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REDUCED PERCEIVED NOISE FOR LOW TIP SPEED FANS AS A RESULT OF ABANDONING CUTOFF STATOR VANE NUMBERS

James Dittmar

SUMMARY

As fan tip speeds are reduced, broadband noise is becoming more important in the calculation of perceived noise. Past experience indicates that lower vane number stators with either constant chord or constant solidity may be a way to reduce broadband noise caused by the interaction of the rotor wake turbulence with the stators. A baseline fan and a low blade number fan were investigated to determine if a noise reduction was possible. The low vane number fan showed a 2 PndB and a 1.5 PNLT noise reduction. These reductions show that this is a viable technique for reducing the perceived noise of low tip speed fans.

INTRODUCTION

In the past the tone noise, blade passing tone and harmonics, has controlled the perceived noise of a fan for airplane engines. Fan tip speeds were typically in the high to medium speed range, 487 to 305 m/sec (1600 to 1000 ft/sec). Some of the newer engines being considered have larger bypass ratios and significantly lower pressure ratios and tip speeds. Some are in the 274 to 213 m/sec (900 to 700 ft/sec) range. For these fans the tone noise does not dominate and broadband noise becomes more important. The importance of the broadband noise has been indicated in reference 1. Therefore ways of reducing the broadband noise of these fans are being considered.

The primary source of broadband noise appears to be the interaction of the rotor wake turbulence with the downstream stators. Broadband noise reductions have been observed in previous experiments by reducing the stator vane number both with constant stator chord and with constant stator solidity (increased chord). The purpose of this report is to discuss these broadband reductions and to investigate a possible perceived noise reduction that would be achieved with lower stator vane numbers. Although these low tip speed fans with lower stator vane numbers would have a cut-on blade passing tone, a perceived noise reduction is possible because of the reduced broadband noise having a larger effect. The perceived noise reduction that might be expected from reducing the stator vane number is the topic of this report.

BACKGROUND

Long Chord Stator Results

In previous experiments, references 2 to 4, the chord length of stator vanes was increased to provide a theoretical tone noise reduction. The theoretical reductions were based on the Sear's function response of individual airfoils. The increased chord would increase the reduced frequency parameter ω and provide a reduction in lift response of the stator vanes to the incoming rotor wakes. This is illustrated in figure 1 which is the magnitude of the response function plotted versus the reduced frequency parameter ω where

$$\omega=\pi C/L$$

with C being the stator chord and L being the incoming gust wavelength. The stator solidity was held constant during these experiments so the number of stator vanes was decreased as the stator chord was increased.

In reference 2, when the technique was applied to an existing fan stage, noise reductions were observed at the harmonics but the blade passing tone did not change. Here the stator chord was increased eight fold and the number of stator vanes was reduced by a factor of eight from 112 to 14 vanes. A sample comparison for the two stator configurations is shown in figure 2 (ref. 2) Here a reduction in the tone at twice blade passing frequency is clearly shown but the level of the blade passing tone is approximately the same.

Two items concerning the blade passing tone need to be discussed. First, in the redesign to increase the stator chord, the number of vanes was reduced to maintain a constant solidity. The original fan was cutoff at the blade passing frequency but the fan with the long chord stators is cuton. The blade passing tone would have been expected to increase as a result. This would be a counterbalancing effect to the expected reduction from the long chord stator.

Second and more importantly, the original fan did not show the expected cutoff of the blade passing tone. Since this experiment was performed on a static test stand without an inlet flow control device, the blade passing tone was controlled by inlet flow disturbance-rotor interaction. This would explain the lack of cutoff for the original fan and the lack of change, either upward for the cuton situation or downward for the reduced stator response, in the data.

The reductions in the harmonics of the blade passing tone were observed but were less than predicted. These reductions were approximately one half of the predicted reductions. Similar results were obtained in reference 3, where a fan stage was redesigned, including long chord stators, to reduce stator lift response (fig. 3).

In addition to the blade passing harmonic noise reduction, significant broadband noise reductions were observed. (figs. 2 and 3) The observed reductions were of the order of 3 to 5 decibels over a frequency range from 1 000 to 20 000 hertz. Reductions of this magnitude over this frequency range could have a significant impact on the perceived noise of a fan controlled by broadband noise. It is this reduction that will be investigated in this report.

Boeing Broadband Experiments

More recent experiments were performed in the Boeing Low Speed Acoustic Facility to investigate broadband noise sources in a model fan (ref. 5). Here an experiment was performed with three variations in stator vanes. The original fan model had 60 stator vanes. The fan was also tested with 30 stator vanes of the same chord as the 60 vanes. A 15 stator vane test was also performed with the stator chord increased to maintain the same solidity as the 30 vane stators. The fan was also tested with no stators to obtain a floor for the amount of noise that might be expected from changing the stator vanes. A sample plot of the results is shown in figure 4. This is the aft power for a low percent fan speed which is representative of the low fan tip speeds that are being considered. (The results for higher fan speeds were essentially the same as these low speed results) The curves in figure 4 have had the tone noise removed by a computer algorithm since this was a broadband noise investigation. Although some tones are visible, they are only the residual that the algorithm did not successfully remove.

As can be seen in figure 4 the broadband noise is reduced on the order of 3 to 4 decibels when going from the 60 vane stators to the 15 vane stators. (A vane ratio of 4 to 1) More reduction might have been achieved but the noise level was reduced to the rotor alone broadband levels at the higher frequencies. The interesting part of this data is that the noise was equally reduced in going from 60 vanes to 30 vanes where the chord was not changed as it was in going from 30 to 15 vanes where the chord was increased to maintain solidity. This gives the indication that the broadband noise reduction might be coming simply from the reduced number of stator vanes and not the increased stator chord. During these tests the stator blade shape or setting angle was not changed in going from 60 to 30 blades. Therefore some change in performance might have occurred that could be responsible for part of the noise reduction. However, the solidity was maintained in going from 30 to 15 blades and that noise reduction probably did occur with constant fan performance.

Regardless of whether the reduced vane number alone or in combination with an increased stator chord would be responsible for the noise reduction, the application of this technique to a low tip speed fan could result in a perceived noise reduction. The possible amount of the perceived noise reduction is calculated in the Results and Discussion Section.

PERCEIVED NOISE CALCULATION PROCEDURE

The intent of this paper is to take a fan representative of a low tip-speed device and modify it with less stators and possibly longer chord stators to determine what perceived noise reduction would be possible. A sample spectra, representative of a full scale low tip speed fan will be used as a baseline. This spectra would be modified to reflect the expected broadband and higher harmonic reductions. Current practice is to have a cutoff blade passing tone for this type of low speed fan. With less vanes the new fan stage would have a cuton blade passing tone. Reference 6 indicates that violating cutoff would add approximately 8 decibels to the spectra at the blade passing tone. This additional 8 decibels does not account for the expected blade passing tone reduction that would be provided by the new stators. In addition, the tones for the low tip speed fans do not protrude above the broadband as much as did the tones for the higher tip speed fans reviewed in reference 6. For these reasons, the increase in the blade passing tone might therefore not be as great as the 8 decibels indicated by reference 5. However, the full 8 decibels is used here in an effort to be conservative in determining the PndB reduction. Therefore, the modified spectra would have a blade passing tone increased by 8 decibels. The modified spectra would then have the broadband and harmonic reductions expected from the new stator and a noise increase at the blade passing tone.

Perceived noise levels would then be calculated for the baseline and new stator spectra. The perceived noise levels are calculated using the table of noys from reference 7. The perceived noise level (PNL) is defined as

$$\mathrm{PNL} = 40 + 33.22 \mathrm{Log}\, \mathbf{N} \tag{2}$$

$$\mathrm{N} = \mathrm{nmax} + 0.15\,(\textstyle\sum \mathrm{n} - \mathrm{nmax}) \tag{3}$$

where nmax is the maximum noy value and $\sum$n is the sum of the noy values in all of the bands.

In addition, a tone noise correction will be applied to both the base and modified calculations. These tone corrected perceived noise levels (PNLTs) will then be compared to determine the possible noise reduction from using less stators on low tip speed fans.

RESULTS AND DISCUSSION

Baseline Fan

In order to determine the noise advantage of using the new low blade number stators, a hypothetical baseline fan was chosen. This fan is 3.3 meters (130 in.) in diameter having 18 rotor blades and 51 stator vanes. The stator vanes have a 25.1 cm (9.9 in.) chord. The tip speed of the fan is 229 m/sec (750 ft/sec). For the 3.3 meter (130 in.) diameter fan this gives a blade passing frequency of approximately 400 hertz.

Based on scale model experience of a similar fan, a typical takeoff spectrum of the baseline fan at 305 meters (1000 ft) would look as the solid curve shown in figure 5. As can be observed, the fan is cutoff at the blade passing frequency but has a measurable tone at twice blade passing frequency. A listing of the sound pressure level in each one-third octave band is shown in Table I.

New Fan Stage

The new fan stage would have 10 stators, about 1/5th the number of blades as the original fan. The chord of the stators could be; 1 held constant , 2 increased to maintain solidity or 3 only increased enough to maintain aerodynamic performance or meet structural requirements. In any case the past data would indicate that the noise at the harmonics and the broadband noise would be reduced.

The long chord stator data show 4 to 5 decibels reduction with 1/8th the number of stator vanes while the Boeing data show 3 to 4 decibels reduction with 1/4th the number of vanes. At 1/5th the number of vanes as for this fan redesign, a reduction of 4 decibels would be a reasonable expectation.

A new spectrum was then constructed using a 4 decibel reduction for the broadband and higher harmonic reductions. In reference 3, the broadband noise reductions were seen from 1 000 to 20 000 hertz for a 1.83 meter (72 in.) diameter fan. Since our fan is almost twice as large, the frequency is assumed to be shifted by a factor of 2. Therefore the 4 decibel reduction is assumed to apply from 500 to 10 000 hertz. This applies the same 4 dB to both the higher harmonics and the broadband.

The blade passing tone is assumed to increase 8 dB for violating cutoff and the new spectrum is tabulated in Table II. A plot of this spectrum is seen as the dashed curve in figure 5. Figure 5 shows that the new spectrum is significantly lower than the baseline spectrum over most of the frequency range except at the blade passing tone and lower frequencies.

A similar perceived noise calculation was done for the high tip speed, high rotor blade number fan of reference 2. For this calculation, the blade passing tone was assumed to be decreased by 8 decibels for the cutoff short chord fan even though an inlet flow distortion kept it higher in the original data. The harmonics and broadband noise were assumed to be reduced 4 decibels for the reduced stator number (long chord stator) case. Because of the high tip speed and large number of rotor blades, the blade passing tone was at the highly noy weighted frequency of 2500 hertz. As a result no PndB reduction was observed in going to the lower stator vane numbered fan. This was because the reduction in the harmonic and broadband noise was balanced by an increase at the blade passing frequency. For the low rotor blade number, low tip speed fan being investigated here, a PndB reduction is expected since the increased blade passing tone is at a low weighted frequency, 400 hz, and the broadband and harmonic reductions are in the highly weighted regions.

Perceived Noise Reduction

The perceived noise levels of the low tip speed fan with the cutoff original stator and with the low blade number stator were calculated using equation 2 of the Perceived Noise Calculation Procedure section and noy values from reference 7. A table of these noy values for both the fans is found in Table III.

The calculations indicate that the new fan with the low stator vane number has a noise level of 87.8 PndB while the base fan has a level of 89.9 PndB. This is a 2 PndB improvement for the new lower blade number fan. Corrections for tones adds 1 dB to the baseline fan and 1.5 dB to the new stator fan giving 90.8 and 89.3 respectively. The fan with less stator vanes then shows a 1.5 dB reduction in PNLT. This is a significant noise reduction and shows the advantage of abandoning the cutoff vane number for lesser vanes in a low tip speed fan.

CONCLUDING REMARKS

The perceived noise of low tip speed fans is being more and more controlled by broadband noise. The primary source of broadband noise appears to be the interaction of the rotor wake turbulence with the downstream stator vanes. A way to reduce this noise is to reduce the response of the stator vanes to the incoming disturbance. Previous experiments have investigated the noise with reduced stator vane number either with the same chord or with the chord increased to maintain solidity. Regardless of whether the vane number was reduced alone or in combination with an increased stator chord, the noise was reduced.

A baseline fan was compared with a fan redesigned to use this lower vane number concept. Reductions in broadband and higher harmonic noise were taken based on these past experiments. The broadband and higher harmonic tones were assumed to be reduced 4 decibels. The use of a low number of stator vanes violates the cutoff criteria for the blade passing frequency. Therefore the blade passing tone , based on past experience, was assumed to increase 8 dB for the fan.

The perceived noise calculations showed that the new low stator number fan had a 2 PndB noise reduction from the baseline fan. When tone corrections were applied, a 1.5 dB reduction in PNLT was observed. These calculations show that violating cutoff by using less stator vanes can provide a significant noise reduction and is a viable technique for reducing the perceived noise of low tip speed fans.

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TABLE I.—BASELINE FAN SOUND PRESSURE LEVELS

1/3 Rd Octave band	Sound pressure level
100	62.5
125	62.0
160	61.0
200	64.0
250	65.0
315	66.0
400	67.5
500	69.0
630	71.5
800	74.0
1000	70.5
1250	70.5
1600	70.0
2000	68.5
2500	67.0
3150	65.0
4000	61.5
5000	57.5
6300	51.0
8000	46.5
10 000	39.0

TABLE II.—LOW VANE NUMBER (LONG CHORD STATOR) FAN SOUND PRESSURE LEVELS

1/3 Rd Octave band	Sound pressure level
100	62.5
125	62.0
160	61.0
200	64.0
250	65.0
315	66.0
400	75.5
500	65.0
630	67.5
800	70.0
1000	66.5
1250	66.5
1600	66.0
2000	64.5
2500	63.0
3150	62.0
4000	57.5
5000	53.5
6300	47.0
8000	42.5
10 000	35.0

TABLE III.—NOY VALUES FOR BOTH FANS

1/3 Rd Octave band	Baseline fan noys	Low vane number (Long chord stator) fan noys
100	2.2	2.2
125	2.45	2.45
160	2.71	2.71
200	3.98	3.98
250	4.71	4.71
315	5.45	5.45
400	6.71	11.70
500	7.46	5.66
630	8.81	6.70
800	10.6	8.00
1000	8.25	6.30
1250	9.50	7.16
1600	12.0	9.09
2000	12.4	9.40
2500	12.8	9.74
3150	12.0	9.74
4000	9.5	7.1
5000	6.7	5.1
6300	3.97	3.02
8000	2.35	1.68
10 000	0.82	0.55

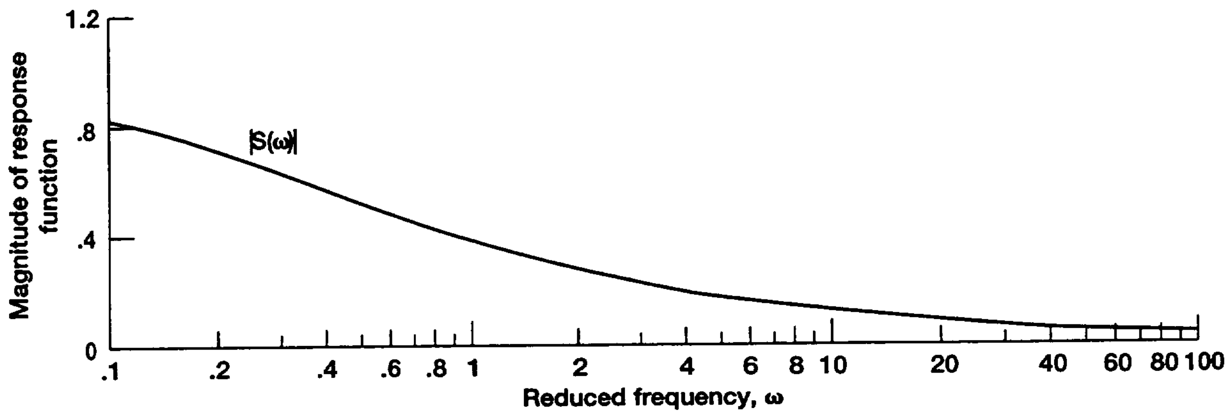

Figure 1.—Change in magnitude of response function with reduced frequency.

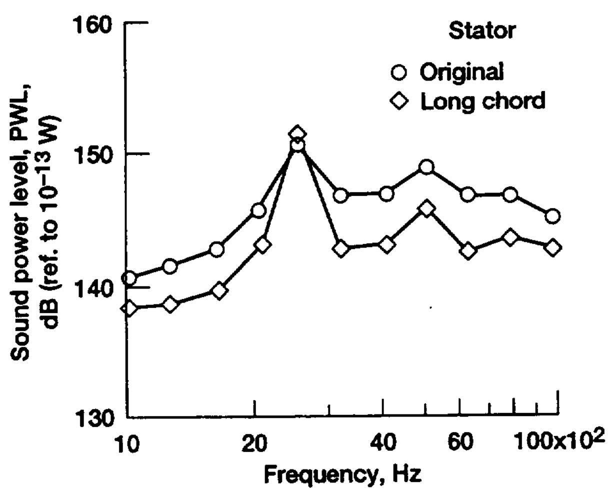

Figure 2.—Comprison of acoustic power spectra for long-chord stator and original stator at 80 percent speed.

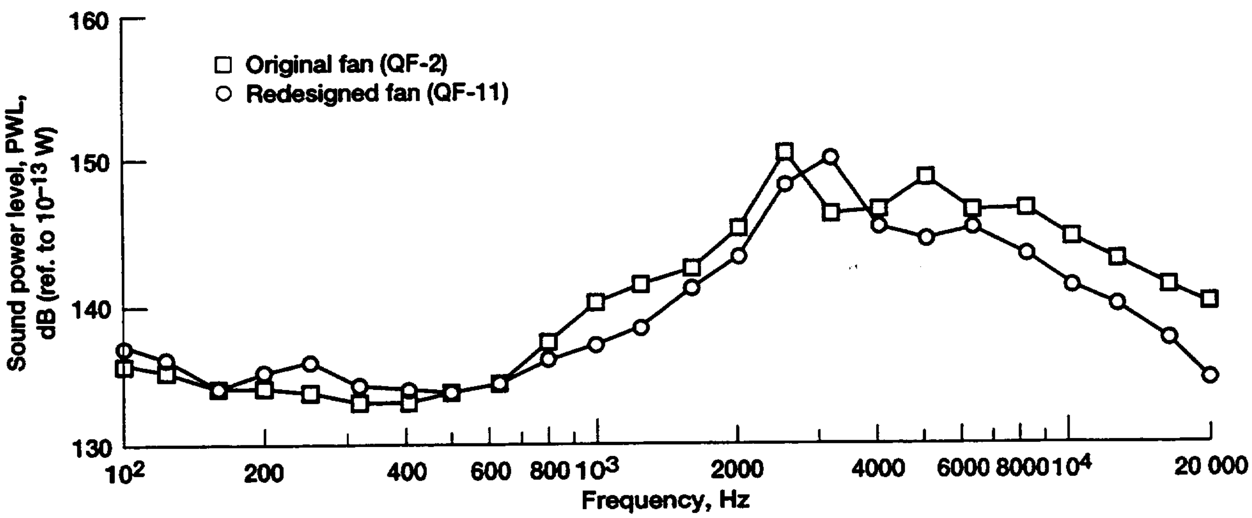

Figure 3.—One-third octave sound power spectra.

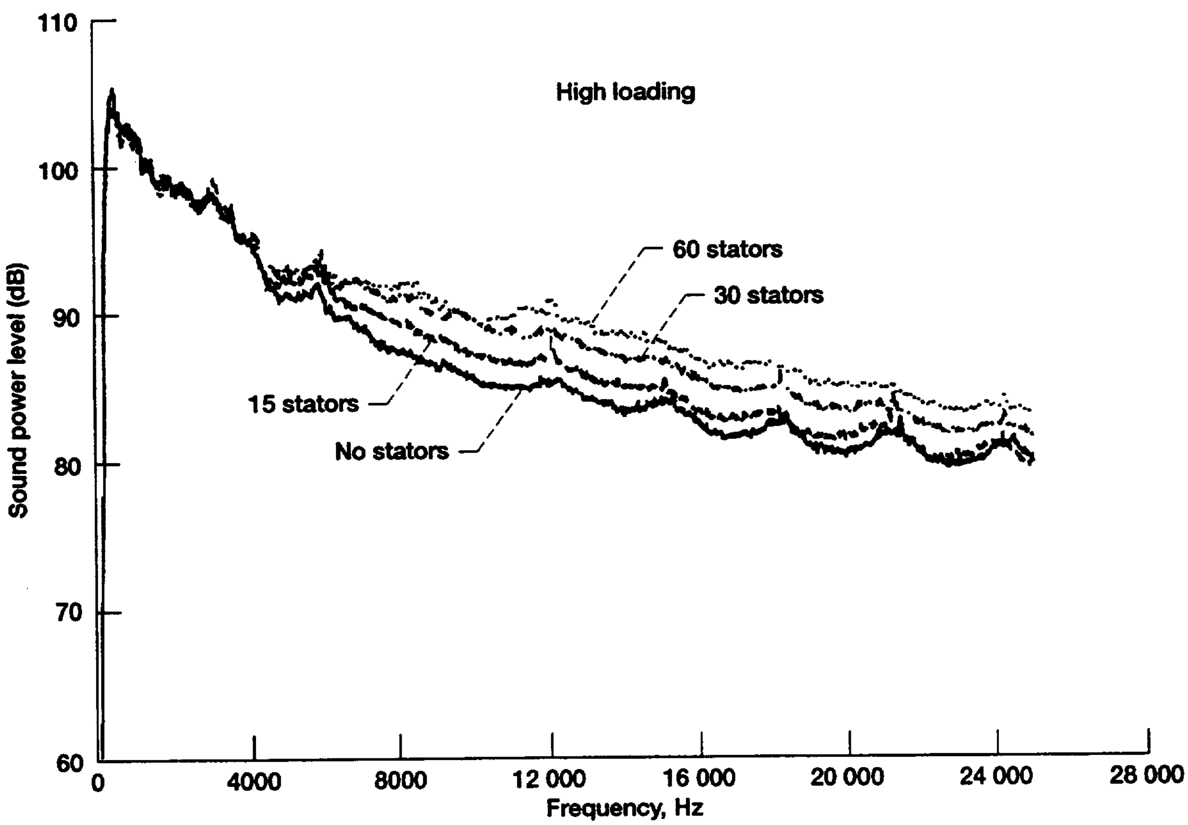

Figure 4.—Effect of various stator configurations on the aft power level (55% speed, 0.020 inch tip clearance, full boundary layer).

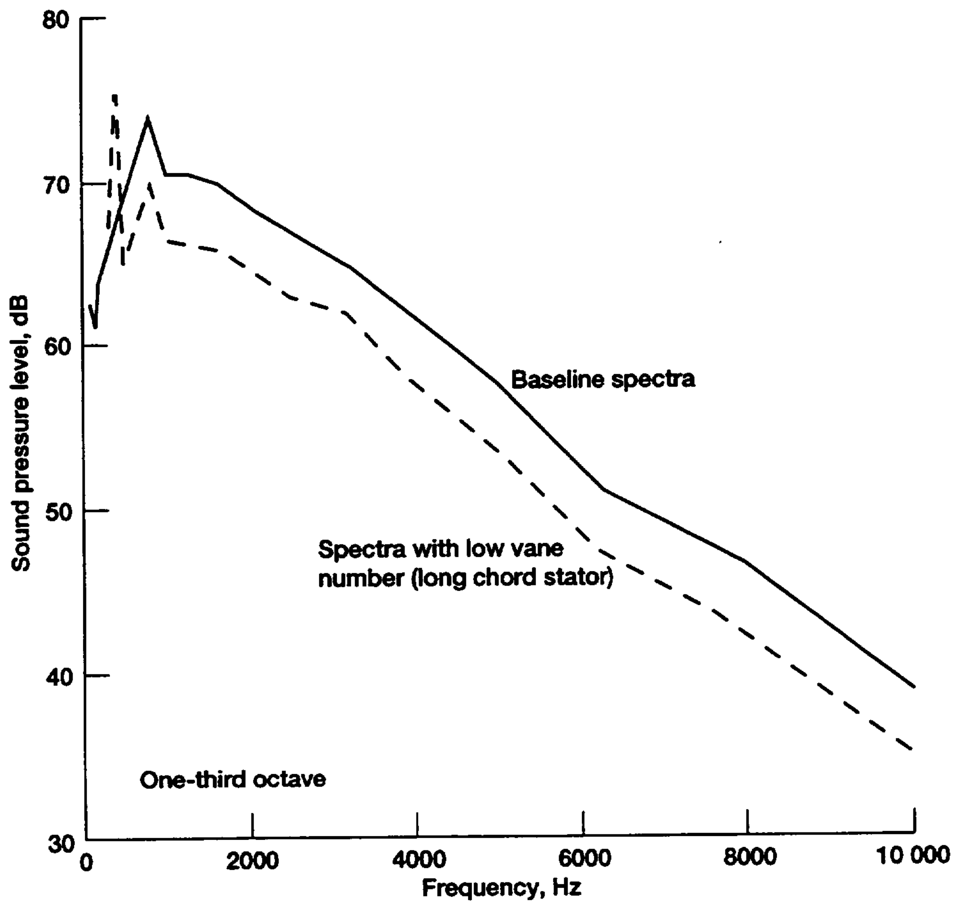

Figure 5.—Comparison of one-third octave spectra.

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