N73 25831

NASA TECHNICAL MEMORANDUM

NASA TM X-68253

NASA TM X-68253

NOISE FROM TURBOMACHINERY

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TECHNICAL PAPER proposed for presentation at
Fifth Aircraft Design, Flight Test and Operations Meeting
sponsored by the American Institute of
Aeronautics and Astronautics
St. Louis, Missouri, August 6-8, 1973

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E-7529

Abstract

This paper reviews turbomachinery noise from turbofan engines as typified by fan noise. The mechanisms and theories of fan noise are reviewed and concepts for its reduction, including acoustic suppression are discussed. Correlations of the overall noise data from several full-scale fans tested at NASA-Lewis Research Center are presented as indicative of the current state-of-the-art. Estimates are presented to show economics versus reduced noise for two quieted experimental engines, one with subsonic and one with supersonic fan tip speed. Finally, some concepts that may have the potential to reduce fan noise are indicated.

Introduction

The prominent noise benefit with high bypass ratio engines such as the JT9D, CF6, and RB211 has been the reduced jet noise resulting from lower jet exhaust velocities. The dominant noise from these engines is produced by the turbomachinery rather than by the jet. The turbomachinery components involved are the fan stage, compressor and the turbine. Of these, the noise from the fan stage is clearly dominant at present. Turbine noise has been identified in narrowband spectra, but it contributes little to annoyance, generally, until the fan noise has been suppressed. The compressor has not been generally identified as a significant source of noise. Since the fan stage is the primary source of turbomachinery noise, it naturally has received the major research emphasis. It is probable, however, that the factors related to fan noise apply equally well to the compressor and perhaps, in large measure, also to the turbine.

Since the turbomachinery noise is generated internally, there is the opportunity to suppress it, for example, by the use of acoustically absorbing surfaces within the nacelle. It is also possible to address turbomachinery noise at the source by selection of appropriate design parameters and configurations.

This paper reviews the status of turbomachinery noise generation and control. For the reasons stated above, most of the information has been obtained from fan noise research. A significant portion of the paper is devoted to presenting the accepted noise generation mechanisms and to the currently used noise reduction concepts as related to the theory. The prediction of fan noise is illustrated by correlations of the data from full-scale fan tests. These correlations show the dependence of overall noise on fan overall performance parameters for subsonic-tip-speed single-stage fans. Trend curves are also presented for supersonic tip speed, single-stage fans and for two-stage fans.

Data are presented to illustrate the effectiveness of acoustic suppression in reducing fan noise. From these data, estimates of the economic penalty associated with noise suppression were made by the General Electric Company for two advanced technology engines, one having a subsonic tip speed and the other a supersonic tip speed fan. Finally, some newer or incompletely evaluated noise reduction concepts are presented.

Noise Fundamentals

Source Noise Characteristics

The spectral characteristics of fan noise depend on whether the stage operates with subsonic or supersonic tip speed as shown by the narrowband spectra of figure 1. At subsonic tip speeds, shown by the upper spectrum, the signature is dominated by tones at the blade-passing frequency and its harmonics. Underlying the tones is a spectrum of noise characterized as broadband in nature.

At supersonic tip speeds, shown by the lower spectrum, the signature is dominated by a multiplicity of tones occurring at multiples of the shaft rotational frequency and called, appropriately, multiple-pure tones. The blade-passing tone is the Bth one of these tones, where B is the number of blades in the fan rotor. In this spectrum, the broadband contribution is generally taken as the lower edge of the trace.

These two spectra display the reasons for the characteristic description of turbofan engine noise. The whine of the engine on landing when fan tip speed is subsonic is due to the prominent blade-passing tone. At takeoff, when the tip speed is supersonic, the buzz-saw sound is due to the multiplicity of tones covering a broad range of frequencies.

Noise Generation in Turbomachinery

There has been in recent years a considerable effort by researchers to understand and describe the origin of and factors influencing the generation and propagation of sound from rotating machinery. Several excellent review papers have appeared in the last year or so that address this research.[1-5] The discussion presented in this paper has drawn upon these and other references.

The requirements generally accepted as needed to generate the far-field spectra of figure 1 depend, as the spectra did, on the tip speed level of the fan. For the discrete tone and broadband noise of the subsonic tip-speed fan, these are a source of unsteady flow and an interaction mechanism producing the pressure fluctuations that can propagate as sound. For a subsonic rotor, an additional requirement is that the sound be produced in modes that will propagate. This point will be discussed subsequently.

For subsonic rotors, the sources of unsteady flow are illustrated in figures 2 and 3 for periodically and randomly unsteady flow, respectively. The periodic flow sources are from blade wakes and nonuniform inlet flows. While these flows are not periodic in the reference frame in which they are generated, they lead to unsteady periodic flows in the reference frame of the downstream blade row. The downstream blade row is the stator in the case of the rotor wakes and the rotor in the case of nonuniform inlet flow or inlet guide vanes.

The randomly unsteady flows are associated with turbulence that may enter the inlet or is generated in wall or blade boundary layers or in the blade wakes. Two other sources suggested in reference 4 are from leakage and secondary flows at the rotor blade tips.

There are several interaction mechanisms or models that have been proposed to describe the conversion of unsteady flows to sound. First is the dipole model that relates sound to the fluctuating forces on the rotor or stator blades resulting from the unsteady flow. This model has received a great deal of emphasis in the literature. The original application was made by Gutin for an isolated rotor or propeller.[6] Later a theory was formulated by Tyler and Sofrin to describe the propagation, in a duct, of tones generated by wake interaction.[7] The first noise estimates due to fluctuating blade forces caused by wake interaction seem to have been made by Hetherington[8] who utilized the theory for unsteady lift developed by Kemp and Sears.[9]

The quadrapole model that has recently appeared in the literature relates sound to the fluctuating Reynolds stresses in the flow.[1,10] In this model, Reynolds stresses rotating with the rotor, like rotating blade forces, produce sound.

The last model is not really a model, but rather an approach wherein the coupled unsteady flow field and acoustic equations are solved either analytically or numerically. The advantage of this approach is that it combines the flow and acoustic fields in a single calculation in which the effect of fluid compressibility on the fluctuating blade forces is taken into account. Analyses using this approach are found, for example in references 5, 11, and 12.

For the supersonic tip-speed fan, the multiple-pure tones arise from the rotating pattern of shock waves on the rotor blade leading edges. Because of manufacturing variations from blade to blade, the amplitudes of the shocks vary from blade to blade. Forward of the fan, stronger shocks overtake and coalesce with weaker shocks. The resulting irregular pattern rotating with the fan leads to a series of tones in the spectrum at multiples of the shaft rotation frequency. At supersonic tip speed, propagation of these waves is assured. This noise is discussed in several recent papers.[13-15]

Fluctuating Lift from Wake Interactions

A key part of the dipole model is the determination of fluctuating blade forces induced by unsteady flow. An important case, considered to be a primary source for tone noise, is wake interaction with a downstream blade row. The situation analyzed is illustrated in figure 4 by rotor wakes interacting with downstream stators.

The velocity diagram in the figure shows how the mean velocity V_2 with wake velocity amplitude V_o in the rotor plane appears in the reference frame of the stators. The wake appears to the stators as a fluctuation in inlet angle of attack ($\bar{\beta}_2$) and in velocity U_2. For the diagram shown, a decrease in stator inlet velocity results in an increase in stator angle of attack. Since the stator lift force increases with both increasing angle of attack and inlet velocity, it can be seen that for the case considered these two parameters act in opposition with respect to the lift force.

The velocity fluctuations in the wake as seen by the stator can be resolved into components transverse and parallel to the stators. The induced lift fluctuation caused by passage of the wakes is not in general quasi-steady, but rather has a dynamic response that depends on a reduced frequency parameter given by the ratio of stator chord length to wave length of the wake gusts (spacing between wakes).

The theory of Kemp and Sears,[9] mentioned earlier, considered the dynamic response of a thin isolated airfoil to a sinusoidal transverse gust in incompressible flow. Subsequently, Horlock[16] analyzed the response for a parallel gust. Still later papers have considered the effects of blade cascading[17] and camber[18] in incompressible flow and cascades in compressible flow.[19]

The following expression for the fluctuating lift $\tilde{L}$ from rotor wakes interacting with a downstream stator now was employed in reference 20.

$$\tilde{L} = \pi\rho U_2 V_o e^{i\nu t}\left[S(\omega)\sin(\beta_2 + \bar{\beta}_2) - \alpha T(\omega)\cos(\beta_2 + \bar{\beta}_2)\right] \tag{1}$$

where $S(\omega)$ and $T(\omega)$ are the response functions derived by Kemp-Sears[9] and Horlock,[16] respectively, and ω is the reduced frequency parameter described previously. The velocities and angles are represented in figure 4.

The magnitude of the Kemp-Sears response function, S, is shown in figure 5 as a function of reduced frequency, ω. It can be seen that as the reduced frequency is increased the magnitude S decreases. The analysis thus suggests that increasing the stator chord to increase the reduced frequency will result in a smaller lift fluctuation and thus less noise due to the interaction. The Horlock function $T(\omega)$, behaves similarly as a function of reduced frequency.

The fluctuating lift expression, equation (1), also suggests that there may be an optimum angle of attack, α, of the stator vanes where the response to the parallel gust component T, will tend to cancel the response to the transverse gust component S. The blade setting requirement to minimize the fluctuating lift may compromise the setting for minimum aerodynamic loss or stall margin, and thus as a practical consideration, limit the degree of cancellation.

The wake decay expression used in reference 20 was obtained from cascade data and is given by:

$$\frac{V_o}{V_1} = \frac{1.6\sqrt{C_D}}{\left(\frac{X}{C_R} + 0.25\right)^{1/2}} \qquad (2)$$

The velocities and dimensions in this relation are shown in figure 4. The quantity C_D is the rotor blade drag coefficient. This relation suggests that the concept of noise reduction by increased rotor-stator separation is related to the additional wake decay and the associated reduction of the fluctuating lift force.

The Tyler-Sofrin Cutoff Theory

This discussion of theory cannot be complete without a description of the conditions that determine whether rotor-stator interaction noise will propagate or decay within the fan duct. In a fan stage, the number of stator vanes generally is not equal to the number of rotor blades (e.g., fig. 4), so that, as the rotor wakes propagate across the stator, there is a sequential phasing of the interactions that sweeps circumferentially around the vane array. If this sequence of interaction events sweeps the circumference at subsonic speed, the sound field is cut off and does not propagate. Conversely, if it sweeps the circumference at supersonic speed, it is not cut off and will propagate. Tyler and Sofrin[7] have shown that cutoff can be achieved by proper selection of the number of blades B and number of vanes V. In general,

$$\left(\frac{nB}{nB + KV}\right) U_t < C$$

is required for cutoff where n is the harmonic number, K is an integer taking all positive and negative values, U_t is the fan tip speed, and C is the speed of sound.

For cutoff of the blade-passing frequency tone ($n = 1$), the vane number must be slightly more than twice the blade number. While this number of vanes can be selected for cut off of the fundamental tone, the higher harmonics would not be simultaneously cut off. In general, the vane number required for cutoff is a little greater than twice nB. Cutoff for the highest harmonics ($n = 2, 3$, etc.) would lead to a very large number of long thin stator vanes for the rotor blade numbers typically employed.

Many fan stages are designed for cutoff of the fundamental fan tone. Yet, as pointed out earlier, this tone often appears quite prominently in measured far-field noise spectra. Thus, some mechanism other than rotor wake-stator interaction must be present. A possible mechanism is thought to be inlet flow disturbances interacting with the rotor.

Current Design Concepts for Noise Reduction

The noise reduction concepts in recent state-of-the-art single-stage fan designs are derived from the results of the theories that have been just discussed. These are: (1) the elimination of inlet guide vanes; (2) wide axial spacing between rotor and stator; and (3) selection of rotor blade and stator vane number to provide cutoff of blade passage tones due to wake interaction.

The noise benefits derived from these features depend on the particular fan stage. Thus the benefit of increased rotor-stator spacing has ranged from about 3 to 6 dB for each doubling of the spacing. A spacing of at least two rotor chord lengths has been used for noise purposes. Similarly, the noise benefit associated with cutoff appears to be 3 to 4 dB. If the noise due to inlet guide vane-rotor interaction were equal to that due to rotor-stator interaction, then the removal of inlet guide vanes would decrease the noise about 3 dB. To our knowledge, there are no published experimental results concerning this effect.

Modern high bypass ratio engines such as the JT9D, CF6, and RB211 employ these noise reduction concepts. NASA-Lewis has tested eight full-scale fan stages incorporating one or more of these features. Correlations of the overall noise from these fans will be presented in the next section. These fans generate noise levels as low as any known to the writers.

It remains to consider the impact of these noise reduction features on the aerodynamic and mechanical design of the fan. The removal of inlet guide vanes, for example, means that the fan must be cantilevered forward of its support bearing. The wide rotor-stator spacing adds length and weight to the stage. Additionally there is some evidence that an increase in rotor-stator spacing from one to four rotor chords reduces fan-stage efficiency by about 1 percentage point.

Meeting the cutoff criteria requires a large number of stator vanes, resulting in vanes with high aspect ratio that could lead to flutter problems requiring the use of midspan dampers. The high aspect ratio vanes also have encountered stall margin problems due to decreased stator range. In one instance, an increase in stator aspect ratio from 3 to 4.1 (stator number increased from 50 to 64) resulted in a decrease in stall margin from 16 to 7 percent.

Fan Noise Comparisons and Correlations

Fan Type

In this section, comparisons are made for a number of fan stages including single stage fans with subsonic and supersonic tip speeds and two-stage fans. The single-stage data are largely obtained from stages having the low noise features described earlier. The conventional, two-stage fan data were derived largely from low bypass engines used on current narrow-body aircraft. The fan stages on these engines employ inlet guide vanes and closely-spaced stage elements and are probably noisier than present-day designs would be.

The data are shown in figure 6 where perceived noise is plotted against fan stage pressure ratio at the thrust level and speed for each fan or engine corresponding to the takeoff condition. The data have been adjusted to show the maximum sideline perceived noise level from a 1000-foot flyover and at a total thrust of 90 000 pounds. The trends are represented by bands about 4 PNdB wide to reflect the uncertainty of the estimates. The band shown for low noise, two-stage fans represents an estimate of the noise level that might be achieved for two-stage fans incorporating the noise reduction features previously mentioned.

Figure 6 shows that subsonic tip speed, single-stage fans produce the lowest noise. As the required fan pressure ratio is increased, it becomes necessary to allow supersonic tip speeds or add stages to the fan, and either results in additional noise. For still higher required pressure ratios, the single-stage fan cannot be used at all. In going to a two-stage fan, existing data would predict another noise increment; however, as was discussed, if low noise features were built into the design, the resulting two-stage fan might be on a noise par approaching or equaling that of the single-stage, supersonic tip-speed fans. Efforts are currently in progress that address this question.

Subsonic Tip-Speed Fan Noise Correlations

In view of the complexity of the sources and mechanisms involved in turbomachinery noise it is not surprising that noise prediction schemes based solely on theory do not exist. Rather, prediction methods are based on a mixture of theory and empirical correlations of data. An interesting correlation has been obtained for subsonic tip speed fans from the data from full-scale fan tests at NASA-Lewis Research Center.[21] The correlation provides a method of noise prediction for fan stages that have similar designs with low-noise features. For nonsimilar designs, these data can still serve as a prediction base to be modified by a particular design feature or features.

The matrix of fans tested is shown in figure 7 where the design pressure rise of each fan is plotted at its design tip speed. Lines of constant average work coefficient, $\overline{\Delta V_\theta}/U_T$ are also shown. This parameter, given by the average turning of the air by the fan normalized by fan tip speed, is taken as a measure of average fan loading. It can be seen that a range of fan pressure ratios (work coefficient) is covered at constant fan tip speed and that a range of tip speeds (work coefficient) is covered at constant pressure ratio. Several of the fans also lie along a line of constant work coefficient. The fans represented essentially cover the range of possible tradeoffs between tip speed and loading that current aerodynamic procedures allow.

The aerodynamic design of the fans employed current state-of-the-art procedures. Specific inlet flows were of the order of 40 lb/ft^2 sec and hub-tip ratios were about one-half or slightly less. Local values of the diffusion factor were not allowed to exceed about 0.5.

Acoustic features in the designs included rotor-stator axial spacing of two or more rotor chords and elimination of inlet guide vanes. Except for the two low pressure-ratio fans, the cutoff theory of Tyler and Sofrin was employed in the selection of blade and vane numbers. The rotor blade number-tip speed combinations were such that blade-passage frequency ranged from 550 to 3200 Hz at the tip speed corresponding to takeoff thrust for the fans.

The far-field acoustic data from these fans is shown in figure 8 where the total sound power normalized to unit thrust, F, is plotted against the fan pressure rise. The data represent fan tip speeds from 60 to 90 percent, or in a few cases, 100 percent of the fan design corrected speed. For most fans, data are shown for several operating lines obtained by varying the fan exhaust nozzle area.

For the subsonic fans, a mean curve through the data given by

$$PWL = 121.9 + 10 \log F + 14 \log(PR - 1)$$

is shown. The total spread of the data about this mean curve is ±2.5 dB.

A similar plot of the data is shown in figure 9 in terms of the maximum perceived noise level on a 1000-foot sideline. The mean curve is given by

$$PNL = 62.4 + 10 \log F + 14 \log(PR - 1)$$

and the total spread is again ±2.5 dB. The functional form of this correlation is extremely useful since the parameters are those commonly used in describing the performance of a fan. From this curve, we can predict the perceived noise level of new subsonic tip-speed fans. From the appropriate data, spectral and directivity correlations also could be obtained, thus providing the necessary ingredients for far-field sound prediction.

It is interesting that the sound power correlation can be expressed in terms of the shaft horsepower and temperature rise of the fan stage to yield an expression of the same functional form but 6 dB less than found by Beranek for ventilating fans.[22] This relation is

$$PWL = 98.5 + 10 \log \Delta T + 10 \log SHP$$

while the relation derived from Beranek's formulation is

$$PWL = 104.5 + 10 \log \Delta T + 10 \log SHP$$

The difference is actually less than 6 dB between these expressions because Beranek's expression was based on rated horsepower of the drive motor which is always larger than the delivered horsepower.

The sound power correlation can also be expressed in terms of fan tip speed and diameter. In this form, the relation is

$$PWL = K + 20 \log D + 50 \log U_T$$

where K depends on the particular design parameters of the fan. Lowson[23] has obtained an expression of this same form starting from a mechanistic approach. It thus appears that the correlation has validity for predicting purposes.

It is somewhat disappointing and surprising that the fans yield a similar noise especially in terms of perceived noise. It was expected that perceived noise would be influenced considerably by locating the blade-passage tone out of the sensitive frequency range. Within the spread of the data, there were no identifiable trends that could be associated with particular fan design parameters such as loading or tip speed. The correlation parameters, thrust, and fan pressure rise, or the equivalent parameters appear to describe the noise.

Fan C, the supersonic tip-speed fan, does not fall into the correlation because of the presence of an additional noise source, leading edge shocks.

It can be seen that this fan approaches the noise levels observed for subsonic tip-speed fans as operating speed is reduced. We have not yet addressed the problem of correlating the data from this fan in any detail.

Fan Noise Suppression

Acoustic Suppression

Even with noise reduction features incorporated in the fan stage design as discussed above, fan noise can still be reduced significantly in the far field by the use of acoustic suppression. Some acoustic suppression is used in each of the three current high bypass ratio engines that have been mentioned. The benefits of acoustic suppression are illustrated by data from experimental engines A and C of the NASA Quiet Engine Program. The design procedures used for the suppressors were derived from suppressor theories, particularly for functional dependence of the variables, with levels guided by prior experimental data. The engine A fan had a subsonic tip speed while engine C had a supersonic tip speed. The spectra thus were different, particularly in the inlet radiated noise due to the substantial contribution of multiple-pure tones to the engine C spectrum.

Figure 10 shows cross-sections of these two engines with the locations of acoustic treatment. Three removable inlet splitter rings and an outer wall only section were used in the inlet on engine A. The acoustic treatment used was perforated plate over honeycomb. The main section of inlet treatment, including the splitter rings, was the hardware described in reference 24. The fan exhaust duct included wall treatment of multiple degree of freedom construction and a single-splitter ring utilizing a bulk absorber material.[25]

The inlet for engine C had four splitter rings and included a wall section designed for attenuation of multiple-pure tones. The entire construction was perforated plate over honeycomb. The fan exhaust duct was treated on the walls and had a single splitter ring, all of bulk absorber material. In addition, the flow area of the engine C fan duct was increased to give a reduced flow velocity on the theory that noise generated by flow over the surface would be reduced. It was thought that noise from this flow source might be limiting the suppressor attenuation.

Both engines had some treatment in the exhaust nozzle of the primary jet. This treatment was designed to suppress turbine blade-passing-frequency noise.

Experimental data are shown in figure 11 for both engines with and without acoustic treatment. The spectra shown were for the inlet quadrant at takeoff engine speed. The spectrum for the unsuppressed engine C shows the appreciable influence of multiple-pure-tone noise. These tones are the source of the large increment in level from about 250 to 2000 Hz for engine C relative to engine A. The engine A spectrum is characteristic of fans with subsonic tip speeds showing a strong blade-passing tone and some higher harmonics.

The suppressed spectra are quite similar and indicate attenuation of nearly all of the blade-passing tone and its harmonics, the multiple-pure tones, and considerable broadband noise. The suppressed spectral levels near the 5000 and 6000 Hz bands are associated partly with turbine tones that are more prominent for the higher speed, more highly loaded turbine of engine C. The suppression goal for engine C was to reach the level of suppressed engine A. The test data showed that this goal was achieved within about 1 PNdB at all azimuthal positions around the engine.

Impact of Acoustic Suppression on Economics

The data for engines A and C with variable suppression levels were analyzed by the General Electric Company to determine estimates of the economic penalties associated with noise suppression for engines having current state-of-the-art quiet fan designs.[26] The study was for an airplane of specified weight and range using advanced technology engines matched to the fans of either engine A or C. The results of this study are shown in figure 12 where the increment in direct operating cost is plotted against the corresponding noise reduction. The initial point on each curve is for the baseline (unsuppressed) engine. It can be observed that the engine using fan C starts at a lower relative value of DOC and at a higher noise level. Both of these results are largely a consequence of the higher fan tip speed of engine C. With the higher tip speed, fewer turbine stages and booster stages are required resulting in a shorter, lighter, and thus more economical engine. The higher noise of engine C is due to the multiple-pure tones that occur at supersonic tip speed.

In order to generate the curves of figure 12, acoustic treatment was added to the nacelle of each engine. The noise reductions and performance loss for various amounts of treatment were estimated from data obtained from tests of the two experimental engines. For each suppressed level, the relative amounts of treatment in the inlet and fan exhaust ducts were selected to balance the front and aft noise levels.

The curves show that wall treatment alone affords several PNdB of noise reduction without severe economic penalties. The somewhat greater effect of wall treatment on engine C compared to engine A reflects the observation that multiple-pure tones are more readily attenuated by wall treatment than are blade passing tones. The knee in each curve reflects the introduction of splitters in the flow path and the attendant weight and pressure-loss penalties. The curves indicate that, if very low noise is required, engine A with lower source noise is the most economical.

These curves show that source noise reduction is still highly desirable if large noise reductions are to be made without large penalties.

Noise Reduction Concepts

Source Noise

The source noise reduction features that are employed in current fan designs have been discussed relative to the generation theory and a correlation of data from fans having these features was presented. A difficulty with the correlation was its inability to point toward ways of further reducing fan source noise. There are, however, a number of other ideas that have been suggested and, in some cases, tried. In a general sense, these ideas may be related to the theory also. In particular, they appear to be aimed at dissipation of wakes before they intercept a blade row or reducing the lift response of a blade row to a disturbance.

Under wake dissipation or control are such ideas as serrations on the blade-leading edges, trailing-edge blowing, and boundary-layer trips or fences. Of these, leading-edge serrations have received the greatest attention. They were tried with marginal success in experiments with a scale-model of fan B (fig. 7) in the Quiet Engine Program, and with somewhat greater success by NASA-Ames Research Center on a 36-inch lift fan.

Under reduced lift response are ideas such as nonradial or leaned stators and long-chord stators. The leaned stators have the objective of reducing the spanwise extent of wake interaction compared to the usual extent in radially aligned stators. The long-chord stators have the objective of reducing the stator response by increasing the reduced frequency parameter appearing in the response model. Leaned stators have been tested on scale-models of fans (fig. 7) B and C of the Quiet Engine Program. For fan B, there was some reduction of tone and broadband noise, but the effect was inconclusive on fan C. They have also been explored by Ames Research Center on a 36-inch lift fan. The long-chord stator concept is currently being tested on a 6-foot fan stage at Lewis Research Center.

These source noise reduction concepts require further evaluation to determine their merit. While their intent or objective seems clear, it is not clear that just any serrations or leaned stators, for example, will produce the desired effect. Achieving the desired impact on noise by these methods is not as assured, as for example, is increasing rotor-stator axial spacing.

Suppression

There are many cases where acoustic treatment has successfully suppressed fan noise to levels that apparently represent noise floors. The need is therefore not for more suppression, but for greater suppression efficiency. Toward this end, the duct propagation theories are being extended to include factors other than attenuation, such as reflection and refraction effects. It is not known at this time how important these effects will be, but there appears to be some promise. Other areas being explored are the optimization of multiple-degree-of-freedom suppressors to improve attenuation bandwidths and lighter weight construction materials to reduce the suppressor weight penalty on performance.

For inlet noise suppression, the sonic inlet is receiving active attention. The noise reduction potential of the sonic inlet is well known. Figure 13 shows some typical data, obtained at NASA-Lewis, where noise reduction is plotted against Mach number.[27] Negligible attenuation was observed at throat Mach number less than about 0.7. As Mach number was increased from 0.7, the attenuation also increased until the facility noise floor was reached at a Mach number near 0.9. In this case, the observed reduction was about 35 dB.

Some of the design or performance problems related to the sonic inlet are also listed on figure 13. These include flow distortion effects that can lead to fan stall problems, pressure loss, mechanical complexity, and mechanisms for fast, reliable response. The mechanical problem is complicated if the inlet is to provide a high Mach number flow at both engine takeoff and approach thrust settings. This difficulty suggests a compromise wherein the suppression is obtained by a combination of high subsonic Mach number inlet flow and acoustic treatment on the inlet wall.

Shielding

The engine-over-the-wing concept has received considerable attention recently to take advantage of shielding the ground observer from noise during flyover. The wing shielding was found to be most beneficial at high frequencies. Studies reported in reference 28 for STOL application showed that engine over-the-wing noise was as much as 8 PNdB less than for under-the-wing installations. This concept is under further study.

Concluding Remarks

This paper has reviewed the current understanding of noise generation by fan stages. The principles described should also apply to compressor and turbine stages although experimental evidence, particularly for turbines, is lacking. Current design concepts for reducing fan noise have been indicated and their relation to generation theories discussed. Some indication has also been given of the impact of these concepts on aerodynamic performance and mechanical design of the fan stages.

In addition to design concepts, the effectiveness of acoustic treatment for noise reduction and its impact on engine economics has been illustrated. Although substantial reductions in fan noise have been achieved to date, there is a need to obtain these reductions with smaller economic penalty. Toward this end some potential noise reduction concepts were discussed. Clearly, there is a need for further theoretical and experimental research if we are to achieve future noise goals economically.

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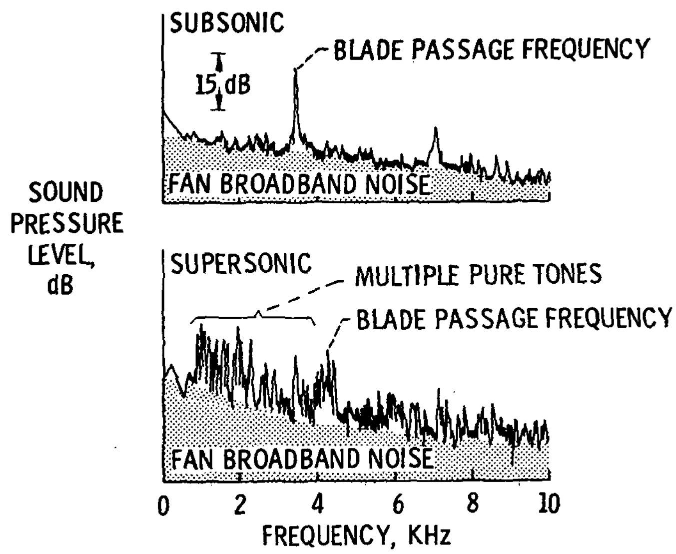

Figure 1 - Fan noise spectra at sub- and supersonic tip speeds.

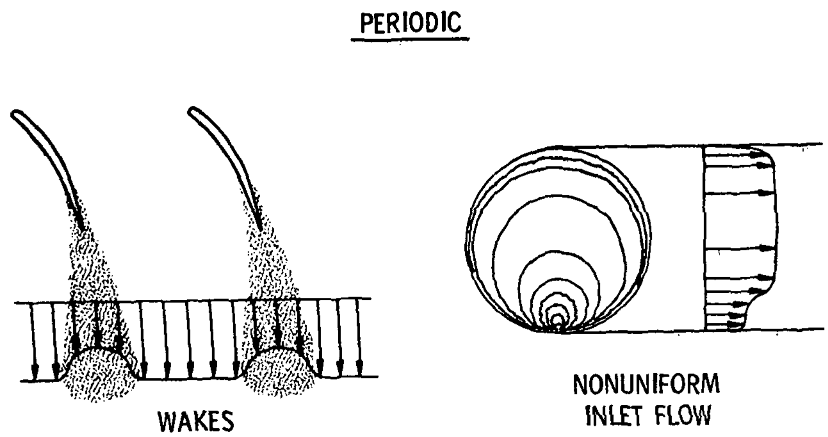

Figure 2. - Sources of "unsteady" flow.

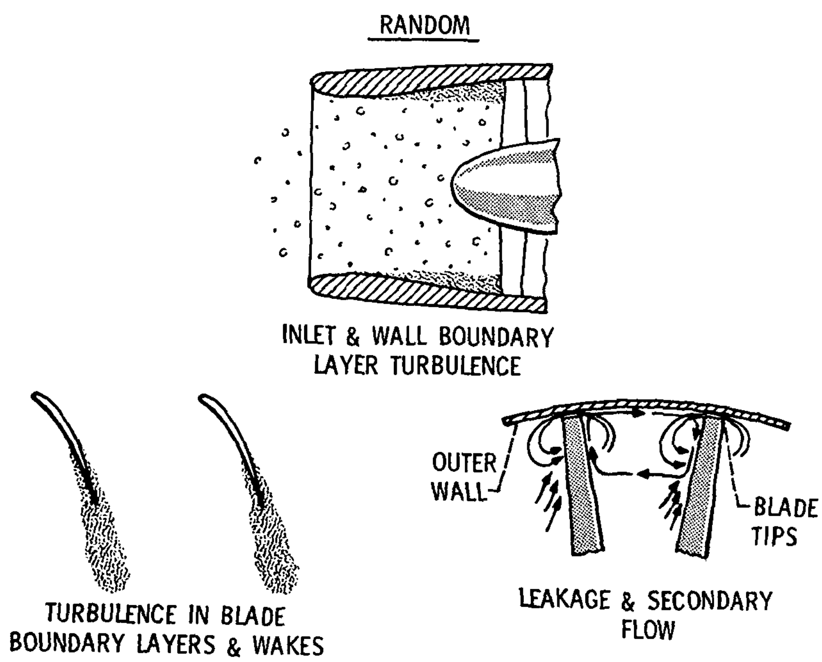

Figure 3. - Sources of "unsteady" flow.

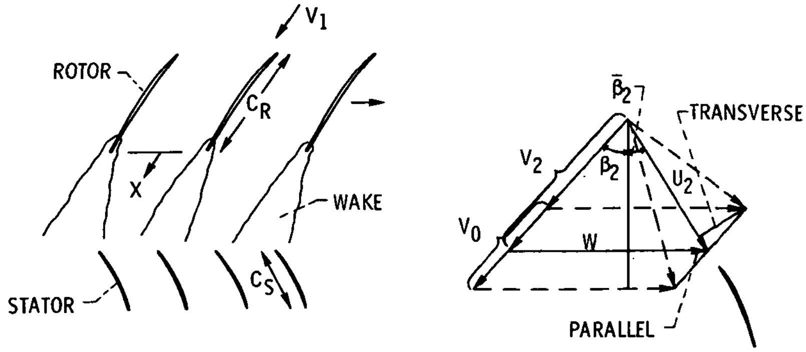

Figure 4. - Fluctuating lift from wake interaction.

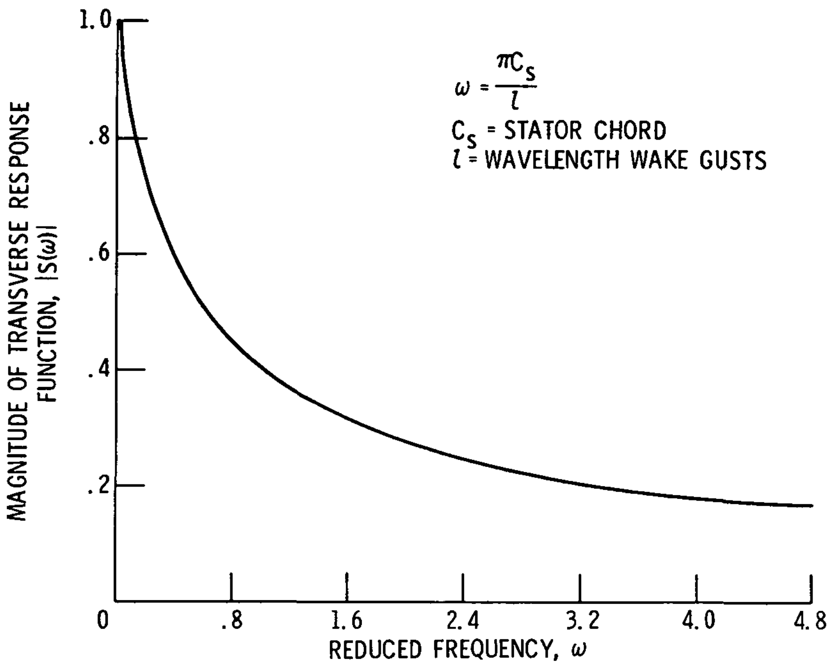

Figure 5. - Transverse response function.

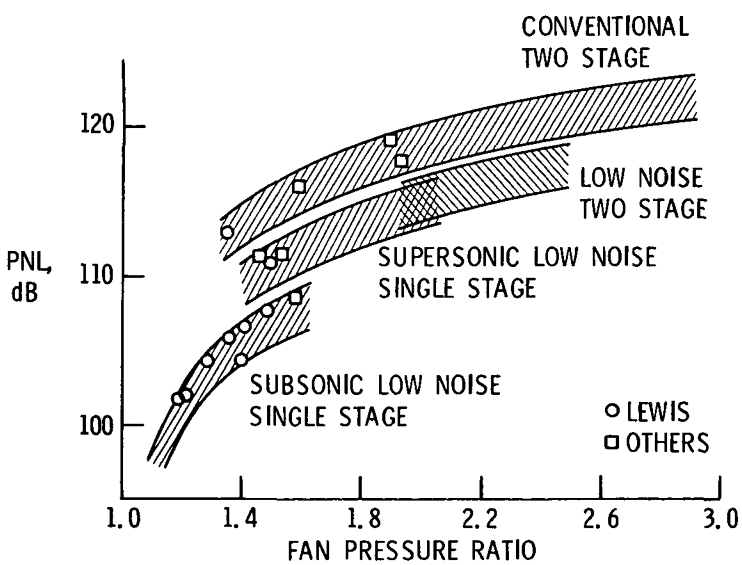

Figure 6. - Fan source noise, 90 000 pounds thrust; maximum value, 1000 ft flyover.

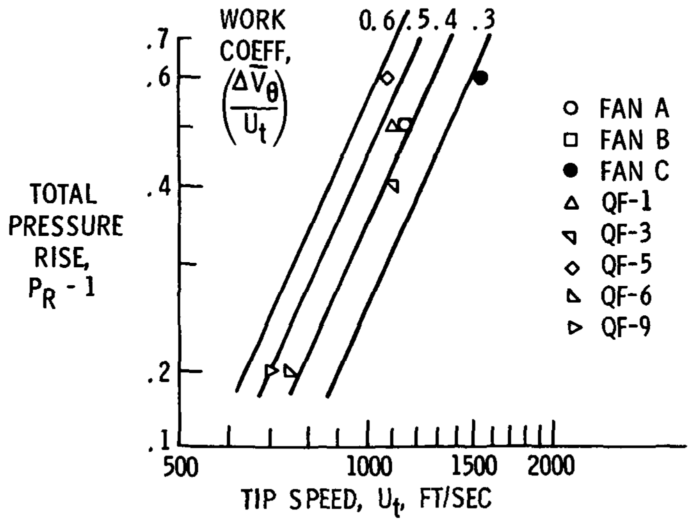

Figure 7. - Fan design parameters.

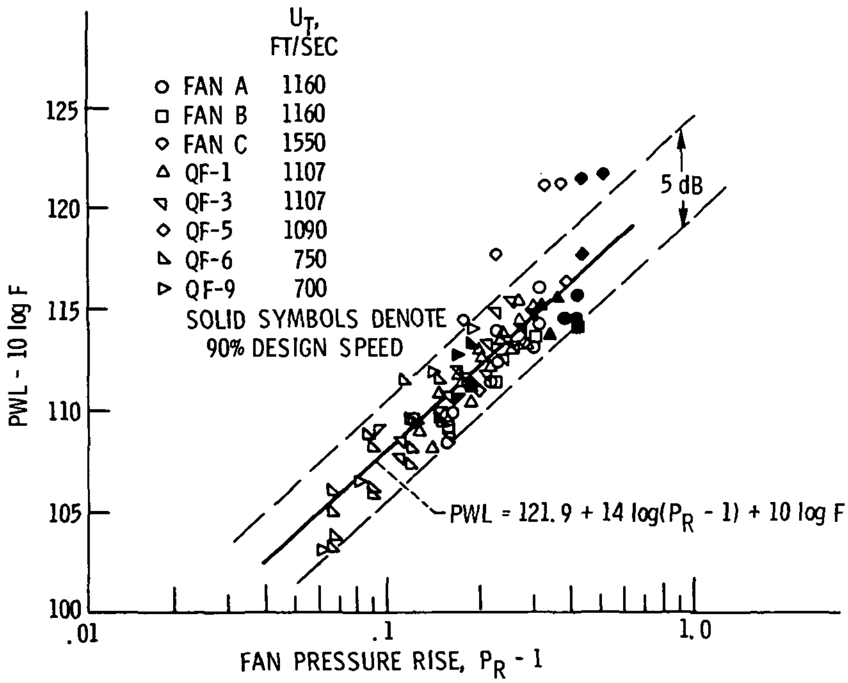

Figure 8. - Correlation of sound power from low tip speed fans.

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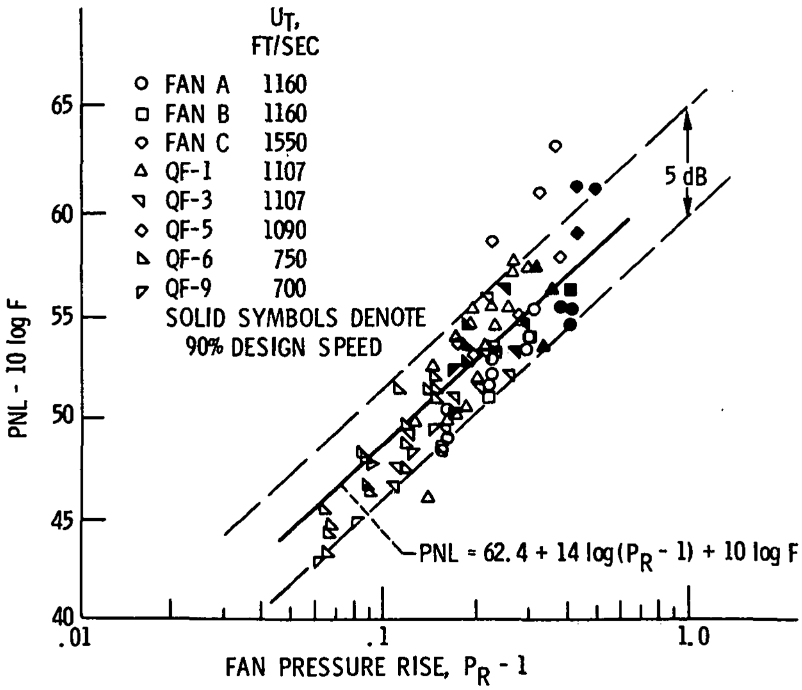

Figure 9. - Correlation of perceived noise from low tip speed fans. Maximum value, 1000-ft sideline.

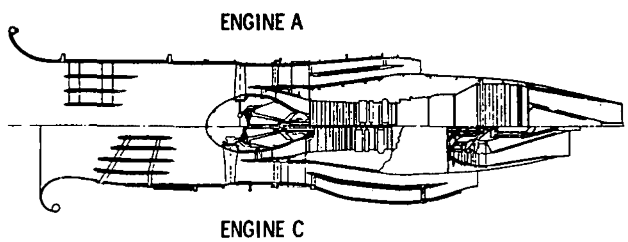

Figure 10. - NASA-GE simulated supersuppressed engine installations.

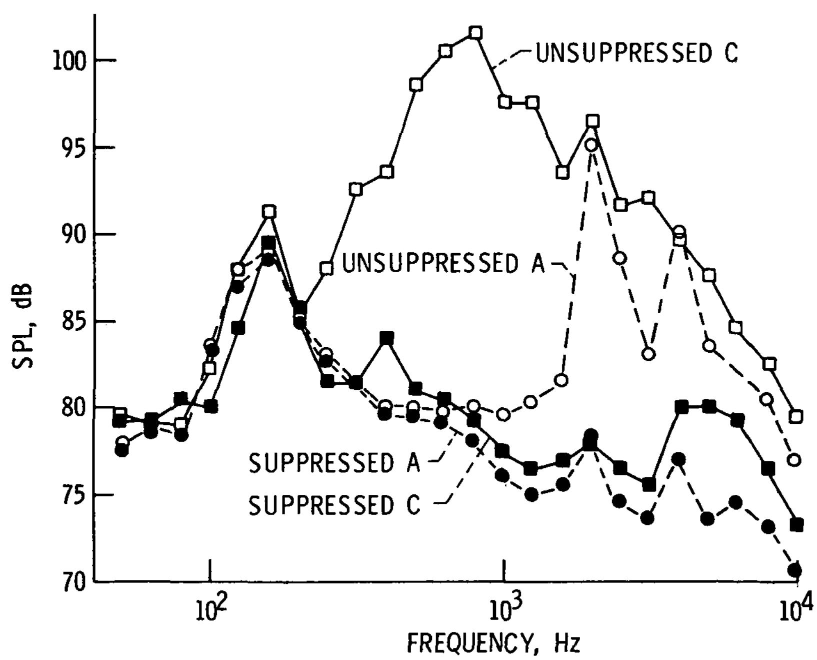

Figure 11. - Performance of acoustic suppressors. Engine inlet spectra 50°, takeoff 200 ft sideline.

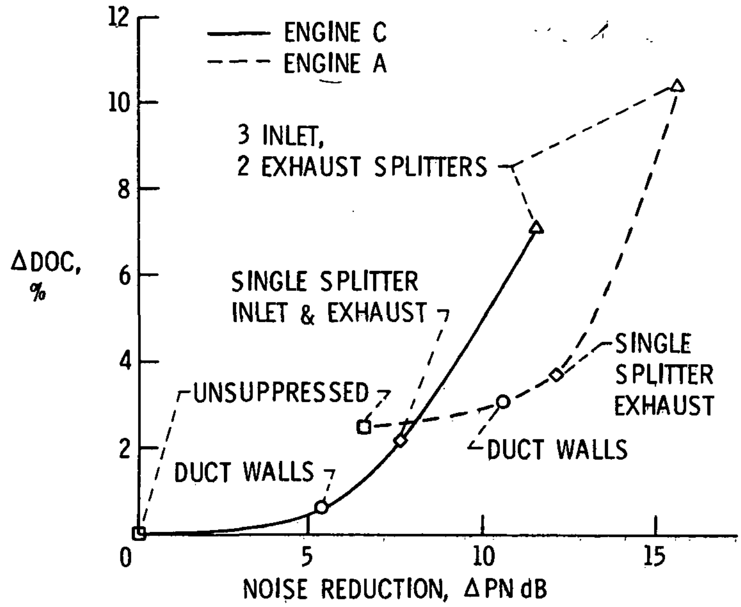

Figure 12. - Effect of acoustic suppression on engine economics.

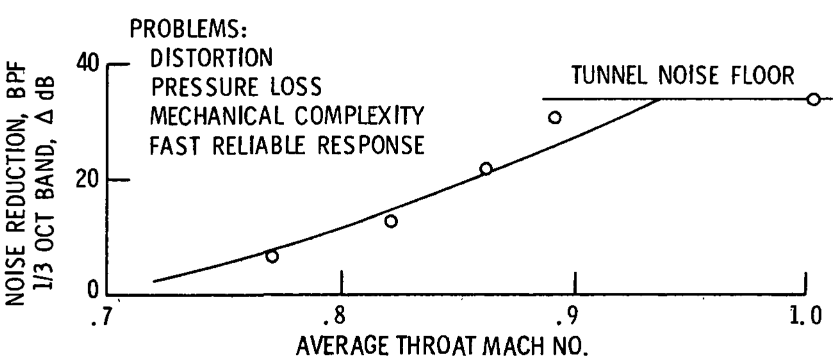

Figure 13. - Sonic inlet acoustic performance.