Acoustic Characteristics of Counterrotating Unducted Fans from Model Scale Tests

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Development of an acoustic technology that describes the noise characteristics of counterrotating fans is an important phase in the design of fuel-efficient, unducted fan engines. In order to obtain the needed data, measurements were made in an anechoic facility with approximately 1/5-scale counterrotating model fan blades. Tests were conducted over a range of power settings to determine the effects of variations in blade number, tip speeds, and rotor-to-rotor spacings on community noise. Selected results are presented and discussed in this paper. Significant overall acoustic benefits were measured with an increase in blade number, a reduction in tip speed for a given thrust, increased rotor-to-rotor spacing, and clipped aft blades.

Introduction

THE counterrotating unducted fan engine concept has attracted considerable attention from the aircraft industry because of its considerably higher propulsion efficiency and lower specific fuel consumption relative to modern high bypass turbofan engines of equivalent thrust. GE Aircraft Engines has designed, built, and flight tested, proof-of-concept UDF® (UDF® is a registered trademark of General Electric Co., U.S.A.) engines on modified Boeing 727 and McDonnell-Douglas MD-80[1,2] airplanes to demonstrate the viability of this concept.

Simultaneously, GE Aircraft Engines in cooperation with NASA and industry has undertaken an extensive scale model program to investigate the influence of various geometric and aerodynamic design parameters on the performance and noise characteristics of the counterrotating unducted fans. Three counterrotating model propulsion simulator (MPS) test rigs were designed and fabricated for testing approximately 1/5-scale blades in either transonic or subsonic wind tunnel/free-jet facilities.[3] They are capable of varying blade-pitch setting angles, number of blades, and rotor-to-rotor spacings. The thrusts and torques of each rotor are measured by force balances. Aero/thermodynamic parameters are measured by traversing probes in front, between, and aft of the rotors. Far-field and near-field acoustic data are measured generally in an anechoic environment for evaluating community and exterior cabin noise.

One of the MPS rigs has been installed in the GE Anechoic Free-Jet Flight Simulation Facility (generally referred to as Cell-41) to obtain community noise data. Under a NASA funded program (NASA-Lewis Contract NAS3-24080; F. M. Humenik, Program Manager), tests were conducted to determine the impact of changes in fan configurations on noise at simulated takeoff, cutback, and approach conditions. This paper presents some of the significant results measured with one of the blade designs, designated as F7A7. Detailed results are given in Ref. 4.

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Test Facility

The installation of the MPS in the anechoic chamber, a description of the Cell-41 facility, measured background noise levels, and the data acquisition and reduction procedures are summarized in Ref. 5. To verify the validity of scale-model testing and the acoustic scaling procedures employed to project engine-scale results, scale models of the proof-of-concept configurations[1,2] were tested at Cell-41. The model results were scaled to engine fan size and compared with the measured flight acoustic data. These comparisons[6] showed that the Cell-41 measured results provide good simulation on engine-scale acoustic flight characteristics.

Model scale blades (designated F7A7) designed for a cruise Mach number of 0.72 were used for all the tests reported in this paper. The front rotor (F7) and aft rotor (A7) blades are 24.6 and 23.9 in. in diameter. The forward rotor hub-to-tip diameter ratio is 0.425. The aerodynamic tip-sweep angles at design conditions are 34 and 31 deg, respectively. The blades, schematically shown in Fig. 1, are graphite/glass composite material laminated to a titanium spar. For this study, tests were conducted with axial spacings between the pitch-change axes of the forward and aft blades of 4.16 and 5.9 in.

Acoustic data are acquired with 24 1/2 in. B&K 4133 microphones that cover a geometric angular range of 43 through 154 deg relative to the fan centerline and recorded on a 28-track tape recorder. The recorded analog data are processed to obtain as measured 1/3-octave band spectral results, which are corrected for microphone, recording and playback system frequency response, and for background noise of the free-jet at the simulated flight Mach number. As the measuring microphones are located outside the free-jet, the scale-model data are corrected for shear-layer refraction effects

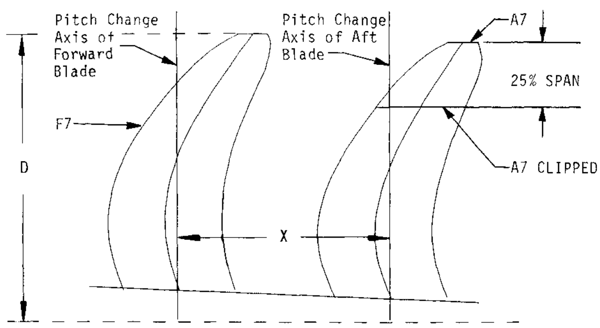


Fig. 1 Schematic of F7A7 with standard and clipped aft blades.

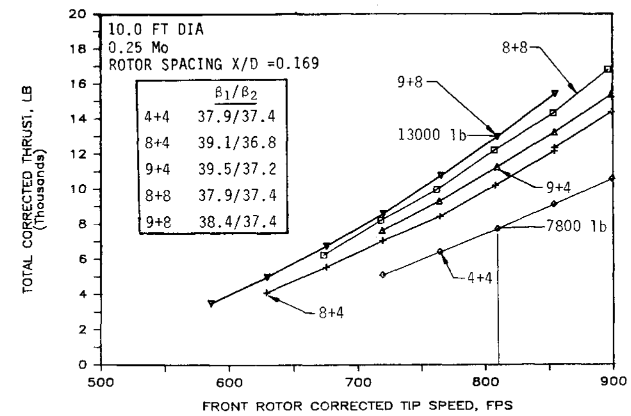
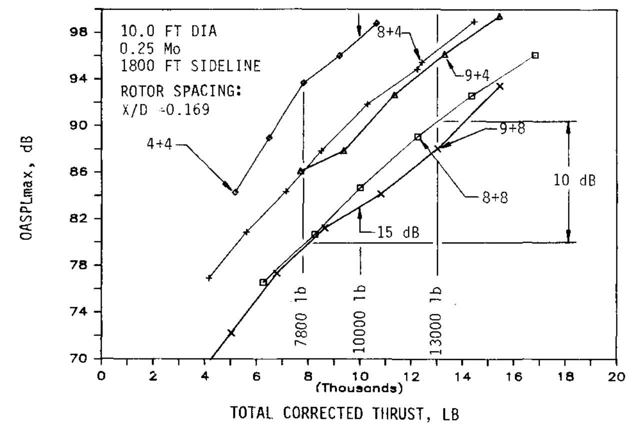
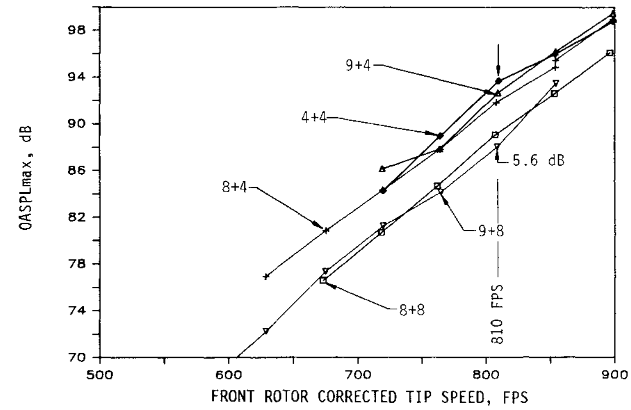


Fig. 2 Thrust vs tip speed for various blade numbers (series-1).



a) OASPLmax vs total thrust



b) OASPLmax vs tip speed

Fig. 3 OASPLmax vs thrust for various blade numbers (series-1).

through a transformation procedure.[7] Atmospheric attenuation corrections[8] are applied to obtain acoustic data for standard day conditions. The model data are scaled to the desired engine size[4-6] and extrapolated to a required sideline distance. This procedure yields 1/3-octave band engine scale spectra and overall sound pressure level (OASPL), perceived noise level (PNL), tone corrected perceived noise level (PNLT), and A-weighted level (dBA) directivities at the corresponding engine test conditions. A flyover analysis of the engine-scale PNLT directivity at the required sideline distance provides the effective perceived noise level (EPNL) value.

The taped analog acoustic data also are digitized to obtain narrowband spectra up to 10 kHz with a bandwidth of 12.5 Hz. The scale-model narrowband spectra are processed with a program that sorts the sound pressure levels at forward and aft rotor blade passing frequencies (BPF) and their harmonics and at the various rotor-to-rotor interaction tone frequencies. The sorted data are corrected for shear-layer refraction effects and extrapolated to a reference sideline to obtain the following directivities: 1) sound pressure levels (SPL) of the various tones; 2) sums of SPL at the forward rotor BPF and harmonics, this is the steady-loading noise component of forward rotor blades; 3) sums of SPL at the aft rotor BPF and harmonics, this is the steady-loading noise component of aft rotor blades; 4) sums of 2) and 3), this is the total steady-loading noise; and 5) sums of SPL at all of the interaction tones, this is the total aerodynamic rotor-to-rotor interaction noise.

The above component noise-level sums can be obtained for test configurations when the frequencies of the various tones are sufficiently apart in the narrowband spectra, e.g., with 1) unequal number of blades on each rotor that rotate at equal rpm and/or 2) equal number of blades on each rotor that rotate at unequal rpm. For those cases where tests were conducted with equal number of blades at equal rpm, the method described in Ref. 5 was used to obtain the sums of the component noise levels.

Results

Acoustic results that describe the effects of variations in blade number, blade-tip speeds, and rotor-to-rotor spacings are presented in this section. The data are measured at a simulated flight Mach number $M_0 = 0.25$ and without a mounting pylon. All the scale-model acoustic results in this section are data corrected to a 27-ft sideline, and all the engine size results are model acoustic data scaled to a 10-ft diam fan and extrapolated to a 1800-ft sideline. For community noise evaluation, single engine fan thrusts in the ranges of 15,000 and 10,000 lb are considered in this section to represent typical takeoff and cutback conditions, respectively.

Evaluation of Blade Numbers

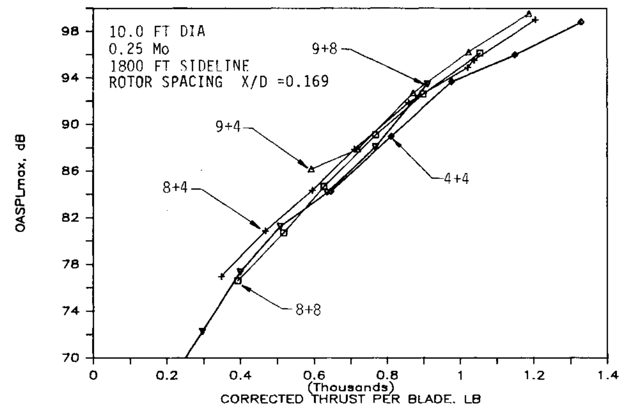
Results from tests with various numbers of F7A7 blades are presented under two sets of comparisons as follows: 1) Series-1: with blade number combinations of 4+4, 8+4, 9+4, 8+8, and 9+8 tested with a normalized spacing of $X/D = 0.169$ and 2) Series-2: with blade number combinations of 8+8, 9+8 and 11+9 tested with a normalized spacing of $X/D = 0.24$ between rotor pitch-change axes. All tests were conducted with the same blades and at blade-pitch settings that were selected to give approximately equal lift per blade at a typical takeoff power tip speed.

Series-1: with 4+4, 8+4, 9+4, 8+8, and 9+8 Blades

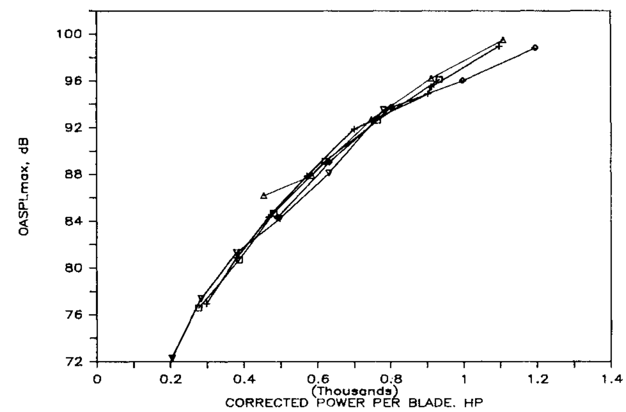
The total thrust for the five different blade number configurations are provided in Fig. 2. For the increase of blade numbers, the data indicate the expected increase in thrust at a given tip speed and a decrease in tip speed for a given thrust.

Acoustic data in terms of scaled OASPLmax as a function of thrust and tip speed are presented in Fig. 3. Fig. 3a demonstrates a significant reduction in noise levels with an increase in blade numbers from a 4+4 to a 9+8 combination over a range of thrust conditions. For example, at a thrust of 10,000 lb, reduction to the extent of 15 dB is measured with a 9+8 configuration relative to a 4+4 configuration. For this increase in blade numbers, Figs. 2 and 3b also indicate that the OASPLmax decreased by 5.6 dB at a fixed tip speed of 810 fps though the thrust increased from 7,800 to 13,000 lb. Note that, for any of the blade number combinations in Fig. 3a, this increase of thrust by only a tip-speed variation would have resulted in an increase in OASPLmax by approximately 10 dB.

OASPLmax data of Fig. 3 are replotted in Fig. 4 as functions of thrust/blade and power/blade. This figure indicates that the OASPLmax of all test blade number combinations correlate within 2 dB. This simple correlation suggests that the noise level is a function of the force per unit area of the blades.

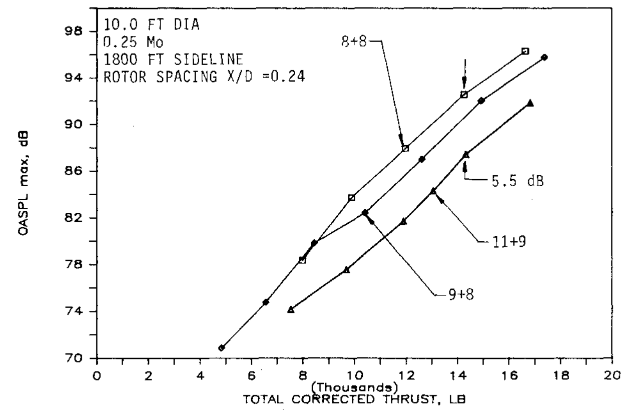


a) OASPLmax vs thrust per blade

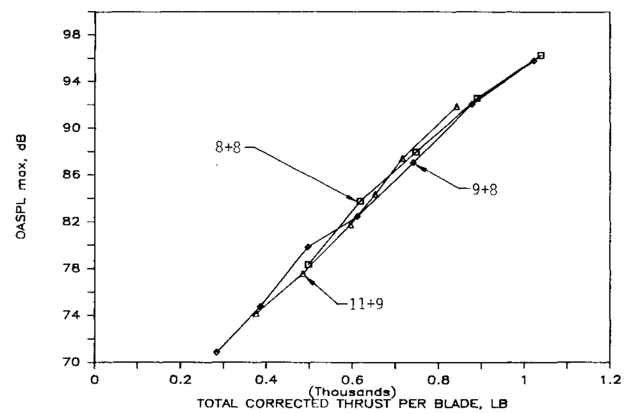


b) OASPLmax vs power per blade

Fig. 4 OASPLmax vs thrust/blade and SHP/blade for various blade numbers (series-1).

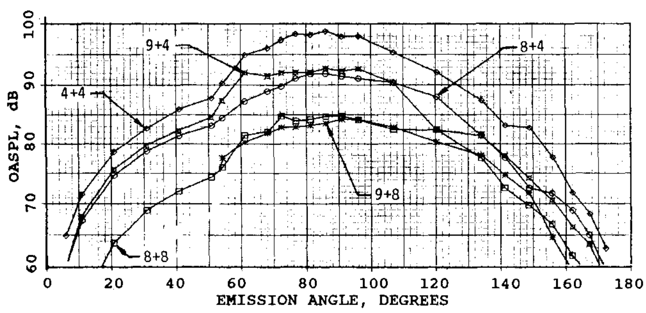


a) OASPLmax vs thrust

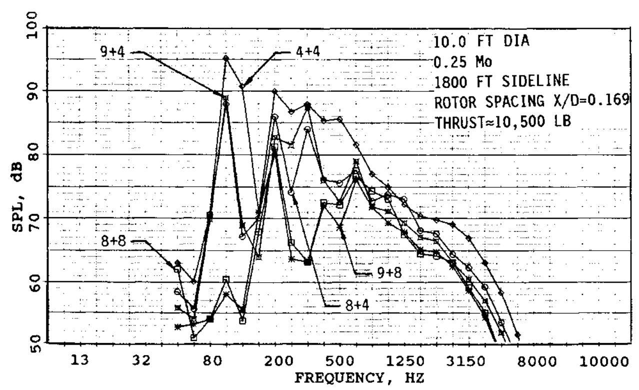


b) OASPLmax vs thrust/blade

Fig. 6 OASPLmax vs thrust and thrust/blade for various blade numbers (series-2).

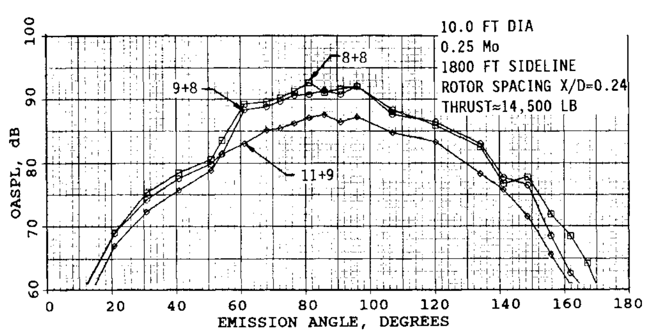


a) OASPL directivity

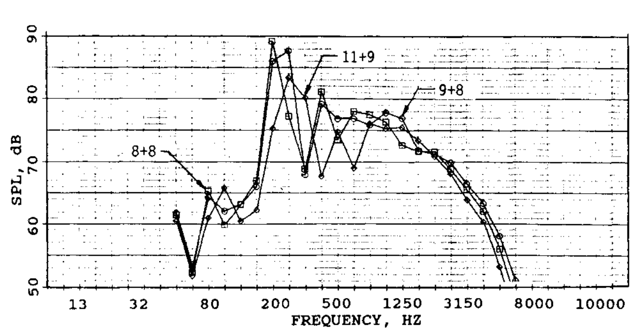


b) Spectra @ emission angle = 86 deg

Fig. 5 Directivity and spectra for various blade numbers (series-1).



a) OASPL directivity



b) Spectra @ emission angle = 86 deg

Fig. 7 Directivity and spectra for various blade numbers (series-2).

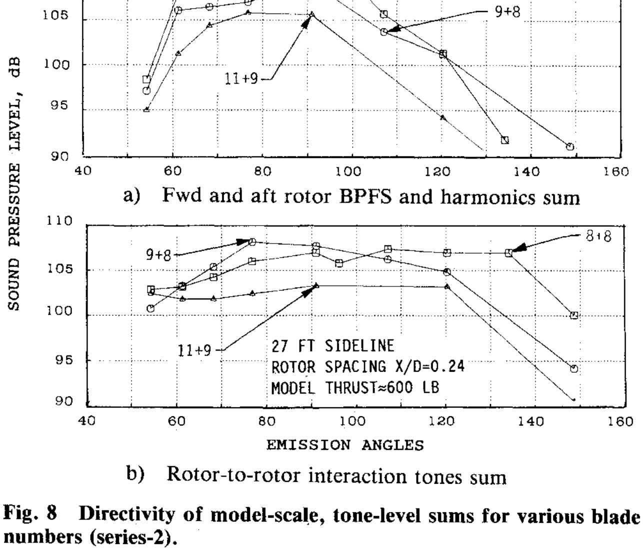
OASPL directivity and a selected spectrum at an emission angle $\theta_e = 86$ deg are presented in Fig. 5 for a cutback thrust of approximately 10,500 lb. In this figure the data plotted outside the test range of 51 deg $< \theta_e < 167$ deg are extrapolated values. Directivity data show significant acoustic benefits with an increase in blade numbers. The typical spectral data show reduced sound pressure levels at blade passing frequencies indicating a decrease in steady-loading noise and reduced levels at higher harmonics due to a decrease in rotor-to-rotor interaction noise with increased blade numbers. One of the reasons for this decrease in interaction noise is the wake and tip-vortex strength reduction that results from decreased blade loading due to increased blade numbers.

Series-2: with 8+8, 9+8, and 11+9 Blades

Similar sets of data for these three blade number combinations at the larger spacing between the rotor pitch-change axes were obtained. The data are illustrated in terms of scaled OASPLmax as a function of thrust and thrust/blade in Fig. 6. As before, the data demonstrate the significant reduction in noise levels with an increase in blade numbers. For example, at a thrust level of 14,500 lb, a reduction of 5.5 dB is obtained in peak value of OASPL for an increase of blade numbers from an 8+8 to an 11+9 configuration. As with series-1, the acoustic data of series-2 correlate within 2 dB when plotted on the basis of thrust/blade and power/blade.

The OASPL directivity and a selected spectrum at $\theta_e = 86$ deg are presented in Fig. 7 for a takeoff thrust condition. The directivity data indicate a significant benefit due to increased blade numbers over most of the test-angle range. The spectral data clearly denote reduction in the sound pressure levels at blade passing frequencies due to a reduction in steady-loading noise with increased blade numbers.

Figure 8 depicts the model-scale SPL tone sum directivities at a model thrust that matches a typical takeoff condition. This figure demonstrates the following two benefits from the increased blade numbers. The first benefit is a significant decrease in steady-loading noise as a result of the reduction in blade loading and tip speed. The second benefit, which is a natural consequence of the first, is a decrease in the interaction noise due to lower tip speed aft rotor blades interacting with the weakened wakes and tip-vortices from the forward rotor blades.



a) Fwd and aft rotor BPFS and harmonics sum

b) Rotor-to-rotor interaction tones sum

Fig. 8 Directivity of model-scale, tone-level sums for various blade numbers (series-2).

Effect of Tip Speed

To determine the benefit of decreasing tip speeds on the acoustic characteristics of counterrotating fan blades at fixed thrust conditions, tests were conducted using 8+8 blades with a spacing of $X/D = 0.169$ and at blade-pitch angles of 36/35.2, 37.9/37.4, 40/38, and 43.3/40.4 deg. The effect of this variation in blade-pitch setting conditions on the normalized axial distance between the trailing edge of a forward blade and the quarter-chord point of an aft blade is depicted in Fig. 9. This figure indicates that this effective distance decreases with an increase in blade-pitch angles (i.e., with more open pitch settings).

Figure 10 presents the total thrust as a function of tip speed. The data indicate that the blade-pitch angles of 36/35.2, 37.9/37.4, 40/38, and 43.3/40.4 deg resulted in typical takeoff thrust of 15,000 lb at sequentially reduced tip speeds of 900, 865, 820, and 780 fps, respectively. However, the power absorbed for the given thrust were noted to increase with a decrease of tip speed indicating a reduction in aerodynamic efficiency. These blade-pitch settings also resulted in typical cutback thrust of 10,000 lb at tip speeds of 795, 765, 725, and 680 fps, respectively.

Figure 11 presents the acoustic data in terms of the scaled OASPLmax as a function of total thrust. The data indicate a 3-dB decrease in noise for a reduction in takeoff tip speed from 900 to 780 fps. The effect of variation in tip speed on OASPLmax at cutback is less significant than at takeoff thrust. This is due to the fact that the relative contributions of steady-loading and rotor-to-rotor interaction noise at takeoff and cutback conditions are different, and their dependencies on tip speed are not the same.

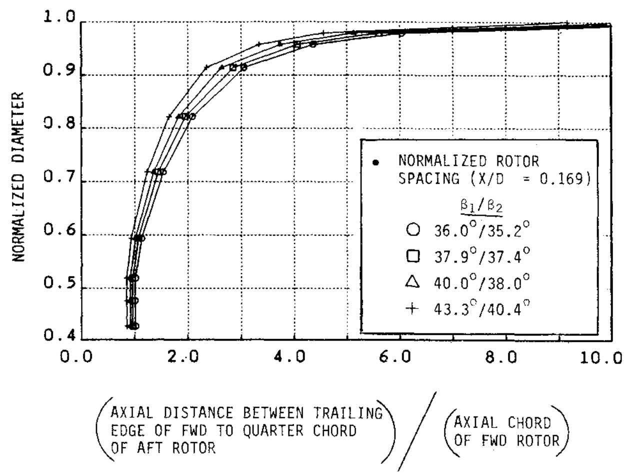


Fig. 9 Axial spacing between blades for several blade-pitch angles.

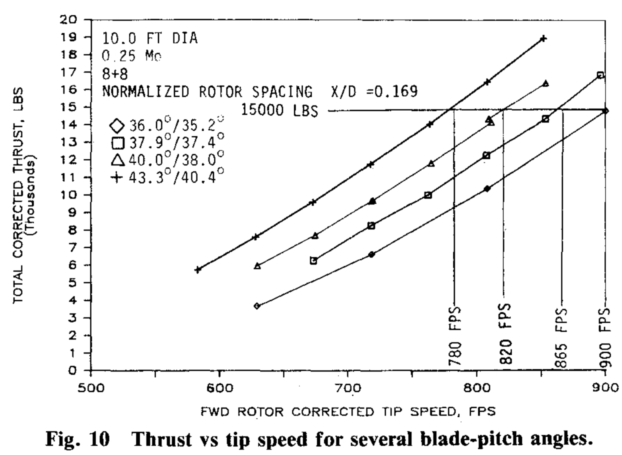


Fig. 10 Thrust vs tip speed for several blade-pitch angles.

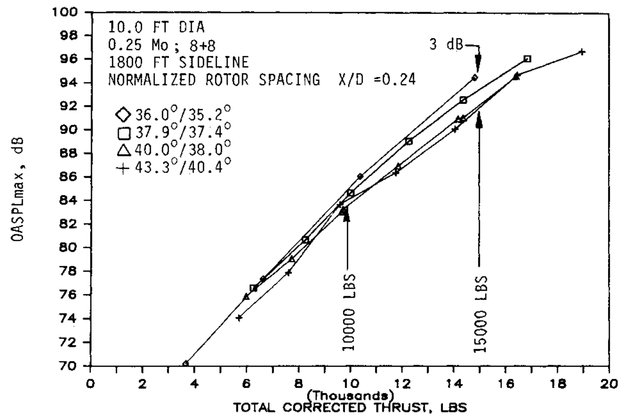


Fig. 11 OASPLmax vs thrust for several blade-pitch angles.

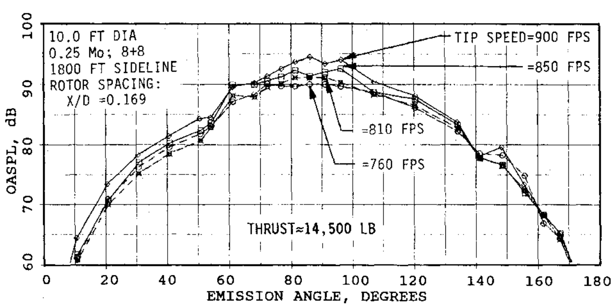
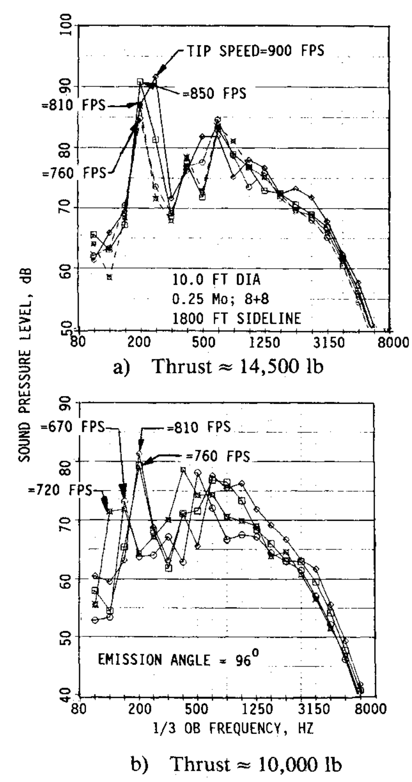


Fig. 12 Directivity at a given thrust and for several tip speeds.



a) Thrust ≈ 14,500 lb

b) Thrust ≈ 10,000 lb

Fig. 13 Spectra at given thrusts and for several tip speeds.

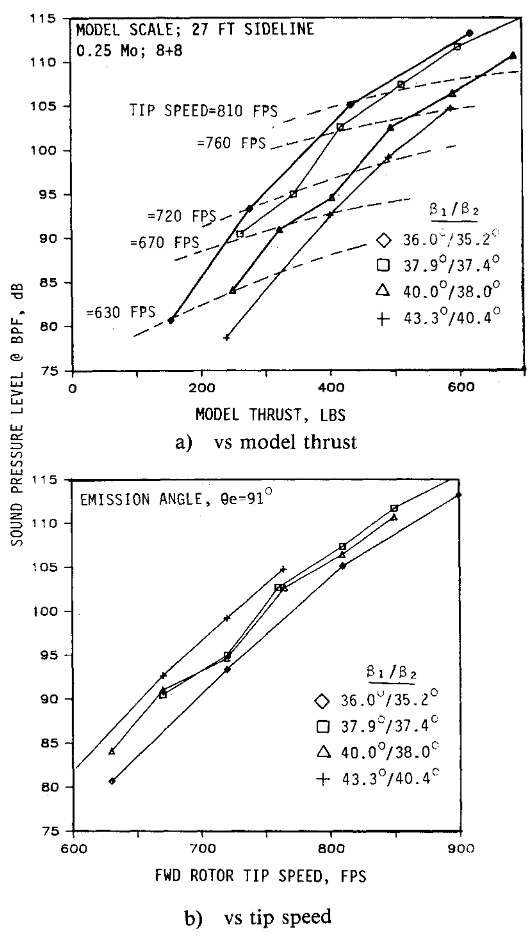
The OASPL directivity at a typical takeoff thrust and selected spectra for typical takeoff and cutback conditions are presented in Figs. 12 and 13, respectively. Acoustic benefit of decreased tip speed in directivity data occurs in the region of the plane of rotation. The spectral data show a systematic decrease in the sound pressure levels at blade passing frequencies indicating a decrease in steady-loading noise with the decrease of tip speed.

The model-scale sound pressure levels at BPF, measured at $\theta_e = 91$ deg with the four blade-pitch settings, are plotted in Fig. 14 as functions of model thrust and tip speed. These levels are a measure of the steady-loading noise in the plane of rotation. This figure indicates that, for a given thrust, the steady-loading noise decreases significantly with a decrease in tip speed.

Effect of Spacing Between Forward and Aft Rotors

To determine the effect of variation in the axial spacing between the forward and aft rotors on the noise characteristics of counterrotating fan blades, tests were conducted with normalized pitch-change axes spacings of $X/D = 0.169$ and 0.24. Blade number combinations of 8 + 8 and 9 + 8 were employed. The 9 + 8 configurations were tested with both standard and reduced diameter aft blades.

The impact of increasing the spacing, in terms of normalized axial distance between the trailing edge of a forward blade and the quarter-chord point of an aft blade, is shown in Fig. 15 for blade-pitch angles of 37.9/37.4 deg. Comparison of the acoustic data at BPF, measured with the 8 + 8 blade configuration, indicated no effect of increased spacing and hence no effect on the steady-loading noise. However, significant reductions in the sound pressure levels at 3 × BPF and 4 × BPF were noted with an increase in spacing. Comparison of the model-scale tone directivities, measured at a tip speed of 760 fps, is shown in Fig. 16. Typical 1/3-octave band spectral comparisons are provided in Fig. 17. Since tip vortices are known to decay at a much slower rate relative to blade wakes with an in-



a) vs model thrust

b) vs tip speed

Fig. 14 Sound level at BPF for several tip speeds.

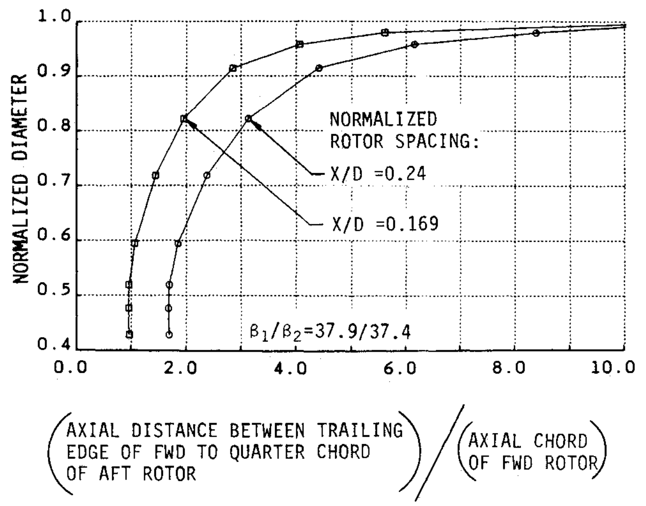


Fig. 15 Axial spacing between forward and aft blades at two pitch-change axis spacings.

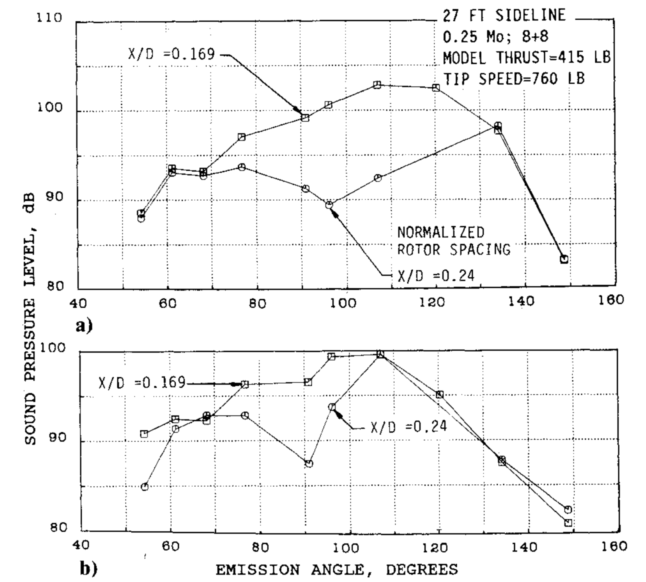


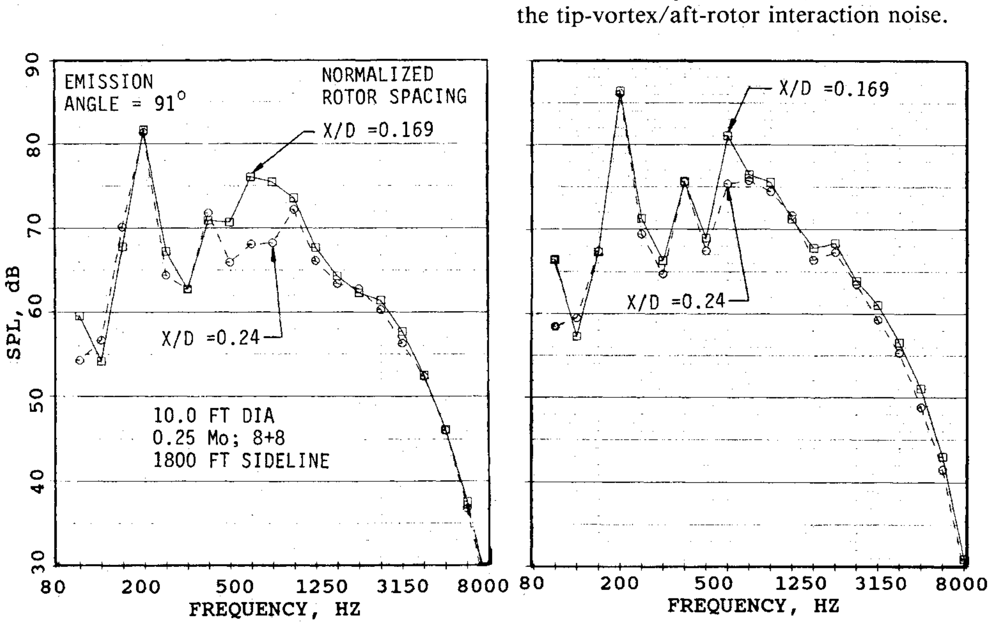
Fig. 16 Axial spacing effect on SPL directivity of a) 3×BPF and b) 4×BPF.

crease in downstream distance,[9,10] the observed sound pressure level reductions at interaction frequencies are attributed mainly to the increased decay of the front blade wakes before they interact with aft blades. This benefit due to spacing increase is noted to decrease with an increase in thrust or tip speed.

The 9 + 8 blade configuration was tested at blade-pitch angles of 38.4/37.4 deg. The aft blades were later clipped at 75% of their span to obtain reduced diameter blades. A schematic of the clipped configuration is presented in Fig. 1. The loss in aft rotor thrust at a given rpm due to clipping was compensated for by setting the aft blades at a more open blade-pitch angle. The clipped configurations were tested at blade-pitch angles of 36.3/42.7 deg.

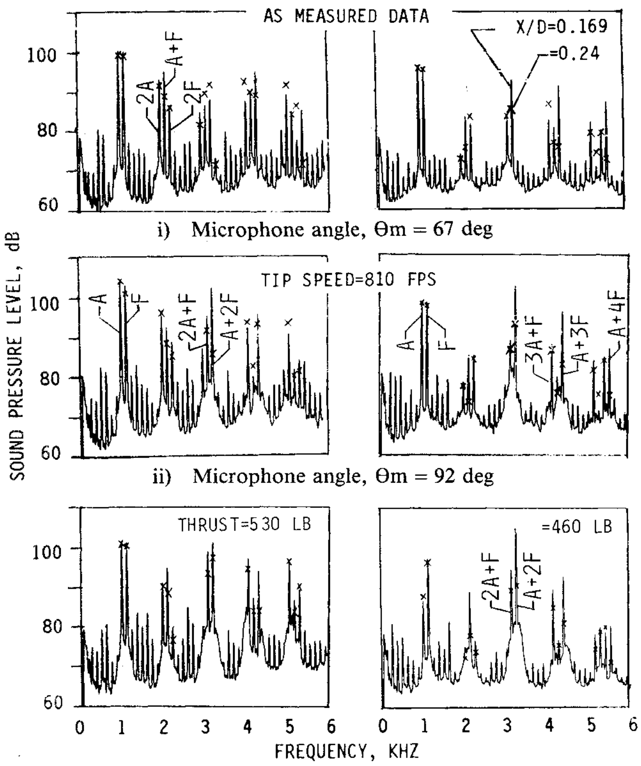
Narrowband spectra, measured with both rotor spacings, are provided in Fig. 18 for the 9 + 8 standard and clipped aft configurations. As with the 8 + 8 blade test, the 9 + 8 configuration does not show any change in sound pressure levels at BPF of the forward and aft blades with an increase in spacing, thus, indicating no effect on the steady-loading noise component. With the standard configuration, significant reduction is seen in the levels of the 1A + 1F tone of the second harmonic and 1A + 2F tone of the third harmonic. Smaller reductions are noted in the aft quadrant at some of the higher frequency interaction tones. However, with the clipped aft configuration, an increase in spacing is seen to give additional significant reductions in some of the interaction tones of the 4th and 5th harmonic and, in particular, in the levels of 1A + 3F and 1A + 4F tones. The combined effect of reductions in these interaction tones due to spacing is clearly shown in Fig. 19, which compares model-scale directivities of rotor-to-rotor interaction tone SPL sums for both the standard and clipped aft configurations at forward-blade tip speed of 810 fps. The noise reduction with increased spacing of the clipped aft configuration is seen to be significantly higher than that measured with standard blades.

For the clipped aft rotor configuration, it can be assumed that the tip vortices of the forward rotor do not significantly interact with the reduced diameter aft blades and, hence, produce reduced noise at tip-vortex/aft-rotor interaction tone frequencies. A consequence of this assumption is that the significant reductions previously noted in the SPL of the interaction tones, with increased rotor spacing, are due to increased decay of the forward-blade wakes. This reduction in interaction tone levels, due to spacing increase, was not fully evident with the standard configuration because their levels were masked by the tip-vortex/aft-rotor interaction noise.



a) Tip speed = 760 FPS b) Tip speed = 810 FPS

Fig. 17 Axial spacing effect on spectra of 8 + 8 configuration.



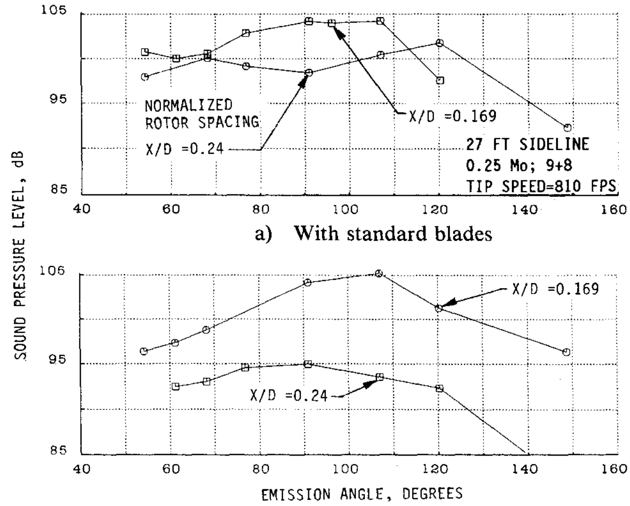
i) Microphone angle, Θm = 67 deg

ii) Microphone angle, Θm = 92 deg

iii) Microphone angle, Θm = 107 deg

a) With standard blades b) With clipped blades

Fig. 18 Axial spacing effect with standard and clipped aft blades on model-scale tone spectra.



a) With standard blades

b) With clipped blades

Fig. 19 Axial spacing effect with standard and clipped aft blades on model-scale interactlon tone level sums.

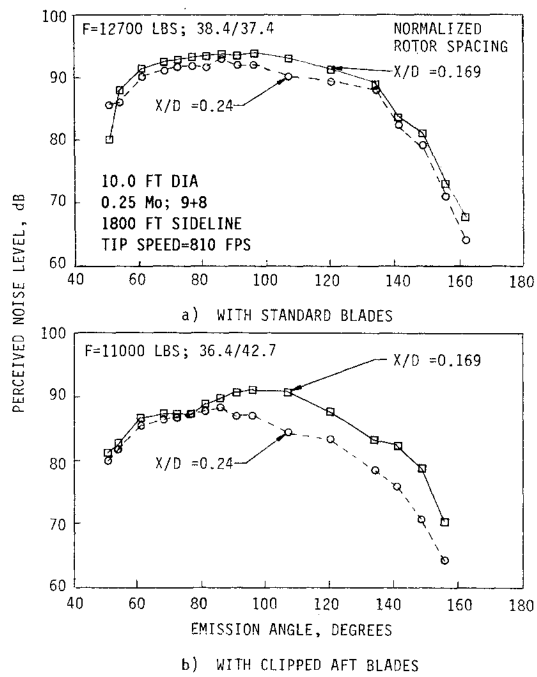
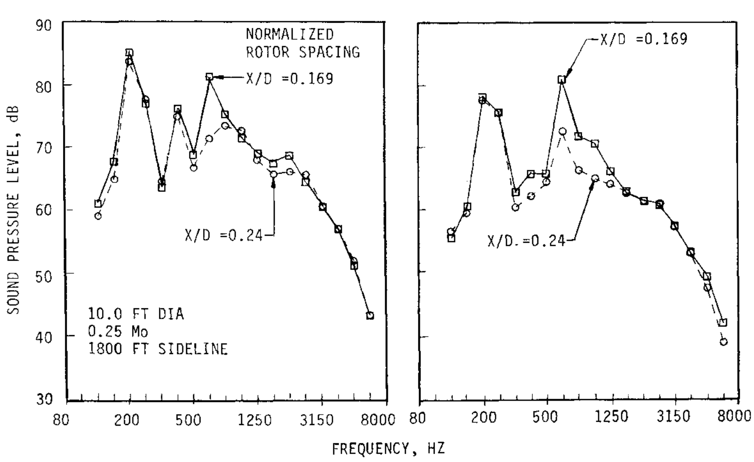


Fig. 20 Axial spacing effect with standard and clipped aft blades on PNL directivity.

Scaled PNL directivity and spectral comparisons are provided in Figs. 20 and 21 for a typical cutback thrust. The data clearly show the different effects of increased spacing with standard and clipped aft configurations. Significantly greater reductions are noted due to an increase of spacing with the clipped aft configuration than with the unclipped configuration, particularly in the aft quadrant.

This study on the effect of increased spacing is concluded by summarizing two observations that are made based on the presented results. Increasing rotor spacing from X/D of 0.169 to 0.24 had no effect on steady-loading noise but did result in a reduction in the aerodynamic rotor-to-rotor interacton noise. The amount of interaction noise reduction depended on the presence or absence of forward-blade, tip-vortex to aft-blade interaction. By minimizing this interaction, as demonstrated



a) Standard b) Aft clipped

Fig. 21 Axial spacing effect with standard and clipped aft blades on spectra.

with the 9+8 configuration having reduced diameter aft blades, the benefit of the increased rotor spacing on interaction noise was found to be substantial. Considering the sum of sound pressure levels of all interaction tones as a measure of the rotor-to-rotor interaction noise level, an 8–10 dB reduction was observed in the peak noise region of the clipped aft configuration. This reduction is attributable to the benefit of increased wake decay resulting from the increased rotor spacing. The corresponding reduction obtained with standard 9+8 blades that contain tip-vortex to aft-rotor interaction was approximately 4dB.

This seems to indicate that the interaction noise levels due to tip-vortex to aft-rotor interaction are of the same order of magnitude as those due to forward-blade wake to aft-rotor interaction. Therefore, only a partial acoustic benefit ($\simeq 3$ dB) would be obtained by substantially reducing either one of these effects. It was concluded from this study that significant reductions in interaction noise could be obtained by first reducing the tip-vortex/aft-rotor interaction by clipping the aft blades and then increasing the wake decay by increasing the rotor spacing. If clipping is not done, the benefit obtainable with an increase in spacing would be masked by noise levels due to tip-vortex/aft-rotor interaction.

The impact of reduction in levels of interaction tones on the total noise (i.e., PNL, OASPL, and dBA) depends on associated levels of the steady-loading tones. Significant benefits in the steady-loading noise levels for a given thrust were noted with configurations at open blade-pitch angles due to a decrease in tip speed and with configurations having an increased number of blades. As a result of this reduction in steady-loading noise, sound pressure-level reductions at higher harmonics due to increased spacing were found to have a greater impact on the total noise of such a configuration.

Conclusions

Comprehensive acoustic tests were conducted at the GE Anechoic Facility with a Model Propulsion Simulator to determine the acoustic characteristics of counterrotating fan systems at test conditions that simulate typical takeoff and cutback conditions. Using model scale F7A7 blade design, tests were conducted to determine the effects of variations in blade number, tip speeds, and rotor-to-rotor spacings on community noise characteristics. Analysis of the data yielded the following conclusions.

1) For a given thrust, an increase in blade count results in a significant two-fold acoustic benefit: steady-loading noise decreases as a result of reductions in blade loading and tip speed, and a decrease in rotor-to-rotor interaction noise results from the aft rotor blades rotating at a lower tip speed that interact with the weakened wakes and tip vortices from the forward rotor blades.

2) For a given thrust and blade number, steady-loading noise of a configuration decreases with tip speed.

3) For standard diameter rotors, the acoustic benefit of an increased spacing between pitch-change axes from $X/D = 0.169$ to 0.24 is limited to reductions mainly in 1A + 1F and 1A + 2F tones. With a reduced aft diameter or clipped configuration, additional benefit of increased spacing occurs in some of the higher frequency (1A + 3F and 1A + 4F) interaction tones. Assuming that the length of clipping on the aft blade is sufficient to minimize any interaction of the forward blade tip vortex with the aft blade, these reductions occur because of the increased decay of the forward-blade wakes with increased rotor spacing.

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