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ACOUSTIC BENEFITS OF STATOR SWEEP AND LEAN FOR A HIGH TIP SPEED FAN

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Abstract

A model high-speed fan stage was acoustically tested in the NASA Glenn 9- by 15-Foot Low Speed Wind Tunnel at takeoff/approach flight conditions. The fan was designed for a corrected rotor tip speed of 442 m/s (1450 ft/s), and had a powered core, or booster stage, giving the model a nominal bypass ratio of 5. The model also had a simulated engine pylon and nozzle bifurcation contained within the bypass duct. The fan was tested with three stator sets to evaluate acoustic benefits associated with a swept and leaned stator and with an swept integral vane/frame stator which incorporated some of the swept and leaned features as well as eliminated some of the downstream support structure. The baseline fan with the wide chord rotor and baseline stator approximated a current GEAE CF6 engine. A flyover effective perceived noise level (EPNL) code was used to generate relative EPNL values for the various configurations. Flyover effective perceived noise levels (EPNL) were computed from the model data to help project noise benefits. A tone removal study was also performed. The swept and leaned stator showed a 3 EPNdB reduction at lower fan speeds relative to the baseline stator; while the swept integral vane/frame stator showed lowest noise levels at intermediate fan speeds. Removal of the bypass blade passage frequency rotor tone (BPF) showed a 4 EPNdB reduction for the baseline and swept and leaned stators, and a 6 EPNdB reduction for the swept integral vane/ frame stator. Therefore, selective tone removal techniques such as active noise control and/or tuned liner could be particularly effective in reducing noise levels for certain fan speeds.

Introduction

A major source of aircraft engine noise comes from interaction of the rotor viscous wake with the exit guide vanes, or stators. The most prominent component of this interaction noise is tones at multiples of the rotor blade passage frequency, although there also exists a broad-band component of this rotor-stator noise. Traditional methods of reducing this interaction noise have been to select blade/vane ratios to satisfy the cutoff criterion for propagation of the fundamental rotor tone[1] and increased axial spacing between the rotor and stator.[2] Increased rotor-stator axial spacing may somewhat degrade the fan aerodynamic performance and increase the overall engine weight.

Stator vane lean and/or sweep have been suggested as a mechanism to reduce the severity of the rotor wake interaction with the stator vane. Vane sweep is the axial displacement of the vane with radius such that the tip region is further downstream than the hub. Correspondingly, lean is the circumferential displacement of the vane stacking line relative to the radial direction. Both of these stator modifications have been proposed as a means to reduce the stator response to the rotor downwash, thereby reducing the rotor/stator acoustic response. Kazin[3] demonstrated rotor/stator interaction tone reductions associated with a stator leaned 30° in the direction of fan rotation. Noise reductions in the 2BPF tone from 1.5 to 3.5 dB with the leaned stator were observed in this study.

Analytical studies[4] have suggested that both stator lean and sweep, if properly applied, may significantly reduce rotor/stator interaction tone noise. Optimal stator lean and sweep offers the possibility of reducing the overall engine weight through decreased axial rotor-stator spacing or achieving additional tone noise reduction for a particular rotor-stator spacing.

This paper presents acoustic results for an advanced high tip speed model fan that was tested in the NASA Glenn 9- by 15-Foot Low Speed Wind Tunnel. The 9- by 15-LSWT provides an anechoic testing environment at representative takeoff and approach flight speeds. The model was representative of what is currently used on a 5 to 6 bypass ratio, 442 m/s (1450 ft/s) rotor tip speed turbofan. The results of Ref. 5 showed that stator sweep and lean could give a 3 EPNdB noise reduction for a lower design tip speed (305 m/s (1000 ft/s)) fan. Thus, it was desirable to explore the acoustic benefits of stator sweep and lean for a higher design tip speed fan. The results presented herein do show that similar acoustic benefits may be achieved for a higher tip speed fan stage incorporating similar stator sweep and lean.

Description of Fan Test

Research Fan

The high-speed fan model was designed and built by General Electric Aircraft Engines under contract to NASA Glenn Research Center (Contract NAS3–27720). Figure 1 is a photograph of the model fan installed in the NASA Glenn 9- by 15-LSWT. The fan was tested at a free stream Mach number of 0.10 in the test section, which is sufficient to achieve acoustic flight effect[6] and provides acoustic data representative of takeoff/approach operation. All data were taken at 0° fan axis angle of attack.

The NASA Glenn Ultra High Bypass (UHB) drive rig was used to power the high-speed model fan. The UHB rig was powered by a high-pressure air turbine drive with the drive air and instrumentation supplied through the floor-mounted support strut, shown in Fig. 1. The drive turbine exhaust air was ducted downstream through an acoustically treated diffuser and exited the end of the treated test section. There was little indication of acoustic contamination of the aft fan data from the turbine exhaust.

Table I shows design point parameters for the high-speed fan stage. The 24-blade rotor (Fig. 2) had a diameter of 56 cm (22 in.). The fan stage featured an active core, or booster stage. The booster pressure ratio was slightly lower than that for the bypass flow, and the fan bypass ratio was 5 at design speed. The fan design and flow path approximated that of the GEAE CF6 engine. The model had a simulated engine pylon and nozzle bifurcation contained within the bypass duct located circumferentially 180° apart. The simulated nozzle bifurcation strut was located in the horizontal plane on the traversing microphone side of the model.

The model fan was tested with three different bypass stator sets. The baseline stator had 14° of leading edge sweep and 0° lean (Table II), which is similar to what is used in the current GEAE CF6 engine design. Figure 3 shows a photograph of this stator set and a cross-sectional sketch of the fan stage with this baseline stator installed. The baseline stator had 80 vanes and therefore satisfied the cutoff criterion of Ref. 1. A 12-vane support strut assembly was located just downstream of the stator. Modified extended strut airfoils are used to blend the airflow into the pylon and bifurcator contours.

The swept and leaned stator likewise had 80 vanes and the downstream 12-vane support strut assembly. This stator had 35° of leading edge sweep and 23° lean in the direction of fan rotation. Figure 4 shows a photograph of this stator set and a corresponding sketch of the installed stator. The rotor-stator axial spacing for the swept and leaned stator was slightly less than that for the baseline stator at the hub, and slightly greater at the tip (Table II). The stator transitioned to radial (from sweep and lean) for the inner 25 percent of the span to maintain efficient aerodynamic performance.

The swept integral vane/frame stator eliminated the need for the downstream support struts (Fig. 5). Two of these vanes were blended into the support pylon and bifurcation struts. This stator had 21° of leading edge sweep and 0° of lean. The absence of the downstream support struts enabled larger axial rotor-stator spacing than for the other two stator sets.

Anechoic Wind Tunnel and Acoustic Instrumentation

The NASA Glenn 9- by 15-LSWT is located in the low speed return leg of the 8- by 6-Foot Supersonic Wind Tunnel. The tunnel test section walls, floor, and ceiling have acoustic treatment to produce an anechoic test environment.[7–9] Figure 6 is a sketch of the test fan installed in the 9- by 15-LSWT. Sideline acoustic data were acquired with a computer-controlled translating microphone probe (also seen in the photograph of Fig. 1) and with three aft microphone assemblies mounted to the tunnel floor. The translating microphone probe acquired data at 48 sideline geometric angles from 27.2° to 134.6° relative to the fan rotor plane. The translating probe traverse was 227 cm (89 in.) from the fan rotational axis (about four fan diameters). A wall microphone assembly placed a reference microphone adjacent to the translating probe home position (134.6°, maximum aft travel). The three fixed microphone assemblies were mounted at the home axial position to acquire aft acoustic data at geometric angles of 140°, 150°, and 160°. Data were also acquired with an acoustic barrier wall installed adjacent to the fan which effectively blocked aft-radiated fan noise (Fig. 7). The acoustic data were acquired through a digital computer system and stored for post-run analysis.

Results and Discussion

Aerodynamic Performance

The three stator sets were designed for equivalent aerodynamic performance. Figure 8 presents the fan operating map for the three stator sets. Acoustic data were taken on the “acoustic operating line.” The fan maps were generated during aerodynamic runs employing a bellmouth inlet and extensive aerodynamic instrumentation. The approach, cutback and takeoff fan speeds were designated, respectively, as 61.8, 84.5, and 100 percent of fan design speed. Acoustic data were taken with a flight inlet and limited aerodynamic instrumentation to verify fan operating line. The swept and leaned stator performed slightly better than the other two stator sets (higher pressure ratio/weight flow at a particular rotor speed). Reference 10 presents detailed aerodynamic results for this fan test. This reference shows the swept and leaned stator to be nominally 2 percent higher in adiabatic efficiency on the acoustic fan operating line relative to the other two stators for most rotor test speeds, with the efficiency differences becoming smaller near 100 percent corrected fan speed. The performance for the three stator sets was basically similar from the stall region to the acoustic operating line. The performance difference does become significant in the choke region (below the design operating line), especially at intermediate fan speeds.

Acoustic Performance

All of the fan acoustic data were acquired at 0.10 tunnel Mach. Sideline data are presented in terms of emission angles. The emission angles are related to the geometric, or observed angles by the relationship:

$$\Theta_{em} = \Theta_{geom} - \sin^{-1}(M_0 \sin \Theta_{geom})$$

where Θ_{em} and Θ_{geom} are, respectively, the emission and observed sideline angles, and M_0 is the test section Mach number. The observed angles for the sideline translating microphone probe are then 25° to 130°, and the three fixed microphones measure aft observed angles of 136°, 147°, and 158°. This angular range was sufficient to define the sideline noise profile for this aft-dominated fan for subsequent EPNL calculations.

Digital acoustic data were processed as constant bandwidth spectra. Spectra were acquired and averaged at each translating probe or fixed mic position with 6 and 59 Hz bandwidths. These constant bandwidth spectra were electronically merged and used to generate 1/3-octave spectra. A flyover effective perceived noise level code was used to generate relative flyover EPNL values at a 457 m (1500 ft) altitude. The code could selectively remove spectral tones to show relative EPNL changes associated with removal of bypass and core rotor/vane interaction tones. Results from this analysis code show relative EPNdB values for various configurations, and are not intended to be representative of any particular aircraft.

Acoustic Performance with Core Tones Present

Effective Perceived Noise calculations were made with the as-measured data, with the bypass fundamental rotor tone (BPF) removed, and with all rotor tones (nBPF) removed. Tones from the core (or booster stage) were not removed, as it was initially thought that these were representative of actual engine data. Figure 9 shows the effect of removing these tones for the baseline stator. Tone removal was only effective near cutback fan speed, which is in the transonic region of fan operation. Tone removal was most effective at the test speed just below cutback, suggesting that tone removal would be most effective in the region of 360 m/s (1180 ft/s) tangential rotor tip speed. Of course, this region of maximum tone sensitivity could be better defined with additional fan test speeds.

Removal of the BPF tone reduced the EPNL by 4 dB at 360 m/s tip speed; removal of all bypass tones resulted in nearly a 5 dB reduction. This result clearly shows that significant noise reductions are possible near cutback fan speed by eliminating the BPF tone with active noise control or a tuned liner. The fundamental blade/vane interaction tone for the 24-blade rotor and 80-vane stator should be cutoff with respect to the BPF tone; however, rotor generated tones are expected at supersonic fan speeds.

The swept and leaned stator was expected to significantly reduce fan noise levels. As previously mentioned, stator sweep and lean was shown to reduce the EPNL by about 3 dB near approach conditions for a lower design speed fan (Ref. 5). The results of that reference used a baseline radial stator without sweep or lean and a stator with 30° each of sweep and lean. The hub leading edge axial spacing from the rotor was common to both stators, while the stator sweep significantly increased this spacing with increasing radius in the test fan of Ref. 5.

Reference 4 predicts acoustic benefits associated with stator sweep and lean. The baseline stator of the current study had 14° of sweep and 0° lean. According to this reference, the baseline stator 2BPF tone should show an acoustic power reduction of about 5 dB for upstream noise at approach speed relative to a true radial stator (0° sweep). The current swept and leaned stator should show about a 2BPF reduction of 22 dB. Corresponding downstream noise predictions were about 1 dB for the baseline stator and 20 dB for the swept and leaned stator. The baseline stator was designed to approximate that of a current CF6 engine; however the moderate sweep of this stator could reduce the apparent benefit of the more aggressively swept and leaned stator.

An additional factor in comparing the results of Ref. 5 with those of the current study would be relative rotor-stator axial spacings. Table II shows that the relative axial spacing for the radial swept and swept and leaned stators was not significantly different. (In Ref. 5 the tip axial spacing increased from 1.2 to 2.2 mean rotor chords between the radial and the swept and leaned stator. Thus the increased tip axial spacing in this earlier study would tend to enhance the apparent noise reduction of the swept and leaned stator.) Smith and House[11] conclude that the rotor-stator interaction tone level relates to rotor-stator spacing as $10 \log_{10}(x/c)^2$, where x/c is the ratio of rotor-stator spacing to axial rotor chord length at the tip diameter. This relationship gives a reduction of 6 dB per doubling of rotor-stator separation. Thus the increased tip spacing with stator sweep for the low-speed fan of Ref. 5 would predict a 5.3 dB reduction in noise generated near the tip region for that fan. Small changes in rotor-stator tip region axial spacing for the high-speed fan baseline and swept and leaned stator would only give a 0.6 dB reduction.

Figure 10 shows the acoustic benefits of the swept and leaned stator relative to the baseline stator. The swept and leaned stator reduced the EPNL by slightly over 2 dB at and below approach fan speed. Lesser benefits on the order of 1 EPNdB were observed at higher fan speeds. Removal of the fundamental rotor-stator interaction tone showed significant benefit near the cutoff fan speed of about 5 EPNdB, similar to what was shown for the baseline stator in Fig. 9.

The acoustic barrier wall (Fig. 7) effectively blocks aft-radiating fan noise. Figure 11 shows the EPNL benefits for inlet-radiated noise for the swept and leaned stator. The swept and leaned stator reduced noise levels near and below approach fan speed by about 3 EPNdB. EPNL benefits associated with removing the fundamental rotor-stator tone and its harmonics near cutback speed were 8 EPNdB for the BPF tone and almost 10 EPNdB with all harmonics of the blade passage tone (nBPF) removed.

Figure 12 shows representative upstream (50° emission angle) and downstream (121° emission angle) constant (59 Hz) bandwidth spectra for the baseline stator at selected fan speeds. Downstream spectra are not relevant with the barrier wall in place. The dominant tone for spectra at 50 percent design fan speed (Fig. 12(a)) are the core IGV-rotor BPF and 2BPF tones in the downstream spectra. The core IGV-rotor interaction is cuton (see Table II) and the IGV-rotor spacing is quite close. Note that there is little evidence of these tones in the upstream spectra. The bypass rotor-stator interaction tones are cutoff and of little significance in these spectra.

These first two core rotor tones are likewise prominent in the downstream spectra at the designated approach, 61.8 percent fan speed (Fig. 12(b)). There is evidence of the fundamental (BPF) bypass rotor tone in the upstream spectra. The source of this tone is not clear. The blade/vane numbers (24/80) would indicate that this tone is strongly cutoff. However, other downstream struts would be cut-on. In particular, the support and bifurcation struts would effectively appear as 2 vanes. Also, the downstream 12-vane support frame would be cut-on. Rotor-downstream strut interaction tones have been observed in previous fan tests,[12] and rotor-inflow interaction noise is a possibility.

Removal of the bypass rotor tones was shown to be particularly effective at 80 percent design fan speed, just below designated cutback. Figure 12(c) shows representative spectra at that fan speed. Although still present, core tones are less important at this fan speed, due in part to the higher overall noise levels. Rotor multiple pure tones, typical of transonic operation, are seen in these spectra. The bypass fundamental tone (which is strongly rotor generated at supersonic tip speeds) is prominent in these spectra.

The designated cutback fan speed was 84.5 percent of design (Fig. 12(d)). The bypass fundamental tone is still prominent—especially in the upstream spectra. The core fundamental tone is evident in the downstream spectra. The bypass BPF tone is the only strong tone present at 100 percent design fan speed (Fig. 12(e)) and is seen in spectra for all three stator sets at this fan speed.

There is significant evidence that the core IGV-rotor interaction tones are predominantly aft-radiating. The active core was included both for aerodynamic considerations and to better model an actual engine application. However, aft-radiating core noise would likely be attenuated in the engine turbomachinery and therefore not be a factor in far-field noise. Figure 13 shows 1/3rd octave directivities for the fan operating at approach (61.8 percent) design speed with the three stators. These directivities are for the 10 KHz band that contains the fundamental core rotor tone. The core BPF tone is aft dominant, as expected.

Sound power level spectra (PWL) integrate the entire far-field noise data and, therefore, provide a good summary of the fan noise. Figure 14 shows 59 Hz bandwidth PWL spectra for the three stator sets. Figure 14(a) shows spectra at 50 percent design fan speed. These spectra are dominated by the core BPF and 2BPF tones. The swept and leaned and swept integral vane/frame stators lowered broadband levels by 2 to 3 dB, with the swept and leaned stator being somewhat more effective at lower frequencies.

The first two core tones dominate the spectra at 61.8 percent design fan speed (designated approach, Fig. 14(b)). There is some evidence of the bypass fundamental BPF tone, although this tone was predicted to be cutoff at subsonic fan speeds. There are a series of "sum tones" first seen between the core BPF and 2BPF tones. These tones appear at frequencies defined as the core BPF + n(bypass BPF) where n is 1, 2, 3…. These modulation tones are quite strong at this fan speed. Both advanced stator sets were effective in reducing broadband noise levels by 2 to 3 dB, with the swept and leaned stator showing the most broadband reduction at lower frequencies.

Sound power level spectra at 70 percent design fan speed are shown in Fig. 14(c). The core rotor tones continue to dominate these spectra, however the sum tones noted at 61.8 percent fan speed are not as significant at this somewhat higher speed.

There was a spectral contamination near 2000 Hz due to a continuing acoustic problem with several boltholes in the fan drive support strut. These holes were filled and covered before each run, but due to oil, etc, this covering tended to tear away during the fan run. The noise hump centered at 2000 Hz was correlated with the degeneration of these hole covers, and was a problem for the baseline and swept and leaned stator data, which were taken earlier in the test series. New hole filling procedures eventually corrected this problem. The compromised data were at 65, 70, and 75 percent of design speed due both to sensitivity to flow impingement at these fan speeds, and that these points were typically taken later in the test day when the degeneration of the hole covering was more pronounced. Directivity results at these fan speeds and frequency showed that flow noise from the exposed bolt holes was not very directional and tended to raise the SPL by 5 or more dB throughout the angular survey.

As previously mentioned, the bypass tones become strongly rotor generated at supersonic fan speeds. Figure 14(d) shows PWL spectra at 80 percent fan design speed, which showed the most sensitivity to tone removal (Figs. 9 to 11). Both bypass and core rotor tones are evident in the PWL spectra at this fan speed. Broadband levels were still reduced with the advanced stator sets, although not as much as for subsonic fan speeds. The PWL spectra at 84.5 percent fan speed (designated cutback, Fig. 14(e)) are essentially similar to those for 80 percent speed.

At 100 percent design fan speed (Fig. 14(f)) the spectra are dominated by bypass rotor tones and multiple pure tones are not present. Core rotor tones are relatively insignificant at this fan speed. Broadband levels were reduced by about 1 dB with the advanced stator sets.

<u>Effect of Core Tones</u> The acoustic results presented up to this point seem to show that the core IGV-rotor rotor tones are significant in the spectra and are highly aft radiating. Figure 15 shows the effect of selectively removing the core BPF and nBPF tones from the EPNL calculations for each stator set. As suspected, these core tones made a significant contribution to the EPNL at fan tip speeds below 270 m/s. Also, the impact of the core tones was greatest for the swept and leaned stator. This stator was the quietest of the three stator sets at subsonic rotor tip speeds, and therefore most easily contaminated by the presences of the core tones.

Figure 16 repeats this exercise for far-field data with the acoustic barrier wall in place. There is essentially no impact from the core tones on inlet-radiating effective perceived noise levels. Thus it is clear that for this model fan, noise radiating from the active core only serves to compromise the acoustic results for the bypass stators. Therefore it was desirable to electronically remove the core rotor tones before proceeding with the acoustic comparison of the bypass stator sets.

<u>Acoustic Performance with Core Tones Removed</u> The remaining figures in this analysis are with all of the core rotor tones removed. The low-frequency tone that was associated with the exposed support strut hole was also electronically removed where evident for the baseline and swept and leaned stators at 65, 70, and 75 percent design fan speed.

Figure 17 shows the benefit of removing the bypass rotor tones for the baseline stator. These results are essentially the same as for Fig. 9, showing that tone removal is effective in the region of cutback fan speed. Again, removing the BPF tone reduces the EPNL by 4 dB; removal of all rotor tones reduces the EPNL by 5 dB. The test point of greatest sensitivity to tone removal was 80 percent of design speed (360 m/s tip speed).

Results for the swept and leaned stator were especially encouraging (Fig. 18). This stator reduced the EPNL by 3 dB at approach and lower rotor speeds without additional tone removal, showing excellent agreement with the swept and leaned stator results for the lower speed fan of Ref. 5. The swept and leaned stator typically reduced the EPNL by 1 to 1½ dB at higher fan speeds. Removal of the bypass BPF and nBPF tones near cutback fan speed again yielded 4 to 5 EPNdB.

The data reduction code that electronically removed the core and bypass tones inspected the spectra for tones at the fundamental rotor tone frequency (BPF) and multiples thereof. As noted in the discussion of Fig.14, there were also significant sum tones in some of the subsonic spectra due to modulation between the bypass and core BPF tones. These sum tones were not removed for the analysis.

Also, the initial 14° sweep present in the baseline stator for this high speed fan would give some sweep-related noise reduction relative to noise levels for a true radial stator. The lower speed fan of Ref. 5 used a true radial stator for baseline noise levels, and additionally had a greater relative rotor-stator tip spacing for the swept and leaned stator of that study, thus enhancing the possibility of noise reduction with stator sweep and lean in that earlier test.

The swept integral vane/frame stator eliminated the downstream 12-vane support frame, although two of the stator vanes were modified to fair into the support pylon and bifurcation strut. Rotor-stator spacing was somewhat greater for this stator than for the other two stators of the present test. Figure 19 shows that this stator reduced the EPNL by about 2 dB through approach fan speed. The swept integral vane/frame stator showed the lowest noise levels in the tip speed range from 310 m/s through cutback. The noise reduction was up to 3 EPNdB in the 310 to 335 m/s tip speed range. Removal of the bypass BPF tone gave a 5 EPNdB reduction at 80 percent design fan speed, just below designated cutback, with removal of all bypass rotor tones giving an additional 1 EPNdB reduction.

Figure 20 shows the relative noise benefits of the swept and leaned and swept integral vane/frame stator relative to the baseline stator with all of the bypass rotor tones present. The swept and leaned stator was most effective in reducing EPNL at lower fan speeds, while the swept integral vane/frame stator was more effective for noise reduction at rotor tip speeds above 290 m/s.

These same trends are evident with the bypass BPF tone removed (Fig. 21), with the swept and leaned stator showing about 3 EPNdB reduction up to cutback, and the swept integral vane/frame stator showing about a 3 EPNdB reduction from 310 to 335 m/s rotor tip speed. Removal of all bypass rotor tones (Fig. 22) showed results similar to what was shown for removal of just the bypass BPF tone.

Summary of Results

A model high-speed fan stage was acoustically tested in the NASA Glenn 9- by 15-Foot Low Speed Wind Tunnel at takeoff/approach flight conditions. The fan was designed for a corrected rotor tip speed of 442 m/s (1450 ft/s), and had a core flow simulation, or booster stage, giving the model a bypass ratio of 5. The model also had a simulated support pylon and bifurcation strut in the bypass flow path. The fan was tested with three stator sets to evaluate acoustic benefits associated with a swept and leaned stator and with an swept integral vane/frame stator which incorporated some of the swept and leaned features as well as eliminated some of the downstream support structure. The baseline fan with the wide chord rotor and baseline stator approximated a current GEAE CF6 engine. A flyover effective perceived noise level code was used to generate relative EPNL values for the various configurations.

Initial analysis of the far field acoustic results showed that IGV-rotor interaction tones from the core stage were strongly aft radiating. Aft-radiated core noise should be absorbed in the downstream turbomachinery of an actual engine installation. Therefore, all core rotor tones were removed from the acoustic data to facilitate a more accurate appraisal of acoustic benefits associated with the modified bypass stator sets.

Flyover acoustic results for the swept and leaned stator relative to the baseline stator showed a 3 EPNdB reduction at subsonic fan speeds. Reductions of about 1 EPNdB were typical at transonic and higher fan speeds. The integral vane frame stator showed a more modest 2 EPNdB reduction at these lower speeds.

Removal of the rotor-stator fundamental BPF tone was shown to offer a significant EPNL reduction near the cutback fan speed, with the maximum benefit associated with this tone removal at a fan speed slightly below designated cutback. Removal of this tone showed a 4 EPNdB reduction for the baseline and the swept and leaned stator, and a 6 EPNdB reduction for the swept integral vane/frame stator. (An additional noise reduction of only 1 EPNdB was achieved by removing all rotor-stator tones for the baseline and swept and leaned stator; removing all harmonics of the rotor tones had no further benefit for the swept integral vane/frame stator.) This result clearly shows that BPF tone elimination techniques such as active noise control or a tuned liner could offer a significant noise reduction near the cutback fan speed.

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Table I.—Aerodynamic Design Point

Fan tip diameter, cm (in.)	56 (22)
Corrected tip speed m/s (ft/s)	442 (1450)
Corrected rpm (100 percent)	15,105
Corrected fan airflow kg/s (lbm/s)	45.4 (100)
Fan inlet radius ratio	0.310
Specific flow, kg/s-m^2 (lbm/s-ft^2)	1.77 (41.9)
Blade tip relative Mach number	1.48
Fan pressure ratio (core/bypass)	1.64/1.76
Bypass ratio	5.00
Booster flow kg/s (lbm/s) (corrected to P_{tot} upstream of rotor)	7.56 (16.67)
Booster overall pressure ratio	1.740

Table II.—Blade/Vane Parameters

Rotor

Design	Number of blades	Leading edge sweep	Design tip speed m/s, ft/s	Design stage pressure ratio
Wide chord	24	N.A. (radial)	442 (1450)	1.76

Stator

Design	Number of vanes	Leading edge sweep, degree	Lean	12 strut frame	Axial spacing, (rotor chords)	
					Hub	Tip
Radial swept, baseline	80	14	0°	Yes	0.76	2.54
Swept and leaned	80	35	23°	Yes	0.62	2.72
Integral vane/frame	52	21	0°	No	1.21	3.38

Core Booster
(Fan stage includes active core (booster) flow path)

Blade/vane	Number blades/vanes
Inlet guide vanes	98
Booster rotor	62
Deswirl vanes	132

Figure 1.—Photograph of research fan installed in the NASA Glenn 9- by 15-Foot Low Speed Wind Tunnel.

Figure 2.—Photograph of the wide chord rotor (pressure side left; suction side right).

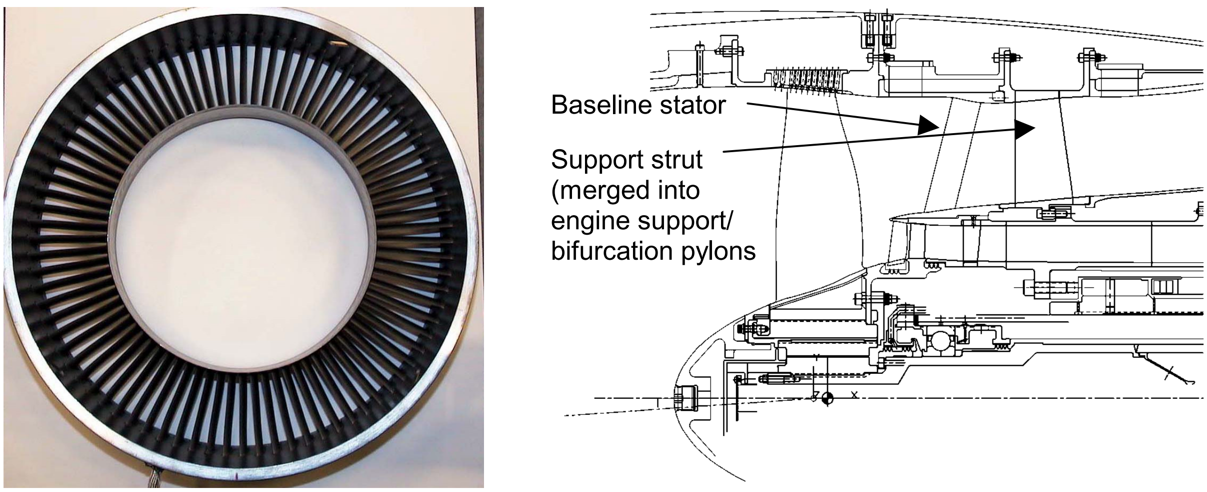


Figure 3.—Photograph of the baseline vanes (viewing downstream) along with a sketch of the fan stage with the wide chord rotor and this stator.

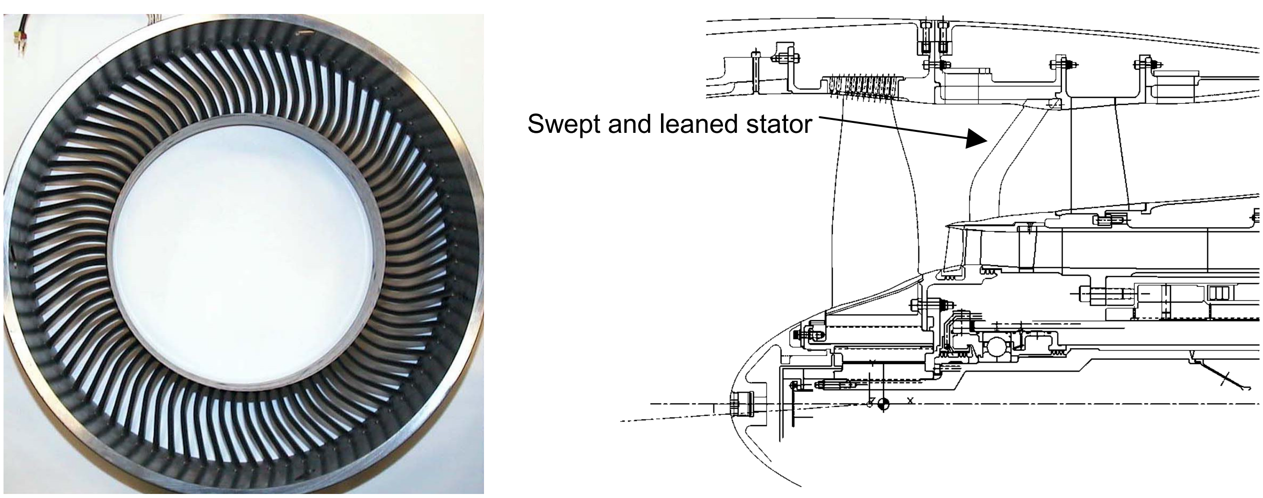


Figure 4.—Photograph of the swept and leaned vanes (viewing downstream) along with a sketch of the fan stage with the wide chord rotor and this stator.

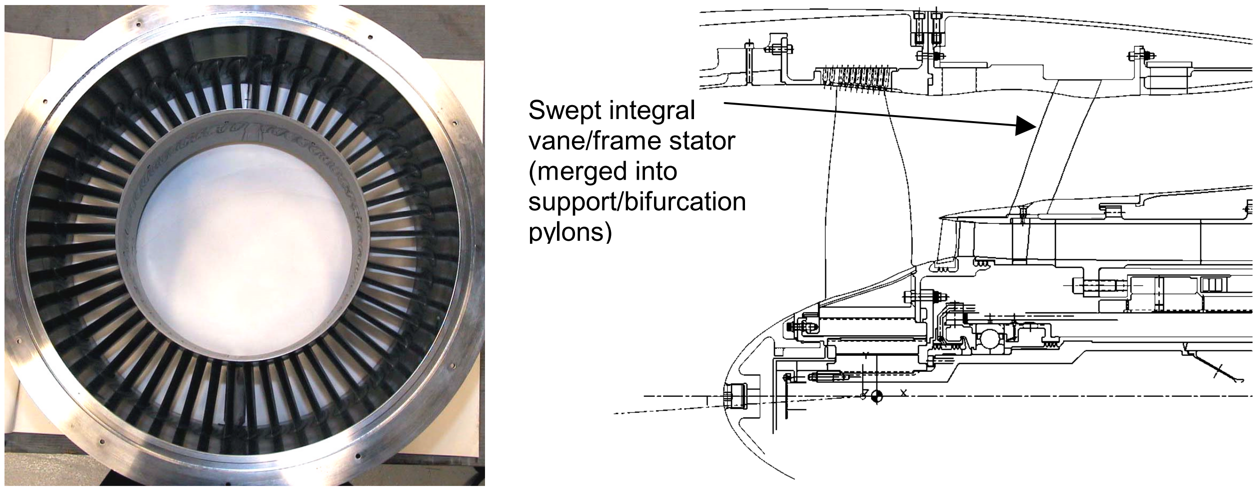


Figure 5.—Photograph of the swept integral vane/frame stator (viewing downstream) along with a sketch of the fan stage with the wide chord rotor and this stator.

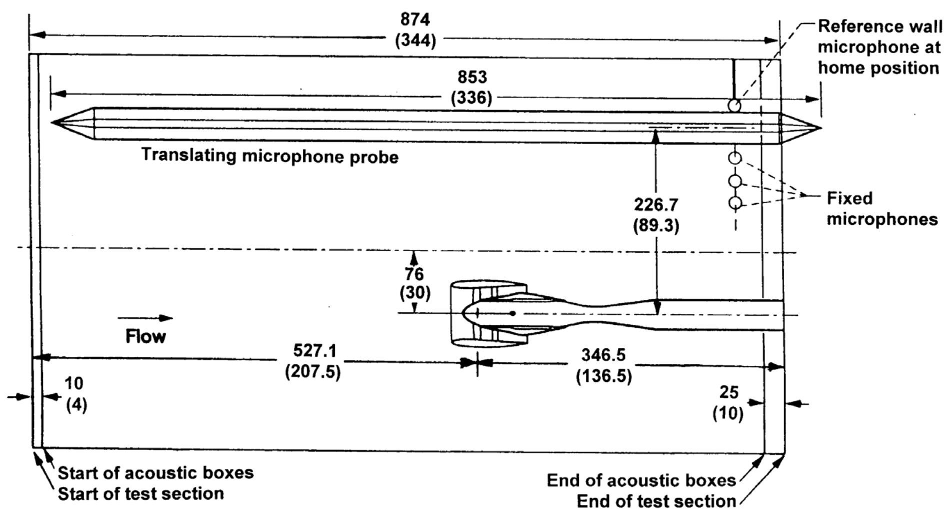


Figure 6.—Sketch of the model fan installed in the 9- by 15-Foot Low Speed Wind Tunnel. Far-field acoustic data were acquired with a translating microphone probe and aft fixed microphones (dimensions in cm (in.)).

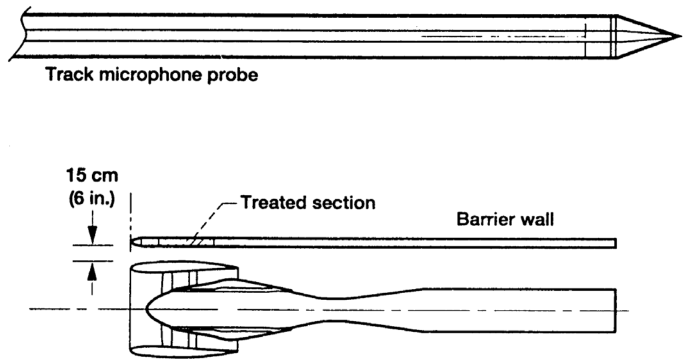


Figure 7.—Sketch showing location of acoustic barrier wall relative to model fan (dimensions in cm (in.)).

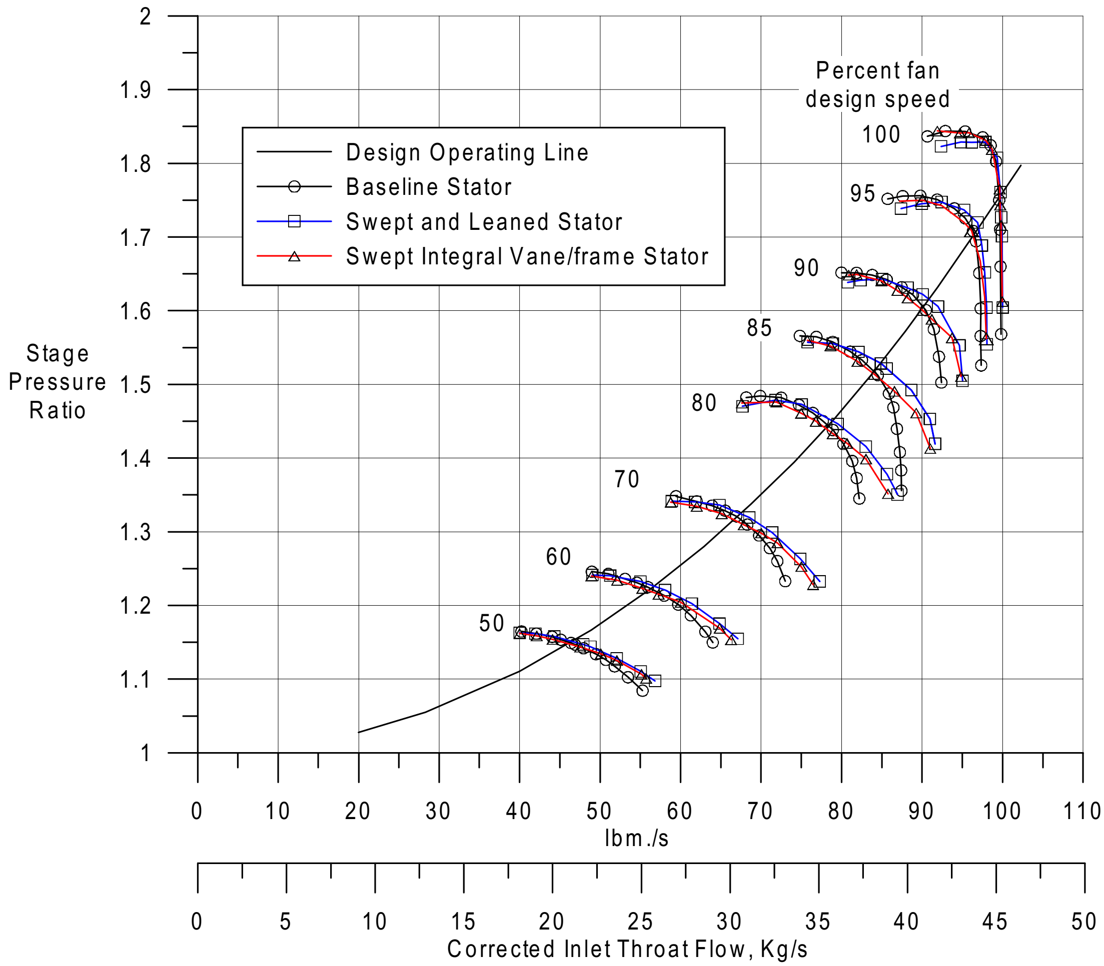


Figure 8.—Fan operating map for the wide chord rotor and three research stator sets.

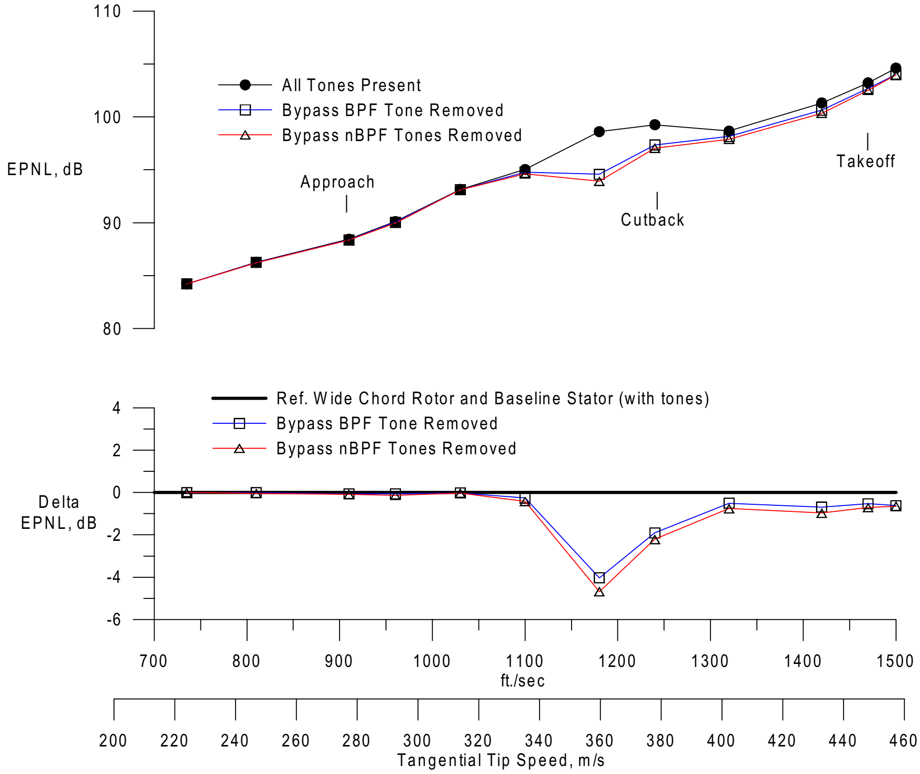


Figure 9.—Effect of removing bypass rotor tones for the baseline stator. Core rotor tones are present, no barrier wall.

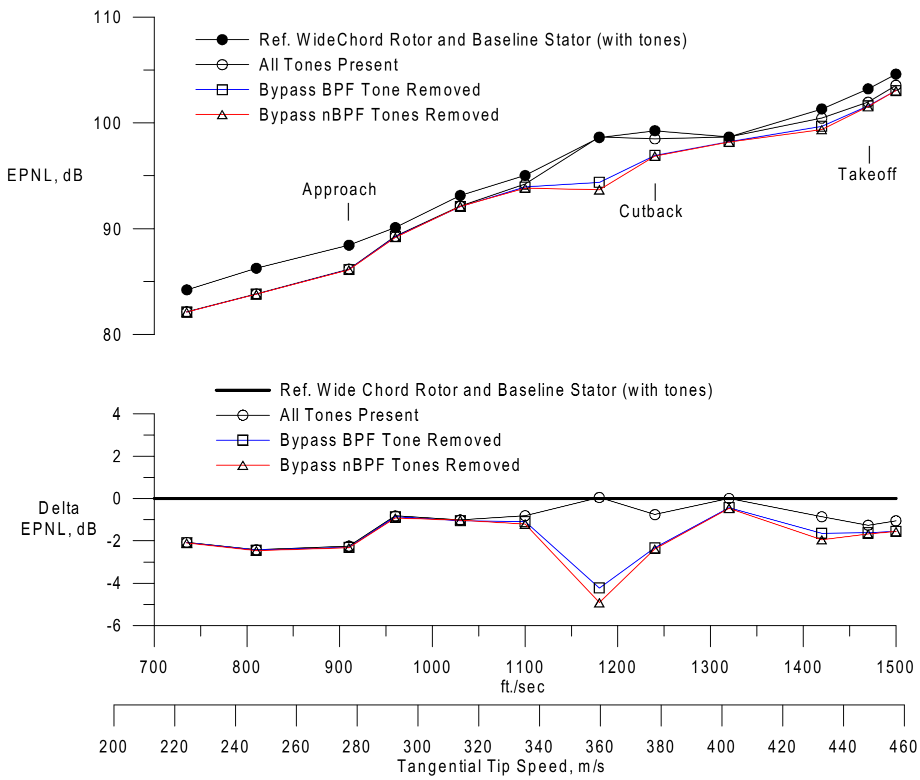


Figure 10.—Effect of removing bypass rotor tones for the swept and leaned stator. Core rotor tones are present, no barrier wall.

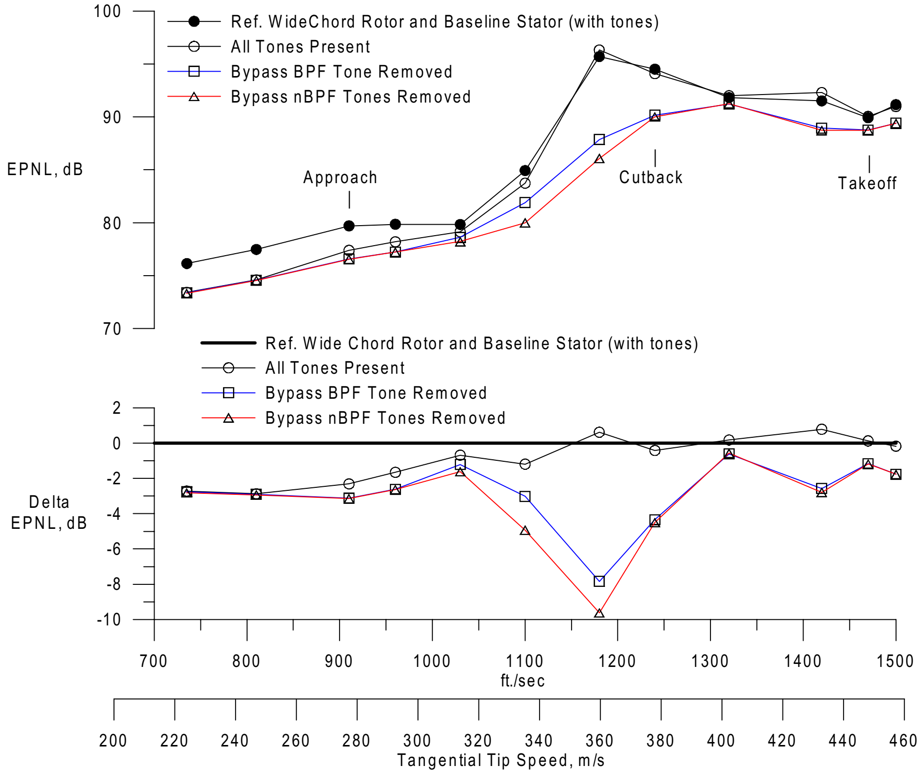


Figure 11.—Effect of removing bypass rotor tones for the swept and leaned stator. Core rotor tones are present, barrier wall in place.

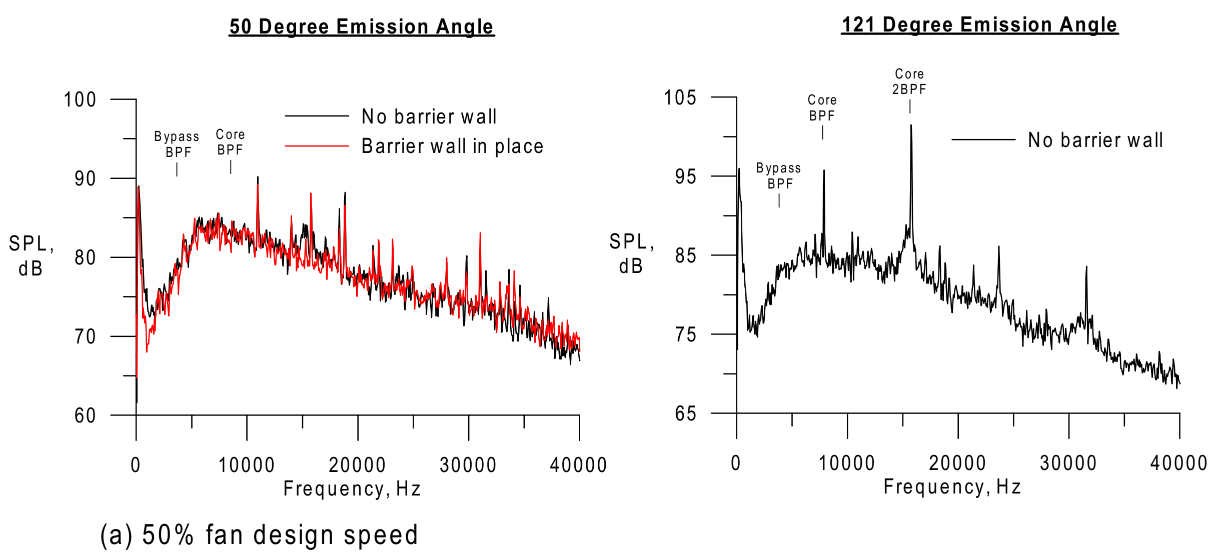
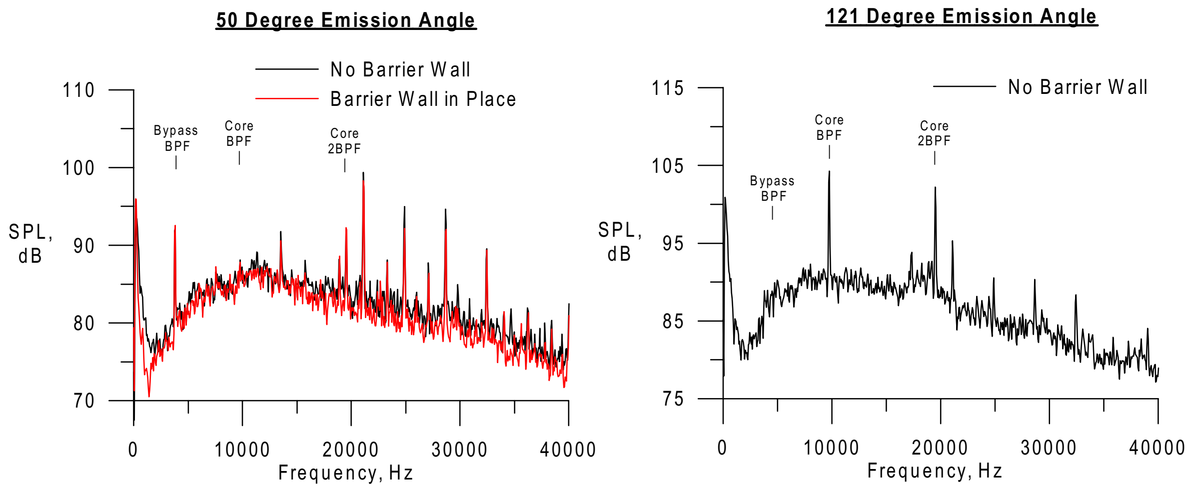
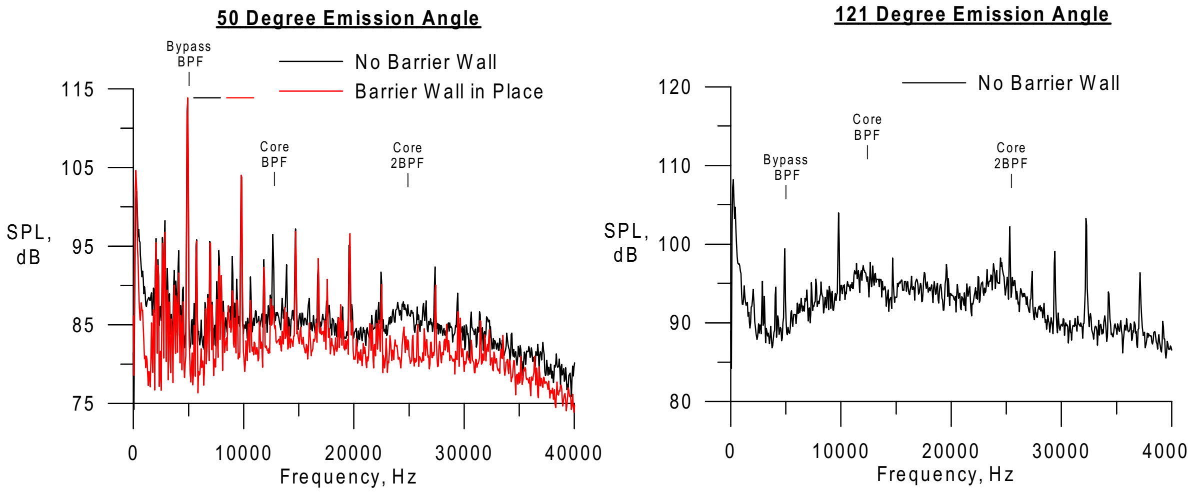


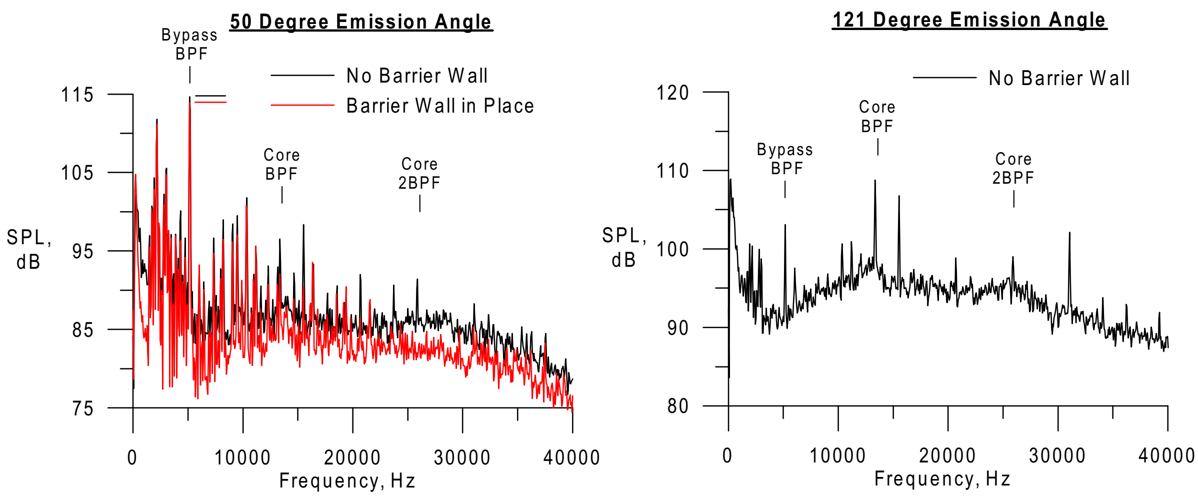
Figure 12.—Constant (59 Hz) bandwidth sound pressure level spectra. (Baseline stator, lossless data on a 227 cm (89 in.) sideline.



(b) 61.8% design fan speed

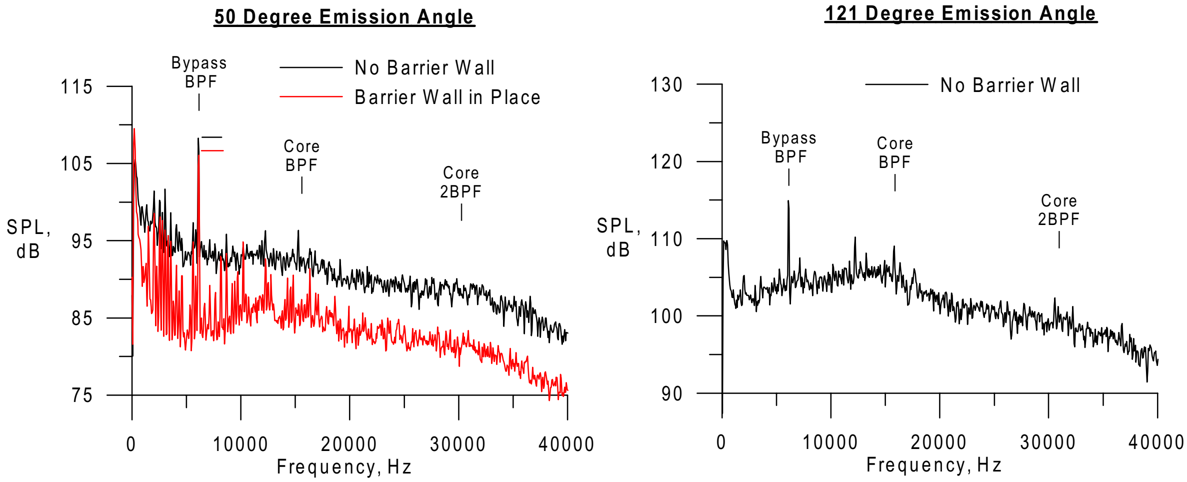


(c) 80% design fan speed



(d) 84.5% design fan speed

Figure 12.—Continued.



(e) 100% design fan speed

Figure 12.—Concluded.

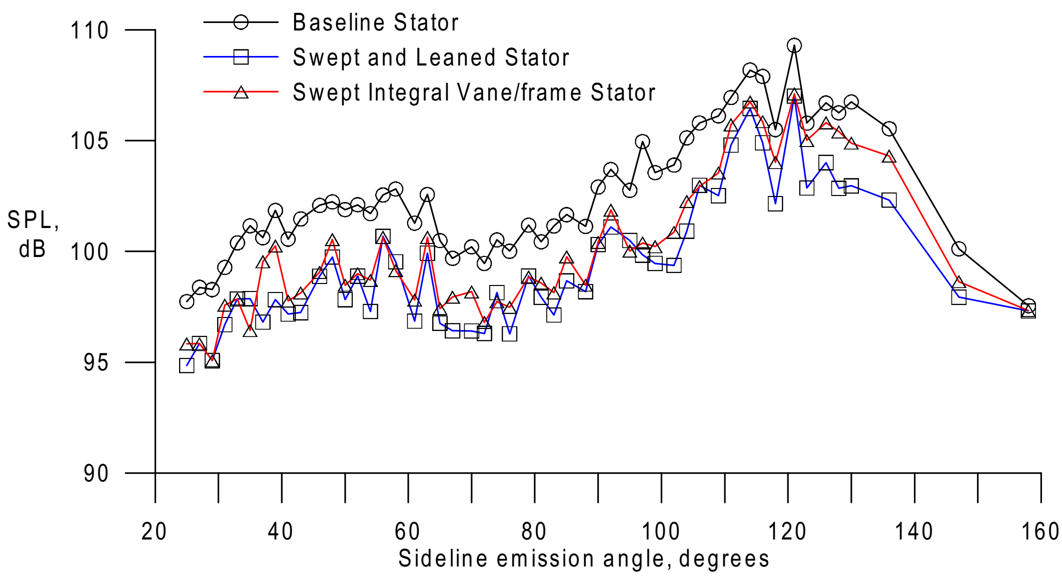


Figure 13.—One-third octave directivities for the core BPF tone at 10K Hz. (Fan operating at 61.8 percent of design speed).

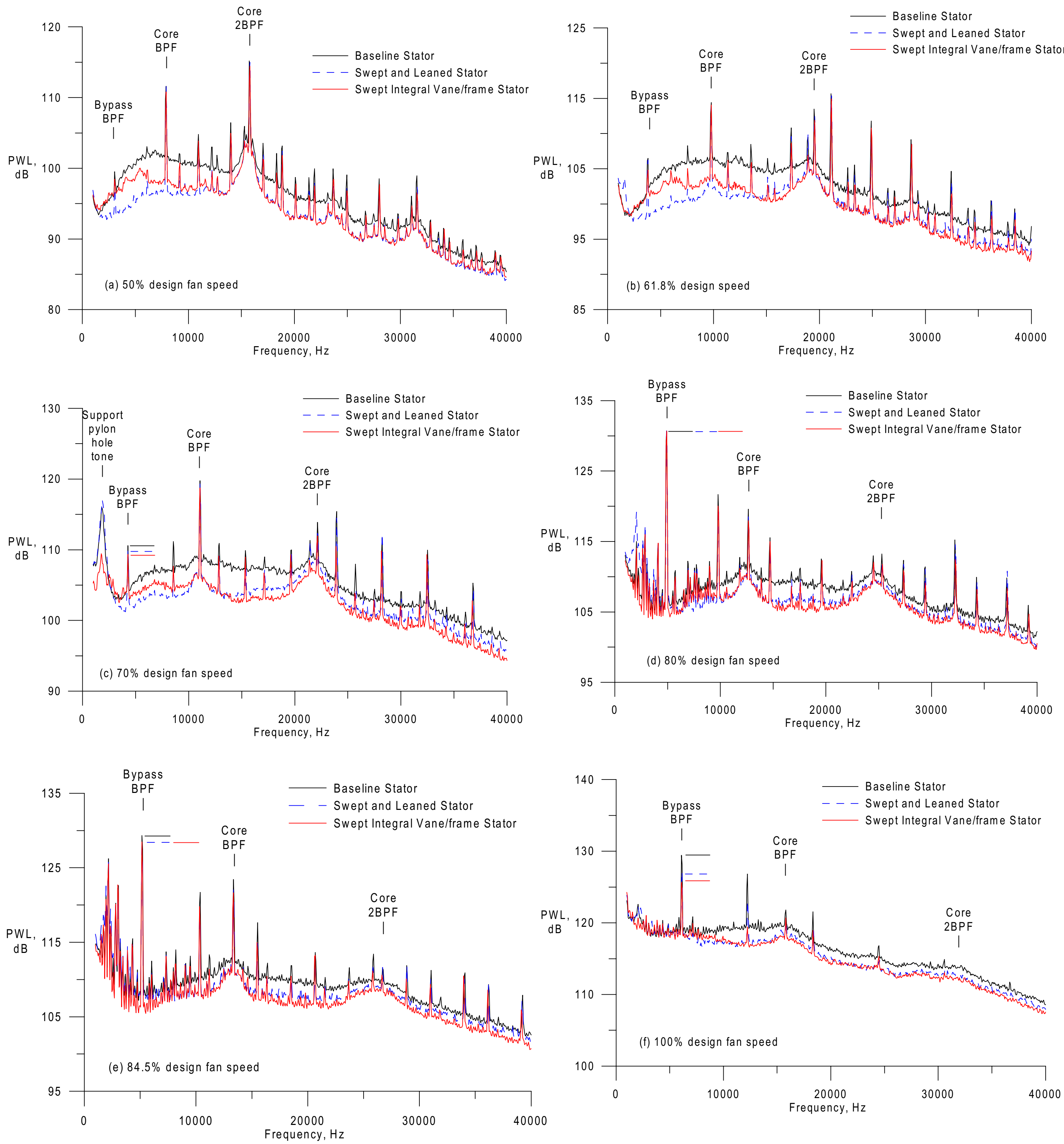


Figure 14.—Sound power level spectra for the three stators sets. (59 Hz bandwidth).

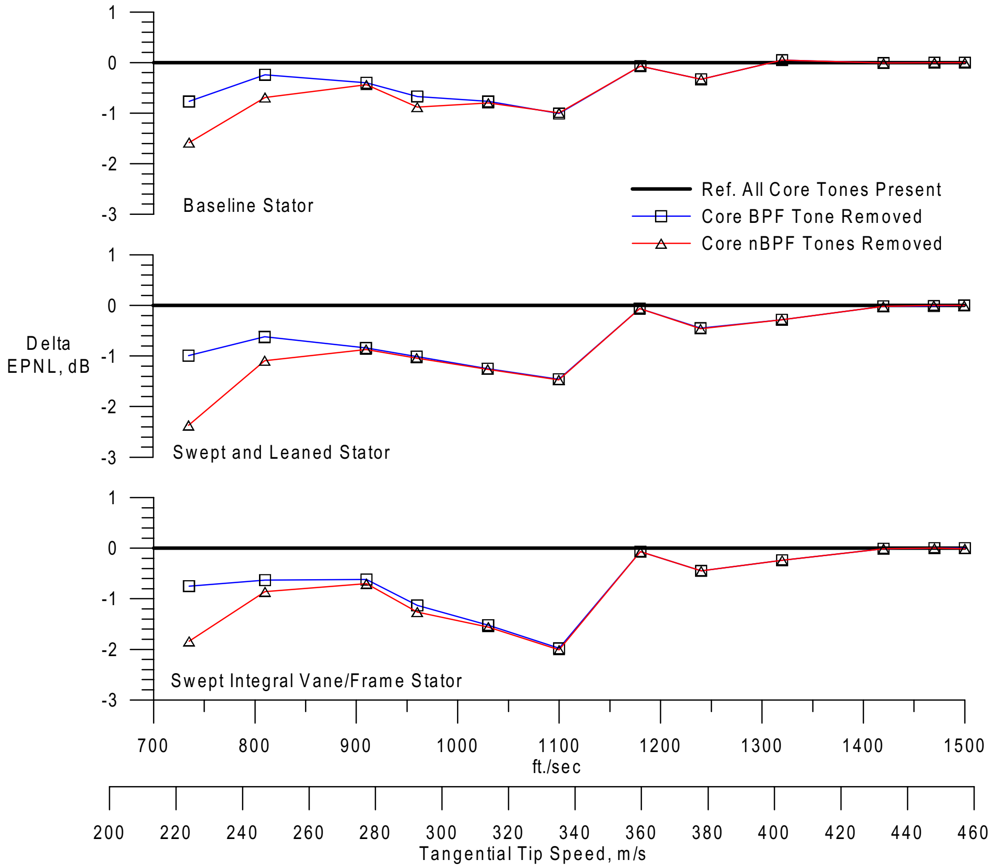


Figure 15.—Effect of removing core rotor tones from EPNL calculations (no barrier wall).

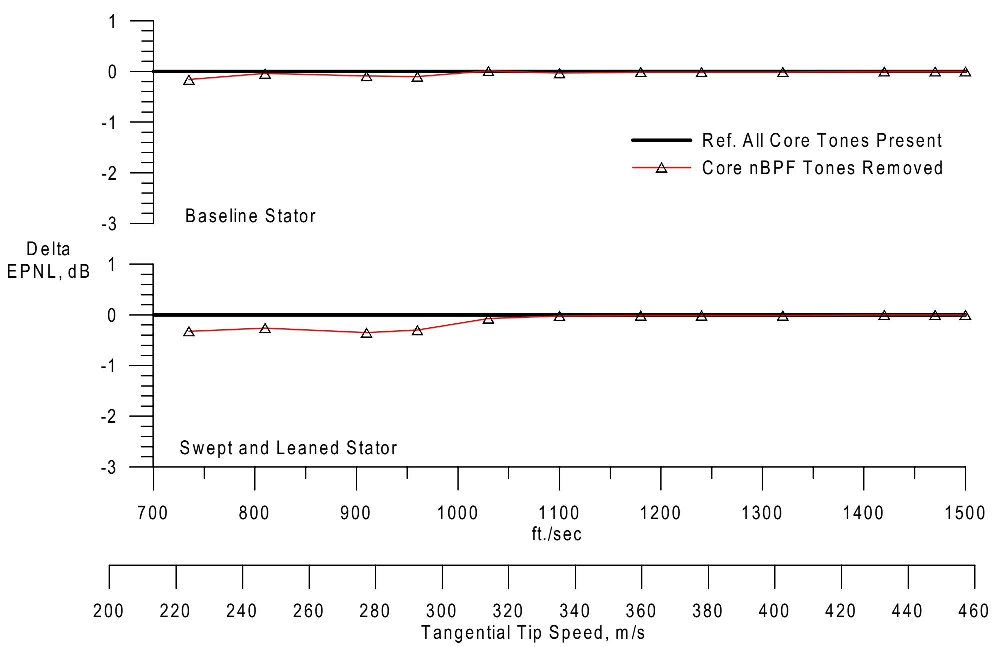


Figure 16.—Effect of removing core rotor tones from EPNL calculation for inlet–radiating noise (barrier wall in place).

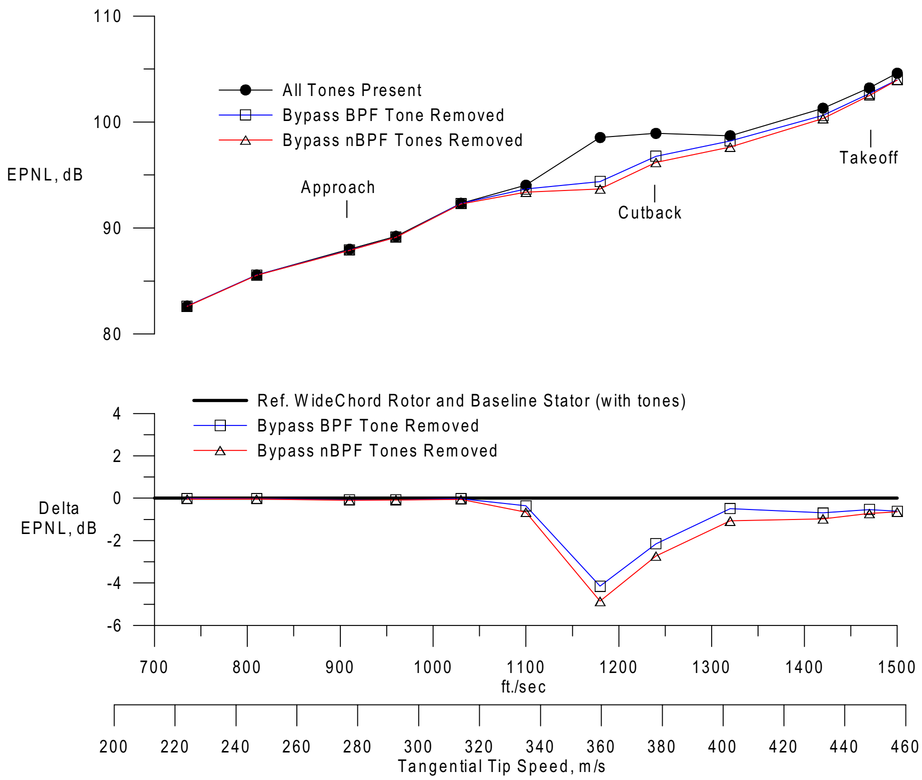


Figure 17.—Effect of removing bypass rotor tones for the baseline stator (core rotor tones removed).

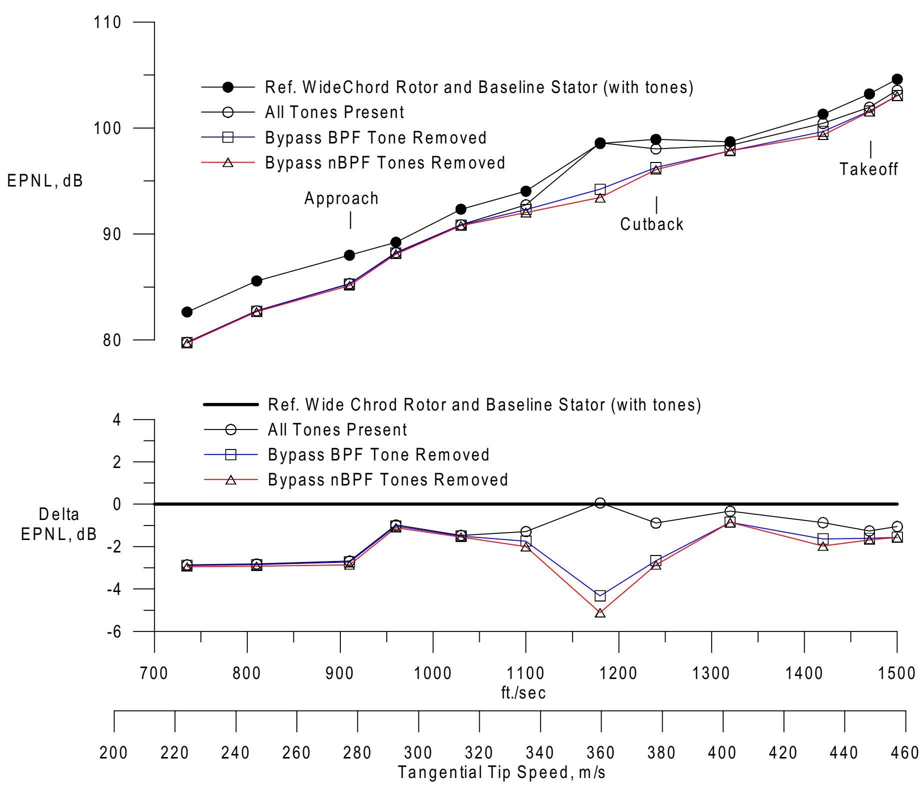


Figure 18.—Effect of removing bypass rotor tones for the swept and leaned stator (core rotor tones removed).

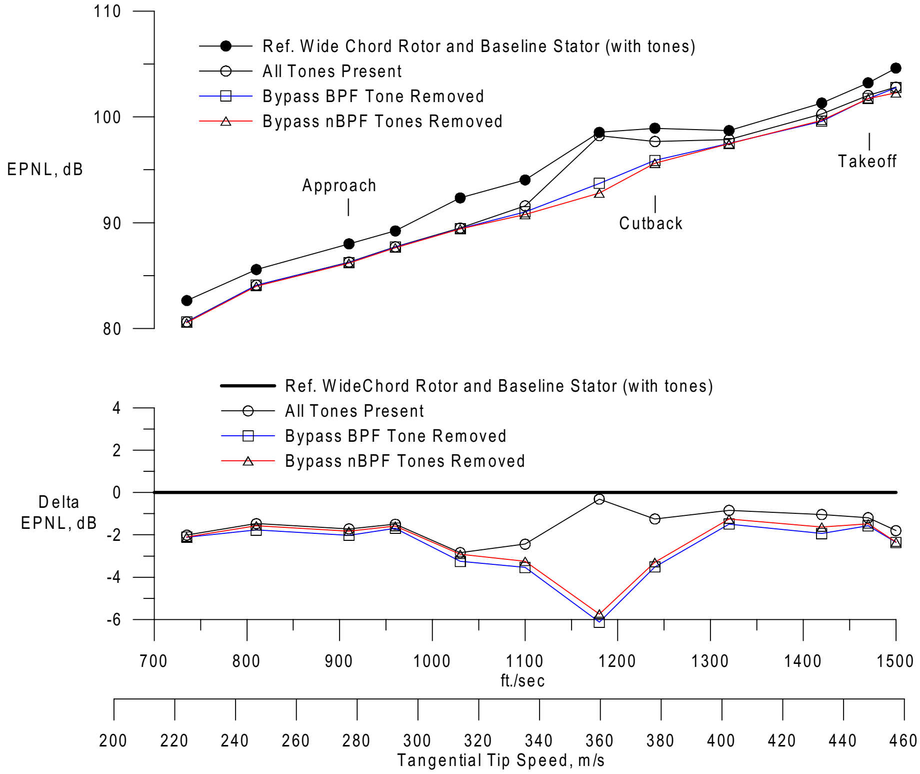


Figure 19.—Effect of removing bypass rotor tones for the swept integral vane/frame stator (core rotor tones removed).

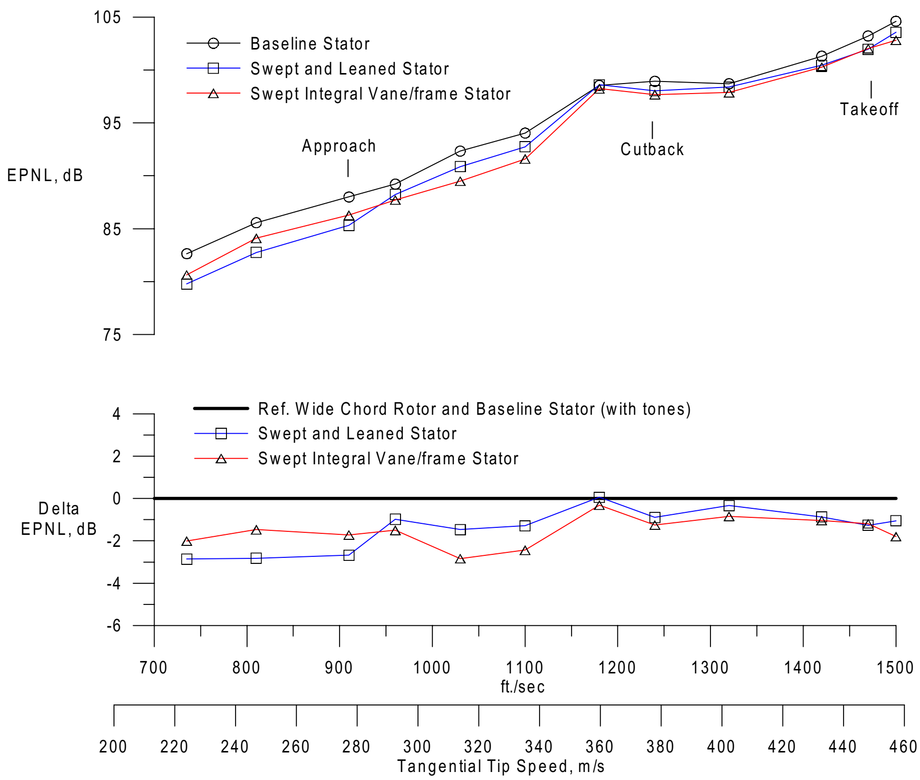


Figure 20.—Relative EPNL for the three stator sets with all bypass rotor tones present (core rotor tones removed).

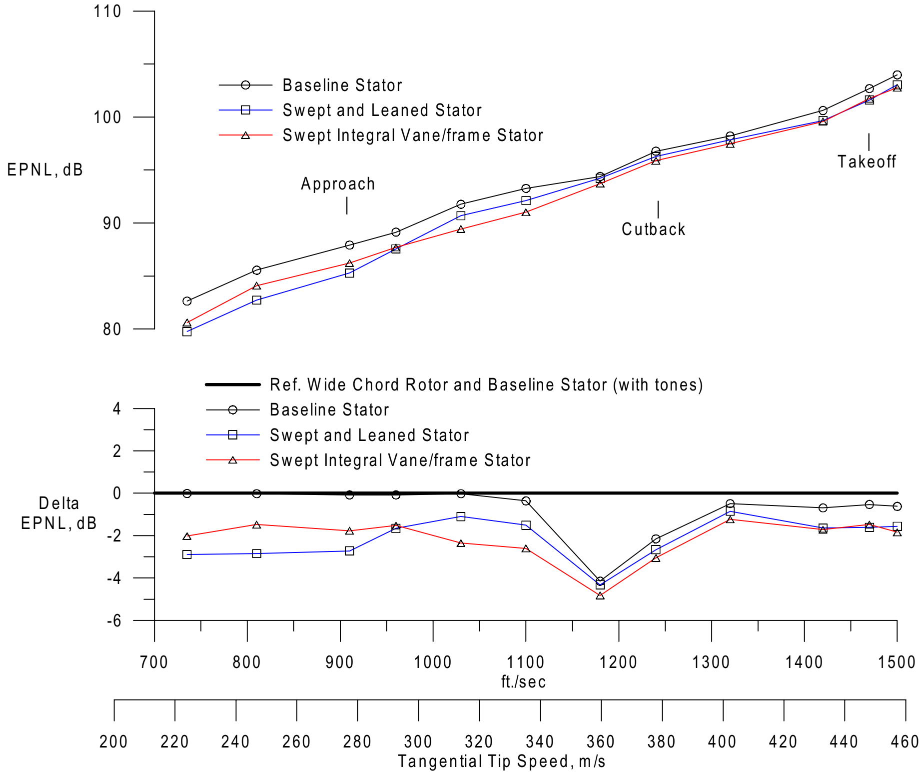


Figure 21.—Relative EPNL for the three stator sets with the bypass BPF tone removed (core rotor tones removed).

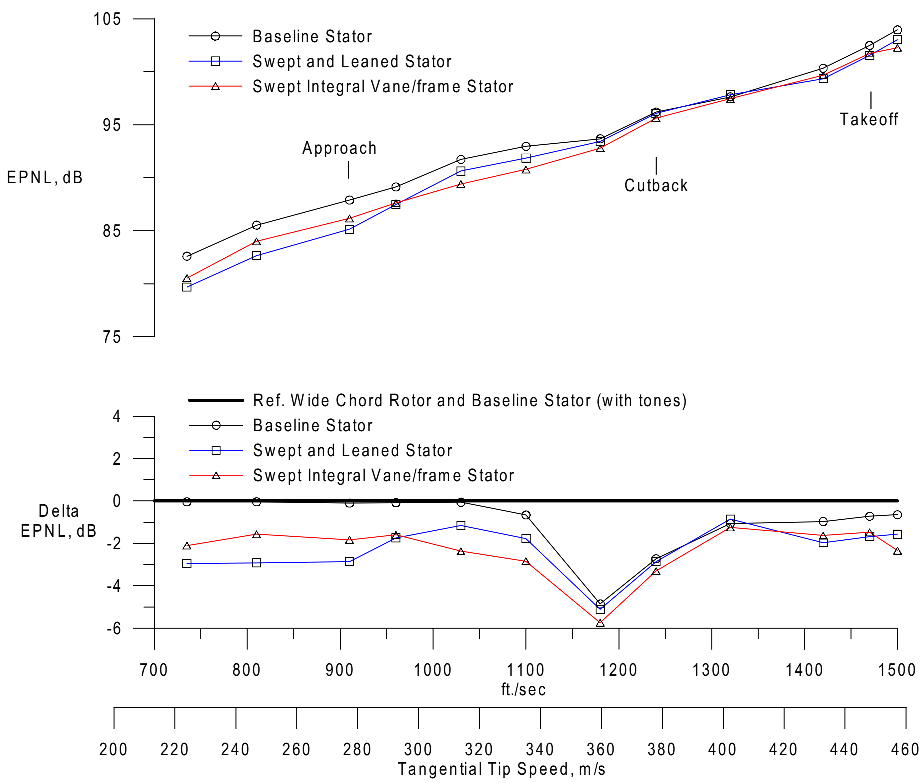


Figure 22.—Relative EPNL for the three stator sets with all bypass rotor tones removed (core rotor tones removed).

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13. ABSTRACT ***(Maximum 200 words)***

A model high-speed fan stage was acoustically tested in the NASA Glenn 9- by 15-Foot Low Speed Wind Tunnel at takeoff/approach flight conditions. The fan was designed for a corrected rotor tip speed of 442 m/s (1450 ft/s), and had a powered core, or booster stage, giving the model a nominal bypass ratio of 5. The model also had a simulated engine pylon and nozzle bifurcation contained within the bypass duct. The fan was tested with three stator sets to evaluate acoustic benefits associated with a swept and leaned stator and with a swept integral vane/frame stator which incorporated some of the swept and leaned features as well as eliminated some of the downstream support structure. The baseline fan with the wide chord rotor and baseline stator approximated a current GEAE CF6 engine. A flyover effective perceived noise level (EPNL) code was used to generate relative EPNL values for the various configurations. Flyover effective perceived noise levels (EPNL) were computed from the model data to help project noise benefits. A tone removal study was also performed. The swept and leaned stator showed a 3 EPNdB reduction at lower fan speeds relative to the baseline stator; while the swept integral vane/frame stator showed lowest noise levels at intermediate fan speeds. Removal of the bypass blade passage frequency rotor tone (BPF) showed a 4 EPNdB reduction for the baseline and swept and leaned stators, and a 6 EPNdB reduction for the swept integral vane/ frame stator. Therefore, selective tone removal techniques such as active noise control and/or tuned liner could be particularly effective in reducing noise levels for certain fan speeds.

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