Wind Tunnel Measurements of Blade/Vane Ratio and Spacing Effects on Fan Noise

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A research fan stage was acoustically tested in an anechoic wind tunnel with a 41-m/s tunnel flow. Two stator vane numbers, giving cuton and cutoff conditions were tested at three rotor-stator spacings ranging from about 0.5 to 2.0 rotor chords. These two stators were designed for similar aerodynamic performance. The cutoff criterion strongly controlled the fundamental tone level at all spacings.

Introduction

RECENT turbofan engine designs aimed at increasing the structural rigidity and reducing the weight of the engine frame lead to a reduced number of stator vanes and an abandonment of vane-blade ratios greater than required for fundamental tone cutoff.[1,2] These designs, which consider stator solidity aerodynamic constraints, consist of a relatively few longer chord, larger thickness stator vanes which are load-carrying members of an integrated vane-frame.

Basic acoustic data on the effects of vane-blade ratio and spacing under conditions which simulate flight are needed to determine the acoustic consequences of adopting alternate designs such as the integrated vane-frame.

Expected noise consequences of varying fan stage design parameters, such as vane-blade ratio and rotor-stator spacing have often been masked in static testing. This is largely due to the fact that the fundamental blade passing tone level and, to a lesser extent, the tone harmonics levels are controlled by rotor-inflow interaction mechanisms,[3,4] which mask the rotor-stator interaction noise. The blade passing tone level of a fan designed for fundamental tone cutoff is greatly reduced with forward velocity.[5] Noise studies performed in an anechoic wind tunnel[6,7] have shown results similar to those obtained in flight tests.

In the present study the noise of a 50.8-cm-diam research turbofan simulator was measured in the anechoic wind tunnel described in Refs. 6 and 7. Both vane-blade ratio and rotor-stator spacing were varied. Specifically, two stator vane numbers were chosen to achieve a cuton and cutoff condition with respect to propagation of the fundamental rotor-stator interaction tone as predicted by the theory of Ref. 8. The noise associated with each of these stator configurations was measured at three rotor-stator spacings ranging from 0.5 to 2.0 rotor chords.

Apparatus and Procedure

Anechoic Wind Tunnel

The NASA Lewis 9×15 low-speed anechoic wind tunnel test section is located in the return loop of the 8×6 supersonic tunnel. Aerodynamic and acoustic properties of this tunnel are given in Refs. 11 and 12. The tunnel test section is considered to have free-field anechoic properties at frequencies above 1000 Hz. All tunnel-on tests in the present study are with a tunnel velocity of 41 m/s. This tunnel velocity has been shown to effectively eliminate the fundamental blade passing tone due to rotor-inflow interaction.[7] Tunnel-off static data were also taken for each simulator configuration.

Turbofan Simulator

The turbofan simulator used in this study allowed for changes in the stator vane number and spacing from the rotor. Two stator vane sets were tested. The 11-vane stator design was cuton with respect to propagation of the fundamental blade passing tone due to rotor-stator interaction. The 25-vane stator design was cutoff at fan speeds below 96% of design speed. For the present study the simulator was operated at 60, 80, 96, and 115% of design speed.

Selected design parameters for the fan are presented in Table 1. The fan stage was designed for a 1.2 overall pressure ratio. The 50.8-cm-diam rotor had 15 blades and a relatively low design tip speed of 213 m/s. Both stator vane sets were designed to be aerodynamically similar. Details of the fan stage aerodynamic performance with the 11-vane stator are presented in Ref. 13. Performance data for the 25-vane stator are presented in Refs. 14 and 15.

Figure 1 shows a cross-sectional view of the turbofan simulator. The view is split—showing both stators at the intermediate (1.2 mean rotor chord) spacing. The research stage exhaust flow was controlled by nozzle tabs to establish the design operating line.[7]

The turbofan simulator stage was powered by a four-stage air turbine drive. Supply air for the turbine entered through the support strut shown in Fig. 1 and exited through the core exhaust. Thus the possibility existed for turbine drive noise to contribute to the far-field levels—especially in the aft quadrant. Figure 2 gives the blade and vane numbers for the drive turbine stages. Also shown in Fig. 2 are the fundamental blade passing tone frequencies for the fan and the four turbine stages at each of the fan speeds used in the present study.

Figure 3 is a front view of the fan installed in the Lewis 9×15 anechoic wind tunnel. The far-field acoustic instrumentation included a boom microphone in the front quadrant and six fixed microphones in the aft quadrant.

Acoustic Instrumentation and Data Reduction

The acoustic instrumentation plan view is shown in Fig. 4. The boom microphone is at a 1.83-m radius from the inlet highlight centerline. Inlet quadrant data was taken from 0 to 90 deg in 10-deg increments. The aft microphones were likewise at a 1.83-m radius, but centered at the nozzle exit plane. Because of data channel restrictions it was necessary to eliminate the 110-deg microphone. Data were not taken beyond 150 deg owing to the fan exhaust flow.

Presented as Paper 81-2032 at the AIAA 7th Aeroacoustics Conference, Palo Alto, Calif., Oct. 5-7, 1981; submitted Oct. 16, 1981; revision received April 15, 1982. This paper is declared a work of the U.S. Government and therefore is in the public domain.

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Table 1 Fan design parameters

Stage	
Pressure ratio	1.2
Mass flow	31.2 kg/s (68.8 lb/s)
Rotor	
Tip diameter	50.8 cm (20 in.)
Tip speed	213 m/s (700 ft/s)
Tip solidity	0.9
Mean chord	7.70 cm (3.03 in.)
Hub/tip ratio	0.46
Number of blades	15
11-vane stator	
Tip solidity	0.71
Tip chord	10.58 cm (4.17 in.)
Rotor/stator spacings[a]	0.62, 1.24, 2.16
25-vane stator	
Tip solidity	0.71
Tip chord	4.71 cm (1.85 in.)
Rotor-stator spacings[a]	0.54, 1.23, 1.77

[a] Mean aerodynamic rotor chords.

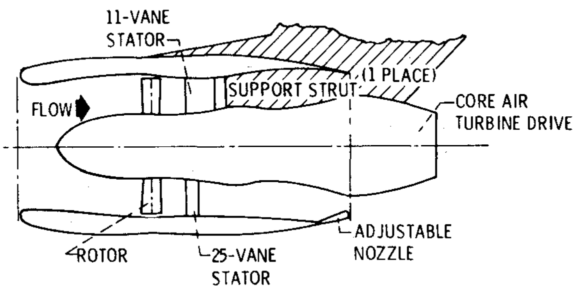
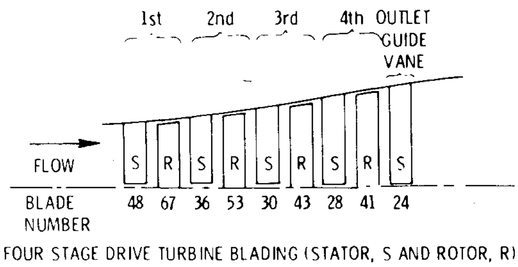


Fig. 1 Cross-sectional view of fan stage. Stators are shown at intermediate spacing location.



FAN DESIGN SPEED, percent	TEST FAN	TONE FREQUENCY, Hz DRIVE TURBINE STAGE 1	2	3	4
60	1203	5374	4251	3449	3289
80	1604	7166	5668	4599	4385
96	1925	8599	6802	5519	5262
115	2306	10301	8148	6611	6303

Fig. 2 Fundamental blade passage tone frequencies for fan and drive turbine (fan design speed is 134 rev/s).

The acoustic data were recorded on magnetic tapes for later 20-Hz constant-bandwidth spectral analysis. The output of this narrow-bandwidth sound pressure level (SPL) analysis was digitized and transmitted to a computer for further analysis. Using a computer reduction program, narrow-bandwidth sound power level (PWL) spectra were generated for the forward quadrant (0 to 90 deg from the fan inlet axis). Sound power levels for the blade passing and overtones were calculated for the aft quadrant by using the average of the corresponding SPL values at 100 and 120 deg for the missing 110-deg position.

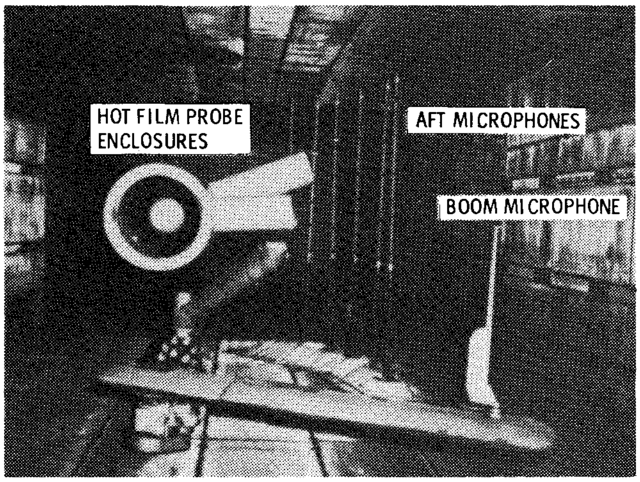


Fig. 3 Front view of fan in anechoic wind tunnel.

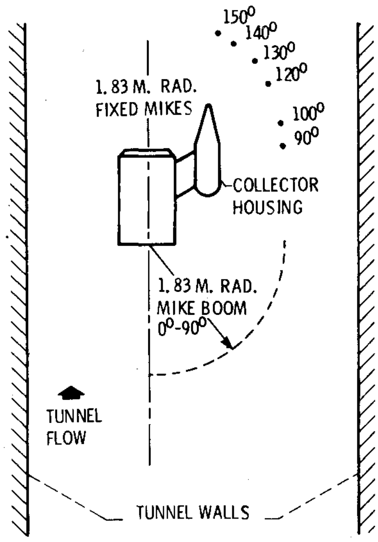


Fig. 4 Plan view of far-field acoustic instrumentation. Aft microphone plane is inclined 30 deg to horizontal to reduce collector housing interference.

Modal Analysis

A consideration of the predicted spinning acoustic modes for a given fan rotor-stator configuration can be a useful tool in analyzing the acoustic results. Those models which have a cutoff ratio greater than 1 are expected to propagate and contribute to the noise signature of the fan. The modal theory developed in Refs. 16 and 17 was applied to the two rotor-stator configurations of the present study.

Figure 5 shows the expected propagating modes for the fundamental blade passing tone for the two stator numbers as functions of fan speed. The cutoff ratio calculations were based on the rotor tip Mach numbers. The $(-10, 1)$ mode of the 25-vane stator "cuts-on" at 96% of design fan speed. Below this speed there are no cuton modes associated with this stator. The blade passing overtones for both stator numbers are predicted to be strongly propagating at all fan test speeds.

Results and Discussion

Acoustic Spectra

The front quadrant sound power level spectra for the two stator vane configurations are presented in Fig. 6. These results are for the nominal 0.5 chord rotor/stator spacing, 80% design fan speed, and a 41-m/s tunnel flow. The cuton, 11-vane stator results (Fig. 6a) show the expected strong fundamental blade passing tone (BPF). The corresponding BPF tone weakly present for the cutoff, 25-vane stator is about 21 dB lower.

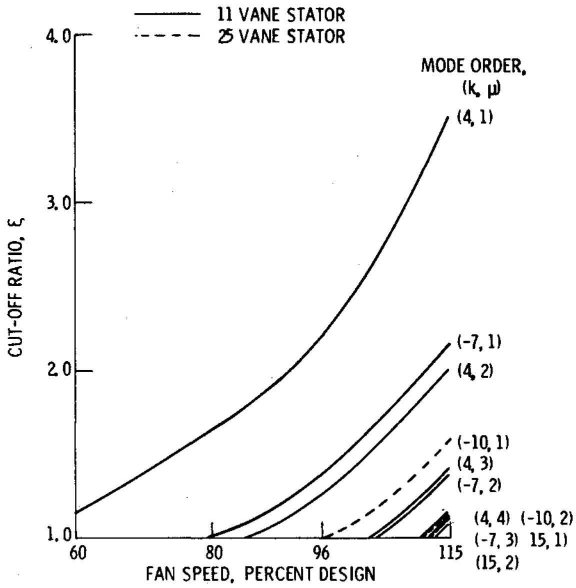


Fig. 5 Predicted propagating rotor-stator acoustic modes at blade passing frequency.

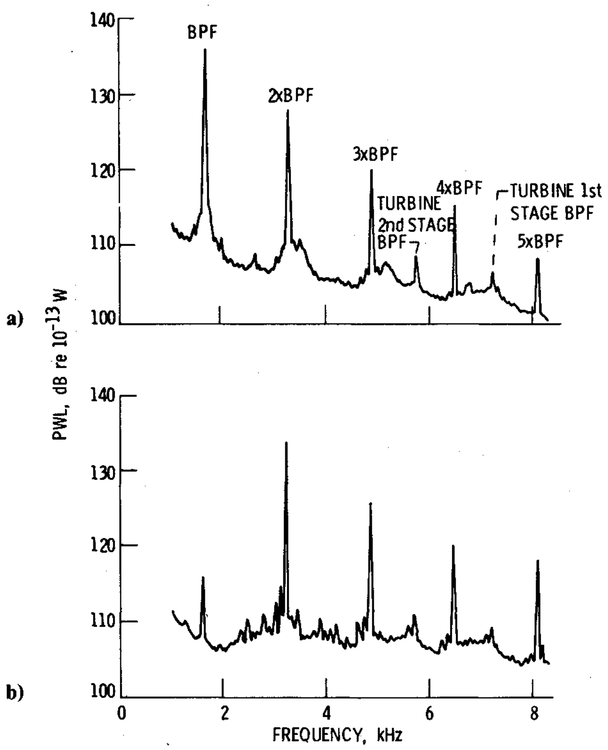


Fig. 6 Front quadrant PWL spectra, 80% design fan speed, 41-m/s tunnel flow (20-Hz bandwidth). a) 11-vane stator, rotor-stator spacing is 0.62. b) 25-vane stator, rotor-stator spacing is 0.54.

Reference 18 offers an explanation for the fact that a cutoff fan stage may still show a residual rotor-stator interaction tone at blade passing frequency. The analysis shows that small manufacturing irregularities in the stator can result in a weak, propagating fundamental tone.

An important result seen in Fig. 6 is that the overtone levels (2×BPF, etc.) for the cutoff, 25-vane stator are approximately 6 dB higher than the corresponding tone levels for the 11-vane stator. Reference 19 develops the concept of decreasing the stator fluctuating lift response (and thereby the rotor-stator interaction tone noise generation) by stator vane design changes, which include increasing the stator chord.

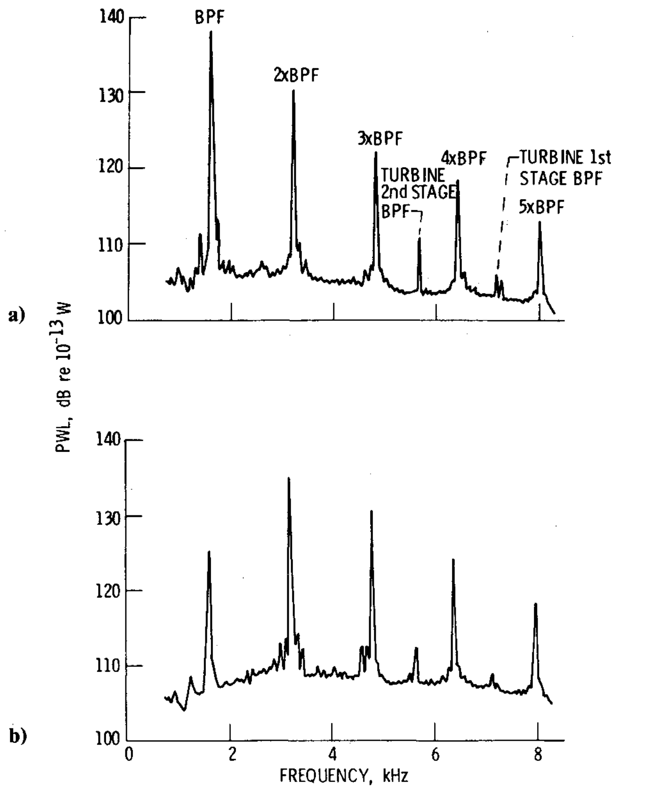


Fig. 7 Front quadrant PWL spectra, 80% design fan speed, no tunnel flow (20-Hz bandwidth). a) 11-vane stator, rotor-stator spacing is 0.62. b) 25-vane stator, rotor-stator spacing is 0.54.

This mechanism may explain the lower overtone levels for the longer chord, 11-vane stator configuration, although this stator was not specifically designed to satisfy the criterion of Ref. 19. This result indicates clearly (for the first time) that a design tradeoff between cutoff and spacing must take both fundamental and overtone levels into account.

There is essentially no difference in the broadband levels near the fundamental tone frequency for the two configurations compared in Fig. 6. The broadband levels for the 11-vane stator are slightly lower at higher frequencies. For both configurations it is possible to identify the turbine drive fundamental tones for the first and second stages in the PWL spectra.

Figure 7 shows the front quadrant PWL spectra for the same operating conditions, but with no tunnel flow. The fundamental tone for the 25-vane stator (Fig. 7b) is still lower in level relative to the fundamental tone for the 11-vane stator (Fig. 7a). Thus the effects of designing for cutoff are still evident at this rotor-stator spacing despite rotor-inflow interaction. The broadband levels are about the same as the corresponding levels with tunnel flow, suggesting that noise generation due to ingested turbulence or other inflow disturbances is only important for the pure tone levels, and that another source mechanism controls the broadband.

The trends in the acoustic results which were noted in the front quadrant (Fig. 6) are also evident in the aft quadrant, Fig. 8. In this figure the SPL spectra at 120 deg are compared. These results are for a 41-m/s tunnel flow at 80% design fan speed. As might be expected, the tones generated by the drive turbine are more prominent in these aft results. However, the noise contributions from the drive turbine do not interfere with interpretation of the fan-generated portions of the spectra.

In these aft quadrant results the fundamental tone is 9 dB lower for the 25-vane stator than for the 11-vane stator, while the overtone levels are about 3 dB higher. The residual BPF tone for the 25-vane stator appears to be more prominent in

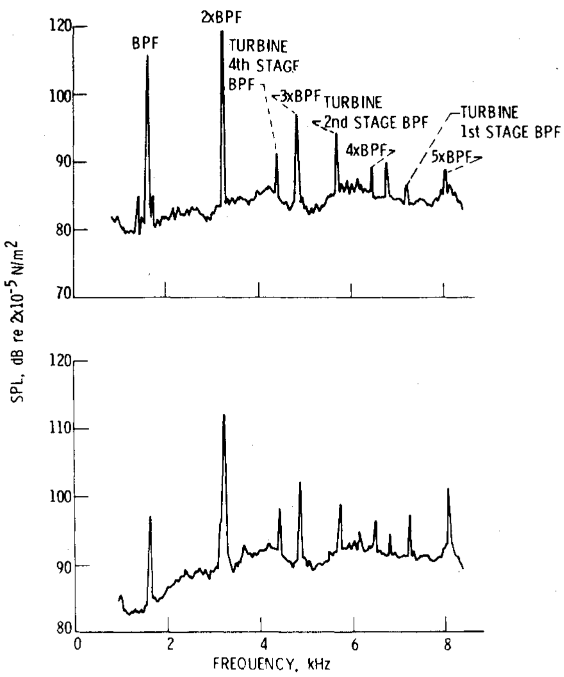


Fig. 8 Aft quadrant SPL spectra at 120 deg, 80% design fan speed, 41-m/s tunnel flow (20-Hz bandwidth). a) 11-vane stator, rotor-stator spacing is 0.62. b) 25-vane stator, rotor-stator spacing is 0.54.

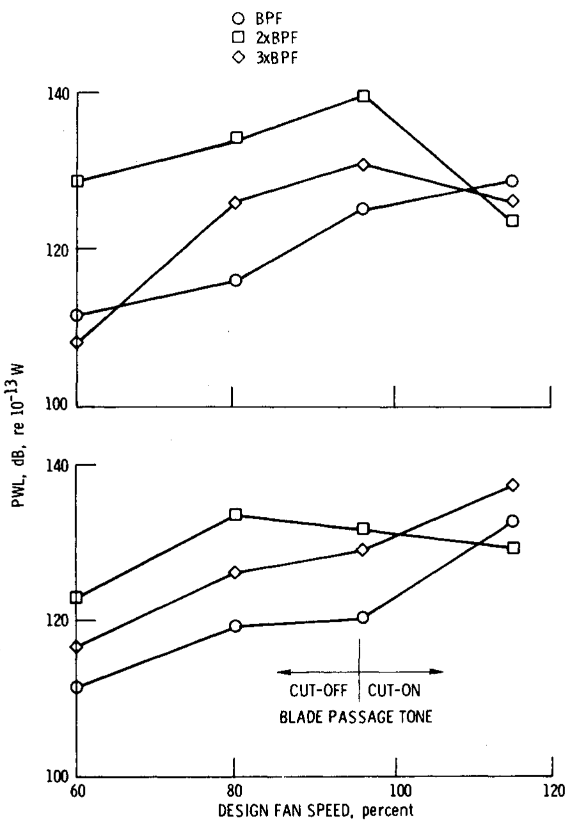


Fig. 9 Tone PWL as a function of fan speed, 25-vane stator, rotor-stator spacing is 0.54, 41-m/s tunnel flow. a) Front quadrant (0-90 deg). b) Aft quadrant (90-150 deg).

the aft quadrant. Perhaps this is due to a transmission loss in forward propagation of the tone through the rotor, as discussed in Ref. 20.

The fundamental and first two overtone levels for the 25-vane, cutoff stator configuration are shown as functions of fan speed in Fig. 9. These data are for the close stator spacing and 41-m/s tunnel flow. The cutoff ratio analysis for the

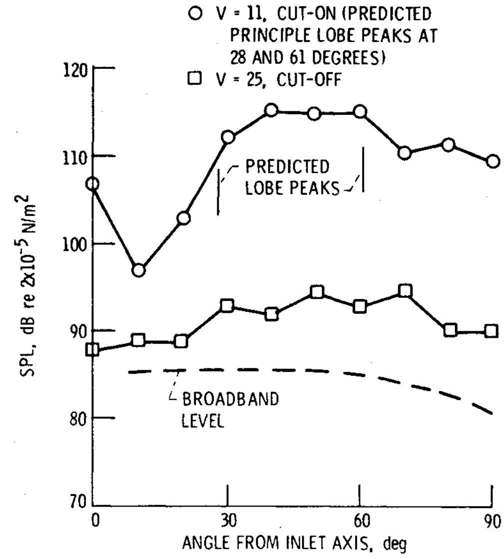


Fig. 10 Comparison of front quadrant blade passing tone SPL directivity patterns (20-Hz bandwidth). Nominal ½-chord rotor-stator spacing, 80% design speed, 41-m/s tunnel flow.

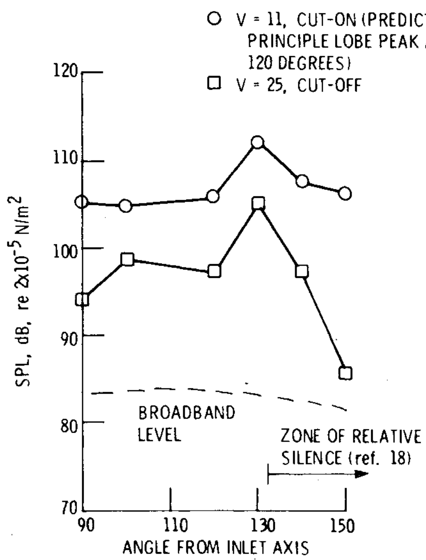


Fig. 11 Comparison of aft quadrant blade passage tone SPL directivity patterns (20-Hz bandwidth). Nominal ½-chord rotor-stator spacing, 80% design speed, 41-m/s tunnel flow.

fundamental tone shown in Fig. 5 predicts that this rotor-stator interaction will become cuton near 96% design fan speed. In the front quadrant (Fig. 9a) the level of the fundamental tone (BPF) does show a slope increase near 96% design fan speed. In the aft quadrant (Fig. 9b) this tone shows a substantial increase between 96 and 115% design fan speed.

The overtone levels control the tone noise level for this 25-vane stator configuration in both quadrants at 60, 80, and 96% design fan speeds. However, all but the aft quadrant 3 × BPF tone drop below the fundamental tone level at the 115% design fan speed where the rotor-alone tone is cuton. These level distributions are typical of a cuton fan in which the tone harmonic levels decrease with increasing tone order.

Directivity Considerations

Figure 10 shows the blade passing tone SPL directivity in the front quadrant for the two stator configurations. These results are for the close stator spacing, 80% design fan speed, and 41-m/s tunnel flow. The 11-vane stator configuration has two cuton modes at this fan speed (see Fig. 5). The analysis technique of Ref. 16 predicts that the principle lobes of these propagating modes will peak at 28 and 61 deg from the fan inlet axis. These peaks appear to be present in the 11-vane stator results of Fig. 10. The BPF tone directivity for the cutoff, 25-vane stator configuration has a reduced amplitude and no major peaks. The pattern tends toward the pattern of the equal energy modal distribution of Ref. 21 observed for fan noise controlled by inflow turbulence and for broadband fan noise as shown by the broadband data (dashed line) from the present experiment.

The corresponding aft directivity, Fig. 11, shows that the fundamental tone for both configurations peaks at 130 deg from the inlet axis. The geometric acoustics analysis of Ref. 22 predicts the aft peak to be slightly forward of this angle for the 11-vane stator case. Although an aft peak was observed, it was not expected for the 25-vane stator case since residual tone noise is likely to tend toward a smooth equal energy distribution as occurred in the inlet quadrant. The directivities for both stator configurations show a decrease beyond 130 deg which is predicted by Ref. 22 as a "zone of silence" due to the shear layer refraction associated with the boundary of the fan exhaust stream.

Spacing Effects

As previously mentioned, it may be possible to increase the rotor-stator separation of a cuton stage such that the interaction tone noise is reduced to acceptable levels. This reduced stator number offers structural benefits in turbofan engine design.

Figure 12 shows the dependence of the inlet quadrant sound power levels for tones on rotor-stator spacing for the two-stator configurations. Although the fundamental tone with the 25-vane stator is cutoff, the results (Fig. 12b) still show a residual tone which decreases in level slightly with spacing. This result was also observed in Ref. 18, where it was attributed to stator manufacturing irregularities. Results for an earlier build and test of this 25-vane stator configuration in the Lewis anechoic wind tunnel showed lower residual fundamental tone with fan operation below cutoff and with 41-m/s tunnel flow. Small stator irregularities which account for these residual tones may not be exactly reproducible in successive fan stage builds. The overtone levels, which propagate in all cases, show essentially the same spacing dependence for both vane numbers.

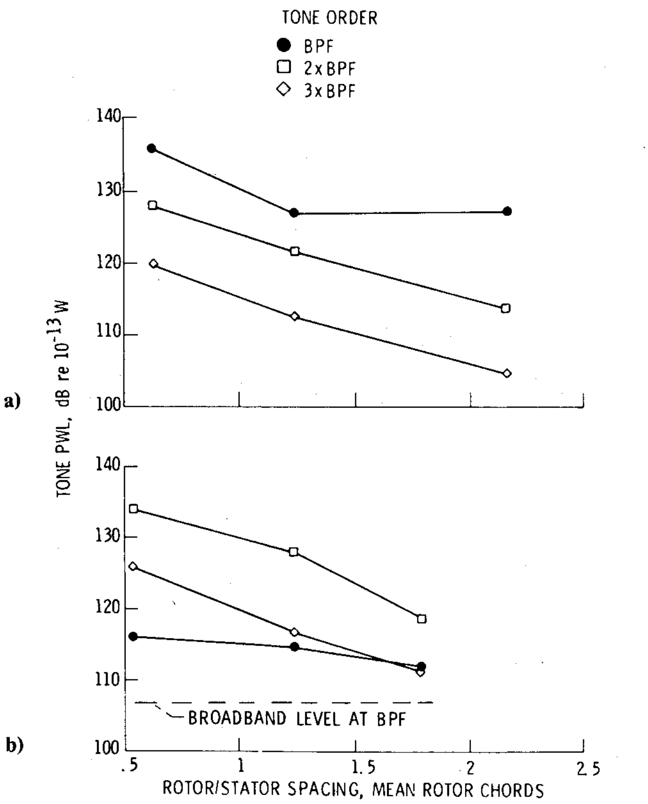


Fig. 12 Spacing effect on front quadrant tone, 80% design speed, 41-m/s tunnel flow. a) 11-vane stator. b) 25-vane stator.

The broadband level (dashed curve, Fig. 12b) at the tone frequencies for both stator configurations did not show a significant change with spacing. This indicates that broadband noise generation and tone noise are due to different mechanisms for the fan stage configurations reported herein.

The fundamental tone level for the cuton, 11-vane stator configuration decreases as do the overtones between the close and intermediate stator spacings. However, no further reduction was observed in this tone level as the spacing was increased somewhat beyond two rotor chord lengths. The reason for this behavior is not known. It is possible that a variation in the fan duct geometry at the farthest stator position may have influenced this result. The installation of the 11-vane stator in the turbofan simulator required a flow path compromise for the 2.16 rotor chord spacing. Facility limitations required that one stator vane be cut about mid-chord and faired into the support strut (see Fig. 1). However, this modification should not have a significant effect on the airflow.

A small, low flow fan test facility was used to investigate rotor-stator spacing effects on stator fluctuating pressures, as reported in Ref. 23. These results suggest that there can be a pressure fluctuation increase at the stator leading edge as spacing is increased for a stator inflow incidence angle and solidity comparable to that of the present 11-vane stator. This pressure fluctuation increase could result in increased rotor-stator interaction noise.[19]

Figure 13 is an overlay of the results of Figs. 12a and 12b. The point to be made is that the fundamental tone level with the 11-vane stator and the first overtone ($2\times$ BPF) level with the 25-vane stator are about the same for the closer stator spacings. Thus, at these spacings, the total tone energy for each configuration is about the same. A choice between stator configurations would have to consider frequency-weighted perceived noise levels.

At 96% design fan speed there is evidence that the fundamental tone with the 25-vane stator begins to propagate as predicted by the cutoff ratio calculation shown in Fig. 5. The data in Fig. 14 show that the fundamental tone (and overtone) level has the same dependence on spacing for this fan speed and stator number as was observed for other tones when they are cuton. This is in contrast with the observed lack of dependence of the BPF tone on spacing at 80% design fan speed in Fig. 12b.

The aft quadrant tone power variations with spacing at 80% design fan speed are presented in Fig. 15. The residual

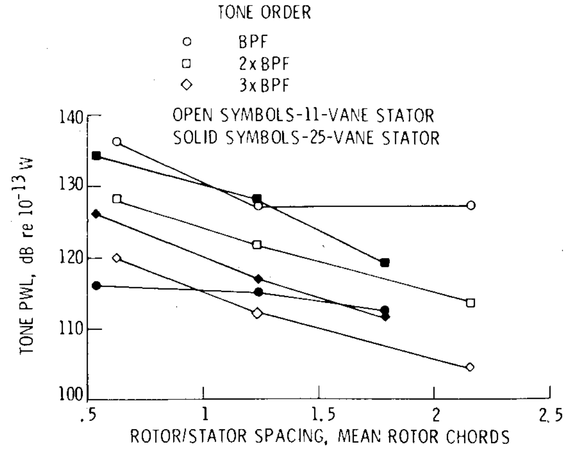


Fig. 13 Comparison of 11- and 25-vane stator front quadrant results with rotor-stator spacing, 80% design fan speed, 41-m/s tunnel flow.

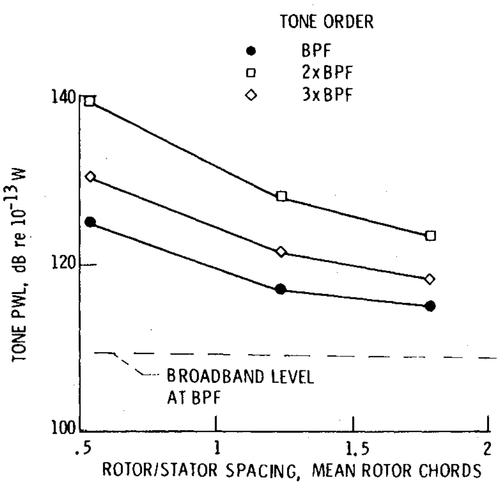


Fig. 14 Spacing effect of front quadrant tone 25-vane stator, 96% design fan speed, 41-m/s tunnel flow.

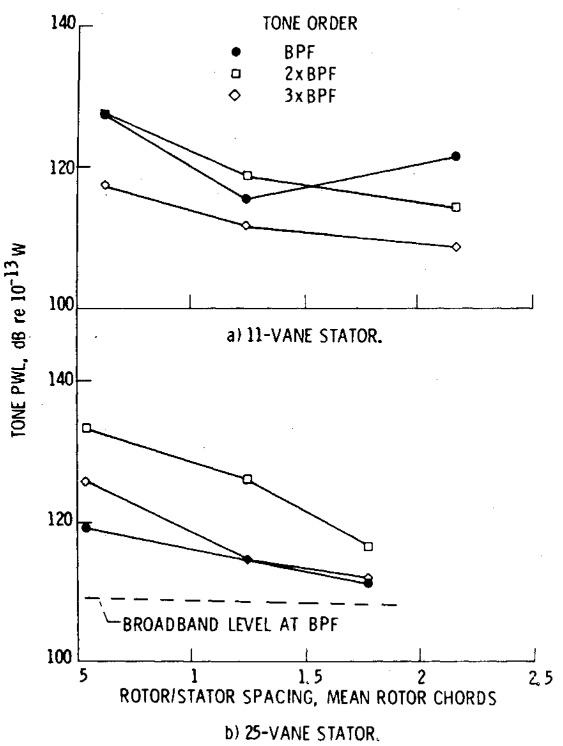


Fig. 15 Spacing effect on aft quadrant tone, 80% design fan speed, 41-m/s tunnel flow.

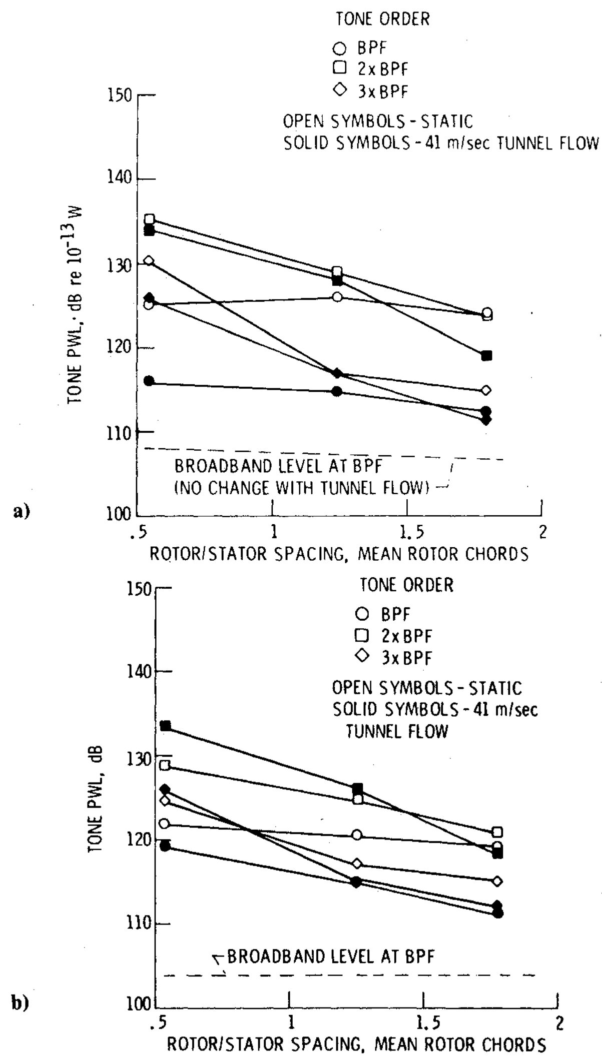


Fig. 16 Effect of rotor-stator spacing and tunnel flow for 25-vane stator, 80% design fan speed. a) Front quadrant (0-90 deg). b) Aft quadrant (90-150 deg).

fundamental tone for the 25-vane stator (Fig. 15b) shows a somewhat greater sensitivity to spacing than was seen for this tone in the front quadrant (Fig. 12b). The overtone levels show a decrease with spacing similar to that which was observed for the overtone levels in the front quadrant. As in the front quadrant, the fundamental tone level for the 11-vane stator shows an unexpected increase at the maximum stator spacing. In the stator spacing study of Ref. 24 aft acoustic measurements were made only inside the fan exit duct. The internal aft overtone levels were found to decrease much more rapidly with spacing than the far-field levels measured in the present investigation.

Figure 16 shows the effect of tunnel flow on the 25-vane stator results of Figs. 12 and 15. In the front quadrant with no tunnel flow (Fig. 16a), rotor inflow interaction clearly controls the fundamental tone level such that there is practically no spacing effect. The first overtone is only slightly affected by inflow interaction at the closer spacings, but shows some

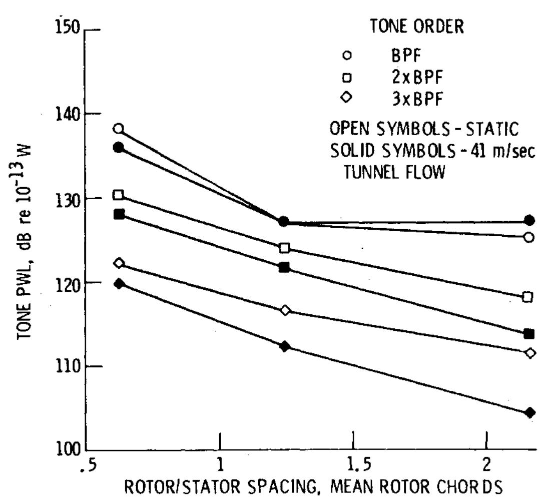


Fig. 17 Effect of rotor-stator spacing and tunnel flow in the front quadrant for 11-vane stator, 80% design fan speed.

evidence of approaching an inflow-controlled noise floor at the 1.8 chord spacing. Similar results are seen in the aft quadrant (Fig. 16b), except for the irregular behavior of the first overtone at the closer spacings, which is not understood.

The fundamental tone level for the cuton, 11-vane stator is controlled by rotor-stator interaction at all stator spacings as

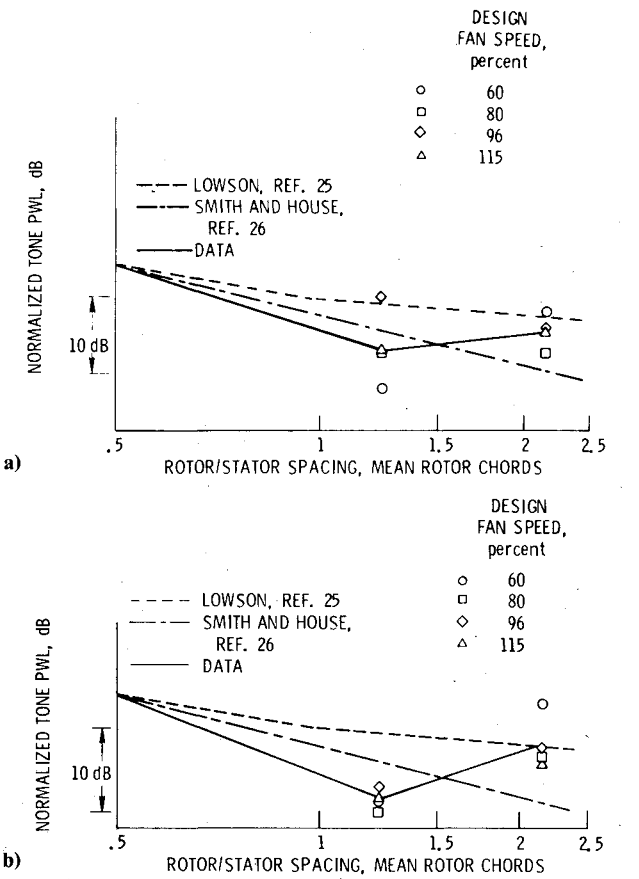


Fig. 18 Dependence of blade passing tone level on spacing and its comparison with other correlations. 11-vane stator, 41-m/s tunnel flow. a) Front quadrant (0-90 deg). b) Aft quadrant (90-150 deg).

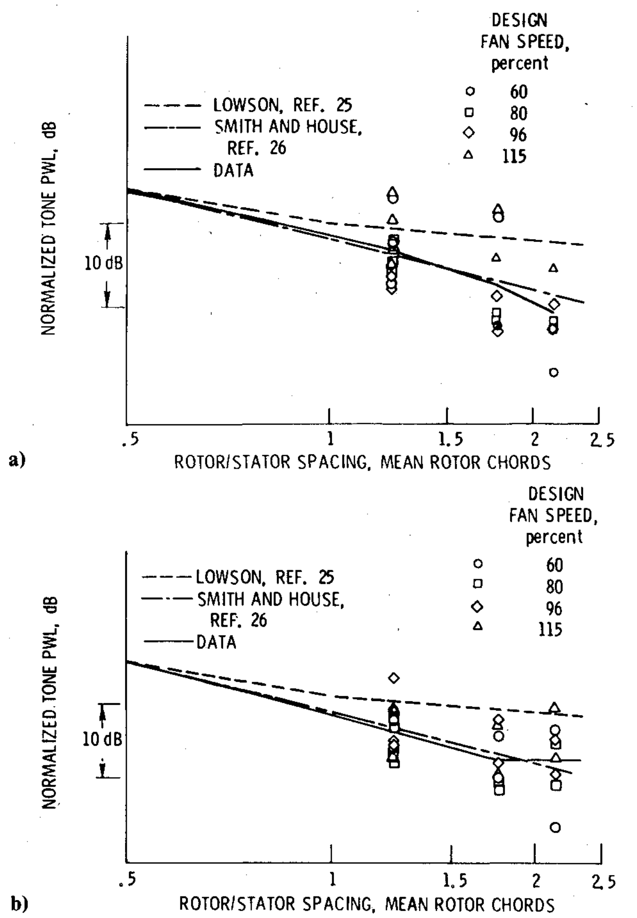


Fig. 19 Dependence of overtone level on spacing and its comparison with other correlations, 41-m/s tunnel flow. a) Front quadrant (0-90 deg). b) Aft quadrant (90-150 deg).

shown by the data in Fig. 17 for the front quadrant at 80% design fan speed. The overtone levels (especially the $3 \times$ BPF tone) are considerably lower than those for the 25-vane configuration and do show evidence of a rotor-inflow interaction noise floor developing at large spacings.

Spacing Effects—Comparison with Other Investigators

A number of investigators have considered the relation between rotor-stator interaction tone levels and spacings. Lowson[25] and Smith and House[26] developed expressions for fan tone level as a function of spacing (x/c_r) based on available fan data from static fan experiments. Lowson's relationship calls for a 4-dB reduction in tone level with a doubling in spacing up to $x/c_r = 1.0$, with a 2-dB reduction per doubling thereafter. Smith and House relate the tone level to $10\log_{10}(x/c_r)^2$, which gives a reduction of 6 dB per doubling of rotor stator separation.

These correlation results are superimposed on the results of the present investigation in Figs. 18 and 19. The solid line represents the average value of the data at each spacing.

Figure 18 considers the fundamental tone level for the cuton, 11-vane stator. As previously mentioned, the reason for the higher tone levels at the 2.2 chord spacing is not understood at this time. Considering only the 1.2 chord spacing results, the average data somewhat exceed the prediction of 6 dB per spacing doubling. There is good agreement between the front (Fig. 18a) and aft (Fig. 18b) quadrant results.

The overtone levels ($2 \times$ BPF and $3 \times$ BPF) for both stator configurations are considered in Fig. 19. In both the front and aft quadrants, the average of the overtone PWL is in good agreement with the Smith and House correlation. Also, these results show that in the far-field the average values for the overtone levels in both quadrants vary in nearly the same manner with stator spacing.

Reference 27 presents results for a research fan stage which was statically tested with relatively severe inflow distortion. However, the far-field overtone results for this fan also followed the 6-dB/doubling prediction of Ref. 26.

Summary of Results

1) The cutoff criterion was shown to strongly control the fundamental blade passing tone level for operation with forward velocity at all rotor-stator spacings studied. However, for the configurations reported herein, the overtone levels for the 25-vane short chord design are higher than for the 11-vane long chord design indicating that design tradeoffs between cutoff and spacing must take both fundamental and harmonic levels into account. This experimental result is probably due to the lower fluctuating lift associated with the long chord stator design.

2) The cuton tone levels, which included the fundamental tone for the 11-vane stator configuration, and the overtones for both stator configurations in both the front and aft quadrants approximately followed the Smith and House correlation showing a 6-dB reduction per doubling of rotor-stator spacing.

3) Although cutoff, the remaining low level fundamental tone for the 25-vane stator configuration showed a small decrease with spacing. This may be due to manufacturing irregularities in the stator which, it has been suggested, account for the low level residual rotor-stator interaction source.

4) Experimental broadband noise showed little change with rotor-stator spacing, thus implying that rotor-stator interaction was not significant in broadband noise generation.

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