NOISE COMPARISONS FROM FULL-SCALE FAN TESTS
AT NASA LEWIS RESEARCH CENTER

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Abstract

The overall aero and acoustic design features of eight 6-foot-diameter, single-stage fans tested in an outdoor acoustic facility are described. A correlation of the acoustic results for subsonic tip-speed fans showed the total sound power to be proportional to the mechanical power imparted to the fan and the specific work performed on the air to within ±2 dB. The correlation was relatively insensitive to fan design variables over a broad range of operating conditions. Maximum perceived noise levels were generally proportional to the sound power levels with both noise levels exhibiting a relatively unique increase with fan pressure ratio when normalized by the delivered thrust.

The spectra of broadband noise attributed to the fan exhibited a bimodal characteristic for most of the fans. A predominant mode centered near the blade-passage tone and another at 8 to 16 times the tone frequency. The broadband power level also varied with mechanical power and specific work, but at a level about 3 dB below the total power. The power level of the blade-passage tones was related to the relative Mach number at the rotor tip.

Introduction

The NASA Lewis Research Center has been engaged for the past four years in a broad-ranging program of research in fan noise generation and suppression. This research was started in support of the Quiet Engine Program for STOL application and more recently has been in support of quiet propulsion for CTOL application.

Acoustic testing at NASA-Lewis is primarily accomplished on an outdoor facility with fans of six-foot diameter. With this facility, far-field acoustic data are obtained in both the inlet and exit quadrants of the full-scale fans. In addition, in-duct acoustic data and aerodynamic performance data are obtained.

To date, eight 6-foot-diameter, single-stage fans have been evaluated covering a broad range of fan design pressure ratios (1.2 to 1.6) and fan tip speeds (700 to 1550 ft/sec). Each fan is generally tested along three operating lines (nozzle areas) over a speed range from 60 percent to 90 percent of the design speed corresponding to engine approach and takeoff speeds, respectively. Some of the stages have also been evaluated with acoustically-treated inlet and exhaust ducts, but this paper will be restricted to results from unacoustically treated configurations. The eight fans embodied a variety of acoustic principles, insofar as aerodynamics permitted, to obtain low noise. The design and acoustic results for some of these fans have been previously discussed.\(^{(1-4)}\)

This paper will describe the full-scale fans that have been tested and some correlations of total acoustic power and perceived noise levels based on fan overall design and performance parameters. In addition, the acoustic power spectra for each fan are examined for distinctive properties of broadband and blade-passage-tone noise. Characteristic properties and correlations of these noise components are presented.

Full-Scale Fan Test Facility

The fan test facility is shown in the photograph of Figure 1. The fan test package to the left is driven by a shaft leading to the main drive motor of the Lewis 10x10-foot supersonic wind tunnel housed in the building to the right. The centerline of the facility is 19 feet above the asphalt surface of the site. Figure 2 shows a cutaway sketch of the fan test package. The fan is supported by an internal pylon housing the bearings and associated gear. The fans are generally driven through the inlet, but some experiments have been performed with a rear drive to evaluate possible facility related airflow distortion effects caused by shaft and fan support structures.

A plot plan of the test site is shown in Figure 3. Far-field microphones are located at 108 intervals on a 100 foot arc. The fan package is some 120 feet from the wall of the drive building. This wall is covered with six inches of polyurethane foam to reduce sound reflections. There are no other nearby obstacles to reflect sound.

Signals from the microphones are recorded on tape and subsequently reduced with appropriate averaging times to 1/3-octave sound pressure levels. The 1/3-octave frequency bands from 50 to 20,000 Hz are covered. Three separate data samples are averaged at each test condition to yield the final data. The data are corrected from test day temperature and humidity to a standard reference of 59°F and to a relative humidity of 70 percent. Acoustic data are taken separately from runs in which aerodynamic data are taken. No data are taken during any kind of precipitation or at wind velocities above 5 knots.

Fan Stage Aero-Acoustic Design

The acoustic features and aerodynamic parameters of the fan stages will be discussed in this section. Several noise reduction principles were used in the design of each fan stage: (1) All stages were designed without inlet guide vanes; (2) a rotor-stator axial spacing of at least two true rotor chords was used; and (3) rotor and stator blade numbers were selected so that the blade-passage-frequency tones due to rotor-stator interaction would be cutoff. Two of the fans were de-

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signed according to the theory of Kemp, Sears, and Horlock(5,6) that relates rotor-stator interaction noise to lift fluctuations on the stator. According to this theoretical treatment, it is beneficial to increase the chord of the downstream blade row, in this case the stator. When this was done, stator blade number was reduced to avoid stator solidities that were unacceptably large, and the cutoff criteria could not be met for these two stages.

At the outset of the program, the acoustic tradeoff between aerodynamic loading and fan tip speed, if any, was not known. Accepted fan noise generation correlations indicated a fifth power dependence of noise on fan tip speed. This motivated a desire to keep tip speeds low at the considerable penalty of an increased number of drive turbine stages that an engine would require. Because of the limited experience relating to this possible tradeoff, the matrix of fans to be tested was selected to provide an evaluation of fan loading relative to fan tip speed. Figure 4 shows the matrix of fans. In this figure, fan pressure rise is plotted against fan tip speed.

To complete the characteristics of the overall fan design, a third parameter, the work coefficient, \( \Delta V / \Delta T \), is included in addition to fan pressure rise and impeller speed. This parameter is used herein as the indicator of the overall loading of the fan. In Figure 4, several lines of constant \( \Delta V / \Delta T \) are shown. It can be seen that several of the fans have about the same value of the work coefficient implying similar overall aerodynamic characteristics. It can also be seen that a range of the work coefficient parameters is covered at both constant pressure ratio and at constant tip speed. It should be noted that these fans were designed for a normal range of limiting values of the local blade diffusion factor or aerodynamic loading.

A more complete tabulation of the fan design parameters is given in Table I. The hub-tip ratio and specific flow were about 0.5 and 41 lbs/sec/ft², respectively, for all fans. It can be seen that the designs encompass a broad range of each parameter. The last fan listed, QF-9, has variable-pitch rotor blades to provide thrust reversal capability. This fan has a very low number of blades to facilitate the variable pitch and to keep the blade-passage frequency tone well below the frequency range of maximum annoyance. Figure 5 is a photograph of this fan while Figure 6 is a photograph of high-speed fan C.

**Correlations of Overall Acoustic Performance**

The data obtained for each fan stage consisted of 1/3-octave sound pressure spectra at 10° intervals from 10° to 160° measured on a 100-foot arc from the fan inlet. Fan speeds in 5 to 10 percent increments from about 60 to 90 percent of the design speed were run generally for three nozzle areas. These tests yielded a considerable amount of noise data.

For a preliminary study of the data, it was convenient to examine the behavior of two measures of noise as functions of overall fan design or operating conditions. These are: (1) the total sound power measured in dB relative to 10⁻¹³ watts, obtained by integration over all frequencies and angular positions; and (2) the maximum sideline value of perceived noise level. The first quantity provides a measure of the total sound produced without regard to frequency or directivity while the second quantity emphasizes the sound at those frequencies found to be most annoying to people. These noise parameters were examined with respect to overall fan design and performance parameters to determine overall correlations of the data.

**Sound Power Correlation**

The correlation that has been developed starts with the assumption given by the expression

\[
\text{Sound Power} = \gamma_c \times \text{shaft power} \tag{1}
\]

where \( \gamma_c \) is the conversion efficiency to be evaluated functionally from the data. The size or scale of the fan as it influences noise is already established by the use of shaft power in Equation (1). The conversion efficiency \( \gamma_c \) was found to vary linearly with the specific work performed by the fan and given by the total temperature rise, \( \Delta T \), across the stage. This is shown in Figure 7 where both \( \gamma_c \) and \( \text{PWL} \times 10 \log \text{shp} \) (a proportionally equivalent quantity in acoustic notation) are plotted against \( \Delta T \) for tests made along the nominal operating line of each fan. The relationships determined from Figure 7 are

\[
\gamma_c = 0.955 \times 10^{-6} \Delta T \tag{2}
\]

and

\[
\text{PWL} = 98.5 + 10 \log \Delta T + 10 \log \text{shp} \tag{3}
\]

where PWL is in dB (re 10⁻¹³ watts), \( \Delta T \) is in °R, and shp is in horsepower. Figure 8 shows the data for all operating conditions tested and plotted according to Equation (3). Except for the high-speed fan C, the total scatterband shown is ±2 dB. Fan C does not fall into the general class of fans represented by the bulk of the data as is shown by its larger sound output. This is due to the significant presence of multiple-pure tones. However, it should be noted that fan C approaches the correlation band at low speeds where multiple-pure tones are less severe. The correlations of Figure 8 show the sound power to depend linearly on the product of total power (shp) and specific work given by \( \Delta T \).

**Alternate Forms of Correlation**

Equation (3) can be expressed in several equivalent forms using other fan parameters. Beranek(7) gives as a correlation for ventilating fans the relation

\[
\text{PWL} = 138 + 20 \log \text{shp} - 10 \log q \tag{4}
\]

where q is in cubic feet per minute, and shp is the rated motor horsepower of the fan drive unit. This relation converted to the form of Equation (3) is

\[
\text{PWL} = 104.5 + 10 \log \Delta T + 10 \log \text{shp} \tag{5}
\]

It can be seen that Equation (5) yields sound power levels 6 dB larger than Equation (3) yields. However, it should be noted that the difference is less than 6 dB because rated motor horsepower is always larger than the delivered power used in the correlation given by Equation (3). Exact agreement would occur with a conservative assumption of a rated power equal to twice the delivered power.

2
Multiple pure tones are related to the shock waves on the blade-leading edges, the correlation of this noise will depend on the relative inlet Mach number of each fan. For this relation, a fan efficiency of 0.85 was assumed. Equation (7) was used. The superposition was accomplished by a systematic translation of the spectra. The frequency abscissa was first aligned by a translation proportional to the change in fan speed. The power level ordinate was then adjusted to superimpose the spectra in a high-frequency region where narrow-band analysis implied a relative freedom from blade-passage tones. For comparison from fan to fan at a given speed, the frequency shift was made with respect to blade-passage frequency.

Noise Spectra Analysis

Both broadband and pure tone noise contribute to the total acoustic power and perceived noise levels used in the previous correlations. A next step in the analysis is to examine the acoustic power spectra for broadband and pure tone content and to compare the behavior of the acoustic power of these noise components with the behavior found for the total acoustic power. The specific spectral composition of each fan is also important because it can show similarities and differences in those fans which are not reflected in total power measurements. In this preliminary study of the spectral data, attention will be focused on the broadband noise underlying the blade-passage tones while exhaust jet and multiple pure tone noise behavior will be neglected at this time.

Properties of the Acoustic Spectra

An examination of spectral data from these fans (1/3-octave power spectra, as well as narrow band and 1/3-octave sound pressure spectra at various angular positions) revealed some characteristic similarities and differences in the spectral shapes for the various fans tested. These similarities were especially pronounced with respect to the apparent broadband noise level generated by the fan stage. Similarities in the apparent broadband spectra were observed both for a given fan as speed was varied, and from fan to fan at the same speed. Those similarities in the broadband spectra were observed from suitable superposition of the sound power spectra.

The broadband noise underlying the tones is often uncertain from an inspection of 1/3-octave intervals. This overlapping or straddling of 1/3-octave intervals by the tones varies with a change in fan operating speed. In an attempt to minimize the uncertainties in broadband spectra caused by the straddling, a superposition of 1/3-octave power spectra for four speed conditions for each fan was used. The superposition was accomplished by a systematic translation of the spectra. The frequency abscissa was first aligned by a translation proportional to the change in fan speed. The power level ordinate was then adjusted to superimpose the spectra in a high-frequency region where narrow-band analysis implied a relative freedom from blade-passage tones. For comparison from fan to fan at a given speed, the frequency shift was made with respect to blade-passing frequency.

Figure 11(a) illustrates the results of superimposing sound power spectra for different speeds for a given fan. The superimposed spectra show that the fan has a high degree of self-similarity in the fan broadband area with changes in speed. This self-similarity with speed was observed for all of the fans.

Figure 11(b) shows a superimposed plot for fans QF-3 and QF-9 at the same speed. Again, a similarity of the spectrum is observed in the region of the blade-passage tones and their harmonics. However, the QF-3 fan exhibits a relatively "rapid" and uniform "fall-off" of the high-frequency portion of the spectra compared to the QF-9 fan where the "fall-off" is relatively "slow" and irregular. This difference in spectral shape (noted to a lesser degree in the other fans) was taken to imply a
difference in broadband noise generation in these two fans.

Analytical Representation

The broadband noise spectral shape for a fan is inferred by the baseline underlying the tones in the 1/3-octave displays. In many instances, the establishment of this baseline, or apparent broadband variation, is a matter of judgment based on inspection of both the 1/3-octave and narrow-band spectra.

A method of characterizing the superimposed apparent broadband noise profiles for these fans (Fig. 11(a)) which provides for the difference in spectral shapes observed in Figure 11(b) is illustrated in Figure 12. The estimated apparent broadband profile is shown by the solid line. It was found that, in all cases, the estimated apparent broadband profile could be characterized by a bimodal log normal distribution shown by the dashed line in Figure 12. The center frequency of the primary (low frequency) mode is given by \( f_p \) and the center frequency of the secondary (high frequency) mode is given by \( f_s \). A log normal distribution function with a geometric deviation \( \sigma \), of 2.2 was used for this purpose. Inspection of the octave and narrow-band spectra showed that this distribution function was adequate for the resolution of spectral content desired in this preliminary analysis of the data. The equation for the power level distribution with frequency for a log normal distribution is given by

\[
PL = PL_{max} + 10 \log_{10} e^{-\frac{(\ln f / fs)^2}{2\sigma^2}}
\]

Figures 13(a) through (h) show the combination of primary and secondary (low and high frequency) modes fitted to each set of superimposed fan spectra. For consistency, two modes are shown for each fan even though the high-frequency mode may be negligible or obscure. The high-frequency mode is shown by a dashed curve when highly uncertain to imply a maximum probable level. The general "fit" of the bimodal for normal distribution to the apparent broadband noise variation is seen to be quite good for all of the fans.

Discussion of Broadband Characterization

The broadband noise characteristics used in Figure 13 show some distinctive properties of the fans. The lower frequency mode of broadband noise dominates the broadband spectra for most fans. It appears typical of what has been observed in other fan tests and is often attributed to turbulent conditions entering the fan.

The high frequency mode of broadband noise is obscure in some fans and difficult to resolve in all fans because of a lack of higher frequency data. The high-frequency mode is strongly evident in fans B and QF-9 where low blade-passage frequency appears to make it more evident. Additional analysis has shown that this high-frequency mode is more pronounced in the forward quadrant spectra which implies that it originates from the fan inlet. Distinctive spectral properties of broadband noise at high frequencies have been discussed and analyzed by various investigators. (9,10,11) Vortex shedding from both leading and trailing edges of airfoils have been proposed as possible sources. Identification and control of such sources within a fan spectrum, however, remain uncertain.

Some additional evidence on the generation of broadband noise in a high-frequency mode was provided by exploratory tests with fan QF-9 directed toward reducing inlet flow distortions. Tests were made using a fine mesh screen in front of the fan inlet. The power spectra obtained from such tests is shown in Figure 14. A high-frequency mode of broadband noise was generated with a center frequency of the Strouhal frequency for flow over the screen wire size. The flow over the screen will generate broadband noise of this type, but the power level observed (equivalent to the blade-passage tones) is higher than expected. The result suggests that turbulent flow properties entering or generated within the fan stage can be the cause of a high level, high frequency broadband noise with definite spectral properties emanating from the fan.

The primary, or low-frequency, broadband mode is seen in Figure 13 to center and peak near the second and third harmonic of the blade-passage frequency in all cases. Analysis of the secondary or high-frequency mode is highly qualified because of the difficulty in identifying the presence and exact location of this mode. From a general observation of Figure 13, the center frequency does not appear to vary directly with the change in speed. For example, both the fan B and QF-9 spectra suggest that a better superposition at high frequencies is possible with a different frequency translation than that used in Figure 13. The available data, however, preclude a more refined study at this time.

Plots of the variation of center frequency for the two broadband modes contained in the bimodal distributions as shown in Figure 13 are given in Figure 15. The center frequency of the low-frequency mode is about 2-1/2 times the blade-passage frequency, while the center of the high-frequency mode is about 8 to 16 times the blade-passage frequency. On the average, it appears that the center frequency of the secondary mode is about four times that of the primary mode, but the data do not give convincing evidence of such a relationship.

Fundamentally the center frequency of broadband noise obtained from a power spectral density analysis has more significance with regard to its origin. Interestingly, a log normal distribution retains its log normal properties when transformed to a power spectral density display. Preliminary analysis of the spectral density indicated that the mode centers between the first and second harmonic of the blade-passage frequency which is near the mean power frequency from blade-passage tones. The close relationship between this low-frequency broadband noise and blade-passage tones implies a common source, but this may be a coincidence resulting from some similarity of aero design for all of these fans.

Correlation of Component Noise

The analytical representation of the apparent broadband power spectra by a bimodal log normal distribution facilitates numerical calculations for the sound power contained in this broadband component. The power content of the blade-passage tones can then be obtained by subtraction of the broadband...
power from the total power in the region of appli-
cability.

Fan Broadband Noise

The total broadband power (the sum of the
powers in the low- and high-frequency modes of the
normal distributions) is plotted in Figure 7 and
compared to the mean level of the total sound power
as obtained from Figure 4. The mean value of the
total broadband power is about 3 to 3.5 dB less
than the total power, indicating the same depen-
dence of broadband noise on overall temperature
rise (specific work) and shaft horsepower.
The mean value of the total broadband power is given
by

\[
(PWL)_b = 95.3 + 10 \log a + T + 10 \log sp
\]  

(10)

The sound power contained in the low-frequency
mode of broadband noise (from an integration of the
primary log normal distribution) is shown in a cor-
relation comparable to that used for total broad-
band power in Figure 17. This broadband noise has
a functional variation similar to total broadband
sound power, but the level is about 1 dB lower. Of
some significance, the supersonic tip speed fan, Fan C, gives a primary broadband noise level com-
parable to the lower tip speed fans.

The sound power contained in the secondary or
high-frequency mode is shown in Figure 18. It is
apparent from the large spread in data that other
fan parameters besides the shaft power and work in-
put affect the power contained in this mode. Obvi-
cously, reliable correlation and characterization of
this mode must await a more precise analysis.

Blade-Passage Tone Noise

The power contained in the blade-passage tone
and its harmonics was obtained from the difference
between total power and broadband power over the
appropriate frequency region. Figure 19 shows that
the power in the tones does not correlate with
shaft power and work input as might be expected be-
cause of such correlations for broadband power and
total power. Figure 19, however, does illustrate
the magnitude of the tone power with regard to the
broadband power. The tone power is not consistently
higher or lower than broadband power and its level
seems to vary with both operating condition and fan
design. Apparently the broadband and total power
exhibit similar correlations because of a combina-
tion of broadband dominance and unusual tone behav-
ior.

Tone generation is often related to rotor tip
speed. One correlation which appears to describe
the tone behavior is shown in Figure 20. Tone pow-
er normalized by the total mass flow rate is shown
to vary with the 5th power of the rotor tip rela-
tive inlet Mach number. A significant deviation
from this trend occurs near a Mach number of unity.
The tone power decreases above a Mach number near
one. This decrease may be attributed to the propa-
gation of tone power as multiple-pure-tone which
remain to be analyzed.

For a given fan, where mass flow rate is pro-
portional to tip speed, the correlation in Figure 20
gives a sixth power dependence of tone power
with tip speed. Broadband power varies with shaft
power and work input which for a given fan gives a
fifth power dependence with tip speed. This dif-
ference in tip speed dependency can cause the total
source power of a given fan to shift from broadband
dominance to tone dominance with increasing tip
speed.

Concluding Remarks

These studies of full-scale fan noise have
shown that for a range of state-of-the-art fan de-
signs, useful correlations of overall noise given
by sound power level and perceived noise level can
be obtained with overall fan performance parameters
such as the shaft power and specific work, or fan
thrust and fan pressure ratio. The correlations
are useful for both sound power and perceived noise
predictions to within ±2.5 dB, and are limited to
fans with no strong multiple-pure-tone generation.

A closer examination of the fan power spectra
in terms of broadband and blade-passage-tone noise
has provided additional noise comparisons. The to-
tal fan broadband noise power has a functional de-
pendence on fan parameters similar to that of to-
tal power but at a level 3 to 3.5 dB lower. The
fan broadband noise appears to originate from two
sources which give spectral modes that appear to
have log normal distributions which are separated
in center frequencies. The lower frequency mode
usually dominates the fan broadband noise and is
centered near the blade-passage frequency. A high-
er frequency mode was pronounced in a few fans.
Its functional dependence differed from the low-
frequency mode, but could not be determined from
the limited amount of data.

The sound power in the blade-passage tones ap-
ppears to vary with the relative inlet Mach number
at the rotor tip rather than shaft power and spe-
cific work. This difference can cause total power
to be either broadband or tone dominated depending
on the specific design and operating condition.

The preliminary spectral analysis of the sound
power has provided some initial insight into simi-
larities and differences of the fans tested. A
continuing analysis should prove useful for both
better predictions of noise levels and a better un-
derstanding of noise mechanisms.

References

1. Anon., "Aircraft Engine Noise Reduction," SP-
311, 1972, NASA, Washington, D. C.
2. Leonard, B. R., Schmidtlin, R. F., Stakolich,
E. G., and Neumann, H. E., "Acoustic and Aero-
dynamic Performance of a 6-Foot-Diameter Fan
For Turbofan Engines. I - Design of Facility
and QF-1 Fan," TN D-5877, 1970, NASA, Cleveland,
Ohio.
3. Goldstein, A. W., Lucas, J. G., and Balcomb,
J. R., "Acoustic and Aerodynamic Performance of
a 6-Foot-Diameter Fan for Turbofan Engines.
II - Performance of QF-1 Fan in Nacelle Without
Acoustic Suppression," TN D-6080, 1970, NASA,
Cleveland, Ohio.
4. Montegani, F. J., "Noise Generated by Quiet En-
gine Fans. I - Fan B," TM X-528, 1972, NASA,
Cleveland, Ohio.


### TABLE I - FAN DESIGN PARAMETERS

<table>
<thead>
<tr>
<th>FAN</th>
<th>PRESSURE RATIO</th>
<th>TIP SPEED, FT/SEC</th>
<th>BLADE NO.</th>
<th>VANE NO.</th>
<th>CUTOFF</th>
<th>BPF, Hz</th>
<th>ROTOR SOLIDITY</th>
<th>DESIGN BY</th>
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<td>1107</td>
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<td>0.89</td>
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Figure 1. - Fan noise test facility with long shaft and front drive.

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