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Benefits of Swept-and-Leaned Stators for Fan Noise Reduction

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An advanced high bypass ratio fan model was tested in the NASA John H. Glenn Research Center 9 × 15 Foot Low-Speed Wind Tunnel. The primary focus of this test was to quantify the acoustic benefits and aerodynamic performance of sweep and lean in stator vane design. Three stator sets were used for this test series. A conventional radial stator set was tested at two rotor–stator axial spacings. Additional stator sets incorporating sweep only and sweep and lean were also tested. The hub axial location for the swept-and-leaned and swept-only stators was at the same axial location as the radial stator at the smaller rotor–stator spacing (upstream stator location), while the tip of these modified stators was at the same axial location as the radial stator set at the downstream rotor–stator spacing. The acoustic data show that swept and leaned stators give significant reductions in both rotor–stator interaction noise and broadband noise beyond what could be achieved through increased axial spacing of the conventional, radial stator. Application of these test results to a representative two-engine aircraft and flight path suggest that about a 3 effective perceived noise (EPN) dB fan noise reduction could be achieved through incorporation of these modified stators. This reduction would represent a significant portion of the 6-EPNdB aircraft noise reduction goal relative to that of 1992 technology levels of the current NASA Advanced Subsonic Technology initiative.

Introduction

A MAJOR source of aircraft engine noise comes from the interaction of the rotor viscous wakes with the fan exit guide vanes or stators. The most prominent components of this interaction noise are tones at multiples of the rotor blade passage frequency (BPF), although there also exists a broadband 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 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 farther downstream than the hub. Correspondingly, lean is a 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 flow by reducing the rotor–stator acoustic response. Rotor–stator tone generation is thought to be a function of the number of rotor wake intersections on the stator vanes. The number of wake intersections is increased with stator lean in the direction of fan rotation. Aft-swept stators achieve a similar effect through increased rotor–stator separation toward the tip region and, thus, delayed rotor wake intersection toward the stator tip. Kazen[3] demonstrated rotor/stator interaction tone reductions associated with a stator leaned 30 deg in the direction of fan rotation. Noise reductions in the two BPF 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.

An advanced high bypass subsonic fan model incorporating stator sweep and lean was designed and built by the Allison Engine Company (Ref. 5) under contract to NASA John H. Glenn Research Center. This fan was tested in the NASA John H. Glenn Research Center 9 by 15-Foot Low-Speed Wind Tunnel[6–8] (9 × 15 LSWT). These fan tests were conducted at a freestream Mach number of 0.10. The test section walls are acoustically treated to provide anechoic conditions down to a frequency of 250 Hz, which is lower than the range of test fan acoustic tones.

The emphasis of this fan test was to evaluate the aeroacoustic performance of the swept-and-leaned stator and the swept-only stator relative to that of a baseline radial stator. All stators had the same vane number and were designed for equivalent aerodynamic performance. Acoustic data are presented in terms of sideline directivities and spectra. These data were also used to generate flyover and sideline fan effective perceived noise level (EPNL) estimates for a representative two-engine aircraft and flight path to give an estimate of the fan EPNL benefit associated with these stator modifications.

Description of Fan Test

Research Fan

Figure 1 shows the research fan installed in the 9 × 15 LSWT. The ultrahigh bypass (UHB) drive rig was used to drive the Allison fan. The UHB drive rig was powered by a high-pressure air turbine drive with the drive air and instrumentation supplied through the support strut. 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. The fan was tested at a freestream Mach number of 0.10 in the test section, which is sufficient to achieve acoustic flight effect[9] and provides acoustic data representative of takeoff/approach operation. All data were taken at 0-deg fan axis angle of attack.

Table 1 shows design characteristics of the Allison fan. The 18-blade rotor had a diameter of 55.9 cm (22 in.). Three stator sets were fabricated, a conventional radial stator and two modified stators with both sweep and lean and with sweep only. A leaned-only stator set

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Table 1 Allison fan design characteristics

Parameter	Value
Rotor diameter	55.9 cm (22 in.)
Rotor blade number	18
Rotor hub/tip ratio	0.30
Rotor aspect ratio	1.754
Stator vane number (all modes)	42
Stator aspect ratio	3.073
Radial stator spacing,	
mean axial rotor chords	
Upstream (close spacing)	1.2
Downstream (maximum) spacing	2.2
Swept-and-leaned stator	30° sweep, 30° lean
Swept-only stator	30° sweep
Design stage pressure ratio	1.378 (1.45 tip – 1.20 hub)
Design specific weight flow	210.4 kg/s/m^2 (43.1 lbm/s/ft^2)
Design corrected tangential tip speed	305 m/s (1000 ft./s)
Design tip relative Mach number	1.080

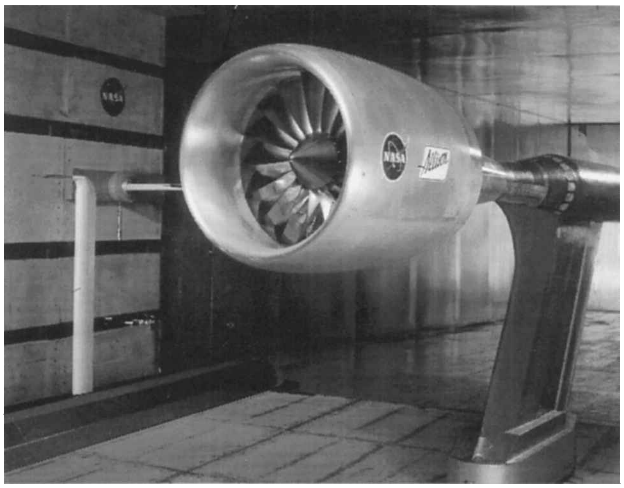
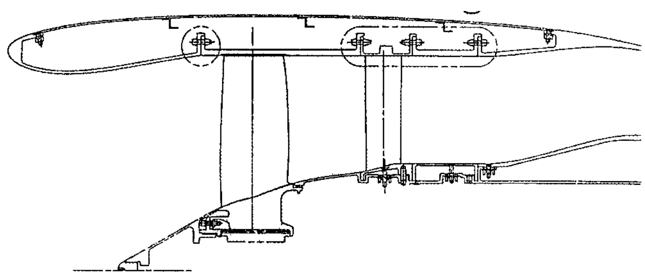
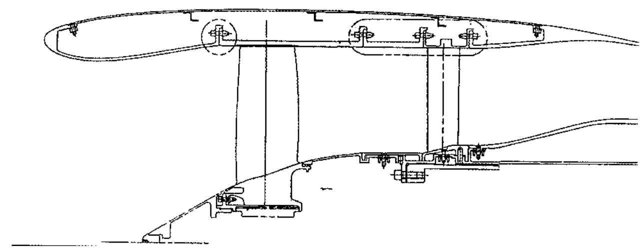


Fig. 1 Allison fan installed in the NASA John H. Glenn Research Center 9 × 15 LSWT.

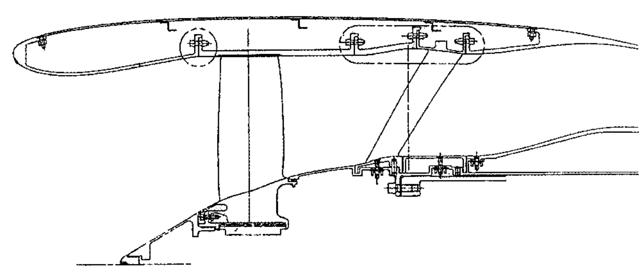


Upstream spacing, 1.2 mean axial rotor chords

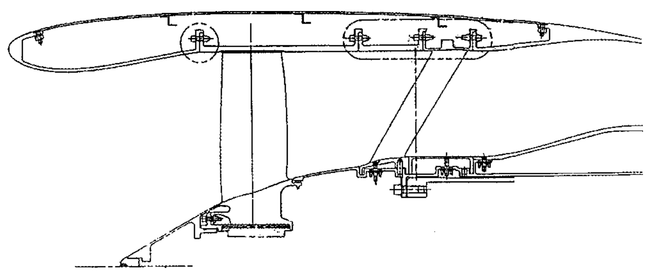


Downstream spacing, 2.2 mean axial rotor chords

Fig. 2 Allison fan with the baseline radial stator in the upstream and downstream positions.



Swept-only stator



Swept-and-leaned stator

Fig. 3 Allison fan with the swept-only and swept-and-leaned stators.

would have been desirable, but was dropped from the program due to budget considerations. All stator sets had 42 vanes and were designed for equivalent fan stage aerodynamic performance. The fan stage did not have a core flow simulation. The baseline stator configuration was the radial stator at the closer, upstream rotor–stator axial spacing, (Fig. 2). The fan was also tested at a larger rotor–stator axial spacing (downstream) position. The swept-and-leaned and the swept only-stators were designed such that the hub was located at the same axial location as the baseline stator location for the smaller rotor–stator spacing, and the tip was located at the axial location corresponding to the radial stator at the higher rotor–stator spacing (Fig. 3). These stators were designed with 30 deg of sweep and 30 deg of lean. The swept-and-leaned stators were leaned in the direction of rotor rotation.

Figures 4–6 are photographs of the partially assembled fan stage. Figure 4 is a photograph of the stage showing the rotor and the swept-and-leaned stator. Figure 5 shows the rotor and the swept-only stator. Figure 6 is a downstream view of the swept-and-leaned stator seen through the rotor.

Anechoic Wind Tunnel and Acoustic Instrumentation

The tunnel test section walls, floor and ceiling had acoustic treatment to produce an anechoic test environment. Figure 7 shows the test fan installed in the 9 × 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 deg relative to the fan inlet axis. The translating microphone probe traversed near the tunnel wall at 227 cm (89 in.) from the fan rotational axis (four fan diameters). A wall reference microphone assembly was placed adjacent to the translating probe home position (134.6 deg, maximum aft travel). Three fixed microphone assemblies were mounted to the tunnel floor at this same axial position to acquire aft acoustic data at geometric angles of 140, 150, and 160 deg. All microphones were located at fan centerline height. The acoustic data were acquired through a digital computer system and stored for postrun analysis.

Results and Discussion

Aerodynamic Performance

Aerodynamic performance for the fan and the four stator vane configurations (radial upstream, radial downstream, swept-only, and swept-and-leaned) on the fan acoustic operating line are presented in Figs. 8–10. The hardware design intent was that the fan performance would not be affected by the stator vane configuration and that the three different stator vane sets operate to the same level of performance. The fan and stator vane performance was determined from fan weight flow and force balance measurements. Fan performance for each of the stator vane configurations is shown in Figs. 8 and 9 as corrected fan weight flow and corrected fan torque as a function of corrected fan speed, respectively. Corrected in this

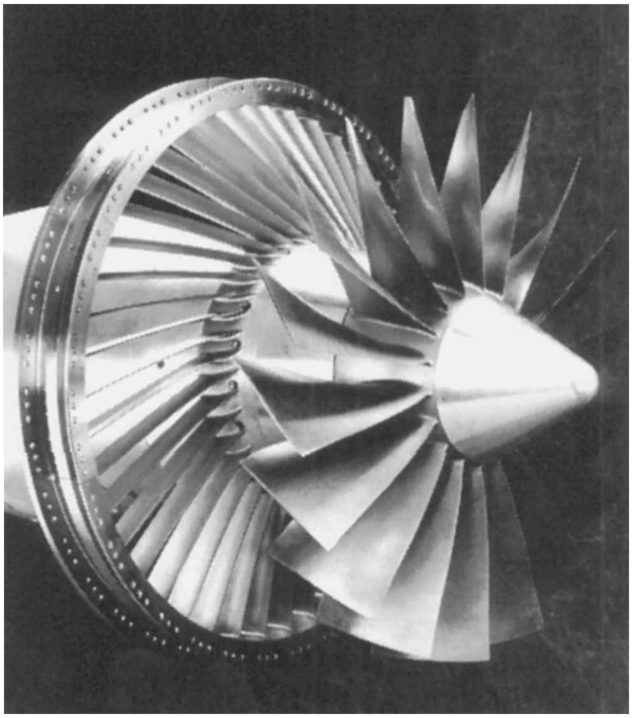


Fig. 4 Partially assembled fan stage showing the swept-and-leaned stator.

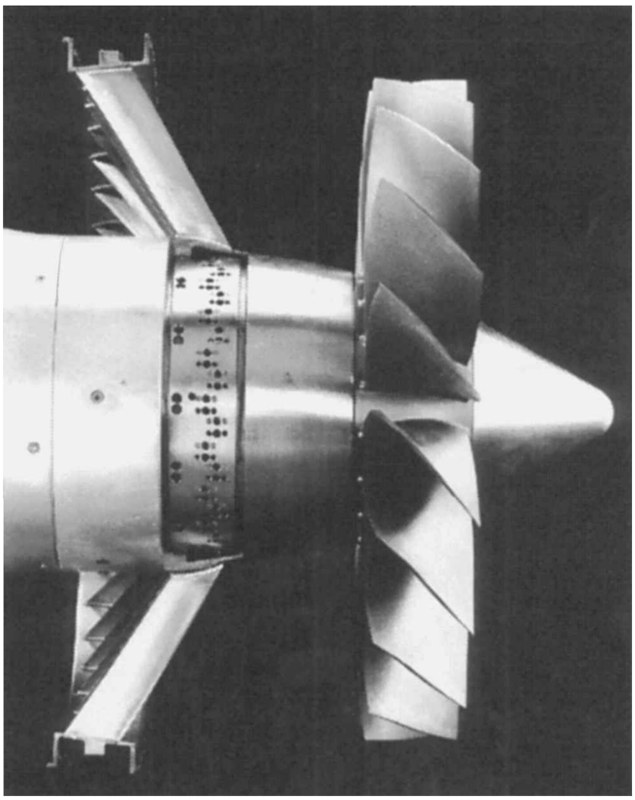


Fig. 5 Partially assembled fan stage showing the swept-only stator.

case means the data are normalized to standard day conditions. The results indicate that the fan was operating very nearly the same for each stator vane configuration.

In Fig. 8, differences in corrected fan weight flow are on the order of ±0.5–0.75%, with the radial stator vane in the downstream position showing the highest weight flow and the swept-and-leaned configuration showing the lowest. Accuracy of the fan weight flow measurements is ±0.5%. In Fig. 9, differences in corrected fan torque, which is a measure of the work produced, between stator

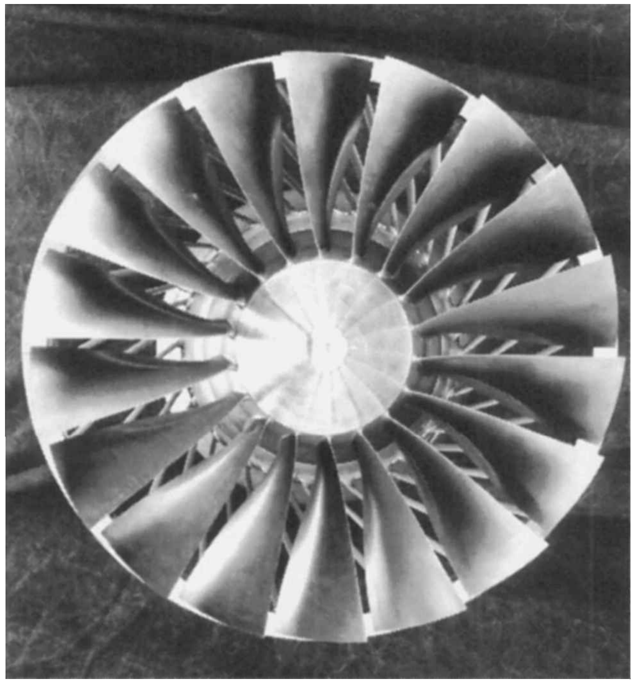


Fig. 6 Downstream view of the swept-and-leaned stator viewed through the rotor; fan direction of rotation is counterclockwise.

vane configurations are negligible. Force balance torque measurements are accurate to ±0.35% of full scale, or ±5 ft.lb. No force balance data were available for the aft baseline stator vane configuration. Figure 10 shows the corrected stator vane thrust from force balance data as a function of corrected fan speed. Again, force balance data were available for the radial stator in the downstream position, but it is assumed that because the same stator vane geometry was used that the forces produced by the radial stator in the downstream position are nearly the same. The results show that the radial stator vanes produced a larger amount of thrust than either the swept-only or swept-and-leaned stator vanes across the entire operating line. At lower speeds, the swept-only and the swept-and-leaned stator vanes performance is nearly the same, but lower than the radial stator vane performance. As the fan speed increased, larger differences between stator vanes can be seen, with the swept-and-leaned stator vanes producing the lowest thrust and the radial stator vanes the highest thrust. At 100% corrected fan speed (full power), the swept-only stator vanes produced about 4.5% less thrust and the swept-and-leaned stator vanes produced about 7.5% less thrust compared with the radial stator vanes. The accuracy of the force balance data is ±0.4% of full scale, or ±8 lb.

The results demonstrate a higher loss associated with the swept-only and the swept-and-leaned stator vanes, typically viscous losses in the hub and tip regions associated with the corner flows at the stator vane/flow surface interface. These flows are increasingly complex for the swept-and-leaned stator vane case, with tight corner areas as a result of the stator vane lean, which cause a local increase in blockage and increase in losses. The fan weight flow results support this result, especially for the swept-and-leaned stator vanes. The larger corner losses produce higher duct losses, reducing the nozzle exit area and, hence, reducing the fan weight flow at a given fan speed compared with the radial stator vanes.

Acoustic Performance

All of the fan acoustic data were acquired at a tunnel test section Mach number M_0 of 0.10. Sideline data are presented in terms of emission angles. The emission angles are related to the geometric, or observed angles by the relationship

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

where Θ_{em} and Θ_{geom} are, respectively, the emission and geometric sideline angles. $\Theta = 0$ deg is defined as the inflow axis. The emission

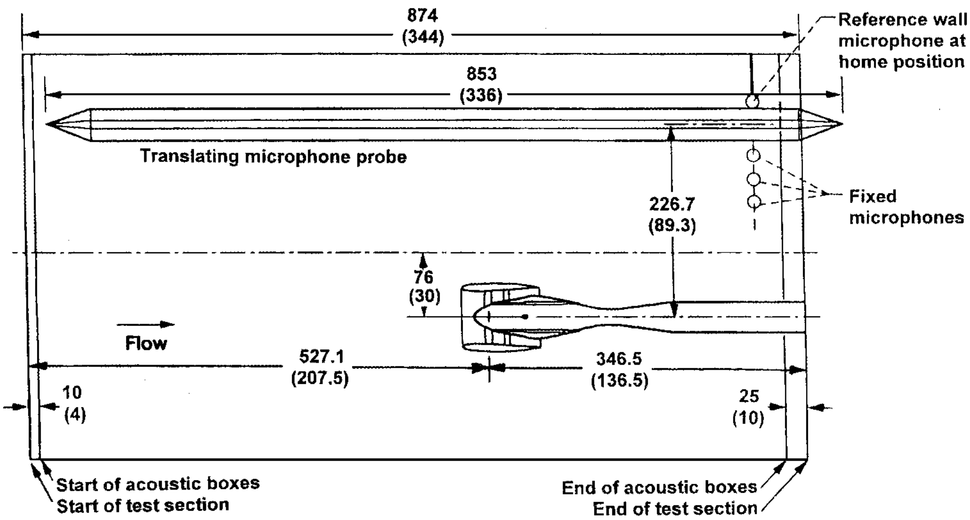


Fig. 7 Allison fan installed in the 9 × 15 LSWT [dimensions are in centimeters (inches)].

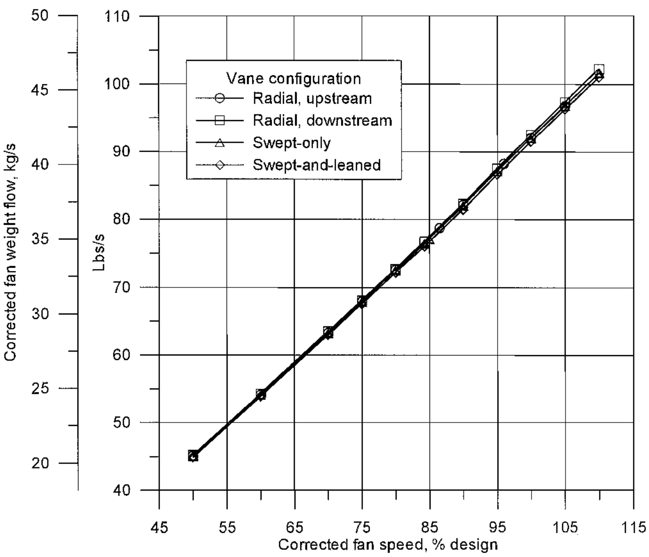


Fig. 8 Comparison of fan weight flow as a function of corrected fan speed for four stator vane configurations.

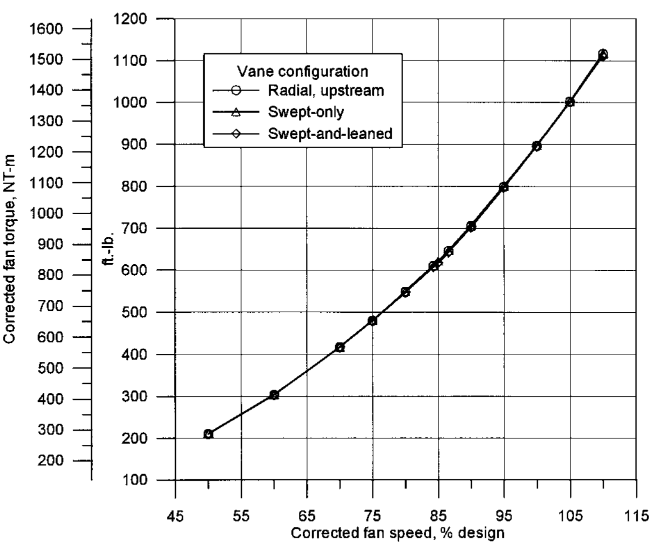


Fig. 9 Comparison of corrected fan torque as a function of corrected fan speed for three stator configurations.

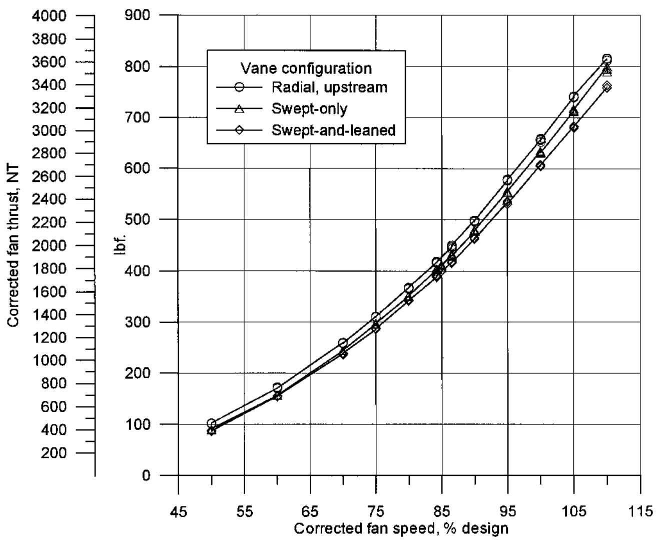


Fig. 10 Comparison of corrected stator vane thrust as a function of corrected fan speed for three stator vane configurations.

angles for the sideline translating microphone probe covered the range 25–130 deg, and the three fixed microphones were at emission angles of 136, 147, and 158 deg. This angular range was sufficient to define the sideline noise directivity patterns for subsequent fan EPNL calculations.

Digital acoustic data were processed as constant bandwidth spectra. Spectra were acquired and averaged at each translating microphone probe or fixed microphone position with 6- and 59-Hz bandwidths. These constant bandwidth spectra were electronically merged and used to generate one-third octave spectra.

Swept-and-leaned and swept-only stators were expected to reduce rotor–stator interaction tones by relieving the severity of the rotor wake interaction with the stator vanes. An additional observed benefit was a reduction in fan broadband noise.

EPNL

The EPNL was the noise metric used to rank the relative noise levels produced by the three stator sets. EPNLs were analytically derived from the measured fan rig one-third octave band sound pressure level data, and they are a function of frequency, duration, tone content, and source–observer geometry. A 3.5 linear scale factor was applied to all sound pressure level test data. EPNLs were calculated for each stator set using two methods: The first method used the measured noise spectra with no modifications, whereas the second method used the noise spectra with the tones at the BPF and its harmonics electronically removed. The former method was used to estimate fan EPNLs with both broadband and tone content, whereas the latter method was used to estimate fan EPNLs with broadband noise components only. No other noise sources were considered in these calculations.

A notional twinjet aircraft was used as the basis for the fan EPNL calculations. This aircraft was assumed to have a field length of 2740 m (9000 ft), a climbout angle of 9 deg and n altitude over the community observer of 550 m (1800 ft). The aircraft climbout speed was assumed to be 311 m/s (160 kn). No correction was made to the source noise levels due to the difference in convective amplification between the tunnel conditions and the assumed flight speed of the notional aircraft.

Propagation effects considered included spherical spreading, atmospheric attenuation, ground reflections, and extra ground attenuation. Sideline and community EPNL calculations were made using procedures commensurate with the requirements described in Ref. 10. EPNL calculations were made every 30.5 m (100 ft) along the 450-m (1476-ft) sideline to ensure that the sideline EPNL reported captured the maximum level. Community EPNLs were carried out for an observer 6500 m (21,325 ft) from brake release on the runway centerline. The computer code documented in Ref. 11 was used to help model the aircraft trajectory, propagation effects, and noise metric calculations.

Figure 11 shows the aircraft EPNL on the 450-m (1476-ft) sideline. Although the throttle setting used at takeoff would be at or near the fan design speed, the sideline noise is evaluated for the range of speeds investigated for illustrative purposes. There is about a 1.5-EPNdB decrease associated with moving the radial stator from the upstream position to the downstream position at all fan speeds except 110% of design, where the change in noise level is negligible. However, the addition of sweep and lean or sweep only results in about a 3-EPNdB reduction from noise levels relative to that for the upstream radial stator at fan speeds up to about 75% of design. The sweep-only stator maintains this 3-EPNdb reduction relative to baseline in the midspeed range of 75–95% design speed. The swept-and-leaned stator showed the most noise reduction at design and above fan speeds. Similar results are seen for flyover EPNL calculations. The use of a range of fan speeds is more applicable for flyover EPNL because a throttle cutback is often used in that segment. The analytical EPNL predictions for sideline and flyover observers differ due to geometric inputs to the extra ground attenuation and ground reflection models. These differences, however, do not significantly affect the trends with respect to fan speed. Thus, although the magnitudes of the sideline and flyover EPNLs are, of course, different, the trends are nearly identical.

The relatively poor performance of the swept-and-leaned stator at fan speeds near 90% design may be explained by the lower aerodynamic performance of that stator. Pressure losses associated with the swept-and-leaned stator are thought to arise from less than optimal flow near the hub and tip regions. It is quite possible that refinements in the aerodynamic design of the swept-and-leaned stator would result in improved performance for this concept throughout the fan speed range.

The theoretical study of Ref. 4 was a tone-based comparison, which did not include broadband effects. In Ref. 4, it is concluded that sweep should be most beneficial at takeoff conditions, whereas lean should be most beneficial at approach conditions. The data results of Fig. 11, which of course include broadband noise, are only marginally supportive of this prediction. In Ref. 12, which reconciles the present test results with the theory of Ref. 4, there is recognition that the predicted tone benefits are only valid when the tone levels are above broadband. It would appear from the data that sweep alone, rather than sweep and lean, achieved essentially all of the noise reduction at the lower fan speeds. At the higher fan speeds, additional noise reduction was achieved with sweep and lean beyond what was observed by sweep only. However, it is clear from Fig. 11, that incorporation of stator sweep and lean results in significant noise reductions throughout the fan operating range relative to what could be achieved through simply increasing the axial spacing of the radial stator.

Sound Pressure Level Directivities

Sideline sound pressure level (SPL) directivities provide a useful tool for evaluating acoustic differences associated with changes in the stator configuration. These directivities were achieved by combining results from the traverse microphone and the three aft fixed microphones, resulting in 227-cm (89-in.) sideline directivities for 25–158 deg emission angles relative to the fan upstream axis and centered on the fan rotor plane.

Figure 12 shows representative SPL directivities for the four test configurations. These results are for the fan operating at 50% speed. These data are for the two BPF tone, which falls within the 3150-Hz one-third octave band. Advanced high bypass ratio fans, such as that reported herein, tend to have aft-dominated directivities. The results of Fig. 12 clearly show that there is a significant noise reduction associated with increased radial stator spacing and additional noise benefits due to the swept-and-leaned and swept-only stator.

The noise reduction trends shown in Fig. 12 are more easily understood in terms of changes in noise level relative to that observed for the baseline radial stator in the upstream position. The

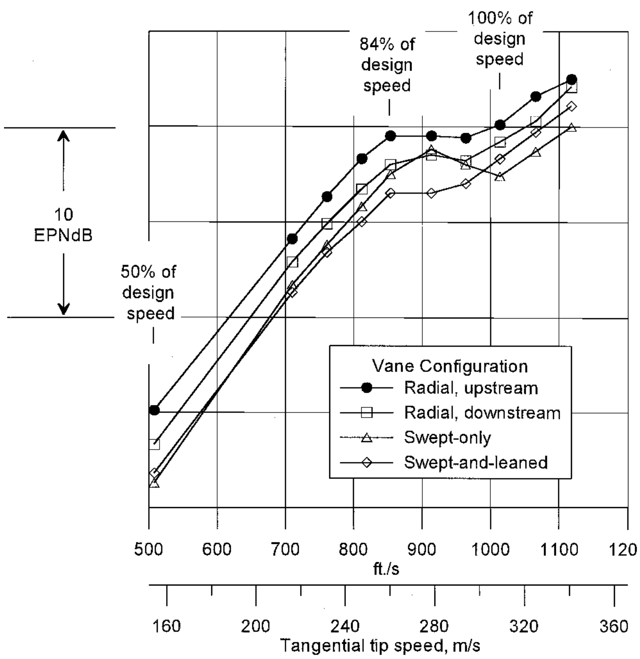


Fig. 11 Sideline EPNL for representative two-engine aircraft and flight path; maximum noise level for an observer on a 450-m (1476-ft) sideline.

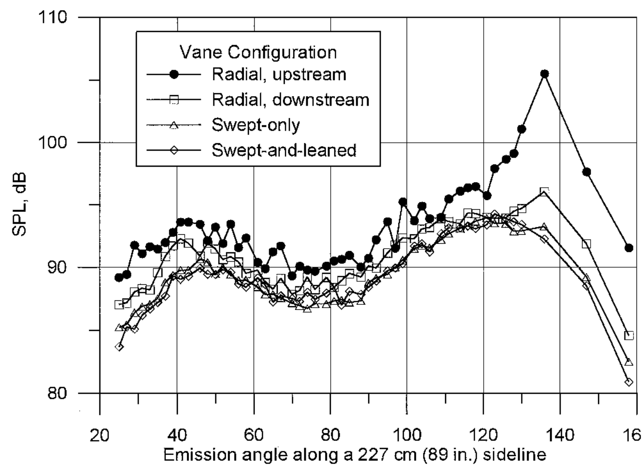


Fig. 12 One-third octave directivities along a 227-cm (89-in.) sideline (50% fan design speed, two BPF tone).

Table 2 Test conditions

% Corrected fan speed	Corrected rotor tangential tip speed, m/s(ft/s)	Tip relative Mach number
50 (Approach)	152 (500)	0.507
84 (Takeoff)	256 (840)	0.900
100 (Sideline)	305 (1000)	1.080
110	335 (1100)	1.187

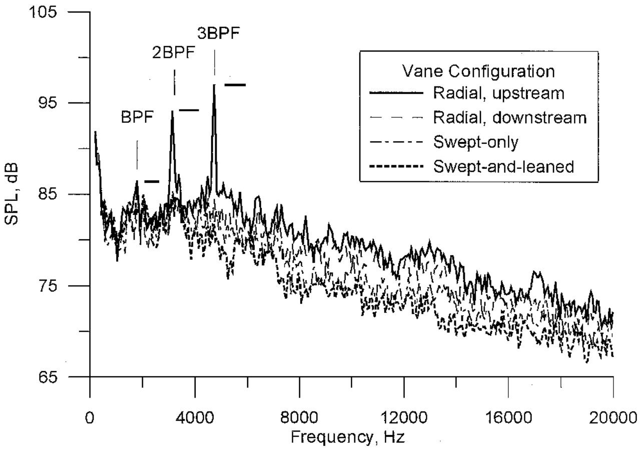


Fig. 13 Constant bandwidth (59-Hz) spectra on a 227-cm (89-in.) sideline at 126-deg emission angle from fan inlet axis; fan operating at 50% design speed.

SPL directivities for the four stator configurations were examined in this manner at four representative fan speeds. Constant bandwidth (59-Hz) spectra were used for this analysis to facilitate separation of the rotor-stator interaction tone from adjacent broadband noise. Table 2 lists the test conditions examined.

Results for each test speed are presented in terms of representative spectra at a 126-deg emission angle, followed by directivities showing the tone and broadband reductions relative to noise levels observed for the baseline radial stator in the upstream axial position. The broadband levels at rotor–stator interaction frequencies were determined by interpolating spectral levels in the region of the interaction tone. That is, the broadband levels at the interaction tones were inferred from typical broadband levels on either side of the tone frequencies. Broadband levels determined by this manual procedure should be accurate within 0.5 dB.

Figure 13 compares spectra acquired at 126-deg emission angle along the 227-cm (89-in.) sideline for the fan operating at 50% design speed. The fundamental rotor–stator interaction tone (BPF) is cut off and essentially not present in the spectra. Strong two BPF and three BPF tones are evident for the radial stator in the upstream position. These harmonics are attenuated either by moving the radial stator to the aft position or employing sweep and/or lean. However, there is clear indication of broadband noise reduction, on the order of 4 dB, by the modified stator sets.

Figure 14 shows the directivity effects on the two BPF fan tone band. SPL reductions in the tone and broadband levels are plotted against the directivity angle. Negative values represent noise reductions relative to what was observed for the baseline configuration with the radial stator in the upstream position. Tone reductions are greatest at aft angles, showing up to 12-dB reduction associated with moving the radial stator to the downstream location. Noise reductions of up to 15 and 19 dB were associated, respectively, with the swept-only and the swept-and-leaned stator.

Moving the radial stator to the downstream location produced little to no reduction in broadband noise. This result is consistent with that reported in the stator spacing study of Ref. 2, where it was also noted that there was little change in broadband noise level with (radial) stator spacing. The swept-and-leaned and the swept-only stators showed up to 4-dB broadband noise reduction.

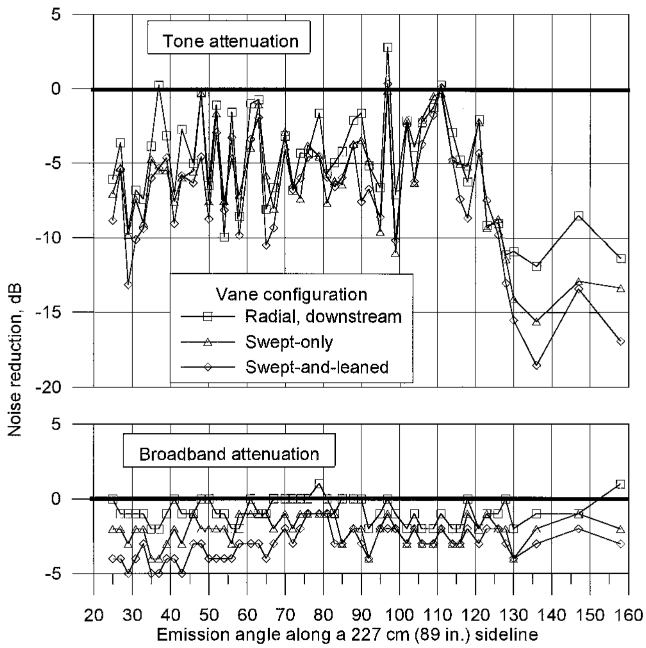


Fig. 14 Sideline constant bandwidth (59-Hz) directivities at two BPF showing noise reduction relative to the baseline (radial, upstream) configuration (50% fan design speed).

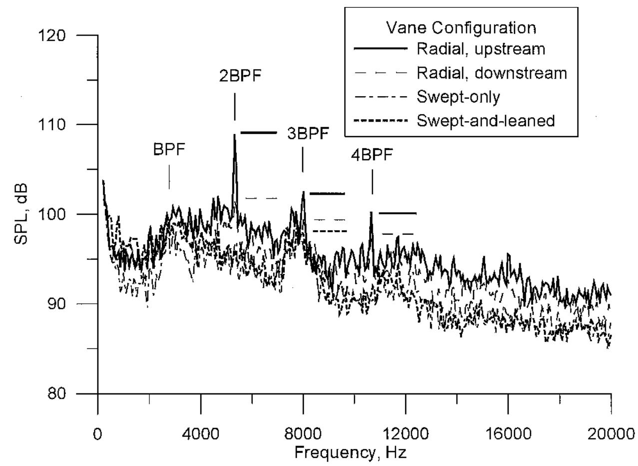


Fig. 15 Constant bandwidth (59-Hz) spectra on a 227-cm (89-in.) sideline at 126-deg emission angle from fan inlet axis; fan is operating at 84% of design speed.

There has been some concern regarding the periodic nature of the tonal directivity data taken in the 9×15 LSWT. Although it is possible that this behavior arises from tunnel wall reflections, it is much more likely that the data accurately show a real interference pattern between aft- and forward-radiated noise at a particular frequency. There are several observations to support the second interpretation. The fan is aft dominated; therefore, one would expect the interference pattern to be more pronounced toward the forward angles where the relative noise levels are more nearly equal in level. This is, in fact, what is observed in the sideline data. An analytical study of predicted sideline noise levels was performed that considered a case for inlet and exhaust radiation for an aft-dominated fan. Again, a similar noise interference pattern was observed for these analytical results. Finally, unpublished results for another advanced fan model, which was tested in a large anechoic freejet facility, showed similar interference in the sideline results; in this case there was no nearby tunnel wall to provide possible reflections.

Figures 15 and 16 present corresponding acoustic results for the fan operating at 84% design speed. The spectral overlay of Fig. 15 is similar to the 50% speed results of Fig. 10 in that the fundamental

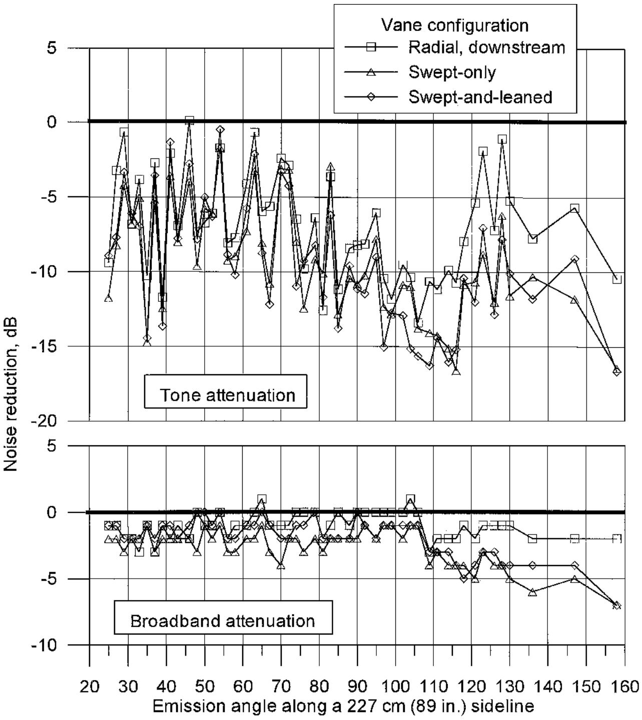


Fig. 16 Sideline constant bandwidth (59-Hz) directivities at two BPF showing noise reduction relative to the baseline (radial, upstream) configuration (84% fan design speed).

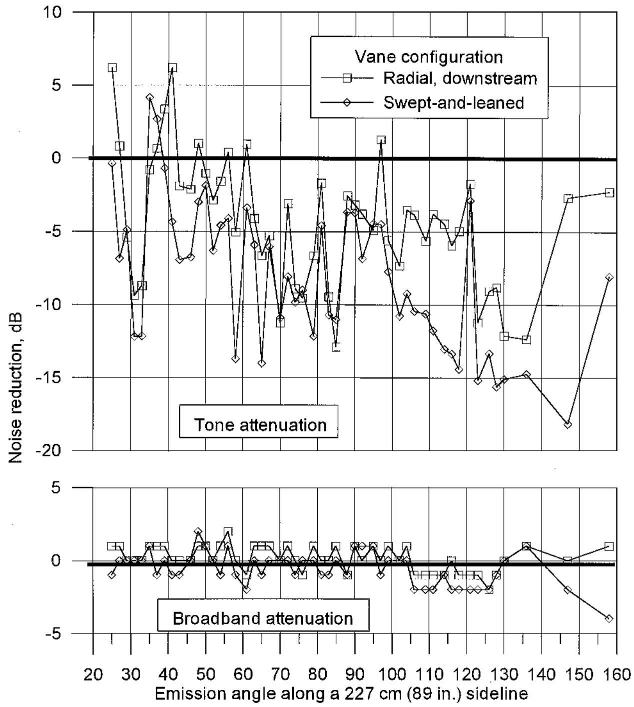


Fig. 18 Sideline constant bandwidth (59-Hz) directivities at two BPF showing noise reduction relative to the baseline (radial, upstream) configuration (100% fan design speed).

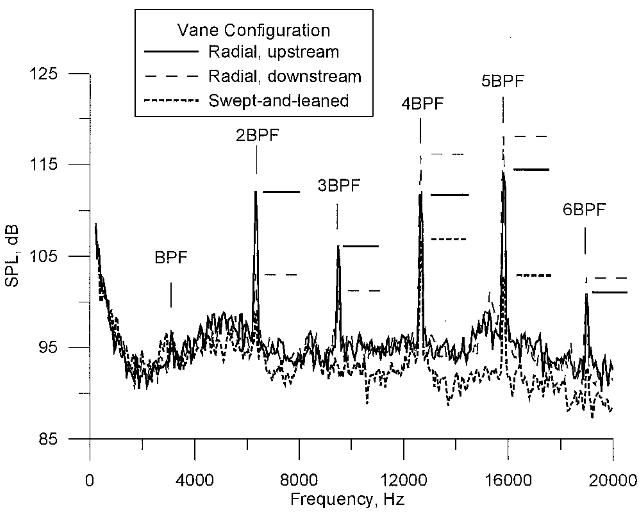


Fig. 17 Constant bandwidth (59-Hz) spectra on a 227-cm (89-in.) sideline at 126-deg emission angle from fan inlet axis; fan operating at 100% of design speed.

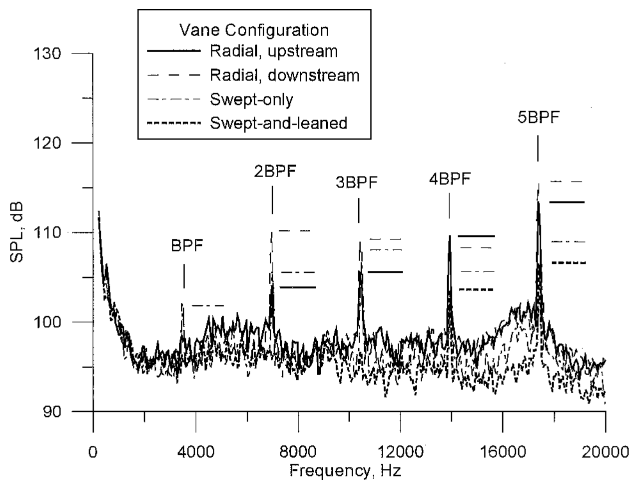


Fig. 19 Constant bandwidth (59-Hz) spectra on a 227-cm (89-in.) sideline at 126-deg emission angle from fan inlet axis; fan operating at 110% of design speed.

tone is essentially cut off, and most overtone energy is associated with the radial stator in the upstream position. The haystacking nature of the swept-and-leaned spectra near three BPF may be associated with flow disturbances caused by the poorer aerodynamic performance of that stator.

Figure 16 shows sideline noise reductions for the two BPF tone and broadband. The swept-and-leaned and the swept-only stators were essentially equivalent in terms of tonal noise reduction. Tone reductions associated with the radial stator in the downstream position were almost as good as those for the modified stators except for downstream sideline angles beyond 100 deg. Broadband noise reductions for the modified stators were about 2 dB at upstream angles, increasing to 4–5 dB at farther aft angles.

The fundamental rotor–stator interaction tone remained cut off at 100% design speed (Fig. 17). However, higher-order tones are now present in the spectra for the radial stator in the downstream position and for the swept-and-leaned stator. Data were not taken at this speed for the swept-only stator due to aeromechanical avoidance zones for this stator and fan speed. There is essentially no interaction tone for the swept-and-leaned stator until four BPF (and higher) harmonics.

The swept-and-leaned stator had much more effect than the radial stator in the downstream position for reducing two BPF tone noise at 100% fan speed (Fig. 18). However, there was essentially no associated broadband reduction at two BPF.

All stator configurations produced significant tone noise at the 110% overspeed condition. The fundamental rotor–stator interaction tone is now weakly cut on and is evident for the radial stator at the two axial locations and for the swept-only stator. However, this tone is not evident for the swept-and-leaned stator (Fig. 19). The swept-and-leaned stator essentially eliminated the two BPF and three BPF tones from the spectra. The swept-only stator was marginally effective in reducing acoustic energy at these tone orders.

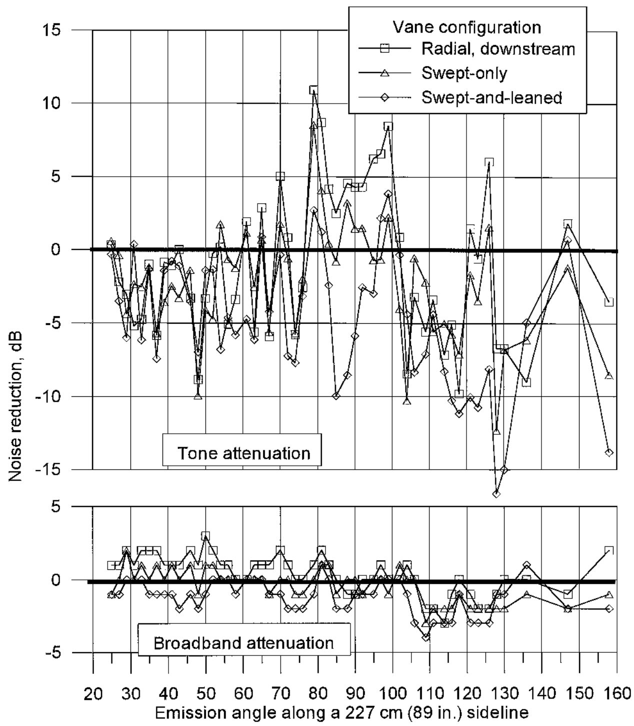


Fig. 20 Sideline constant bandwidth (59-Hz) directivities at two BPF showing noise reduction relative to the baseline (radial, upstream) configuration (110% fan design speed).

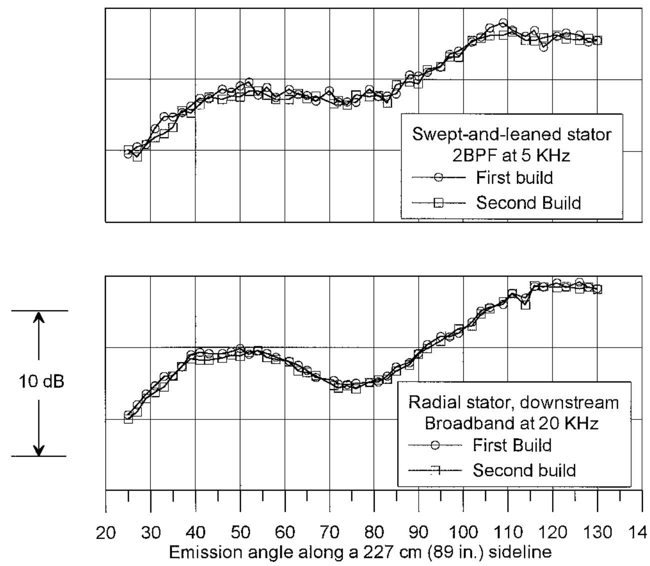


Fig. 21 Data repeatability comparison for two builds of the fan (one-third octave directivities, 84% of design fan speed).

The two BPF tone directivity results of Fig. 20 likewise show significant noise reductions associated with the swept-and-leaned stator, with somewhat less attenuation (relative to the radial stator in the forward position) seen for the swept-only stator and radial stator in the downstream position. The broadband levels at two BPF were slightly lower for the swept-and-leaned stator at upstream directivity angles. Reductions in broadband level were typically seen for all stator sets relative to the baseline stator configuration at aft directivity angles, especially in the 115–130 deg range.

These results for the constant bandwidth tone and broadband directivities are consistent with those presented earlier for the representative aircraft effective perceived noise levels (Fig. 11). Stators incorporating sweep and lean, or possibly sweep only, have been shown to reduce significantly both rotor–stator interaction tone and broadband noise levels. However, the acoustic results are not consistent as to whether sweep and lean or sweep only is the preferred design. Sweep-and-lean and sweep-only stators provide additional noise reduction relative to the radial stator in the downstream position; however, sweep only is more effective at lower fan speeds whereas sweep and lean provides somewhat more noise attenuation at higher fan speeds at and above design. This conclusion is further complicated by the observation that the swept-and-leaned stator showed greater aerodynamic losses than did the other stators, suggesting that its acoustic performance, likewise, was compromised. On the other hand, one could infer that the expected acoustic benefits of a better designed swept-and-leaned stator would be at least as good as that shown herein and perhaps better.

Data Repeatability

The modified stator sets showed significant reductions in fan tone levels; therefore, there is a need to validate the repeatability of these results. Repeat data runs for the swept-and-leaned stator and the radial stator in the downstream position were made to quantify repeatability of the acoustic data. In each instance, the second set of data represent a fan rebuild and was acquired at a totally different test time. Thus, these comparisons were rather rigorous toward validating the acoustic data.

Sideline one-third octave directivities comparing these repeat data sets are shown in Fig. 21 for the 5000-Hz (two BPF) and 20,000-Hz (broadband) one-third octave frequency bands. In each instance, the data repeatability is excellent.

Conclusions

The results clearly showed that incorporation of stator sweep and lean or sweep only can significantly reduce rotor–stator tone levels. Tone levels for the modified stators were significantly reduced beyond what was achieved by simply relocating the conventional radial stator to the downstream location, with maximum noise reduction benefits typically observed at downstream directivity angles. It is not clear if stator sweep alone is adequate to achieve substantial reductions in rotor–stator interaction noise, or if there are significant additional benefits to be realized through incorporation of both sweep and lean. In particular, the aerodynamic performance of the swept-and-leaned stator showed somewhat higher losses than that of the other stators, suggesting that noise reductions associated with this stator may be further improved through enhanced aerodynamic design of a swept-and-leaned stator.

Increased axial spacing of a conventional radial stator has little impact on the fan broadband noise level, except, perhaps, to increase the potential for broadband noise generation through increased scrubbing surface, etc. However, the results for the swept-and-leaned and the swept-only stators reported herein did show a significant reduction (often on the order of 4 dB) of the broadband noise relative to that generated with the radial stator.

Acoustic results scaled to a representative two-engine aircraft and flight path suggested that about 3-EPNdB fan noise reduction could be realized through incorporation of these modified stators, a result which could represent a significant part of the current NASA Advanced Subsonic Technology initiative goal of a 6-EPNdB fan noise reduction relative to 1992 technology levels.

These results suggest that incorporation of some combination of stator sweep and lean may significantly reduce both tone and broadband noise levels for future advanced turbofans. Additional research in this area is needed to quantify the aerodynamic and aeroacoustic performance of these stator design features and to gain insights into methodology for additional engine noise reduction.

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