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SUMMARY

As subsonic jet engines move toward higher bypass ratios to reduce jet noise, the fan noise becomes a significant part of the perceived total noise. The conventional method of reducing fan tone noise is to design a low-speed device with a low number of rotor blades and a large enough number of stator vanes to "cut-off" the blade passing tone. The potential of two alternative approaches for reducing fan tone noise is investigated in this report. One of these approaches increases the number of rotor blades to shift the tone noise to higher frequencies that are not rated as strongly by the perceived noise scale. This alternative fan also would have a small number of long chord stator vanes which would reduce the stator response and lower rotor-stator interaction noise. Comparison of the conventional and alternative fan concepts showed that this alternative approach has as large or larger a perceived tone noise reduction potential as the conventional approach. The other alternative, a high Mach number inlet, is evaluated both for its noise attenuation and for its change in noise directivity.

INTRODUCTION

As subsonic jet engines move toward higher bypass ratios to reduce jet noise, the fan noise is becoming a more important part of the perceived noise level. The common method for reducing the fan tone noise is to design a low-speed device. This low-speed fan would have a low number of rotor blades and a high number of stator vanes to achieve "cut-off" conditions for the blade passing tone. The cut-off condition is one where the sound pressure level of the rotor-stator interaction tone decays rapidly as it passes down the duct (ref. 1). The tip speed for such a device would be as low as possible and still achieve acceptable fan operation. The typical limit on lowering the tip speed is the stall margin of the fan. This current method for noise reduction has several advantages. The lower number of rotor blades allows for thicker and therefore stronger blades. In addition, a reduction in blade number typically results in a cost reduction. These low-speed, lower-blade-number fans are currently preferred for high bypass ratio fans.

The purpose of this report is to evaluate the noise reduction potential of some alternative approaches for reducing fan tone noise. In particular, two approaches will be discussed and evaluated.

The first is the use of a fan with a high number of rotor blades to reduce the perceived noise level. The perceived noise level is a subjective scale developed to measure the annoyance of a sound. It not only represents the intensity of the sound but also its frequency content. The frequency range is divided into fixed bands, and the sound pressure level in each of these bands is determined. Each of the bands is weighted as to how much a noise in those frequencies annoys the listener. The weighted contents in each of the bands are then combined to achieve a perceived noise level. The high number of rotor blades generates tones at higher frequencies that are not weighted as strongly by the perceived noise scale and thereby results in a reduction. The fan would have a small number of long chord stator vanes which, although resulting in propagating duct modes, would reduce the stator response and act to lower the rotor-stator interaction noise.

The second noise reduction approach is the use of a high-Mach-number inlet. The noise reduction potential of this inlet is investigated both for the noise attenuation at the high Mach number and for the change in noise radiation angle resulting from the higher inlet velocity.

Figure 1 shows the noise reduction concepts included in both the conventional low-speed approach to designing a fan and the alternative high-blade-number approach. To evaluate the noise reduction potential of these approaches, the noise reductions from a baseline fan will be calculated. In this paper study the noise reduction potential of both the conventional and alternative fans will be evaluated with fan designs that are presently beyond current practice. In particular, the conventional fan potential will be evaluated for a fan speed lower than what is currently practical from a stall margin standpoint, and the alternative fan will be evaluated with blade numbers that result in aspect ratios that are higher than current metals would permit. Details of the conceptual fan designs and the practical limitations are discussed in the report. A high-Mach-number inlet could be applied to either the low-speed fan design or the high-blade-number design. Therefore, the reduction potential of this approach is just investigated as a noise reduction and is not compared with the two fan designs.

METHOD OF EVALUATION

The procedure to be followed in this report is to start with a medium-range tip speed fan which has a "cut-on" vane to blade ratio as a baseline. The perceived noise reductions are evaluated first for the conventional low-speed, low-rotor-blade-number approach and then for the alternative fan design approach. The perceived noise levels are calculated as if they were occurring at the peak sideline noise position regardless of it's location. The fan characteristics are discussed as they are used in the calculations.

The perceived noise levels for the tones are calculated using the table of noys from reference 2. The perceived noise level (PNL) is defined as

$$\mathrm{PNL} = 40 + 33.22 \log_{10} \underline{N}$$

where

$$\underline{N} = n_{\max} + 0.15 \left(\sum n - n_{\max} \right)$$

and where $n_{\max}$ is the maximum noy value, and $\sum n$ is the sum of the noy values in all of the bands. The noy values are obtained for each one third octave band that contains a tone. When tones occur at frequencies between two one-third-octave bands, the tonal energy is split equally between them. Tones occurring above the 10 000-Hz band are not considered in PNL calculations. No specific tone corrections (PNLT) are made here for the additional perceived noisiness of tones as opposed to broadband.

The perceived noise reductions for the alternative fan design are compared with the reductions obtained from the low-speed fan design. The noise attenuation of the high inlet Mach number and the change in noise radiation angle are addressed separately as noise reductions.

RESULTS AND DISCUSSION

Noise Reduction Potential of Fan Concepts

A hypothetical conventional fan design with a cut-on vane to blade ratio is the baseline fan. This baseline fan is then modified to reduce tone noise. First, the conventional method of a low-speed design with a low number of rotor blades and the proper number of stator vanes to provide cut-off of the rotor-stator interaction tone at blade passing frequency is investigated. Then an alternative design with a high number of rotor blades and a set of long-chord stator vanes will be investigated for its perceived noise reduction. In each of the fan design concepts, an attempt will be made to quantify the noise reduction of each of the elements of the design, and an explanation of the values used will be provided. The effect of a high-Mach-number inlet is also addressed. The descriptions of the fan variations used in this study are found in table I. All of the fans have a pressure ratio of 1.5 and a diameter of 6 ft, so that the comparisons are all on the basis of equal thrust.

Baseline fan. — The baseline fan chosen for these calculations is loosely based on the QF–1 fan previously tested at NASA Lewis Research Center (ref. 3). This is a 6-ft-diameter fan with 53 rotor blades and 90 stator vanes, so it is "cut-on." It has a 1.5-pressure ratio with a rotor tip speed of 1100 ft/sec. The stator vanes have a 2.67-in. chord, and the inlet Mach number is assumed to be 0.3. The blade passing frequency of this fan at design speed is approximately 3000 Hz.

For purposes of obtaining relative perceived noise numbers, it is assumed that, at the maximum noise location, the blade passing tone sound pressure level is 100 dB. The tone levels of the baseline fan are assumed to decrease by 3 dB per harmonic, as described in figure 8 of reference 4. The baseline fan then has a 100-dB tone at 3000 Hz, a 97-dB tone at 6000 Hz, and a 94-dB tone at 9000 Hz. Tones at 12 000 Hz and above are not rated in the perceived noise calculation. The tone at 9000 Hz is assumed to split equally between the 8000- and 10 000-Hz one-third-octave bands. The resulting perceived noise level is 113.4 PNdB. The predicted reductions for the fan concepts are then in reference to this fan B baseline spectrum. A summary of these noise levels is found in table II, and a bar graph representation of the results is shown in figure 2.

Conventional noise reduction concept. — The calculations for the conventional low-speed design concept will be performed in stages to observe the importance of the various elements. If the number of stator vanes is increased to 112, the rotor-stator interaction blade passing tone would be cut-off. If the blade passing tone were totally due to interaction noise, the tone would virtually be eliminated by cut-off. Even though large reductions in tone have been observed in specific fans, the practical effect of cut-off, based on experimental data, is to lower the blade passing tone only about 8 dB (fig. 8 of ref. 4). The blade passing tone at 3000 Hz is then reduced to 92 dB. The higher harmonics are unchanged. The perceived noise level for this fan (C1) with cut-off becomes 109.1 PNdB, a reduction of 4.3 PNdB. It should be noted that, if the blade passing tone were completely removed by cut-off, the resulting perceived noise level would be 107.7 PNdB, a 5.7 PNdB reduction from the baseline. (See table II, and fig. 2).

The effects of lowering the blade number and tip speed are calculated without and with cut-off. The rotor blade number is reduced from 53 to 20, and the tip speed is lowered from 1100 to 800 ft/sec for this fan (C2). This significantly increases the loading on the fan blades to maintain the 1.5 pressure ratio, and advanced techniques would be necessary to provide enough stall margin on such a fan. This case is analyzed to show what future noise reduction might be possible by this method.

Reference 4 indicates that the tone varies as 50 times the log of the ratio of the inlet relative Mach number at the blade tip. With an assumed inlet Mach number of 0.3, the tip relative Mach number of the baseline fan is 1.04, and that of the low-speed fan it is 0.79. This gives a predicted reduction of 6 dB. It is assumed that this 6-dB reduction applies to all tones. For a blade number of 20 and tip speed of 800 ft/sec, the blade passing frequency is reduced to approximately 800 Hz. There are then 14 harmonics of the blade passing tone in the perceived noise range. The levels of the tones and their frequencies are shown in table II (fan C2). The calculated perceived noise level is 105.3 PNdB. This is an 8.1-PNdB reduction from the baseline fan.

As can be seen from table II, because of the reduction in blade number and the lower speed, more tones are now included in the PNdB rating. Also, because of the shift in frequency, the blade passing tone does not have the highest noy rating. The inclusion of cut-off on the 53-blade fan calculated earlier (fan C1) yielded a practical reduction of 4.3 PNdB (5.7 PNdB if the tone were completely removed). Here, on the low-speed, 20-blade fan, because the PNdB level is controlled by higher harmonics, the reduction from cut-off is not expected to have as much effect. If cut-off provides the expected 8-dB reduction indicated from reference 4, the blade passing tone would be reduced to 86 dB, and the resultant PNdB becomes 104.8 PNdB (see table II, fan C3). This is a total of 8.6 PNdB less than the baseline fan, but cut-off has only added 0.5 PNdB of this improvement. This fan was also calculated where cut-off completely removed the blade passing tone (table II), and its noise level was 104.3 PNdB. This is 9.1 PNdB less than the baseline fan but only a 1-PNdB reduction due to cut-off. Note that cut-off is not very important for low-speed, low-blade-number fans because of the dominance of the higher harmonics.

In order to show if lowering the blade number to 20 has limited the noise reduction potential of the low-speed fan, a 53-blade fan with the low-speed and cut-off features is shown for comparison (table II, fan C4). It also has added harmonics in the PNL range because of the lower tip speed, and the blade passing tone does not have the highest noy rating. This fan (C4) with the expected 8-dB reduction from cut-off has a noise rating of 105.5 PNdB, a reduction of 7.9 PNdB from the baseline fan, and, with complete removal of the blade passing tone, the noise rating is 104.6 PNdB, an 8.8-PNdB reduction. This is almost the same as the 20-blade fan. These results show that the low blade number has not hurt the noise reduction potential of going to a low-speed fan.

In summary, a low-blade-number (20), low-tip-speed (800 ft/sec) fan with the expected noise reduction from "cut-off" (8 dB) would lower the baseline fan noise 8.6 PNdB. This reduction would represent a significant lowering of the annoyance of this fan.

Alternative noise reduction concept. - The noise assessment of the alternative fan concept will also be done in stages. The effects of increasing the rotor blade number and of long-chord stator will be addressed separately.

The increase in rotor blade number results in lower perceived noise because it increases the frequency of the blade passing tone and harmonics to a region of lower noy weighting. In particular some of the tones are not rated because the PNdB rating only goes up to include the 10 000-Hz one-third-octave band. The main reason for not rating noise above this frequency range is that the noise is highly attenuated by atmospheric absorption. For example, from reference 6, the attenuation at 70 °F and 70-percent humidity is approximately 31 dB per 1000 ft at 12 500 Hz. With this high a noise reduction with distance, the higher frequencies are unlikely to be a problem on the ground. The increase in frequency also reduces the noy values of some of the other tones. The net result of the higher blade number is to reduce the perceived noise level of the fan. It should be noted that added benefits due to increased atmospheric attenuation have not been included in the evaluations of these fans.

The original QF–1 fan (ref. 1), upon which the baseline fan was loosely based, had 53 rotor blades and 112 stator vanes. To a certain extent, the cut-off criteria built into the QF–1 fan limited the number of rotor blades. The number of stator vanes was limited to 112 in this design because of stator choking concerns. The number of rotor blades was limited by the need to maintain the proper vane to blade ratio for cut-off. Other limitations on the number of rotor blades stem primarily from interrelated flow path and stress considerations. As the number of blades increases, the thickness of the blades becomes a factor in the blockage of the flow path. To allow for more blades, the thickness of the blades needs to decrease. This lowers the resonant frequencies of the blade and makes it more prone to areoelastic problems. Because of these possible problems, two separate fans with increased rotor blade number will be discussed. One of the fans discussed can possibly be built with existing metals while the other fan, with even more blades, would require improved materials for its construction. The highest blade number fan is included here to provide the maximum potential for noise-reduction from the alternative fan design.

Because of the design difficulties inherent in fans with large numbers of rotor blades, fans A1 and A2, with 80 and 106 blades, respectively, are considered. The first fan might be built with existing metals. The second fan, A2, probably exceeds present technology. In the future, advanced materials could probably allow such a fan to be constructed. The high number of rotor blades in either of these designs precludes building a "cut-off" set of stator vanes since the number of stator vanes would be too high.

The blade-passing-tone level of the 80-blade fan, A1, is 100 dB, as for the baseline fan but with frequency increased to 4500 Hz because of the increased number of rotor blades. The second harmonic is at 9000 Hz with a 97-dB level, and all higher harmonics are above the PNL range. The calculated perceived noise level is 111.4 PNdB (table II). This is a 2.0-PNdB noise reduction from the baseline fan.

For the extreme case of 106 blades (fan A2), the blade passing frequency is 6000 Hz, and the second and higher harmonics are moved beyond the rating range. The perceived noise level is 108.7 PndB (table II), a 4.7-PNdB noise reduction from the baseline fan.

Each of these high-blade-number rotors would have a set of long-chord stators. Long-chord stators reduce the rotor-stator interaction noise by lowering the response of the stators to the incoming rotor wakes. In reference 7 a set of 14 long-chord stators was tested behind the 53-blade, QF–1 rotor (fig. 3). In figure 3 the stators are shown with the acoustically treated surfaces. The results discussed here are from experiments with the treatment inactivated by taping. In these experiments the blade passing tone at all locations and the second harmonic in the inlet quadrant were masked by tones caused by inlet flow distortion. Noise reductions for the second harmonic were observed in the aft quadrant, and these will be used to provide an experimental indication of the noise reduction potential of the long-chord stators. It should be noted that reductions due to the long-chord stator apply at all of the harmonics.

From reference 7, it is seen that the theoretical tone noise reduction varies approximately as 20 times the logorithm of the ratio of the Sear's response function for the stator vanes. The Sear's function, $S(\omega)$, varies with ω, the reduced frequency, as shown in figure 4 (from ref. 7, fig. 2). The reduced frequency is

$$\omega = \pi C_s / L$$

where C_s is the stator chord, and L is the incoming gust wavelength.

The stator chord length for the QF–1 fan tests was increased from 2.67 to 24 in., resulting in a reduced-frequency change from 6.2 to 55.8 for the second harmonic. The corresponding change in the

Sear's function $S(\omega)$ is from 0.165 to 0.06, so the predicted reduction is 8.8 dB for the second harmonic. Experimentally, the second harmonic noise reduction in the aft quadrant was of the order of 4 to 5 dB, or approximately one half of the predicted reduction (ref. 7, fig. 26).

The benefits of the long-chord stator are calculated for both the 80- and 106-blade cases. Noise levels are calculated for the full-tone reduction predicted by the Sear's function and for one-half the predicted reduction found experimentally. The baseline fan has the same $\omega = 3.1$ as the QF–1 fan tested in reference 7 since the stator chord is the same. The alternative fan with 80-blades (fan A3) has an incoming gust wavelength reduced by a factor of 1.5 because of the increased number of rotor blades. With the long chord of the stators, $\omega = 41.85$ for the blade passing tone (1.5 times the ω of the fan in ref. 7). The magnitudes of $S(\omega)$ are 0.225 for the baseline fan and 0.07 for the 80-blade fan with long-chord stators. At twice blade passing frequency the reduced frequencies become 6.2 and 83.7 for the baseline and 80-blade fans, respectively, and the magnitudes of the response functions become 0.165 and 0.055. The predicted reductions for the first two harmonics are then 10.0 and 9.5 dB. The predicted perceived noise levels were 101.5 PNdB for the 80-blade fan with the full reduction from the long-chord stators and 106.5 PNdB using one half of the reduction. These were 11.9- and 6.9-PNdB reductions from the baseline fan. The perceived noise reduction for the 80-blade fan with the practical long-chord stator reduction (6.9 PNdB) is only 1.7 dB less than that for the low-speed, 20-blade fan with practical cut-off (8.6 PNdB). The 80-blade fan with the complete long-chord reduction (11.9 PNdB) has 2.8 PNdB more reduction than the 20-blade low-speed fan with the complete cut-off reduction (9.1 PNdB).

The alternative fan (A4) with 106 blades and a long-chord stator has an ω of 55.8. The response function magnitudes were 0.225 for the baseline fan and 0.06 for the 106-blade fan. The predicted reduction in the blade passing tone is 11.5 dB. With this reduction the PNdB of the 106-blade fan would be 97.7 PNdB and with the practical one half of this reduction the level is 103.0 PNdB. These represent reductions of 15.7 and 10.4 PNdB, respectively. These are both more than the 20-blade low-speed fan with complete cut-off (9.1 PNdB). It is apparent that, as advances in blade technology permit, the noise benefits from higher blade numbers increase significantly.

The relative tone noise reduction potential of the low-blade-number, low-speed approach and the alternative high-blade-number, long-chord stator approach are summarized in table II and figure 2. The 80-blade fan with the practical noise reduction (A3) has 1.8 PNdB less noise reduction potential than the 20-blade low-speed conventional approach fan with practical cut-off reduction (C3). The 80-blade fan with the theoretical rduction from the long-chord-stator has 2.8 PNdB more reduction potential than the 20-blade low-speed fan with complete cut-off. The 106-blade alternative approach fan (A4) shows more noise reduction potential than any of the low-speed fan configurations. This fan has 1.8 PNdB more reduction potential than the low-speed approach, when comparing fans with practical noise reduction features, and 6.6 PNdB more noise reduction potential, when comparing the theoretical noise reduction potentials. The noise reduction potential for the alternative fan approach of high blade number with long-chord stator vanes is as large as if not larger than the conventional low-blade-number, low-speed approach.

Additional alternative fan advantages. — Several other factors are advantageous for the alternative fan. The effect of excess atmospheric attenuation was not included in these comparisons. Because of the higher frequencies of the alternative fan, its noise would have more atmospheric attenuation for the same distance than would that of the conventional fan. The higher rotor blade number would also tend to reduce generated noise by the rotor alone. The higher rotor blade number fan would probably also have shorter rotor blade chords. The distance from the rotor to the stator, measured in rotor blade chords would be larger for the alternative fan. This would theoretically give more wake decay and a reduction in rotor-stator generated noise.

The use of long-chord stators in a fan design presents other advantages as well as the above-mentioned noise reduction from reduced stator lift fluctuations. The additional thickness of the long-chord stators allows the inclusion of acoustic treatment directly on the stator surfaces where the noise is being generated. The authors of reference 8 tested acoustic treatment on the stators vanes and showed that significant noise reductions could be obtained by this method. The new concept of active noise control is also very applicable to the long-chord stators. The system would provide some method of stator lift control, which would be of equal magnitude to the wake-induced lift fluctuation but applied exactly out of phase such that the lift fluctuation is cancelled. The additional thickness of the long-chord stator vanes would allow such lift control devices to be more easily applied. Some combination of active noise control and acoustic treatment on the stators is also possible. In addition, the long-chord stators could act as load bearing members in the engine to replace the fan cowl to engine core struts. It might even be possible to attach the engine to the airplane with a strut that connected to the fan cowl and have the long-chord-stators support the core engine. This would provide a weight savings and the noise generated by the flow over the internal strut would be eliminated. The alternative fan concept with the long-chord stator vanes then shows significant additional potential advantages for incorporation in an engine.

Broadband noise. — Although this paper deals specifically with fan tone noise reduction, a short discussion of broadband noise is included since it can be a significant portion of the perceived noise rating. Both the low-speed, low-blade-number fan concept and the high-blade-number, long-chord-stator concept have potential for reducing fan broadband noise.

The low-speed-fan broadband noise reduction can be estimated using reference 9 (p. 222). Here the broadband fan noise is indicated as varying with the sixth power of the velocity. Assuming the appropriate velocity to be used is the tip relative Mach number, the noise reduction is then expected to be

$$60 \log_{10} M_{\text{tip, baseline}}/M_{\text{tip, low speed}}$$

With the tip relative Mach number ratio of 1.32, as calculated before, the estimated broadband noise reduction is approximately 7 dB for the low-tip-speed fan.

The long-chord stators also show potential for broadband noise reduction. In reference 7, the long-chord stator vanes reduced the broadband noise. In figure 5 (a reprint of figure 25, part c, from ref. 7), the broadband noise above 800 Hz, the region most highly rated in the perceived noise scale, was reduced with the long-chord stators. The decrease in noise was attributed to the long-chord stator reducing the stator response to incoming wake turbulence and irregularities. (The increase in broadband noise below 800 Hz was attributed to increased vortex shedding as a result of nonoptimum stator blade turning required to have the stator turning section have a radial trailing edge.) Figure 5 shows broadband noise reductions of 3 to 4 dB, which, based on the reduction in the Sear's function at 3000 Hz, is again about one half of the predicted reduction for the long-chord stator.

Broadband noise reductions were also observed in reference 10 where a fan was redesigned to minimize stator lift fluctuations. Here, broadband noise reductions of the order of 5 dB were observed over a large frequency range, and the reduction was roughly uniform at all angles.

If, indeed, the broadband reduction is one half of the predicted reduction in response function then the 106-blade design would have the order of 5.5-dB broadband noise reduction. This is similar in magnitude to the 7-dB predicted broadband noise reduction for the low-speed fan. In addition, the previously discussed inlet-flow distortion controlled the blade passing tone, and it is probable that associated inlet turbulence also had a significant impact on broadband noise. In this case the inlet-distortion-caused broadband noise may present a floor on the long-chord-stator data, and the long-chord stator may result in even more broadband noise reduction in an actual engine where there is clean inlet flow. In short, it appears that the low-speed, low-blade-number fan concept and the alternative high-blade-number, long-chord stator fan concept have similar potential to reduce the broadband fan noise.

High Subsonic Mach Number Inlet Noise Reduction

The following is a discussion of the noise-reduction benefits of using an inlet with a high subsonic throat Mach number. This section does not attempt to exactly quantify the perceived noise reductions but just to indicate roughly the level of inlet noise reductions possible and show that this concept should be considered as a possible noise reduction method for future engines.

Noise attenuation. — The noise attenuation potential of high subsonic Mach number inlets has been shown in a number of experiments (refs. 11 to 14). Reductions of the inlet blade passing tone ranged from 17 dB (ref. 11) to over 30 dB (ref. 13) where the fans were tested statically. Significant harmonic noise reductions were also observed. The blade passing tone was virtually eliminated from the spectrum, and a broadband noise floor limited the measurable amount of attenuation. In reference 11, the broadband noise floor was from the engine exhaust, while in reference 13 the exhaust was ducted away. The removal of the exhaust broadband noise floor probably explains the additional noise reduction measured in reference 13. In either case the tone noise reduction potential of the high subsonic Mach number inlet is very significant.

The noise reductions for high subsonic Mach number inlets occur before the inlet throat Mach number is increased to 1.0. Reference 12 showed a peak angle reduction in the blade passing tone of 29 dB with an average throat Mach number of 0.82, and the over 30-dB reduction of reference 13 occurred at an average throat Mach number of 0.865. In reference 11, a study of the reduction with inlet centerline Mach number (fig. 16 of ref. 11) showed that 15 of the total of 17 dB reduction were obtained by an inlet centerline Mach number of 0.7 and the entire 17 dB were obtained by a centerline Mach number of 0.8. The data of reference 14 showed that the noise reduction was obtained before the inlet was choked. The net result of these various data is that an inlet Mach number of 1.0 is not necessary to achieve the noise attenuation and that most of the inlet noise reduction could be obtained by an unchoked inlet that had an average throat Mach number of 0.80 to 0.85.

The noise reductions obtained by references 11 and 13 indicate that the reductions obtained were reductions in inlet sound power and not just reductions at the peak angle. In particular, in reference 13, the noise data were obtained in a reverberant section of a wind tunnel upstream of the inlet, and these reductions represent reductions in the total power radiated from the inlet. Changes in the directivity of the noise from the inlet will be discussed in the next section.

Even though this paper deals specifically with tone noise, it should be noted that inlet broadband noise reductions equivalent to the tone reductions were observed. At the peak noise angle, (ref. 12, fig. 15), broadband noise was reduced 15 dB in the 2500 Hz band, 28 dB in the 5000 Hz, band and 24 dB at 20 000-Hz band for the average throat Mach number of 0.82. (The blade passing tone one-third octave band was reduced 29 dB at these same conditions.) These broadband noise reductions from the high subsonic Mach number inlet would significantly reduce the broadband noise of either of the fan concepts.

The noise reductions from the high subsonic Mach number inlet should result in reductions in the perceived noise of the fan, but all of the reduction would not be observed because the noise normally radiated from the exhaust would not be lowered and because some of the noise normally radiating from the inlet would now be radiated from the fan exhaust duct. The use of acoustic treatment in the exhaust duct would be needed to reduce this noise. The alternative fan design has some advantage here because, as discussed previously, the long-chord stators provide extra area for noise suppression material.

In summary, the high subsonic Mach number inlet can provide significant reductions in both tone and broadband sound power radiated from the inlet. The inlet Mach number does not have to be increased to 1.0 to obtain this noise attenuation and the attenuation could probably be obtained by an inlet with an average throat Mach number of 0.80 to 0.85.

Directivity change. — In addition to the noise attenuation of a high subsonic Mach number inlet, a change in noise directivity is also observed. In reference 15 the radiation angle for spinning duct modes with various duct and free-stream Mach numbers is derived. The expression for the radiation angle, Ψ_ρ (eq. 32 of ref. 15) is

$$\cos \psi_\rho = \frac{\left[M_\infty - M_D + (1 - M_D M_\infty)\sqrt{1 - \frac{1}{\xi^2}}\right]}{\left\{\left[1 - M_D\sqrt{1 - \frac{1}{\xi^2}}\right]\left[1 + M_\infty\left(M_\infty - 2M_D\right) + \left(2M_\infty - M_D M_\infty^2\right)\sqrt{1 - \frac{1}{\xi^2}}\right]\right\}^{1/2}}$$

In this expression M_∞ is the free-stream Mach number, M_D is the duct Mach number, and ξ is the cut-off ratio, defined as

$$\xi = \frac{k r_o}{\alpha\sqrt{1 - M_D^2}}$$

where k is the wave number and α is the hard wall duct mode eigenvalue.

In table III, calculated values for the angle of the peak of the principle radiation are shown for a number of different cut-off ratios, α, and duct Mach numbers for the case of a free-field Mach number of 0.2. Increasing the duct axial Mach number at a constant cut-off ratio causes the noise to radiate closer to the inlet axis of the fan, that is, the noise radiates at lower angles. An additional effect of increased axial duct Mach number is to increase the cut-off ratio (see eq. 11 of ref. 15). As can be seen from table III, an increase in cut-off ratio also causes the noise to be radiated at lower angles. The combined effect of the two is then that an increase in the inlet duct Mach number causes the noise to radiate at an even lower angle.

This change in directivity can have a significant effect on the noise of an airplane at the noise rating locations. When the noise is radiated closer to the axis, it must travel farther to reach a specific location on the ground, resulting in a noise reduction. This is particularly evident in the takeoff and landing locations that are directly under the airplane flightpath (ref. 16). To illustrate this effect a hypothetical airplane flight path will be chosen and the effect of the change in duct Mach number will be evaluated for the takeoff noise location when applied to the baseline fan.

For a fan 6 ft in diameter with 53 rotor blades and 90 stator vanes, the first radiation mode encountered is the 37,1 mode, which has an eigenvalue ,α, of 39.72. Other propagating blade-passing-tone modes have their radiation angles closer to the axis to start with so this represents the worst-case situation for noise radiation at the low inlet duct Mach number. For a blade passing frequency of 3000 Hz and inlet Mach number of 0.3 the cut-off ratio is 1.357. If the inlet duct Mach number is increased to 0.8, the cut-off ratio becomes 2.157. When the free-stream Mach number (flight speed) is 0.2, the predicted radiation angle for the inlet Mach number of 0.3 is 44°, and when the inlet duct Mach number is 0.8, the angle is 12°. This change in the radiation angle of the peak can have a significant effect on the noise under the aircraft flight path.

To illustrate the effect of this change in directivity on takeoff noise, a hypothetical flight path is chosen. The measurement point is taken as being 3.5 nautical miles from the start of the airplane takeoff roll. The plane is assumed to lift off 6000 ft from the takeoff roll and follows a 7° climb. The plane (and the engine inlet axis) is assumed to be at a 4° angle of attack to the flight path. This is illustrated in figure 6. Using the previously calculated peak noise radiation angles, the position of the airplane on the flight path can be calculated for when the noise at this peak radiation angle would intersect the noise measurement location. The distance from the airplane to the measurement location can then be calculated. As can be seen in figure 6 the case which has the lower radiation angle is closer to the end of the runway and farther from the noise measurement location. For an inlet duct Mach number of 0.3 and radiation angle of 44°, the propagation distance from the engine to the noise measurement location is 2924 ft. When the duct Mach number is increased to 0.8, with a radiation angle of 12°, the propagation distance is increased to 13 368 ft. Using a distance adjustment of 20 times the logorithm of the propagation distance ratio, this corresponds to a 13.2-dB noise reduction. An additional noise reduction is obtained if the excess atmospheric attenuation is applied. The difference in distance is 10 444 ft. If the atmospheric attenuation from reference 5 at 70 °F and 70 percent humidity in the 3150-Hz one-third-octave band is applied, the excess attenuation is over 57 dB. The combination of the atmospheric attenuation and the distance adjustment is 70 dB. This, of course, only shows the reduction for the peak noise radiation angle from the fan. The shape of the noise directivity from this mode, that is, how much the noise decreases with angles away from the peak, will determine how much the peak noise at the measurement location will be reduced. If, for example, the noise from this mode had a very broad directivity pattern, decreasing only 1/2 dB per degree away from the peak, the noise of the fan with the 0.8 Mach number inlet would be down 16 dB at the airplane location where the peak noise radiation had occurred for the fan with the 0.3 Mach number inlet. This 16 dB is then the probable noise reduction that could be realized by the change in directivity resulting from the increase in the inlet Mach number from 0.3 to 0.8.

The combined reductions that occur from attenuation and directivity shifts indicate a significant noise reduction potential for the high Mach number inlet. The additional weight of such an inlet and the complexities of operation are negative factors that have to be considered. However, the potential noise reduction appears large enough that this type of inlet should be considered for future low noise fan engines.

CONCLUDING REMARKS

The conventional approach to reducing fan perceived tone noise is to lower the tip speed of the device. This low-speed fan would have a low number of rotor blades and enough stator vanes to achieve cut-off conditions for the blade passing tone resulting from rotor-stator interaction. The potential of some alternative approaches for reducing fan tone noise have been investigated in this study. In particular, two approaches were discussed and evaluated. The first increases the number of rotor blades to move the tone noise into higher frequencies that are not weighted as strongly by the perceived noise scale. This fan had a small number of long-chord stator vanes, which, although this results in propagating duct modes, would reduce the stator response and act to lower rotor-stator interaction noise. To evaluate the future noise reduction potential of the conventional and alternative approaches, the noise reductions from a cut-on baseline fan with 53 rotor blades and 90 stator vanes were calculated. In this paper study the noise reduction potential of both the conventional and alternative fan designs were evaluated with fan designs that are presently beyond current capability. In particular, the conventional fan potential was evaluated for a fan tip speed lower than what is currently practical from a stall margin standpoint, and the alternative fan was evaluated with blade numbers that result in aspect ratios higher than current metals would permit.

The conventional low-speed fan had 20 rotor and 44 stator blades. With the expected noise reduction from the low tip speed and an expected blade-passing-tone reduction of 8 dB from cut-off this fan showed an 8.6 PNdB reduction from the baseline fan. (When the blade passing tone were completely removed by cut-off, 9.1 PNdB was calculated.) An alternative fan with 80 blades and the practically observed reduction from the long-chord stators showed a noise reduction of 6.9 PNdB from the baseline fan. A 106-bladed alternative fan with the practically observed reduction from the long-chord stator vanes showed a reduction of 10.4 PNdB from the baseline fan. This indicates that the alternative fan approaches have as large as if not a larger noise reduction potential for fan tone noise than does the conventional low-blade-number, low-speed approach.

The alternative fan has other noise reduction potential that was not specifically evaluated in these calculations. These included more atmospheric attenuation, reduced rotor alone noise, and additional space for acoustic treatment and active noise control on the long-chord stators. For these reasons the noise reduction possible from the alternative fan may even be greater than indicated from the basic calculations done in this report.

The second noise reduction approach investigated the potential of a high Mach number inlet both for the noise attenuation and for the change in noise radiation angle resulting from the higher inlet velocity. A check of the literature showed that inlet duct sound power noise reductions from 17 to over 30 dB were obtainable by the use of inlets with an average throat Mach number of 0.80 to 0.85.

In addition to the noise attenuation, a change in noise directivity was also shown to reduce the observed noise. As the inlet Mach number is increased, the radiation angle of the inlet noise moves closer to the axis of the fan. In an example, a reduction in takeoff noise of over 15 dB was calculated. A high Mach number inlet would therefore have a significant effect on the inlet radiated tone noise.

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TABLE I. — DESCRIPTIONS OF FANS EVALUATED

[1.5 pressure ratio; 6-ft fan diameter; inlet duct Mach number, 0.3.]

Concept	Fan	Rotor blade number	Stator blade number	Tip speed, ft/sec	Descriptive features
Baseline	B	53	90	1100	Baseline fan, cut-on, stator chord = 2.67 in.
Conventional	C1	53	112	1100	Increased stator number to achieve cut-off. Practical value of 8-dB reduction of BPT.[a]
		53	112	1100	Increased stator number to achieve cut-off. Complete removal of BPT.
	C2	20	~30	800	Reduced speed, low blade number. 6-dB reduction all tones, cut-on.
	C3	20	44	800	Reduced speed, low blade number 6-dB reduction for all tones. Cut-off, 8-dB practical reduction of BPT.
		20	44	800	Reduced speed, low blade number, 6-dB reduction for all tones. Cut-off, complete removal of BPT.
	C4	53	112	800	Reduced speed, no reduction in blade number; 6-dB reduction for all tones. Cut-off, 8-dB practical reduction of BPT.
		53	112	800	Reduced speed, no reduction in blade number; 6-dB reduction for all tones. Cut-off, complete removal of BPT.
Alternative	A1	80	~90	1100	Increased rotor blade number to reduce annoyance. No effect of long chord stators.
	A2	106	~90	1100	Increased rotor blade number to reduce annoyance. No effect of long chord stators.
	A3	80	14	1100	Increased rotor blade number to reduce annoyance. Stator chord = 24 in. One half of predicted long-chord stator reduction.
		80	14	1100	Increased rotor blade number to reduce annoyance. Stator chord = 24 in. Full long chord stator reduction.
	A4	106	14	1100	Increased rotor blade number to reduce annoyance. Stator chord = 24 in. One half of predicted long-chord stator reduction.
		106	14	1100	Increased rotor blade number to reduce annoyance. Stator chord = 24 in. Full long-chord stator reduction.

[a] Blade passing tone.

TABLE II. - PERCEIVED NOISE LEVELS OF VARIOUS FAN CONFIGURATIONS

(a) Conventional noise reduction

Harmonic, $n \times$ BPF		Fan[a]							
		B (baseline fan)	C1		C2	C3		C4	
			Reduced BPT[b]	Removed BPT		Reduced BPT[b]	Removed BPT	Reduced BPT[b]	Removed BPT
		Blade passing frequency, BPF, Hz							
		3000	3000		800	800		2180	
1	SPL; noy	100; 134	92; 77.2	0; - -	94; 42.2	86; 24.3	0; - -	84; 36.1	0; - -
2	SPL; noy	97; 94.9	97; 94.9	97; 94.9	91; 51.0	91; 51.0	91; 51.0	91; 72.0	91; 72.0
3	SPL; noy	94; [c]51.0, 41.5	94; [c]51.0,41.5	94; [c]51.0,41.5	88; 54.7	88; 54.7	88; 54.7	88; 51.0	88; 51.0
4	SPL; noy	(d)	(d)	(d)	85; 47.6	85; 47.6	85; 47.6	85; 33.7	85; 33.7
5	SPL; noy	(d)	(d)	(d)	82; 38.7	82; 38.7	82; 38.7	82; 22.3	82; 22.3
6	SPL; noy	(d)	(d)	(d)	79; (e)	79; (e)	79; (e)	(d)	(d)
7	SPL; noy	(d)	(d)	(d)	76; [e]33.0	76; [e]33.0	76; [e]33.0	(d)	(d)
8	SPL; noy	(d)	(d)	(d)	73; (e)	73; (e)	73; (e)	(d)	(d)
9	SPL; noy	(d)	(d)	(d)	70; [c,e]19.4	70; [c,e]19.4	70; [c,e]19.4	(d)	(d)
10	SPL; noy	(d)	(d)	(d)	67; (e)	67; (e)	67; (e)	(d)	(d)
11	SPL; noy	(d)	(d)	(d)	67; [e]12.8	67; [e]12.8	67; [e]12.8	(d)	(d)
12	SPL; noy	(d)	(d)	(d)	61; (e)	61; (e)	61; (e)	(d)	(d)
13	SPL; noy	(d)	(d)	(d)	58; (e)	58; (e)	58; (e)	(d)	(d)
14	SPL; noy	(d)	(d)	(d)	55; [e]6.2	55; [e]6.2	55; [e]6.2	(d)	(d)
PNdB		113.4	109.7	107.7	105.3	104.8	104.3	105.5	104.6
ΔPNdB from baseline		- - -	4.3	5.7	8.1	8.6	9.1	7.9	8.8

[a] See table I for fan descriptions.

[b] Practical reduction of blade passing tone (BPT), 8 dB.

[c] Tone split between two one-third octave bands.

[d] Frequency above rated range.

[e] More than one tone in the band. The highest harnmonic has the noy value.

TABLE II. - PERCEIVED NOISE LEVELS OF VARIOUS FAN CONFIGURATIONS
(b) Alternative noise reduction

Harmonic, $n \times$ BPF		Fan[a]						
		B	A1	A2	A3		A4	
					Long-chord stator noise reduction (theoretical)			
					Half	Full	Half	Full
		Blade passing frequency, BPF, Hz						
		3000	4500	6000	4500		6000	
1	SPL; noy	100; 134	100; [c]109,102	100; 117	95; [c]77.2, 72.0	90; [c]54.7, 51.0	94.25; 78.6	88.5; 54.7
2	SPL; noy	97; 94.9	97; [c]62.7, 51.0	(d)	92.25; [c]45.2, 36.7	87.5; [c]32.1, 26.5	(d)	(d)
3	SPL; noy	94; [c]51.0, 41.5	(d)	(d)	(d)	(d)	(d)	(d)
4	SPL; noy	(d)	(d)	(d)	(d)	(d)	(d)	(d)
5	SPL; noy	(d)	(d)	(d)	(d)	(d)	(d)	(d)
6	SPL; noy	(d)	(d)	(d)	(d)	(d)	(d)	(d)
7	SPL; noy	(d)	(d)	(d)	(d)	(d)	(d)	(d)
8	SPL; noy	(d)	(d)	(d)	(d)	(d)	(d)	(d)
9	SPL; noy	(d)	(d)	(d)	(d)	(d)	(d)	(d)
10	SPL; noy	(d)	(d)	(d)	(d)	(d)	(d)	(d)
11	SPL; noy	(d)	(d)	(d)	(d)	(d)	(d)	(d)
12	SPL; noy	(d)	(d)	(d)	(d)	(d)	(d)	(d)
13	SPL; noy	(d)	(d)	(d)	(d)	(d)	(d)	(d)
14	SPL; noy	(d)	(d)	(d)	(d)	(d)	(d)	(d)
PNdB		113.4	111.4	108.7	106.5	101.5	103.0	97.7
ΔPNdB from baseline		- - -	2.0	4.7	6.9	11.9	10.4	15.7

[a] See table I for fan descriptions.

[b] Practical reduction of blade passing tone (BPT), 8 dB.

[c] Tone split between two one-third octave bands.

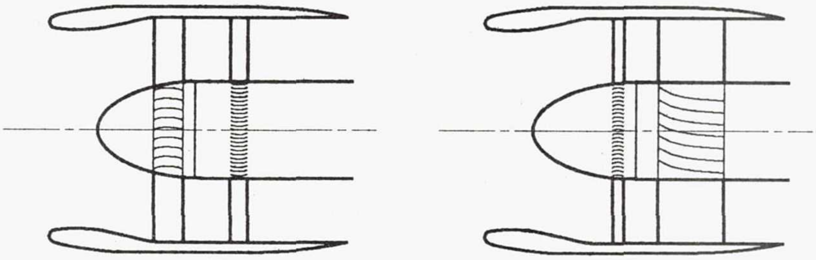
[d] Frequency above rated range.

[e] More than one tone in the band. The highest harnmonic has the noy value.

TABLE III. — MODE PRIMARY SIDELINE ANGLES AS FUNCTIONS OF CUT-OFF RATIO AND INLET MACH NUMBER

[$M_\infty = 0.2$]

Cut-off ratio, ξ	Inlet duct Mach number									
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
	Sideline angle, deg									
1.00	101	96	90	84	78	71	63	55	45	32
1.01	93	88	82	76	70	64	57	49	40	28
1.02	90	85	79	73	67	61	54	46	38	26
1.03	88	82	76	71	65	58	52	44	36	25
1.04	86	80	74	69	63	57	50	43	35	24
1.05	84	78	73	67	61	55	49	42	34	24
1.10	77	71	66	60	55	49	43	37	30	21
1.15	71	66	61	56	51	45	40	34	27	19
1.20	67	62	57	52	47	42	37	31	25	17
1.25	63	58	54	49	44	40	35	29	23	16
1.30	60	55	51	46	42	37	33	28	22	15
1.40	55	51	46	42	38	34	29	25	20	14
1.50	51	46	42	38	35	31	27	23	18	12
1.60	47	43	39	36	32	28	25	21	17	11
1.70	44	40	37	33	30	26	23	19	15	11
1.80	41	38	34	31	28	25	21	18	14	10
1.90	39	36	32	29	26	23	20	17	14	9
2.00	37	34	31	28	25	22	19	16	13	9
2.50	29	27	24	22	19	17	15	13	10	7
3.00	24	22	20	18	16	14	12	10	8	6
3.50	21	19	17	15	14	12	10	9	7	5
4.00	18	16	15	13	12	10	9	8	6	4
4.50	16	14	13	12	11	9	8	7	5	4
5.00	14	13	12	11	9	8	7	6	5	3
6.00	12	11	10	9	8	7	6	5	4	3
7.00	10	9	8	8	7	6	5	4	3	2
8.00	9	8	7	7	6	5	4	4	3	2
9.00	8	7	7	6	5	5	4	3	3	2
10.00	7	6	6	5	5	4	4	3	2	2
15.00	5	4	4	4	3	3	2	2	2	1
20.00	4	3	3	3	2	2	2	2	1	1



Conventional method

- Low tip speed
- Low number of rotor blades
- Stator vane number chosen to achieve cut off

Alternative method

- High number of rotor blades to shift tones to low perceived noise range
- Low number of long chord stator vanes to reduce stator response and interaction noise

Figure 1.—Noise reduction concepts.

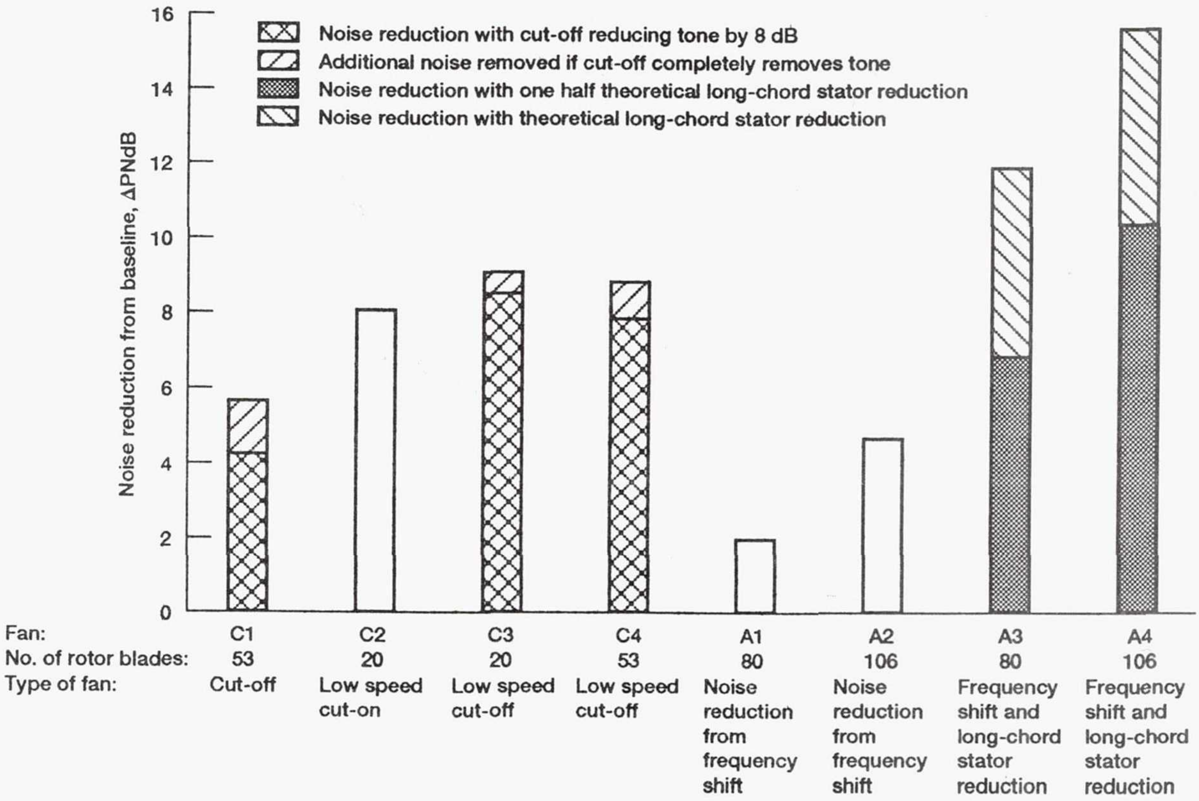
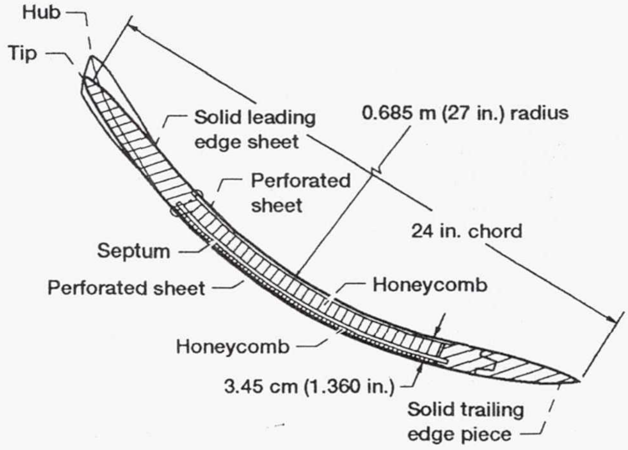
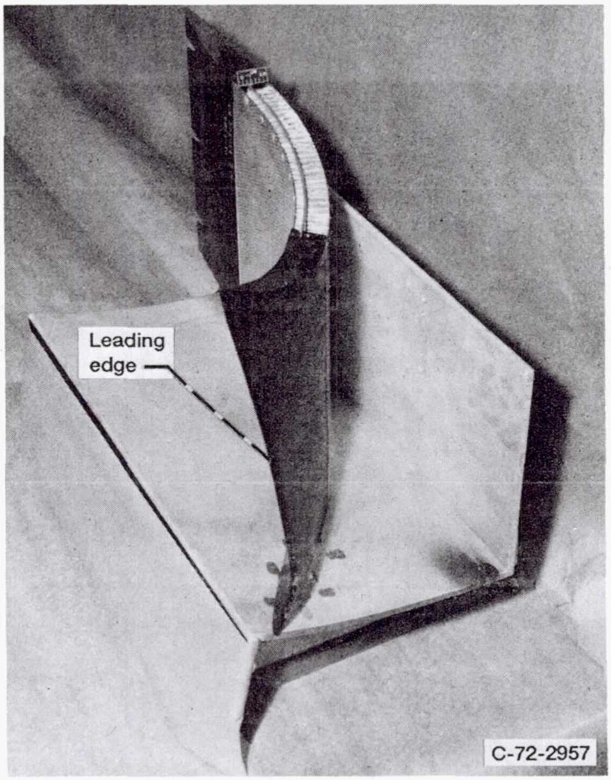


Figure 2.—Summary of noise reductions.



(a) Cross-sectional sketch.



(b) Stator on work table.

Figure 3.—Long-chord stator.

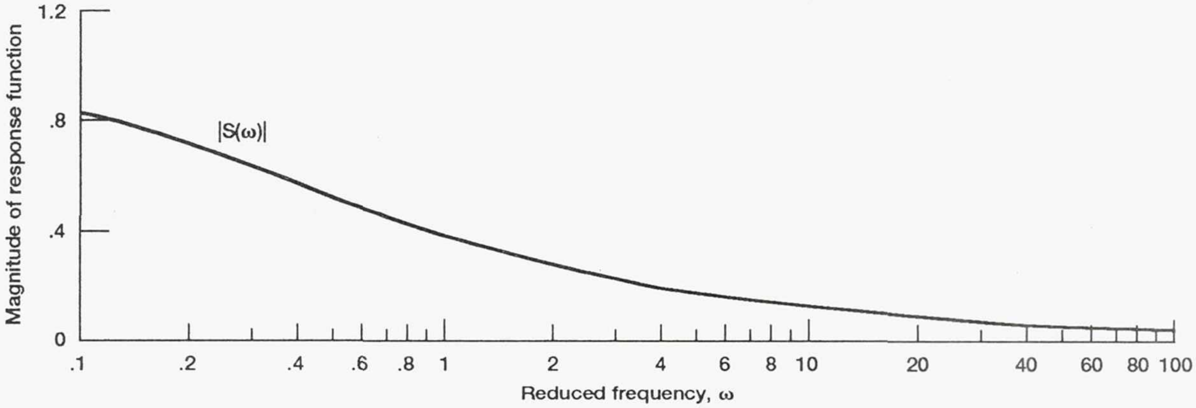


Figure 4.—Change in magnitude of response function with reduced frequency.

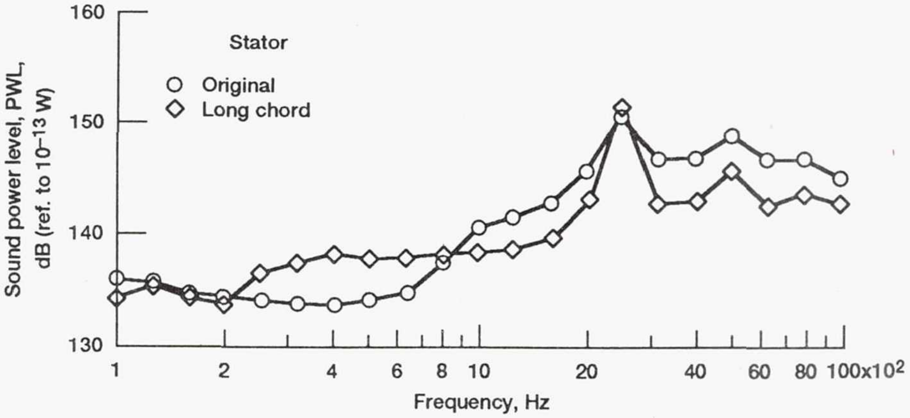


Figure 5.—Comprison of acoustic power spectra for long-chord stator and original stator at 80 percent speed.

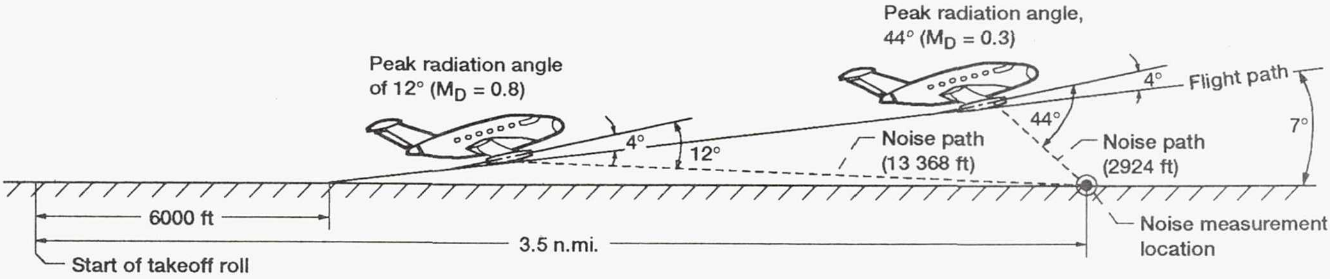


Figure 6.—Airplane locations along flight path for peak radiation angle intersection with noise measurement location. (Not to scale.)

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13. ABSTRACT *(Maximum 200 words)*

The potential of two alternative approaches for reducing fan tone noise was investigated in this study. One of these approaches increases the number of rotor blades to shift the tone noise to higher frequencies that are not rated as strongly by the perceived noise scale. This alternative fan also would have a small number of long chord stator vanes which would reduce the stator response and lower rotor-stator interaction noise. Comparison of the conventional and alternative fan concepts showed that this alternative approach has as large or larger a perceived.tone noise reduction potential as the conventional approach. The other alternative, a high Mach number inlet, is evaluated both for its noise attenuation and for its change in noise directivity.

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