce the noise radiated from the fan. A careful design balance was made between fan rotational speed and blade aerodynamic loading to reduce fan noise. Acoustic absorptive treatment was placed on the inside and outside walls of the airflow passage through the fan to reduce fan noise propagation. A proven CF6-6 core was used. The low pressure turbine stages were designed with low aerodynamic loadings to reduce turbine noise. Further acoustic treatment was used to line the core inlet and exhaust ducts (See Fig. 1) to reduce compressor and turbine noise.

Aerodynamic Evaluation of Fan "A"

The core components in Engine "A" as well as the low pressure turbine were adapted with some modifications from the CF6-6 engine and were thus proven components. The fan, however, represented an all new design and ne-

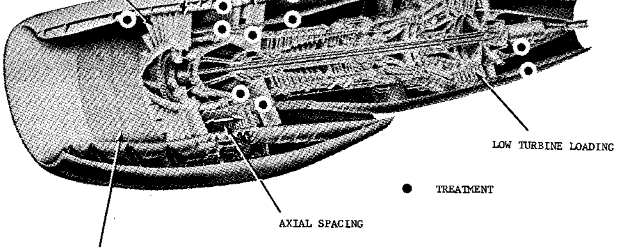

Fig. 1 Noise reduction design features.

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Index categories: Aerodynamic and Powerplant Noise; Aircraft Propulsion System Noise.

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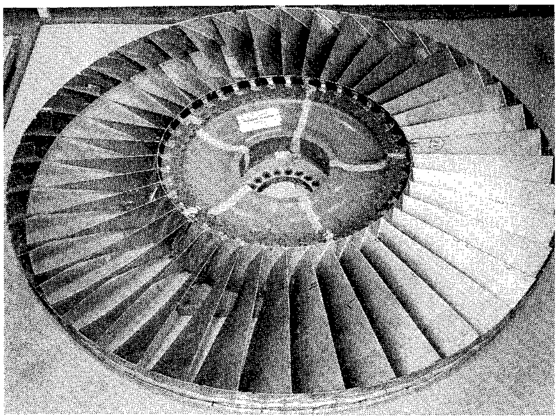

Fig. 2 Fan "A" rotor.

cessitated a thorough aero-mechanical evaluation at the General Electric's full scale fan test facility. A photograph of the fan is shown in Fig. 2. The fan was designed with tip shrouds thus eliminating part span shrouds and resulting in an improvement in fan efficiency.

The over-all fan performance was determined from the measurement of fan inlet and fan discharge total temperatures and total pressures. At the fan inlet, the total pressure was measured by four six-element rakes located in the cylindrical section of the inlet duct between the bellmouth and the fan inlet. Twenty-four thermocouples attached to an inlet screen were used for the determination of inlet total temperatures. The pressure and temperature sensors were located approximately on centers of equal area. At the fan discharge, the total temperature and total pressure were measured by circumferential arc rakes. Seven 12-element arc rakes were located behind the fan bypass Outlet Guide Vanes (OGV's) and five seven-element arc rakes were located behind the fan core OGV's. The elements were circumferentially spaced so as to span two OGV passages. Radially, the arc rakes were located on centers of equal design mass flow of the fan bypass and fan core, respectively.

The measured performance of the Fan "A" stage is shown in Fig. 3. The measured flow at the design bypass pressure ratio of 1.5 was 973 lb/sec (2.4% greater than the design value of 950 lb/sec) and was equivalent to 42.5 lb/sec ft^2 annulus area at the rotor inlet. The efficiency at the design cruise condition was measured at 88.3% and exceeded the design value by over two points. The fan therefore represented a significant aerodynamic accomplishment by exceeding current engine performance levels in terms of airflow per unit frontal area and in terms of efficiency.

Acoustic Evaluation of Fan "A"

Fan "A" was tested for acoustic performance at the NASA full-scale fan noise test facility at the Lewis Research Center. A plan view of the test site is given in Fig. 4. The facility is located in the vicinity of the drive motor building of the 10′ × 10′ supersonic wind tunnel, and utilizes the wind-tunnel drive motors as the fan prime mover. The drive is accomplished by the use of a front-end shaft.

Noise measurements were made on a 100 ft arc at 10° increments from 10° to 160° from the fan inlet axis. The microphones were located at the same height (19 ft) as the fan axis.

The acoustic characteristics of Fan "A" were determined for various suppressed and unsuppressed configurations over a range of operating conditions. The results obtained with the "baseline" and the "fully suppressed" configurations are of major interest and are described in the following.

The baseline configuration contained only wall acoustic treatment incorporated into the fan frame proper (see Fig. 5). All other inlet and exhaust duct walls were untreated. The fully suppressed configuration had an inlet duct suppressor with wall acoustical treatment and three splitter rings with acoustic treatment on both sides. In addition the bypass exhaust duct walls were acoustically treated and one treated splitter ring was employed. Neither inlet nor exhaust duct suppressors were aerodynamically contoured nor were they tailored to the noise signature of Fan "A." Nevertheless, the results obtained are indicative of the feasibility of fan noise suppression and the order of magnitude of suppression that may be expected in tailored suppression systems. Both baseline and suppressed configurations employed bellmouth inlets.

Projections were made from the static noise data obtained at the Lewis tests, to sidelines parallel to the fan centerline at distances which are typical of the distances to the ground of current-DC-8/707 class aircraft during takeoff and landing operations. Perceived noise levels were computed and are presented versus angle from the fan inlet at the takeoff and approach fan speeds at the respective sidelines on Figs. 6 and 7. For the baseline case, the maximum sideline perceived noise levels at takeoff in the front and rear quadrants are 97.2 and 97.6 PNdb, re-

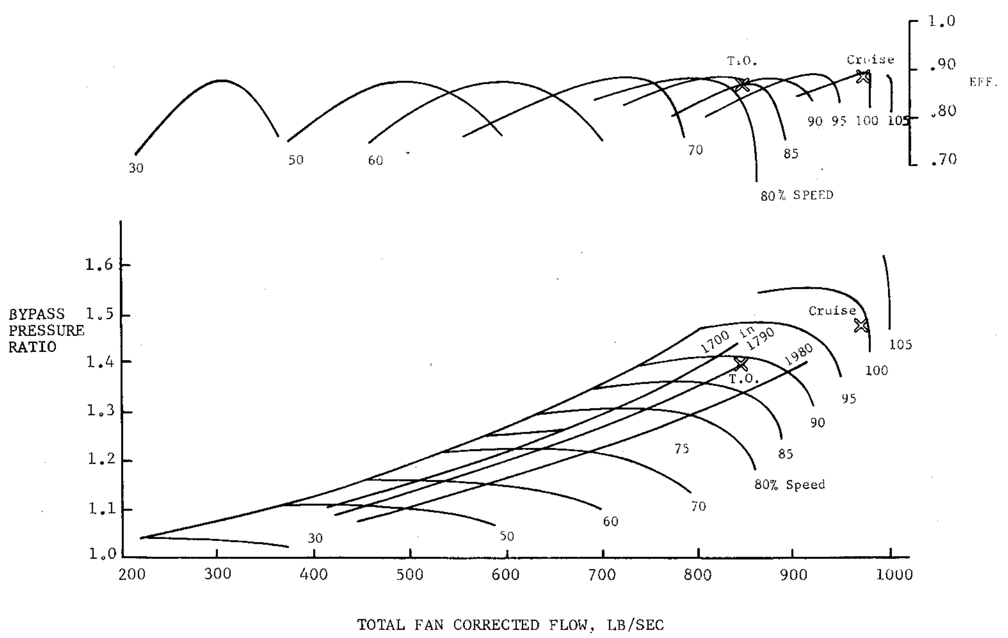

Fig. 3 Fan "A" performance.

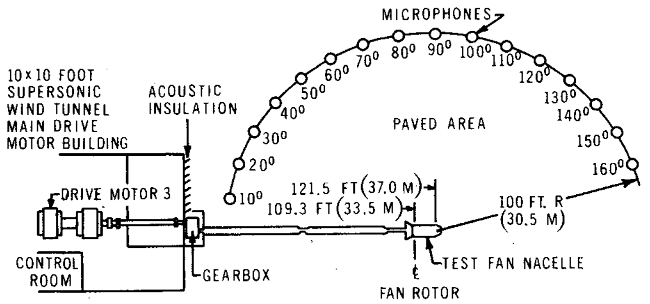

Fig. 4 Acoustic site at Lewis.

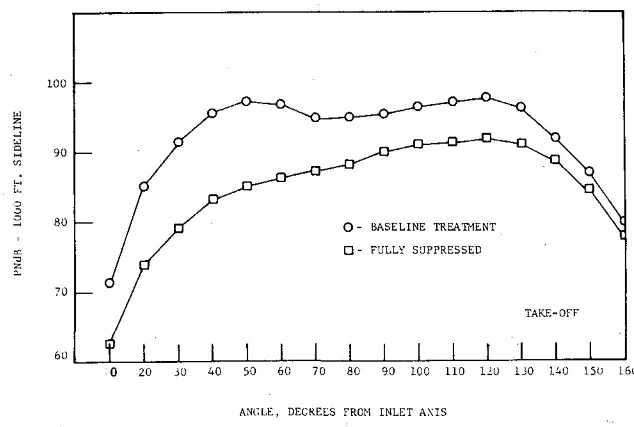

Fig. 6 Lewis acoustic results—sideline perceived noise levels at takeoff.

spectively (see Fig. 6). Addition of the suppressors reduces these levels to 85.0 and 91.8 PNdb. The results for the approach speed condition are given in Fig. 7. At this condition the peak front and rear sideline levels are 97.8 and 98.2, respectively. The suppressors reduce these values to 86.2 and 89.7 PNdb.

The examination of the aft quadrant (120°) noise spectra at the takeoff and approach condition (see Figs. 8 and 9) shows that most of the reduction was obtained with the fully suppressed configuration at frequencies above 1000 Hz. The one-third octave bands below 1000 Hz on the fan seem to be controlled by the fan low-velocity jet noise[1] which might constitute a floor for further fan noise reduction.

Engine "A" Acoustic Testing

At the completion of the fan component acoustic evaluation at the Lewis test site, Fan "A" was shipped to the General Electric facility where it was assembled into the engine. The engine consists essentially of the TF39/CF6 engine core, Fan "A", and the first 4 stages of the CF6 low pressure turbine. The assembled engine was shipped to the General Electric acoustic test facility located in Peebles, Ohio. The test facility permits outdoor full scale engine measurements of acoustic and aerodynamic performance characteristics.

Engine "A" is shown in Fig. 10 mounted on the engine test stand. The engine contained the necessary instrumentation for measuring thrust, fuel consumption, air flow and other performance characteristics. The engine was operated at its rated 22,000 lb thrust level for evaluation of takeoff characteristics and at other power settings for a complete documentation of engine noise under different operating conditions. Calibrated microphones were located along the 150 ft arc around the engine at 10° increments at a height of 40 feet to simulate ground reflections typical of flyover conditions. The ground surface was covered with gravel. The engine centerline height was 13 ft.

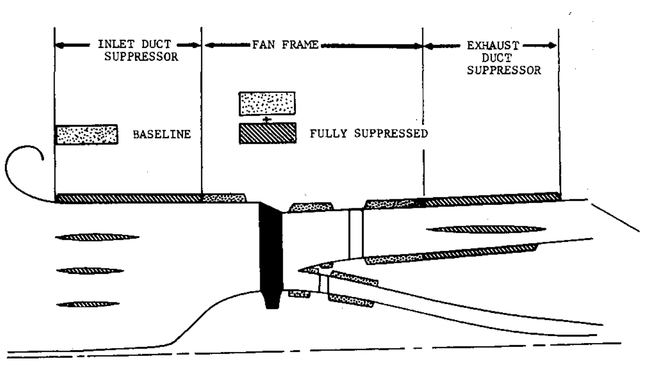

Fig. 5 Cross section Fan "A".

Over thirty aerodynamic and acoustic runs were taken on Engine "A" at the Peebles Proving Grounds. Extensive near and farfield data have been recorded and are being analyzed. The most significant results to be discussed are: Comparison of Fan vs Engine "A" data; Inlet design effects on over-all engine noise characteristics; Fan duct treatment effects on over-all engine noise characteristics.

Comparison of Fan vs Engine "A" Data

The data taken by NASA at the Lewis Research Center on the fan components as well as the data taken by General Electric at Peebles on the "baseline" engine configuration were extrapolated to the same sideline distances (1000 ft for the takeoff power setting and 370 ft for the approach power setting). Figure 11 shows the comparisons of the fan and engine data from the two facilities at the takeoff condition. It can be seen that the agreement is in general quite good. Some small differences exist in the front quadrant where the Lewis data is slightly higher. The engine data is slightly higher in the rear quadrant indicating the presence of core jet noise as evidenced in the second pressure spectrum shown in Fig. 12. An eaually close agreement was obtained at the other power settings.

Inlet Design Effects on Over-All Engine Noise Characteristics

It was suspected that the engine inlet design could affect the fan noise generation and radiation characteristics and therefore have a significant effect on the over-all engine noise level. It was therefore decided to investigate this effect with a series of back to back tests on Quiet Engine "A." The three inlets compared were a standard bell-

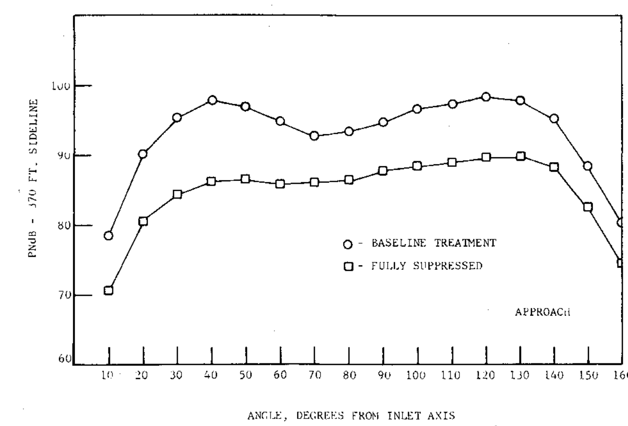

Fig. 7 Lewis acoustic results—sideline perceive noise levels at approach.

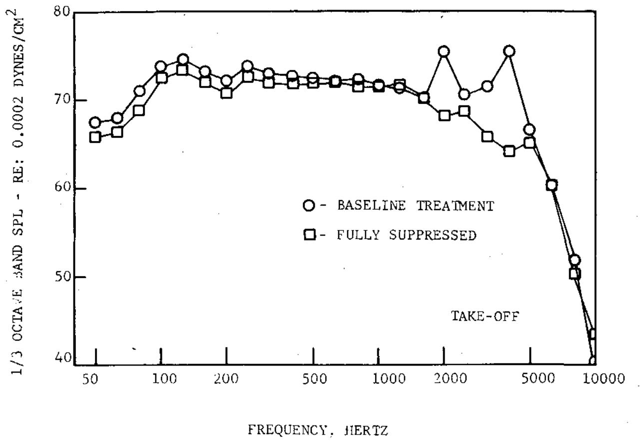

Fig. 8 Lewis acoustic results—sound pressure level spectrum at 120°.

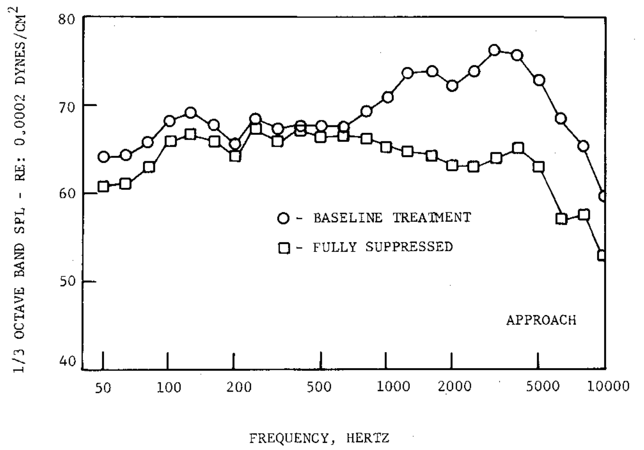

Fig. 9 Lewis acoustic results—sound pressure level spectrum at 120°.

mouth inlet, a thick lip inlet (see Fig. 13), and a thin lip inlet incorporating blow-in doors which were held fixed in an open position (see Fig. 13).

The three inlets were tested with acoustic treatment in the fan frame, in the compressor inlet, and in the turbine exhaust. The results in terms of sideline perceived noise levels (PNL's) are shown in Figs. 14 and 15 at, respectively, the takeoff and approach power settings.

It can be seen that at the takeoff point both the thick lip and the blow-in door inlet provide a slight reduction at the angles close to the inlet axis (this effect is probably due to the higher inlet Mach number associated with these designs) but result in higher noise levels at all other angles (this is attributed to the higher amount of flow distortion associated with these inlets resulting in an increase in fan noise generation). It can be seen on Fig. 14

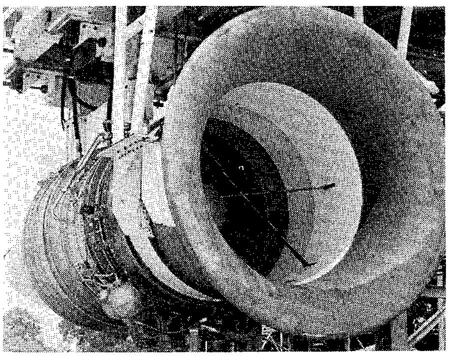

Fig. 10 Quiet Engine "A" on test.

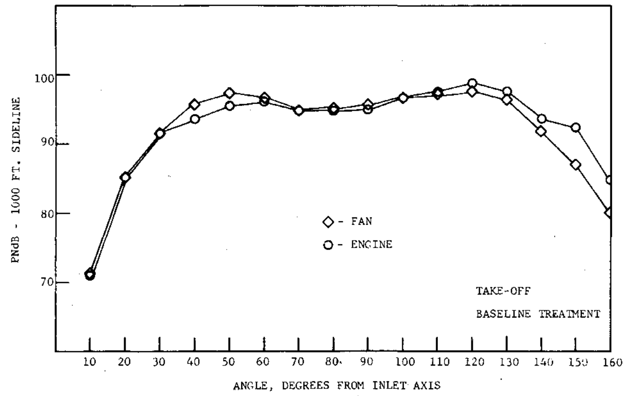

Fig 11 Comparison between fan and Engine "A" data—sideline perceived noise levels.

that the blow-in door inlet results in the highest noise levels.

At the approach point, as shown in Fig. 15, this trend is even more pronounced. Both the thick lip and blow-in door inlets are radiating higher noise levels than the bellmouth inlet. Here the blow-in door inlet is slightly noisier, especially at 80° and 90° from the inlet axis. It is suspected that these higher noise levels are due to the inlet distortions created by the doors and the sound radiating through the open doors. In conclusion, the results indicate that while both flight inlets have similar characteristics, the thick lip design is quieter than the blow-in door configuration at both the takeoff and approach conditions.

Fan Duct Treatment Effects on Over-All Engine Noise Characteristics

The effect of fan duct treatment was investigated on Engine "A." The basic engine incorporating a bellmouth, inlet treatment in the compressor, and turbine exhaust treatment was tested with four different levels of fan duct treatment (see Fig. 16).

1) Fan Frame Treatment (Baseline).

2) Duct Wall Treatment—This configuration contained wall treatment extending 20 in. beyond the frame treatment in the inlet and 37 in. in the aft duct on both the inner and outer walls. Both the fan frame treatment and the duct wall treatment were multiple degree-of-freedom resonator designs providing more effective suppression than single degree-of-freedom panels.[2]

3) Long Inlet Treatment—This configuration incorporated 58 inches of treatment in the inlet beyond the "duct wall" treatment configuration. This additional amount of

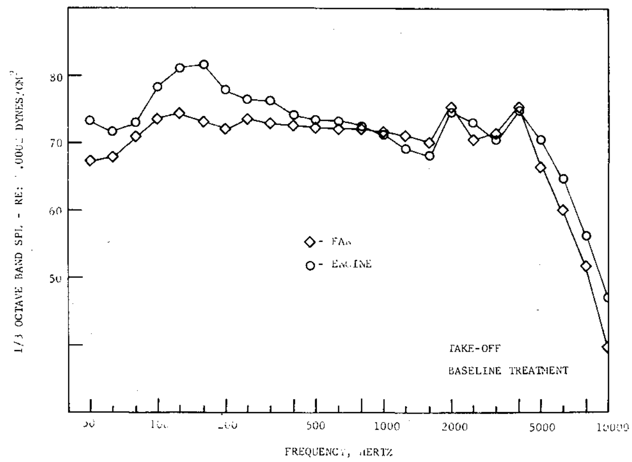

Fig. 12 Comparison between fan and Engine "A" data—sound pressure level spectrum at 120°.

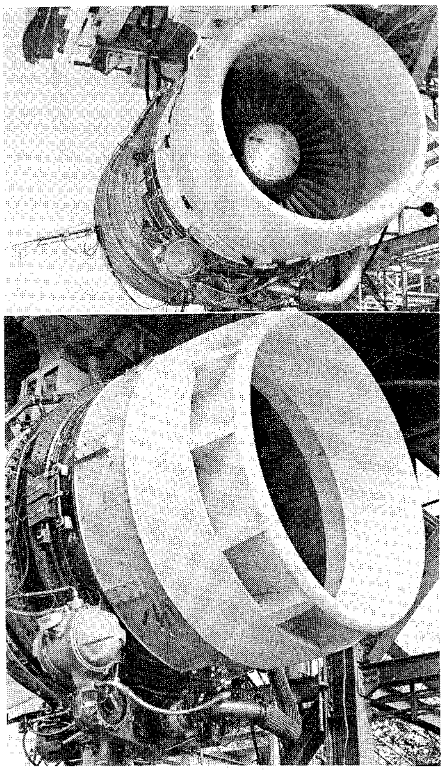

Fig. 13 Thick lip and thin lip.

treatment was made of single degree-of-freedom resonators. The same configuration incorporated a splitter in the aft duct treated on both sides with thick polyurethane foam (Scottfelt) treatment covered by a porous plate.

4) Fully Suppressed Configuration—This configuration is essentially the same as 3 preceding but incorporates three inlet splitters (see Fig. 17) acoustically treated on both sides with single degree-of-freedom resonators.

The results of this investigation are shown in Figs. 18–21. The first two figures present the data in terms of sideline Perceived Noise Levels (PNL's) at the appropriate distances. It is interesting to note in the front quadrant that a major noise reduction is obtained with just the presence of a long inlet treated on the outer wall and that the incorporation of splitters provided only a moderate further reduction in front end noise. Typical sound pressure level spectra are shown on Figs. 20 and 21 for a front and an aft angle, respectively. It can be seen in Fig. 20 that the long inlet provided an appreciable reduction over a wide range of frequencies. The splitters seem to help mostly at the high frequencies (above 2000 Hz).

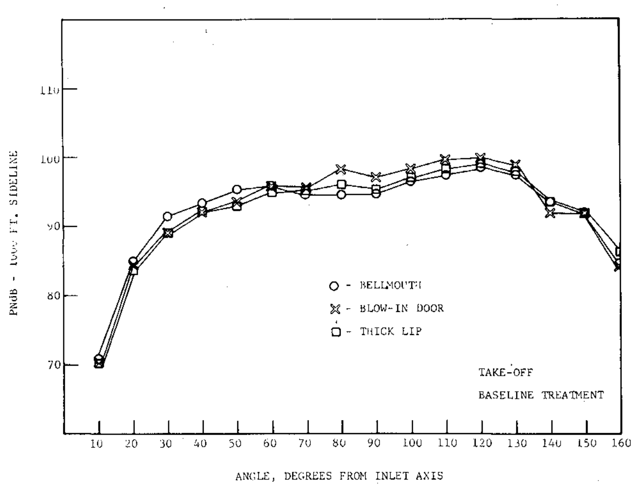

Fig. 14 Inlet effect on sideline perceived noise levels.

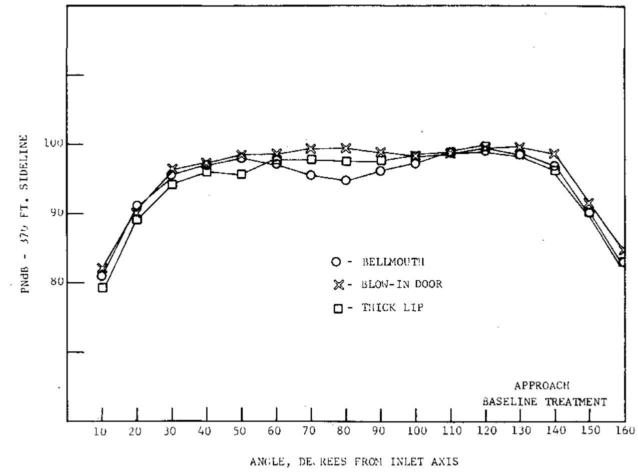

Fig. 15 Inlet effect on sideline perceived noise levels.

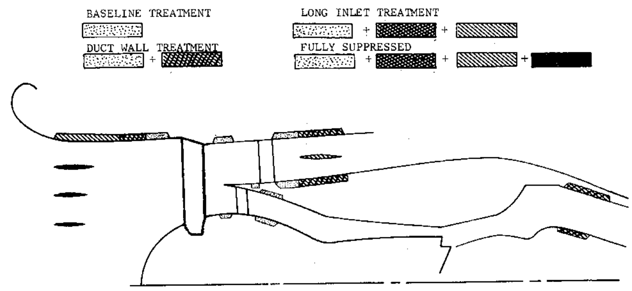

Fig. 16 Treated areas Engine "A".

Flight Noise Projections

Some of the results obtained on Engine "A" have been discussed in the previous sections. Turning now to the over-all payoff in the alleviation of airport community noise a basic question still remains to be answered. How quiet is Engine "A" compared to comparable size engines in similar applications? While Engine "A" was not designed for actual flight application, an indication of the potential reduction available from the application of the technology evolving from this program to actual flight hardware can be obtained by comparing the effective perceived noise levels (EPNL's) at the FAA (FAR 36) reference points[3] at approach and takeoff for 1) A DC8-61 aircraft powered with four JT3-D engines, a typical low bypass ratio turbofan engine.[4] 2) The Federal Aviation Administration FAR 36 requirements for an aircraft of the size of DC8-61 (325,000 lb takeoff gross weight). 3) An aircraft of the size of a DC8-61 powered with four Engine "A"s incorporating duct wall treatment. 4) An aircraft of the size of a DC8-61 powered with four Engine "A"s in a fully suppressed configuration.

The DC8-61 EPNdb levels with JT3D's were measured and reported in Ref. 4. The effective perceived noise levels

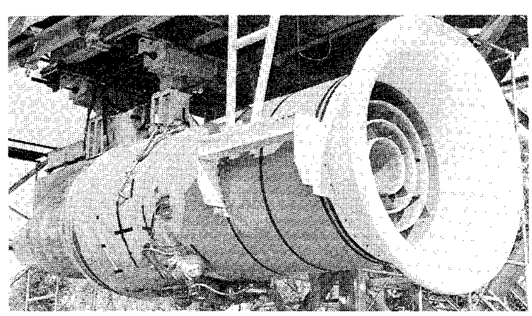

Fig. 17 Engine with splitters.

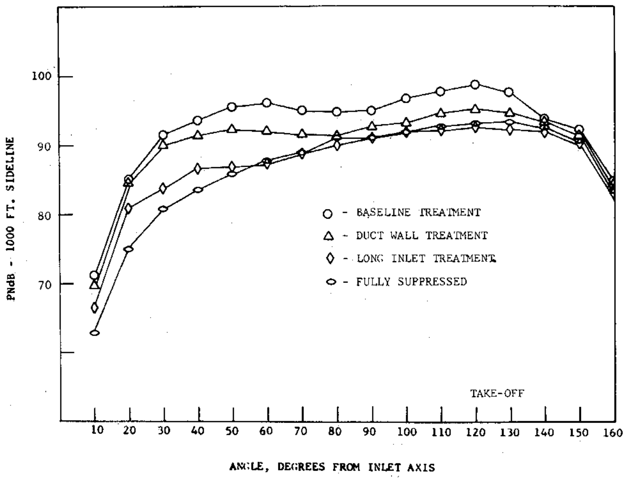

Fig. 18 Acoustic treatment effects—sideline perceived noise levels.

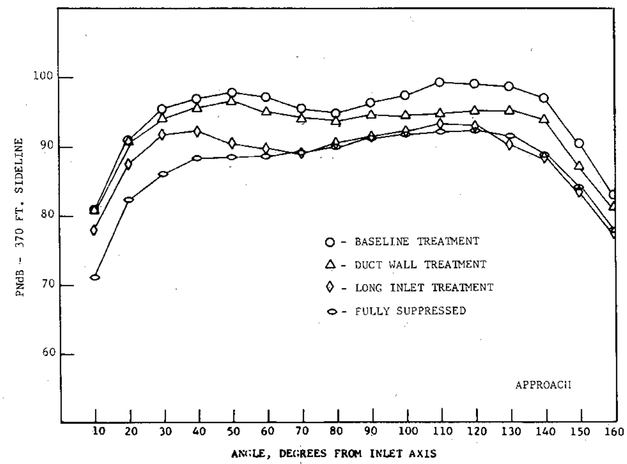

Fig. 19 Acoustic treatment effects—sideline perceived noise levels.

obtained with Engine "A" were computed starting from the static data measured at Peebles using estimated flight paths for the aircraft powered by four quiet Engines "A"[5] in the approach and takeoff mode. The results of this comparison are presented in Table 1. Sideline noise levels for this class of aircraft are considerably below the FAR36 requirements. The predicted performance of a DC8 type aircraft with four Engines "A" with duct wall treatment shows noise reductions of more than 20 EPNdb's relative to current DC-8's and 8 EPNdb's relative to FAA noise regulation. The predicted noise levels of the DC-8 type aircraft with four Engines "A" in the fully suppressed

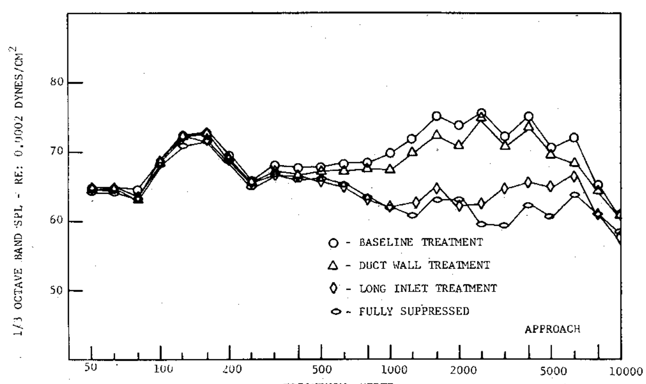

Fig. 20 Acoustic treatment effects on inlet noise at 50°.

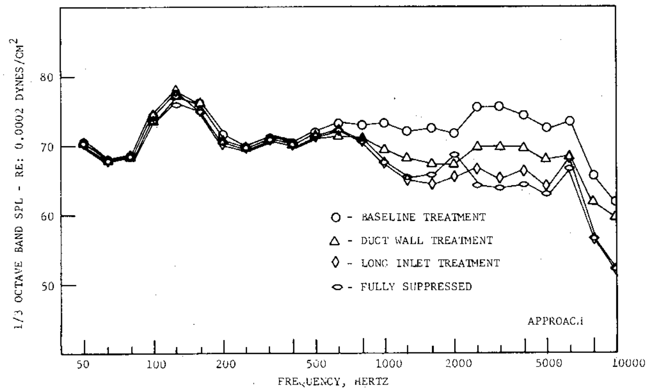

Fig. 21 Acoustic treatment effects on aft noise at 120°.

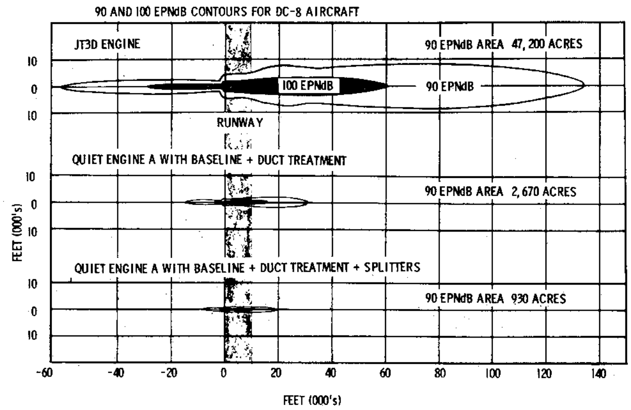

Fig. 22 90 and 100 EPNdb contours for DC-8 aircraft.

configuration are more than 25 EPNdb's below those of the existing DC-8 and more than 10 below FAR36.

A meaningful way to portray the noise reductions quantified on Table 1 is the presentation used in Fig. 22 which shows the contours on the ground plane of 90 and 100 EPNdb for the three aircraft. The vertical band superimposed on each contour represents the 10,000 ft runway chosen for this case. The striking difference between the noise footprint of the existing DC8 aircraft and the two Quiet Engine-powered aircraft is exemplified by the areas of the 90 EPNdb contours, i.e., 44,700 acres, 2670 acres and 930 acres, which are at once grasped in terms of annoyance to people living near an airport. These noise reductions obtained are significant and adequately meet the goals of the Quiet Engine Program. The results provide ample incentive to extend the technology to new production engines. In the application to production engines,

Table 1 Noise levels at FAR-36 reference points

DC8 Aircraft configuration	Approach, 1 naut mile from runway	Full power takeoff, 3.5 naut miles from brake release
	EPNL	EPNL
JT3D engine[a]	118	117
FAR 36 limits	106.3	103.5
Quiet Engine "A" with baseline plus duct treatment[b]	98.0	95.1
Quiet Engine "A" fully suppressed[b]	92.6	89.2

[a]See Ref. 4.
[b]Based on flight profiles documented in Ref. 5.

proper consideration must however by given to the added weight, reliability and cost factors.

The data just presented covers Engine "A" with a relatively low tip speed fan. The next major step in the NASA/GE experimental Quiet Engine Program is to evaluate an engine incorporating Fan "C" which is representative of a high speed fan. Such an engine offers the advantage of having shorter length and fewer components, both of which permit important improvements in engine weight and engine cost. It is expected that the acoustic investigation of the Engine "C" technology demonstrator will be pursued into the Spring of 1973. At that time comparable data will have been obtained on both "A" and "C" technology demonstrators and tradeoff studies will be performed to evaluate their relative merits acoustically and in terms of direct operating costs on a number of airplane applications.

References

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[5]"The Integration of Quiet Engines with Subsonic Transport Aircrafts," Rept. DAC-68256, June 24, 1968, McDonnell Douglas, Long Beach, Cal.; also NASA CR-72548, Aug., 1969.

Measurements of the Boundary-Layer Growth in Annular Diffusers

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Low speed tests have been carried out on two-optimum straight walled, annular diffusers. One diffuser had a uniform diameter center body, the other an expanding diameter center body (divergence angle 40°). Curved passages of constant flow path area were situated up- and downstream of the expanding center body diffuser. Measurements were made of the pressure recovery, mean total pressure loss, and the growth of the boundary layers in terms of the mean velocity profile and turbulence structure. The rate of growth of the shape parameters was found to be significantly greater along the outer wall, this effect is attributed to the distortion caused by flow curvature at inlet which is then accentuated by the adverse pressure gradient. Whereas the pressure recovery of the two diffusing systems was comparable, a significant increase in losses occurred in the expanding center body diffuser, due to the higher turbulence level of the flow from the curved inlet passage increasing the energy dissipation.

Nomenclature

A = area of cross section
AR = area ratio
B = blocked area fraction, $1 - 1/A_0\int_0^A (u/U)dA$
C_f = local skin friction coefficient
$\bar{C}_p$ = pressure recovery coefficient based on $\rho\bar{u}_1{}^2/2$
$\bar{C}_p{}^*$ = the locus of maximum pressure recovery at prescribed nondimensional length
$\bar{C}_{p_{comp}}$ = the pressure recovery associated with a component in a duct system
D = diameter of cross section
D_h = hydraulic mean diameter
H = shape parameter
L = average diffuser wall length
L_e = length of approach pipe upstream of diffuser
N = diffuser axial length
P = static pressure
P_T = total pressure
R_m = radius of the point of maximum velocity
ΔR = annulus height
u = local velocity in x direction
$\bar{u}$ = mean velocity in cross section $\int_0^A u dA/A$
u_τ = friction velocity, $(\tau_w/\rho)^{1/2}$
$\langle(u'^2)\rangle^{1/2}$, $\langle(v'^2)\rangle^{1/2}$ = rms velocity fluctuation in x and y directions, respectively
$\langle -\rho u'v' \rangle$ = Reynolds shear stress
U = maximum velocity in cross section
x = distance along the mean flow line from diffuser inlet
y = distance perpendicular to wall
α = velocity profile energy coefficient $\int_0^A (u/\bar{u})^3 dA/A$
γ = pressure gradient parameter $(\nu/\rho u_\tau{}^3)dP/dx$
δ_o, δ_i = boundary-layer thickness on outer and inner walls, respectively
$\delta_o{}^*, \delta_i{}^*$ = displacement thickness of boundary layer on outer and inner walls, respectively, $\delta_o{}^* = \int_0^{\delta_o} (1 - u/U)(R/R_o)dy$, $\delta_i{}^* = \int_0^{\delta_i} (1 - u/U)(R/R_i)dy$
θ_o, θ_i = momentum thickness of boundary layer on outer and inner walls, respectively, $\theta_o = \int_0^{\delta_o} (1 - u/U)(u/U)(R/R_o)dy$, $\theta_i = \int_0^{\delta_i}(1 - u/U)(u/U)(R/R_i)dy$
λ = loss coefficient, $\Delta P_T/(\rho\bar{u}_1{}^2/2)$
ν = kinematic viscosity
ρ = fluid density
τ = shear stress
ϕ = diffuser wall angle
$'$ = fluctuation quantity
$\langle\ \rangle$ = time average

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