An Improved Correlation for the Broadband Noise of High-Speed Fans

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Broadband noise data have been obtained from tests on a wide variety of transonic design speed fans. These fans show considerable differences in noise level at a given tip speed which are often inconsistent with trends expected from previous correlations; in particular, fan loading does not appear to be of primary importance. A new correlation has been developed using rotor blade incidence and relative Mach number as primary parameters. The use of incidence accounts for variations in noise between the fans and also for the effects of throttling at constant tip speed, resulting in a good collapse of data. However, the remaining scatter shows that some second-order effects do exist, and these are discussed.

I. Introduction

FAN broadband noise can be an important component of modern high-bypass-ratio engine noise, particularly during aircraft approach. The relative importance of broadband noise is likely to increase in future quiet engine designs and, as these may employ increased bypass ratios and low tip speeds with consequent reductions in jet and buzzsaw noise that will not necessarily be matched by reductions in broadband noise, could even result in it becoming important at takeoff as well as approach. Fan tone noise may also become more important but, as the generation process and reduction methods are well understood, this source should be controllable so long as there is some flexibility in engine layout. Unfortunately, the same is not true of broadband noise, and further understanding is needed to achieve noise reduction by design. In particular, there is a need for reliable prediction methods demonstrating the dependence, if any, on fan aerodynamic parameters such as loading. This would assist in engine design optimization for minimum noise.

A wide variety of fans has now been noise tested at Rolls-Royce and NGTE, and attempts have been made to correlate the range of data obtained. Straightforward correlations against relative Mach number as suggested by Benzakein, et al.,[1] or with loading parameters like Burdsall and Urban,[2] were inappropriate. The direct use of blade-drag coefficient as a correlating parameter as put forward by Mugridge[3] did not seem to apply either but, because the idea of a relationship between drag and broadband noise generation seems physically reasonable, a related approach using rotor blade incidence was adopted.

The idea of using incidence is not new[1,2,4,5] but only Smith and House[4] and Wright[5] have included it in a general correlation. Whereas Smith and House concentrated on multistage compressors and fans with inlet guide vanes (IGV's) and Wright mainly used low-speed fan and open-rotor data, the present work concerns modern single-stage transonic fans. Initially, incidence effects are demonstrated using results from three typical fans, and then a general correlation suitable for noise prediction purposes is derived.

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II. Importance of Incidence

Three fans representative of the range of data available were used for an initial study; they are fans 1, 2, and 4 in Table 1. All are realistic model fans of transonic design speed and, although of single-stream layout, they have design features appropriate to the modern high-bypass-ratio engine. They were originally for aerodynamic research and attained acceptable efficiency. All these fans have very similar diameters and blade numbers, so that any dependence of noise on these factors can be ignored at this stage. The fans differ mainly in their design speed and pressure ratio. The differences in loading resulting from this are illustrated in Fig. 1, which compares the pressure ratio at a tip speed of the three fans.

Typical forward arc broadband noise data for the fans are illustrated in Fig. 2. The changes in noise caused by throttling, which are similar to those noted by other workers,[1,2] are considered important because the effective throttle setting of a real engine fan will change on going from static to flight. Also the effects of throttling may be a significant pointer to the underlying generating mechanisms and hence to appropriate correlating parameters. However, some very "off-design" data, such as near to surge or with wide-open throttle, may not be relevant to practical cases and attempts to correlate this may be misleading.

The data in Fig. 2 shows a spread of more than 20 dB in measured noise at a given tip speed. This makes it clear that correlating solely against tip speed or relative Mach number as in Ref. 1 is inappropriate. Additional parameters are required to account for the differences between fans and also for the effects of throttling. A dependence on loading[2] is unlikely to do this, because the quietest fan is, in fact, the most heavily loaded. An attractive alternative method of correlating broadband noise data is in terms of rotor blade losses or drag. Burdsall and Urban[2] suggested such an approach, although it did not form part of their final correlation. The work of Mugridge[3] advanced this further, and he demonstrated a linear relationship between blade-drag coefficient and broadband sound power for isolated aerofoils and low-speed model fans. Such a dependence is not consistent with the spread of data in Fig. 2, as it would imply changes in blade drag near 300:1. However, even if this particular relationship does not apply, the argument that blade drag and rotor self-noise generation were connected seemed worth pursuing. Unfortunately the detailed drag data

Table 1 Fan design characteristics

Fan	1	2	3	4	5	6a	6b	6c	7[a]
Design tip speed, ft/sec	1450	1100	1200	1300	1500	900	900	900	1500
Design pressure ratio	1.39	1.55	1.55	1.55	1.55	1.2	1.2	1.2	1.6
Number of blades	27	29	20	25	25	22	34	66	33
Tip chord, in.	1.96	2.39	3.33	2.7	1.97	2.25	1.5	0.75	4.1
Diameter, in.	15.7	15	15	15	15	15	15	15	34
Camber angle, deg	0	8.6	6.1	0	1	4.9	4.9	4.9	0.04
Deviation from correlation									
Forward arc	0[b]	+1[c]	+2[b]	...	0[b]	−1[b]	+1[b]	0[b]	0[c]
Rear arc	−2[c]	+1[c]	...	−2[d]	...	...	...	...	+0.5[c]

[a] Model engine fan with separate engine section and bypass flow.
[b] Rotor-only test.
[c] Rotor with outlet guide vanes at wide spacing.
[d] Rotor with outlet guide vanes at close spacing.

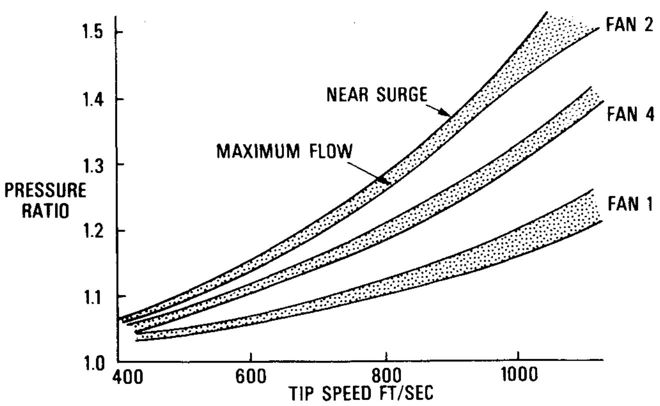

Fig. 1 Variation of pressure ratio with tip speed for three fans. Shaded area shows the change in pressure ratio caused by throttling.

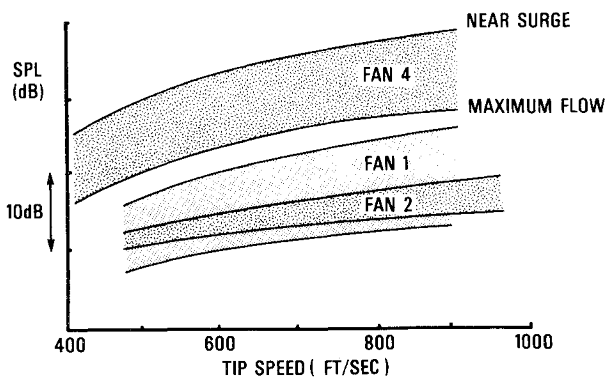

Fig. 2 Broadband noise vs tip speed for three fans. Shaded area corresponds to throttling.

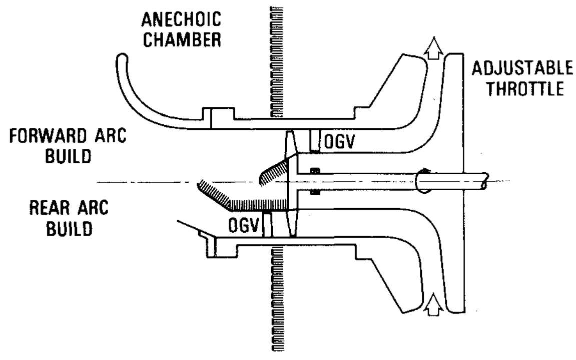

Fig. 3 Typical fan build.

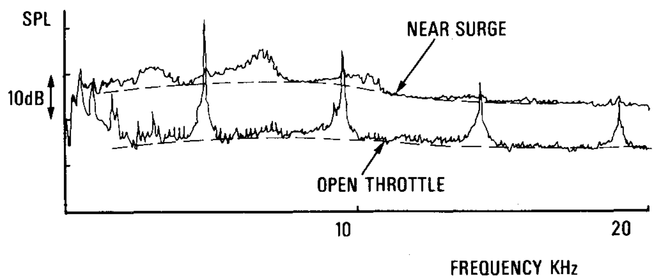

Fig. 4 Typical spectra showing increase in noise with throttling.

needed to do this were not available, and instead a simpler approach was adopted. This consisted of using rotor blade incidence as a correlating parameter, on the argument that for modern transonic blade sections the drag coefficient will be mainly a function of this incidence. This is difficult to justify rigidly, especially when variations in camber and solidity occur, but its validity should become apparent by the degree of success of the attempted correlation.

Rotor blade incidence is a convenient parameter to use, since it is fairly easy to measure or estimate, and in the present work further simplification results from using incidence at the tip. Tip incidence will be relevant if the tip is the dominant noise generating region. This seems reasonable, because the largest relative velocities occur there. Even though loading will increase with incidence for a given fan, incidence cannot in itself be regarded as a loading parameter as loading will depend on other factors such as camber and solidity.

Data Measurement and Analysis

Most of the noise data used in both the initial and more general studies were obtained in the Ansty anechoic facility[6] with some additional tests carried out in the smaller NGTE fan noise facility.[7] Figure 3 shows the general arrangement of a fan in the Ansty facility for either forward or rear arc measurements. The inlet to the fan consists of a flare that draws air from the anechoic chamber for forward arc testing. For rear arc testing, the fan discharges into the chamber through a conical nozzle, and throttling is achieved by changing the nozzle area. Noise recordings were obtained from a polar traverse centered on the inlet or nozzle planes at a distance sufficient to approximate to far-field conditions.

Typical narrow-band spectra taken at an angle near the peak for broadband noise are shown in Fig. 4. The spectra shown are at the same speed but different throttle settings, and the increase in broadband noise is clearly shown. A smoothed spectral shape, ignoring tones and humps, was used to represent broadband noise and is shown on the sample spectra. The peak level of this curve was used as a convenient measure of broadband noise for the initial correlation. Spectra at an angle of 30° to the intake for forward arc and approximately 110° for rear arc were generally used. These levels are reasonably representative of sound power (which would be used ideally) due to the generally flat and similar field shape observed on all fans, although small corrections were needed in some cases when spectra at other angles were used or when significant differences in field shape were found.

To highlight incidence effects in the initial study, data from various fan speeds had to be collapsed. As only subsonic tip speeds were considered at this stage, total sound power was assumed to vary with tip relative velocity as $V_{rel}{}^6$ in accordance with simple dipole theories.[8] V_{rel} was calculated using axial velocities just outside the duct wall boundary layer. Because the overall frequency range covered by a broadband noise spectrum will be roughly proportional to V_{rel}, a $V_{rel}{}^6$ dependence for overall sound power corresponds to $V_{rel}{}^5$ for levels in a fixed frequency band. Hence broadband noise levels in fixed bandwidth spectra were normalized by substracting 50 $\log_{10} V_{rel}$. For this preliminary study, the rotor tip inlet air angle was calculated using tip axial velocities obtained from inlet mass flow via an assumed velocity profile. In the later work, the axial velocity was derived from wall static pressure readings just in front of the fan face. In both cases, the incidence was then calculated using known rotor inlet blade angles (after corrections for untwist effects); some checks showed that the two methods gave results generally agreeing to within $\pm 1°$.

Correlation with Incidence

The broadband noise data obtained and normalized as described above are shown in Figs. 5 and 6 for the forward and rear arcs, respectively. The forward arc data for fan 4, which cover a complete range of throttle settings for tip speeds from 400-900 ft/sec, show a fairly good collapse (within ± 2 dB) providing some confirmation for the $V_{rel}{}^6$ law for this fan. Most of the data from fan 1, which cover open-throttle points from 435 to 1015 ft/sec, plus throttling at 580 and 1015 ft/sec, also show a reasonable collapse. However, the data at 1015 ft/sec, although following a similar trend to the remainder are consistently lower in level. This fall in level is probably associated with sonic blockage effects within the rotor passages, as the tip relative Mach number is near unity at this speed. The individual data collapses are encouraging, but the most striking feature is the degree of correlation between fans 4 and 1, which demonstrates the very strong effects of blade incidence. However, the data for fan 2, which generally cover a lower incidence range, are not so consistent. It does not appear to collapse with $V_{rel}{}^6$, as fairly distinct trends appear for each tip speed, and the variation with incidence seems to be much less marked than for the other fans.

These trends cannot be explained at this stage, although there is a possibility that the data for fan 2 may be distorted by the effect of non broadband sources, because of irregularities that appear in the spectra. On the other hand, other model fan tests[2] have shown a similar effect in that noise levels at low incidences were observed to increase less markedly with velocity than noise levels at higher incidences.

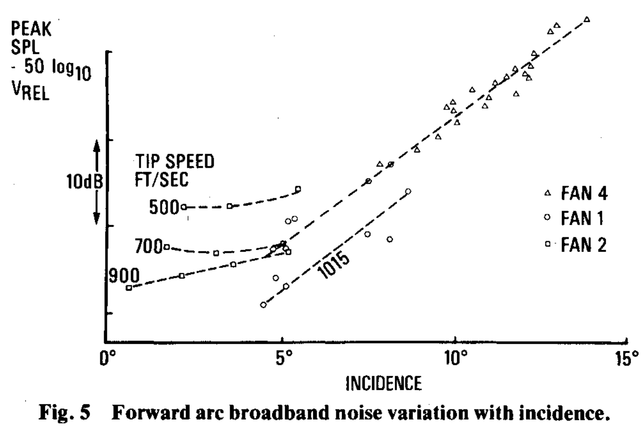

Fig. 5 Forward arc broadband noise variation with incidence.

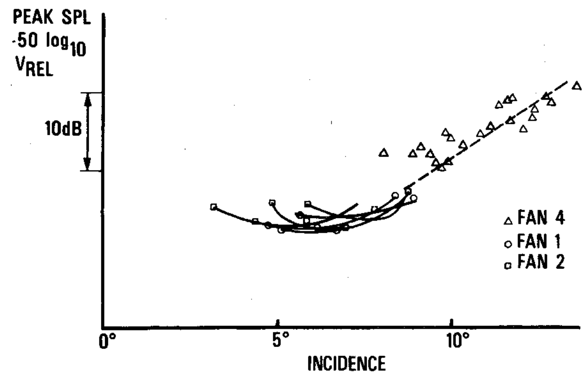

Fig. 6 Rear arc broadband noise variation with incidence.

Whatever the explanation for the behavior of this forward arc data, it is encouraging that similar trends do not appear in the rear arc, as can be seen in Fig. 6, and the data collapse there is generally much better. A minimum noise region now appears both for fans 1 and 2; this could be associated with a minimum drag point, which might be expected at low incidences, but this is by no means certain because of the different trends in the forward arc. An alternative explanation for these different trends is that a new noise source is contributing at lower incidences, and this is more pronounced in the rear arc. Stator noise could possibly be the cause, but it has not been possible to positively identify this source.

More detailed discussion is postponed until a wider range of data can be considered, but we can conclude from this initial study that incidence is a very useful parameter to clarify comparisons between fans and may, in itself, be a useful correlating parameter. The variation of noise with incidence seems to be most marked (and the general collapse of data best) at high incidences. At low incidences, the data collapse is poorer and discrepancies both between fans and between forward and rear arc noise occur, suggesting that parameters other than incidence might be important.

III. Generalized Correlation

The analysis in the previous section has demonstrated the importance of blade incidence to broadband noise; however, for use as a noise prediction method, it requires the inclusion of a wider range of fan data. At the same time the analysis has been modified to one-third octave, since this is more relevant to the specific aim of producing a fan broadband noise prediction method.

Over the years, a wide range of transonic tip speed research fans has been tested in the fan noise facility at Ansty. They were selected to cover the range of possible engine fan designs as fully as available hardware would permit, and data from all these fans have been included in the correlation. All the fans have transonic tip sections and were run without inlet guide vanes. For forward arc measurements, fan builds have included rotor-only tests and those with outlet guide vanes at typical engine spacings, while all rear arc measurements were obtained with outlet guide vanes fitted.

All together, nine research fans of 15-in. nominal diameter have been used in this exercise, as well as a 34-in. model of an engine fan, complete with splitter and engine section stators. Design details of these fans are shown in Table 1. Although it may appear that fans 2-5 form a simple family, this is not the case. In practice, the aerodynamic rules used have evolved considerably over the period covering their design, and this increases the generality of this correlation.

The only true family consists of fans 6a-c, which were designed for the same duty but with a different number of blades. Apart from the aspect ratio, which varied in proportion to blade number, all other design parameters such as space/chord ratio, camber, and blade section were kept constant.

Data Analysis

As a compromise between simplicity and the requirements of engine noise prediction, it was decided to base the correlation on the maximum one-third octave levels occurring over the entire frequency and polar angle range. However, to ensure that only true broadband noise was included, narrow-band spectra were used, a smoothed broadband curve being integrated up to give one-third octave levels as shown in Fig. 7. In some cases, the broadband noise was noted at a frequency below the peak in order to avoid errors due to high atmospheric attenuation and system response. These errors can be severe, as the peak broadband frequencies found on small fans are often in the 20-30 kHz region and even higher. An extreme example is shown in Fig. 7 for fan 6c. In order to correct such data to peak level, a standard one-third octave spectrum shape was used.

Spectrum Shape

One-third octave spectra were constructed for a number of test points, near fan design working lines, by integrating the narrow band spectra with due allowance for atmospheric attenuation. To normalize the frequency scale, a Strouhal number was defined based on the tip space between blades and the tip rotational speed. This is numerically equal to frequency divided by blade-passing frequency. This method was found to give an acceptable collapse of the data. The more usual Strouhal number based on chord length and relative velocity also was tried but did not give a better correlation. Figure 8 shows the mean spectrum shape obtained. Data from all fans are included.

Variation with Incidence and Mach Number

As blade incidence varies with fan speed, it is difficult to separate the effect of each. Initially, a mean variation with incidence of 1.7 dB/deg was derived by observing changes in noise along constant speed lines as fans were throttled. Using this variation, the data were corrected to a standard incidence and normalized for rig scale before plotting against the logarithm of tip relative Mach number (M_{rel}) in Figs. 9 and 10.

Data from all the fans are included in these correlations with the exception of some extreme "off design" points. The lines drawn through the data make the assumption that the sum of the rear and forward arc levels will follow a sixth power law with Mach number. At low Mach numbers, the forward and rear arc levels are the same, the divergence at transonic tip speed being explained as a convective attenuation effect. This is similar to the effect observed by Smith and House except that the divergence occurs at a higher Mach number for the present data. In general, the data follow these lines quite closely except, in the forward arc at transonic speeds. The increased scatter in this region is discussed in Sec. IV.

The incidence variation assumed is confirmed in Fig. 11. The one-third octave sound pressure level (SPL) normalized for rig size was compared with the curves in Figs. 9 or 10 and the difference plotted against incidence is shown. Again data for all fans are included. The incidence variation is different from that observed with the constant bandwidth results in Figs. 5 and 6. This is due partly to the omission of some of the "off design" data, but also demonstrates a slight change in spectrum shape at points near surge. For these points, low frequency level can rise rapidly so as to dominate a constant bandwidth spectra as in Fig. 4, but having little effect on one-third octave levels at the higher frequencies.

IV. Discussion

General Comments

The correlation developed in Sec. III has reduced the systematic spread of 25 dB in measured data to an apparently random scatter band of ±5 dB. The scatter is particularly large in the forward arc at transonic and supersonic tip speeds, and there are two probable reasons for this. First, the forward arc noise may no longer be controlled by tip con-

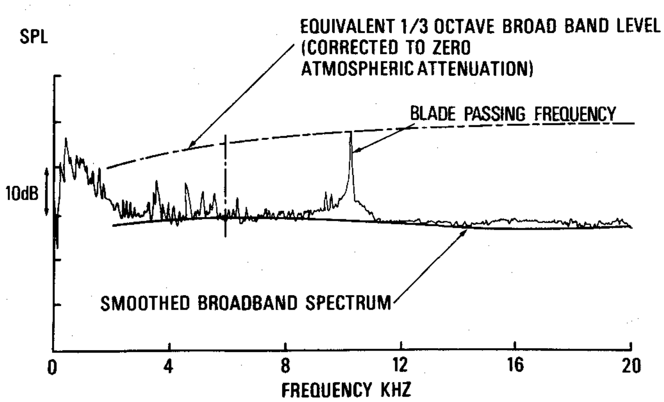

Fig. 7 Spectrum for fan 6c.

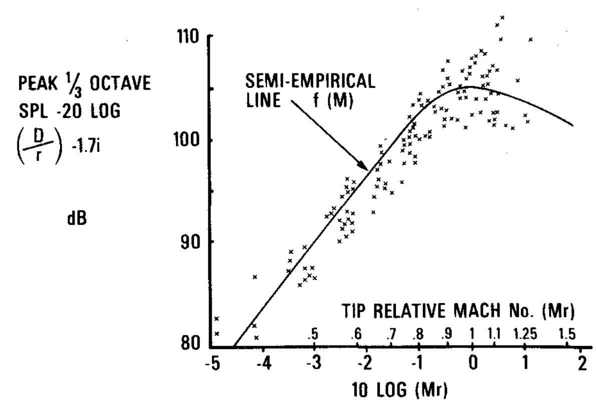

Fig. 9 Forward arc correlation.

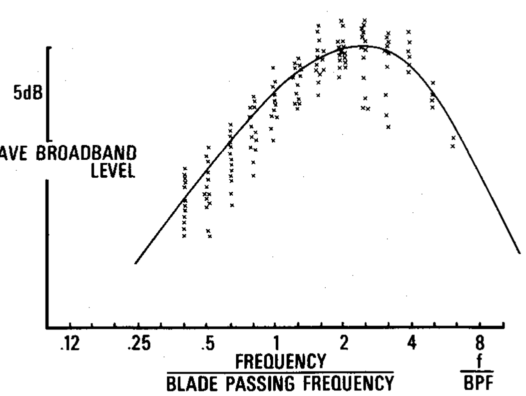

Fig. 8 Fan broadband noise spectra.

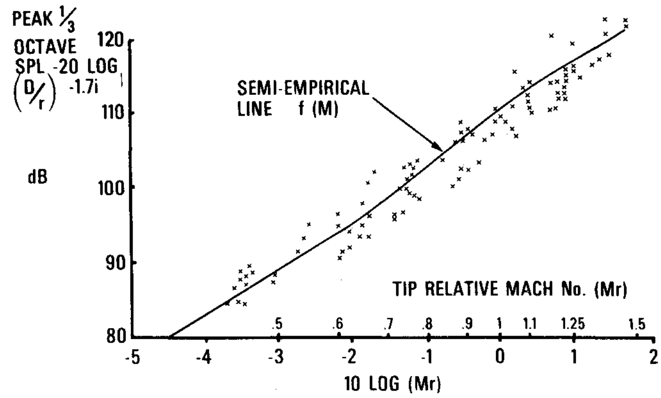

Fig. 10 Rear arc correlation.

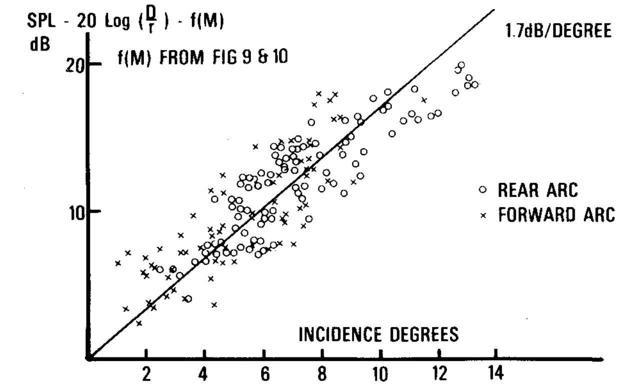

Fig. 11 Variation with incidence all fans.

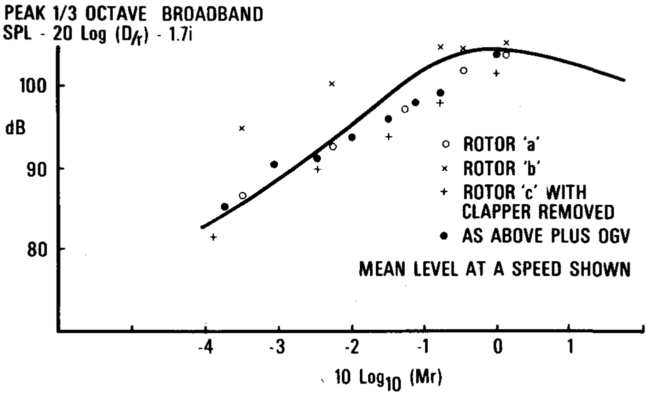

Fig. 12 Forward arc noise levels of four builds of fan 1.

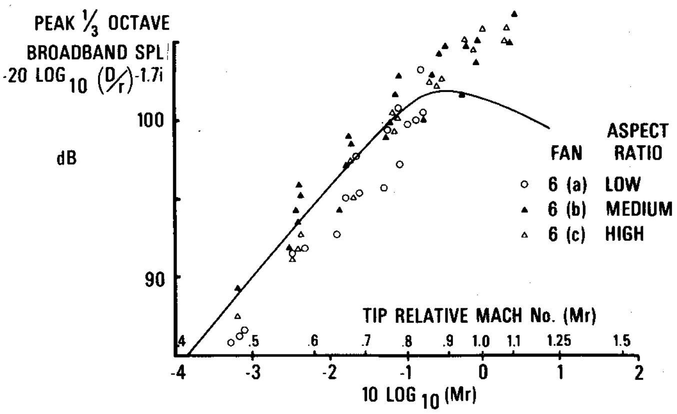

Fig. 13 Forward arc noise variation for three aspect ratio builds of fan 6.

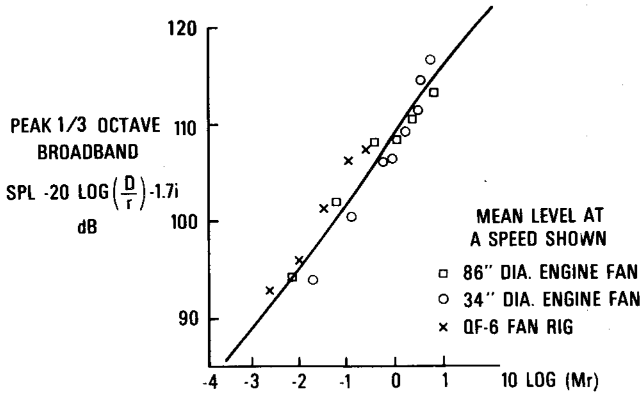

Fig. 14 Rear arc noise of three engine fans.

ditions, due to convective attenuation. Second, the broadband noise becomes masked by the high levels of buzz tones. Fortunately, due to the presence of these buzz tones, forward arc broadband noise is of only academic interest at supersonic tip speed. Neglecting this region, the correlation gives a standard deviation of about ± 2 dB, whereas individual fans have a mean deviation from the correlation of less than 2 dB. Table 1 shows the mean deviation of each fan from the correlation and no systematic effect of design parameters other than incidence is obvious. Although the remaining scatter is still significant, the correlation is the best we have seen for such a wide range of fans and points strongly to relative Mach number and incidence being the primary parameters that control the broadband noise of high-speed fans.

Before considering the implications of this work in detail, it is worth considering repeatability effects as they apply to this correlation. The set of rotor blades for fan 1 used in this work is one of two nominally identical sets (rotors a and b) for which we have noise data. In Fig. 12, the results for these two rotors are compared with the correlation. For clarity, the mean noise level at a tip speed is shown in each case. It can be seen that the second rotor b is up to 7 dB noisier than the first, a difference that is more remarkable when it is noted that each rotor has shown a repeatability of 1-2 dB in its own right. On detailed inspection, the only differences that could be found were slightly greater tip stagger angle variations and more blade dressing to correct damage on set b. Neither of these differences would have normally caused concern. The conclusion of this exercise is that tolerances on blade manufacture can have a significant effect on broadband noise, and this poses a limit on the likely accuracy of any correlation.

Effect of Clappers and OGV's

Two further tests on fan 1 have looked at the effect on broadband noise of removing the blade part span clappers and of fitting a set of outlet guide vanes (OGV's) behind the rotor. The results are also shown in Fig. 13. The reduction of some 2 dB observed between rotor a and the rotor with clappers removed c is so small compared to the difference between rotors a and b that no definite conclusion can be drawn. The small increase on fitting OGV's behind the rotor c is consistent with results on other fans, including the noisy rotor b where a 1-2 dB increase has been seen. In general, however, it has not been possible to include the effect into the correlation and builds rotor alone and with OGV are not distinguished in Fig. 9.

Varying Aspect Ratio

Figure 13 shows the results used in the correlation for the three versions of fan 6. In view of the nonrepeatability observed above the results are very close. It can be concluded that the effect of aspect ratio (or blade number) is very small, the 34-bladed rotor being about 1 dB noisier, and the 22 bladed rotor 1 dB quieter, than the 66-bladed rotor. However, the frequency at which the peak noise occurs will vary with blade number because it is related to blade-passing frequency. It is important to note that for these fans the blade chord was altered with blade number to keep the total surface area of all blades a constant. Indeed for all the fans tested, the solidity and hence total blade area at a rig scale varied over only a small range (see Table 1).

Comparison with Engine Fans

The data considered so far have all been for small model fans. In Fig. 14 data from two engines and from the NASA quiet fan QF-6[9] are shown compared with the rear arc correlation. Data are shown as the mean at a speed and have been corrected for ground reflection. In calculating incidence from fan speed and mass flow, a velocity profile was assumed over the fan face.

The scatter seen with these fans is less than observed with the model fans and can thus be regarded as further justification of the correlation. It should be noted, however, that the QF-6 results show a much lower increase in noise with throttling than incidence variations would suggest; this could be caused by the subsonic blade design of this fan.

Turbulence Interaction

It has been assumed throughout this paper that the broadband noise is rotor self-noise and not, as often proposed,[10] a result of rotor interaction with inflow turbulence. This assumption is thought to be valid because broadband noise varies markedly with incidence, whereas there is evidence that turbulence-interaction noise does not. For example, the tone at blade-passing frequency generated by the present rigs, which is known to be an interaction with inflow distortion, is not observed to vary consistently with blade incidence. Furthermore this distortion tone can be reduced by testing with a turbulence reducing screen[11] over the intake whereas no reduction in broadband noise was observed.

V. Conclusions

A correlation for predicting the broadband noise of transonic design speed fans of high solidity, as used on modern high-bypass-ratio engines, has been developed. The major points to emerge from the correlation are:

1) Blade tip relative Mach number and incidence angle are the dominant parameters.

2) Aerodynamic loading in itself is not of primary importance.

3) Rotor self-noise is the major broadband source.

4) A single spectrum shape, normalized to blade-passing frequency, has been defined.

Although the present work forms the base for an acceptable prediction method, the approach adopted is fairly simple and may need further refinement if accurate correlation over a wide variety of conditions is required. In particular the deviations from the correlation that have been attributed to slack blade tolerances and off-design aerodynamic performance may repay further attention.

Acknowledgment

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