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Abstract

The available experimental data comparing the in-flight and static behavior of fan noise are reviewed. These results are then compared with recent data obtained for a fan stage tested with forward velocity in the NASA Lewis 9x15 low speed wind tunnel. Tentative conclusions are presented, based on the author's judgments, about the significance and nature of the changes in noise observed when a forward velocity is imposed. Finally, the implications of the emerging picture of in-flight fan source noise for suppressor design are discussed.

Introduction

Over the past several years, since the appearance of aircraft flyover noise data, the chief emphasis in fan noise has centered around the reductions in flyover noise relative to ground static test noise. Questions that arise are: What are the causes of the reductions? What is their spectral extent? Over what range of fan operating conditions do they occur? What methods or techniques will allow adequate simulation of flight behavior in ground static testing? Although these can be answered to some extent, fully satisfactory answers will have to come from current or planned programs.

The importance of the problem is first, that predictions of flyover noise levels from static test data are in error. From the standpoint of source noise the degree of impact will depend on the particular fan stage, its spectrum and the sources present. For flyover noise prediction, source noise error is only a part of the problem since atmospheric propagation effects and installation effects also appear to contribute significantly.

The second aspect of the problem concerns evaluation of source noise reduction concepts in ground static tests where the concept benefits may be totally or partially obscured. This factor has direct impact on our understanding of noise generation mechanisms. Thus for a number of years there was some doubt of the benefit of designing a fan stage for cutoff of the blade passing tone due to rotor-stator interaction because of the prominence of this tone in static test data from such fan stages. Other concepts intended to reduce rotor-stator interaction noise quite likely have been incorrectly evaluated also.

This paper reviews some of the data and observations previously published concerning the flight/ground static behavior of fan noise. The recent data obtained in the NASA Lewis 9x15 acoustic wind tunnel have provided some especially interesting results that are included in the review. Also, reviewed, briefly, are recent theoretical results relating to the modal structure of fan noise and to the implications for acoustic suppressors. Views that are expressed about what is known and what is unknown in the overall problem may not be universally shared. Even so, they may serve to promote further discussions of the subject to aid in resolution of the problem.

Causes of Flight/Static Noise Difference

The accepted and often postulated causes for the changes in fan source noise occurring between static and flight testing are illustrated in figure 1 which appears in this or a similar form in a number of references. The figure suggests that the condition of the inflow is the cause and that the inflow is very clean in flight, where in accord with the relatively low contraction ratio, the air is drawn essentially from in front of the inlet. Thus the only disturbances in the flow are those of the atmosphere which, due to the low contraction ratio, pass through the inlet with little scale or intensity changes.

Conversely, in ground static testing, the inflow undergoes a large contraction and is drawn from a spherical region that includes reverse flow over the exterior cowl. The flow thus passes over any support structure and any protuberances from the cowl. The resulting disturbances and any atmospheric turbulence then undergo elongation along flow streamlines in proportion to the large flow contraction. These disturbances are seen by the rotor for a number of revolutions and the interaction results in tone noise. A leading proponent of the importance of atmospheric turbulence as a source of inflow disturbance is Hanson.[1]

Another static source suggested is the ground vortex which has the same effect as the other flow disturbances.

The relative importance of these different static test flow disturbances probably depends on the particular test installation. Thus, an outdoor test stand with structural ironwork probably differs from a clean inlet protruding from the wall of an anechoic chamber. Their relative importance has not been clearly delineated in any test installation to the authors' knowledge but from the favorable comparisons of fan noise data, all static test installations seem to have sufficient total disturbance levels such that comparable noise levels result. Information on disturbance sources would seem to be essential to establish the kind of passive flow conditioning structure to be used and where and how to deploy it to enable simulation of flight behavior.

Comparison of Fan Inlet Duct Flight and Static Noise Data

In-flight fan noise data are published for the Rolls Royce RB211[2,3] engine and the General Electric CF6-6[4,5] and CF6-50[6] engines. These engines are similar in several respects pertinent to fan noise. They all have supersonic fan tip speeds at take-off conditions; they all are designed with cutoff of the fan fundamental tone due to rotor-stator interaction at approach conditions; and as fan tip speed is increased the fundamental tone due to the rotor alone cuts on before that due to rotor-stator interaction.

Induct data are also available for the JT8D refan engine. These data were obtained in the flight part of the NASA Refan program by Douglas Aircraft Company. The refan engine differs from the three previous engines in that it has inlet guide vanes that are the source of a cut-on fan fundamental tone. The fundamental tone from the rotor-stator source is cut off at approach conditions.

The last set of data to be included in the comparison was obtained for a fan stage operating in the Lewis 9x15 acoustic wind tunnel.[7,8] This fan stage (rotor-55 used in the NASA QCSEE noise research program) operates with a subsonic tip speed and is designed for cutoff of the rotor-stator fundamental tone. The data from this fan were taken in the acoustic far field. This fan differs from the others in the comparison in that the operating speed range never permits the fundamental tone from the rotor alone source to cut on while the tone from the rotor-stator interaction should cut on near the fan design speed.

The purpose of reviewing these data is to try to develop a consistent picture of the impact of forward velocity on fan source noise including those aspects that need further study. Figure 2 compares the in-duct spectra from each of the fans for static and forward velocity operation. Figure 3 shows the far field spectra measured in the wind tunnel. The comparisons are made at a subsonic tip speed typical of aircraft approach engine speed and at a higher tip speed nearer to takeoff speed.

Broadband Noise

At first glance at figures 2 and 3, the chief difference between these spectral pairs is the substantially reduced level across the spectra seen in the flight data for the CF6-50 engine at both speeds. This general decrease in broadband noise does not occur in any of the other spectra including the far field data for rotor 55. Some smaller reductions are seen over more limited spectral ranges that are often within the tone skirts. It would seem that the inflow cleanup pictured as the cause of the in-flight reductions, should reduce broadband noise; however, the bulk of the data seem to suggest otherwise. This result suggests that the source of broadband noise is dominated by another mechanism such as rotor-stator interaction or inlet boundary layer turbulence interacting with the rotor.

Turbulence in the rotor wakes interacting with the stators appears to be a highly likely source for the broadband noise. Hanson quotes results by Clark and Mugridge which show that the rms turbulence velocity in the rotor wakes is equal to the mean wake velocity defect.[9] This result has also been obtained more recently by Lakshminarayana.[10] Further support for rotor wake turbulence as the source of broadband fan noise is found in the results of a recent experiment to reduce fan noise by increasing the stator chord length (increasing the stator length reduces the response of the blade to incoming flow perturbations).[11] Reductions of up to 5 dB were observed over a range of broadband spectral regions when the stator chord length was increased. This result was observed in ground static testing where the blade passage tone level, since it was not reduced by increased stator chord, appeared to be totally controlled by inflow disturbances. Thus, in the presence of considerable inflow disturbance, broadband noise appeared to be controlled by rotor wake turbulence via the rotor-stator source mechanism.

Fan broadband noise has been observed to be quite sensitive to changes in the particular operating line or loading of the fan.[12] An example of the effect is shown in figure 4 where one-third octave sound power spectra over the inlet quadrant are shown for the NASA Lewis QF-6 fan stage at four operating lines and a single fan speed.[13] The data show a regular increase in the broadband spectral content as nozzle area is reduced (as the stall or surge line is approached). In this sequence the angle of incidence of the air to the rotor blades and thus the blade loading are continually increasing. The fundamental tone level shows no change while the tone harmonic levels increase somewhat over this range of parameters.

These results are quite revealing with regard to the sources of the noise. The lack of loading effect on the fundamental tone is consistent with a dipole source model involving inflow disturbances interacting with the rotor. In the dipole model there is no coupling between the steady blade loading and the unsteady flows for the rotor alone. On the other hand, the loading effects on the tone harmonics and broadband noise are consistent with a dipole model for rotor-stator interaction. In this case the loading effects appear through the increase of the rotor wake velocity defect and turbulence which are known to increase with loading. In reference 12 it is postulated that the broadband source is due to the rotor alone. It is possible that if a fan stage were operated with low loading (far from stall), that the resulting low levels of broadband noise from the internal sources would allow the effects of forward velocity on other broadband noise sources to be observed. Perhaps such a low loading condition accounts for the observations made for the CF6-50 engine.

From the foregoing discussion, it appears that the most general conclusion regarding fan broadband noise is that forward velocity has little effect on this source noise component because it is controlled by a source not flight dependent such as rotor wake turbulence interacting with the stators.

Tone Noise

A closer examination of the spectral comparisons of figures 2 and 3 shows that with forward velocity the level of the fan fundamental tone is reduced compared to the static test level. This result is displayed more clearly in figures 5 and 6 where the fundamental tone sound pressure levels are plotted as a function of fan tip relative Mach number. Here the fan data follow several different patterns.

The data for the CF6-50 engine show a reduced in-flight tone level throughout the range shown. In fact, the reduction is somewhat greater for tip relative Mach numbers greater than one where the tone due to the rotor alone source can propagate and where multiple pure tones are possible. In contrast, data for the CF6-6, RB211, and JT8D refan engines show the largest reductions at the lower speeds with substantially diminished reductions at tip relative Mach numbers near and greater than one. This convergence of static and flight tone levels at high tip speeds has been rationalized by arguing that shock related multiple pure tone generation should be insensitive to inflow conditions. Yet questions remain. Are multiple pure tone levels accentuated or diminished in flight? Reference 5 argues that they are increased. Does the presence of acoustic treatment in these inlets (all except rotor 55) change the apparent source characteristics?

The rotor 55 data (fig. 6), all at low values of tip relative Mach number, show a wide divergence between forward velocity and static conditions. A third curve, representing the broadband noise at the blade passing frequency, is also shown. It can be seen that the tone level is not far above the broadband level over much of the operating range. In this fan with clean inflow, the only fundamental tone source, rotor-stator interaction, exceeds the cutoff speed at a tip relative Mach number of about 0.9. The very low tone level at and above this speed suggests that the rotor-stator source, while above cut-off, propagates upstream very weakly, possibly the result of the rotor-stator spacing which was one rotor chord. A similar situation exists for the JT8D refan engine where the fundamental tone was reduced several dB in flight even though the inlet guide vane-rotor source tone can propagate. The effect of sound transmission through the upstream blade row is another consideration that may enter into the behavior observed.

The rotor 55 data and the JT8D refan data may be the best indication of the true levels of blade row interaction noise. The rotor alone source is cutoff and with clean inflow the chief tone source remaining should be blade row interaction. As was already mentioned this spacing was equal to one upstream chord length for rotor 55 while it was nearly two chord lengths for the JT8D refan engine. Recent wake decay results obtained by Lakshminarayana[10] show a decay rate higher than the rate from the often used Silverstein[14] results for an isolated airfoil and, therefore, the interaction noise should also fall off at a faster rate. The results all point to the need for experimental data on blade row spacing including aft noise levels in a clean inflow environment to clearly establish the effect of this parameter. The present data suggest that this source may be weak enough so that unnecessarily large blade row separations have been employed for tone noise reduction purposes.

The remainder of the spectra, mostly consisting of tone higher harmonics, show no consistent effect of flight which could be generalized from the limited published data. Since higher tone harmonics include rotor-stator interaction as a source, the arguments applied to the cut on fundamental tone in terms of spacing and blade row transmission apply.

Other Characterizations of Flight/Static Effects

One of the interesting findings differentiating flight and static noise is the reduction in tone unsteadiness observed in going from static to flight conditions. This result is taken to substantiate the finding that the source of tone noise in static testing is unsteadiness of the inlet flow that is alleviated in flight. It is not clear that the unsteadiness is due solely to atmospheric turbulence in the inflow as opposed to fluctuations in the other possible sources mentioned earlier in reference to figure 1, but this is one possibility.

Another result is shown in a comparison of the directivities of the different spectral components. These results are from the 9x15 tunnel tests of rotor 55.[7] Detailed spectral directivities from flight experiments are not published and the problems encountered in obtaining such data in any accurate form are formidable.

Figure 7 shows directivities, measured with and without tunnel flow, of the fan first and second harmonic tones and two broadband regions represented by 1/3-octave bands, at 0.7 and 1.4 of the fan fundamental tone.[7] The amplitude width of the bands is related to the unsteadiness of the sound. The directivities, excluding that for the second harmonic with tunnel flow, are remarkably smooth and similar to each other in their variation with angle. The level decrease with angle is somewhat greater with tunnel flow than it is statically. The smoothness of the directivity patterns suggests a multimodal noise source and the flight-static change suggests that the forward velocity may have eliminated some of the modes near cutoff that were contributing to the levels near 90° in the static case.

The directivity of the second harmonic tone, with its lobular appearance, suggests that only a few modes are present, presumably the five possible from rotor-stator interaction. These results will be considered again in relation to suppressor design.

Before leaving figure 7, we note that the second harmonic measured statically was also quite unsteady and that it became steady with essentially no reduction in average sound pressure level with tunnel flow. Apparently the two sources of this tone, inflow disturbances and rotor-stator interaction, were nearly equal strength so that elimination of the unsteady source produced no mean level reduction. In fact the switch from many to a few modes indicated by the directivity change implies a profound change in the second harmonic generation processes. It is possible that the rotor wakes and, therefore, the rotor-stator interactions are strongly modulated and altered in strength by inflow disturbances.

A third interesting finding is the relatively small forward velocity required to bring about the flight effect on noise. Figure 8 shows the decrease in mean tone level as a function of tunnel speed for rotor 55[7] and as a function of flight speed for the RB211 engine.[3] It is interesting that two such diverse experiments should give such similar results. Both showed a rapid initial reduction of tone level with increasing forward speed with a knee in the curve at about 15 m/sec or less. As forward speed was increased above 15 m/sec very little or no further reduction in tone level was observed. Again, the data do not reveal which of the possible sources of unsteady flow are involved and what their relative importance is. Perhaps the two experiments really are not so different, but are from similar environments where a common effective noise producing source is present. Other static test installations, such as outdoor engine or fan stands with all their support structure or anechoic chambers, where the fan stage is mounted through the wall of the chamber whose walls aspirate to supply inlet air, certainly seem to be different in an overall sense. As was mentioned earlier, the lack of knowledge of the importance and strengths of possible sources of unsteady flow is felt to be a deficiency in our understanding that will be particularly important when selecting a passive control system (honeycomb or screens) for simulating flight behavior statically. The sense of this statement is that, while the sources all take the form of some kind of inflow unsteadiness or disturbance, one will still have to know if the disturbance is localized in a single or few regions within the inlet or whether it is a random disturbance occurring throughout the inlet flow field (i.e., the difference between atmospheric turbulence and a ground vortex or structure generated wake). The alternative is to design the system for the worst case with all types of disturbances present.

While substantial reductions in fan noise have been effected with forward speed, it has been difficult to increase fan noise deliberately in the same baseline static test installations under discussion. For example, experiments have been performed in an anechoic chamber to evaluate the influence of turbulence generating grids[15] and the effect of a ground vortex[16] on fan source noise. In the first case, tone levels that were expected to increase with the turbulence grids present did not change. Some increases in broadband level were observed. In the second case two strong ground vortices located to each side of the 6 o'clock position in the inlet caused increases of 2 to 4 dB in fundamental tone power. The vortices were generated by a ground plane located 0.9 inlet diameter below the inlet centerline which placed it in contact with the inlet lip. Other attempts to influence the tone noise from a fan stage in a static test facility have resulted in the same lack of impact. The behavior suggests that the naturally occurring inflows are already so unsteady or disturbed that any further increase in noise requires a large change in disturbance level. It seems incredible, in view of the widely disparate test installations, that there could be a single controlling disturbance such as atmospheric turbulence or a ground vortex, common to all cases. We reiterate the feeling that any passive control device will have to be customized for the particular installation, a problem of practical concern. Forward velocity represents a unique solution that eliminates the flow disturbances from all of the different sources possible. This suggests that active flow control schemes to alter the flow field in the vicinity of the inlet lip, short of the creation of the full forward velocity flow field, deserve exploration.

Theoretical Effects

There have been several theoretical studies of the effects of inflow distortions and turbulence on fan source noise.[15,17-23] Both dipole and quadrupole noise source mechanisms have been studied, singly and combined. We are interested in what these theoretical results show about the dependence of noise on the different parameters describing the inflow disturbance. These studies differ in details and direct comparisons are difficult to make. Some generalities appear to be possible, however.

The relevant parameters in the theory include the axial and transverse extent of the disturbances and the strength of the associated flow perturbations. In the case of turbulence, scales and intensities specifying the degree of anisotropy are key, while for spatially fixed disturbances such as ground vortices or facility wakes, an axially persistent velocity defect of specified width characterizes the inflow.

Three general theoretical results may be summarized as follows:

First, the sound power produced by the rotor/inflow disturbance interaction is proportional to the disturbance energy, that is, to the square of the turbulence intensity or to the square of the magnitude of the wake defect. Second, the bandwidth of the acoustic energy generated is inversely proportional to the axial extent of the disturbance. Long axial turbulence scales or persistent wake defects produce narrow tones at harmonics of the blade passing frequency since the blades consecutively cut the disturbance many times emitting a relatively long pulse train. Conversely, short axial perturbations produce brief, relatively erratic acoustic pulses which are rich in broadband spectral content. Finally, given relatively long axial scales, there are preferred values of transverse scales which maximize the conversion of turbulence energy interacting with rotating blades into radiated acoustic energy as shown in figure 9.[20,22] As transverse scale is increased beyond the peak, blade response and the number of disturbance-coupled circumferential duct modes which propagate decrease toward the limit where no sound is generated because disturbance size exceeds the fan diameter and the flow is uniform with respect to the fan disk. On the other hand, as transverse scale becomes small with respect to fan radius, the number of circumferentially propagating modes which are potentially excited increases but the correlation area for radiation from the blades becomes negligibly small and sound levels decrease.

Beyond the obviously implied approaches to controlling inflow by reducing streamtube contraction and decreasing disturbance magnitude and axial scale, the theoretical results suggest that passive inflow control devices must result in transverse scale lengths which do not strongly couple to blade response. A device optimized for a given fan design may be less effective for a different fan scale and blade number. Correlation of the results of more thorough parametric calculations with the existing models are desirable to better define the interplay of scales and intensities in determining generated noise levels and to suggest the most fruitful inflow control strategies.

Impact on Flyover Noise

An important practical concern is the extent to which the source noise changes observed in flight affect community noise. Since the dominant flight effect seems to be the reduction of the fundamental fan tone, a calculational exercise was performed to determine the impact of this reduction on perceived noise. Also we wished to see if spectral placement of the tone could be used to advantage in low noise fan design. The exercise was performed on the 1/3-octave fan noise spectra shown in figure 10. This spectrum resembles that measured statically for fan A of the NASA Lewis Quiet Engine program. The data were for 80% of the fan design speed (tip relative Mach number, 0.96) and were for the peak inlet noise angle. At this speed the fundamental tone due to rotor-stator interaction is cut off; the spectrum shows the strong fundamental tone due to infloe disturbances.

Also shown in the figure is a "flight" spectrum in which the in-flight inflow cleanup has been credited with an 8 dB reduction in the fan fundamental tone. These two spectra were translated in frequency so that the blade passing tone was centered in each 1/3-octave band from 0.5 to 8 kHz. In each case the perceived noise PNL and tone corrected perceived noise PNLT were calculated to yield the comparisons shown in figures 11(a) and (b), respectively.

Both measures show a relatively weak dependence on the spectral centering for the static case. The highest values occur when the spectra are in the frequency range of greatest annoyance and then fall off when they are either less than or greater than this range, an expected result. There is no great gain to be made in selecting the blade passing tone to be in any 1/3-octave band between about 1 and 4 kHz based on the static data. On the other hand, both measures show that the "flight" data diverge from the static data as the spectrum center is increased beyond about 2000 Hz. These differences, static-flight, are shown for both noise measures in figure 11(c). The reduction in PNLT is seen to be about 3 PNdB up to a center frequency of about 2 kHz, increasing to a peak reduction of about 7 PNdB for the spectrum centered at 4 kHz. This range of reductions in PNLT is in agreement with that reported by Merriman, et al.[4,5,24] The result indicates the significant contribution of the fan source noise reduction toward reconciling the reported discrepancies between the time histories of flyover noise measured in flight and those projected from static data.

The results also suggest that locating the blade passing tone in the range of 3 to 4 kHz and designing for its cut-off due to forot-stator interaction could be advantageous from a community noise standpoint. The reason for the result is that the fan second harmonic is then at 6 to 8 kHz, beyond the frequency range of maximum annoyance. The weak fan fundamental in flight is not a major contributor. The foregoing ideas should also apply if the flight effect did not occur and if its role were replaced by acoustic treatment.

These conclusions may be too general. They pertain to inlet noise only. Very little has been published about the impact of flight inflow cleanup on aft fan noise. The meager data that are available suggest that the aft reduction also may be limited to the fan fundamental tone.[4] If community noise is aft controlled, as it appears to be for most published flight data, then the reductions in aft PNLT must be comparable to reductions in inlet PNLT or the net flight effect will not impact the Effective Perceived Noise Levels greatly. This question needs further examination. The most recently published comparisons of flight and static projected time histories suggest that some discrepancies in aft noise reported earlier[4,23] have been reconciled.[5]

Implications for Suppressor Design

The almost trivial conclusion that the supressor be designed from consideration of the in-flight source noise spectra carries with it the idea that less attention will be given to fan fundamental tone suppression if the rotor-stator source is cut off. There is more, however. The questions as to what the in-flight modal structure is and whether it differs in the static test environment must be addressed.

It has been recognized for several years that one of the very weakest links in the use of supressor theory was thelack of knowledge about the modal content of the input wave generated by the fan. Lack of this knowledge led to arbitrary input choices including modes corresponding to a plane pressure wave, the least attenuated mode, equal modal amplitude and equal modal energy. Recent efforts to identify and characterize the modal structure of fan source noise have been most interesting. In the absence of proven accurate experimental measurements or theoretical calculations of modal structure, NASA Lewis has been attempting to infer modal content by comparison of multimode source models with experimental fan directivity data. Saule[25] found that the far-field directivities of both the first and second harmonics of the blade passing tones of two different fan stages measured statically were reasonably matched by a directivity model that included all the possible propagating modes.

The experimental directivity patterns shown earlier for rotor 55 in the 9x15 tunnel are compared with a multimodal source model in figure 12.[26] The agreement again is reasonably good. The conclusion is that a multimodal souce description, such as equal energy in all the propagating modes, or a similar energy distribution inferred from directivity patterns, describes static and flight sources that are broadband in nature or tones that are controlled by inflow disturbances. The exclusion is for tones, such as the second harmonic in the rotor 55 tests that are controlled partially or totally by rotor-stator interaction or the rotor locked multiple pure tone source. In these cases the source description would include only those modes that can propagate from these respective sources.

Much progress and simplification has been made by Rice[26-31] in characterizing the sound propagation, attenuation by acoustic suppressors, and radiation from multimodal sources. It has been found, for example, that the cut-off ratio, as classically defined, serves to replace and make unnecessary the consideration of individual modes in propagation and attenuation analyses. All modes having the same value of cutoff ratio, regardless of their lobe number and radial content, behave identically with regard to their propagation and attenuation in a soft-walled or hard-walled duct and with regard to their far-field directivity. This finding appears to be a conceptual breakthrough in the handling of fan noise and suppressor design. Preliminary correlations of optimum wall impedance and maximum possible attenuation by a suppressor have been obtained in terms of cutoff ratio.[27,28] Supressor design strategies have been developed for multimodal sound sources using the power gained from these correlations. The use of cutoff ratio to replace individual modes has also been found to lend itself nicely to the description of multimodal sources having an arbitrary distribution of energy including equal energy per mode as a special case. This is achieved by the addition of an exponent on cutoff ratio in the describing equation[26] whose value determines the degree to which the energy distribution is biased toward the modes nearer to cutoff. The inferences about the source noise mode structure drawn for both forward velocity and static test conditions, feed into these theoretical suppressor results to allow designs that are, in principle, matched to the source characteristics.

Concluding Remarks

The discovery and evaluation of flight effects on fan source noise, while pointing to large problems with static testing of fans, have been a constructive influence in reestablishing confidence in such long-standing theoretical notions as cutoff and rekindling interest in attacking fan noise at its source. There is now reason to reevaluate old noise reduction concepts and to pursue new ones. Techniques and procedures must be found to allow simulation of the flight environment in static testing. Meanwhile, an anechoic wind tunnel appears to be a useful tool to begin to reinvestigate such fan geometry variations as rotor-stator spacing and clarify forward velocity effects on aft fan noise.

While the flight effects on fundamental tone noise may be exploited by designing for cutoff and choosing blade passing frequency to minimize annoyance, harmonics and broadband remain as components to be suppressed. The limited directivity evidence at hand indicates that the forward velocity environment does not alleviate the need for the suppressor designer to address a source having multimodal character, particularly for broadband noise. A promising new approach to describing such a source approximates the modal distribution as a continuum which can be defined in terms of a single parameter, cutoff ratio. A suppressor design methodolody built around the cutoff ratio approach has been developed.

In sum, recent progress in all these areas discussed has been remarkable and encouraging in our opinion. The agenda for further work includes: analyzing flight data for aft fan noise effects of forward velocity; exercising rotor-inflow disturbance generation models to define controlling parameters describing inflow disturbances which must be reduced and controlled; resolving the seemingly contradictory results concerning the strength of the rotor-inflow disturbance source relative to the rotor alone and rotor-stator sources; and clarifying the impact of inflow disturbances on broadband noise. These are all the objects of recent and ongoing work in this field whose results we await.

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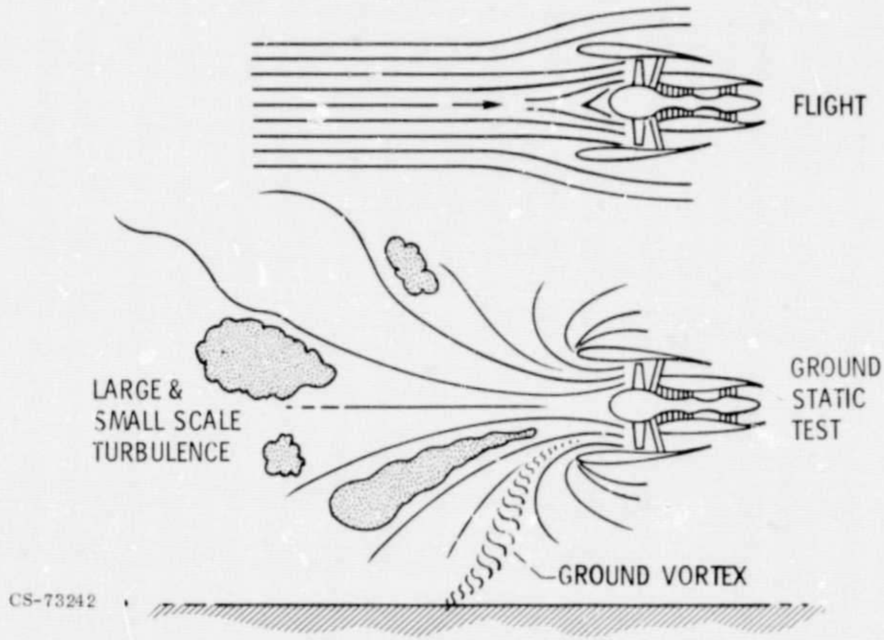


Figure 1. - Effect of flight on inlet flow.

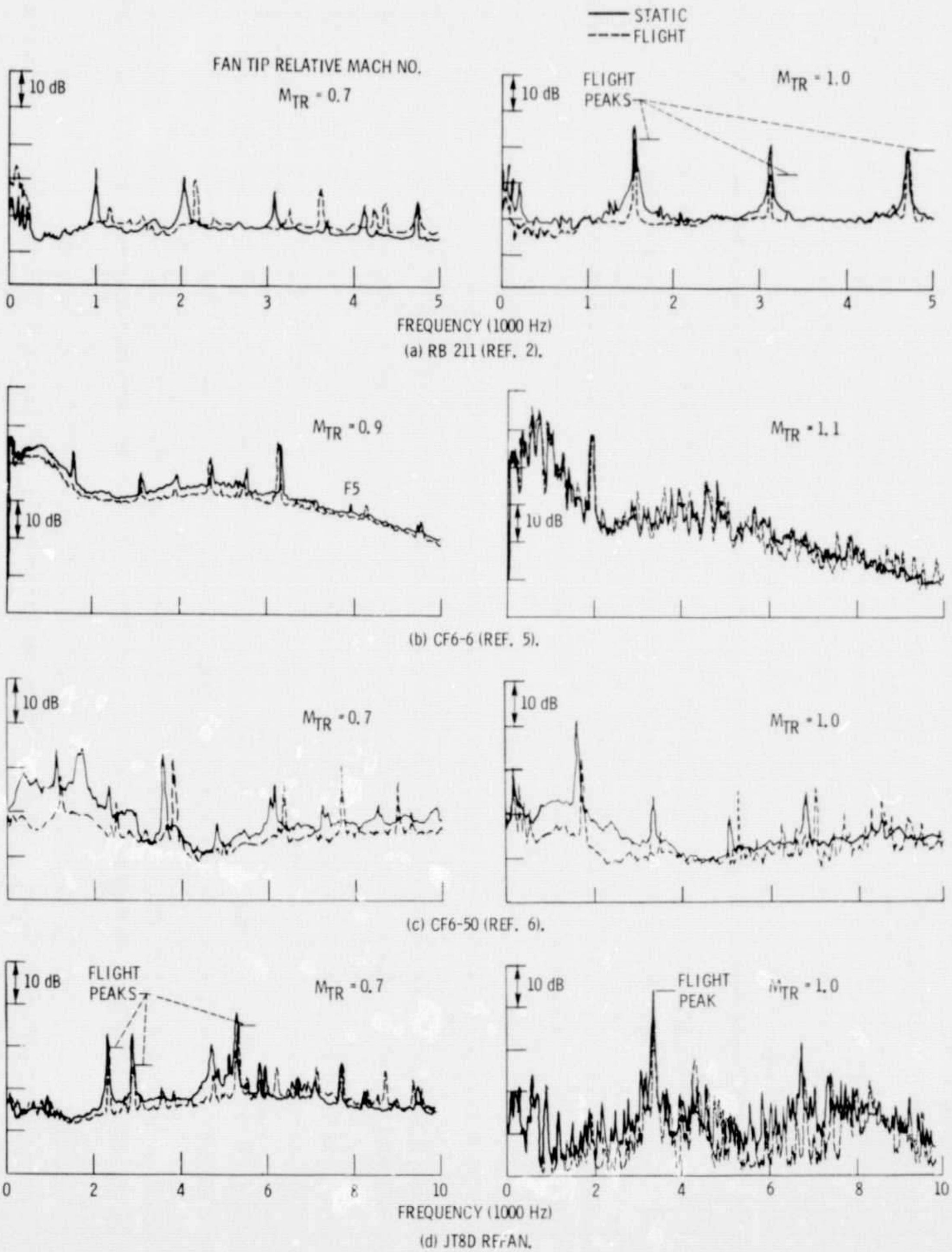


Figure 2. - Inlet wall pressure spectra.

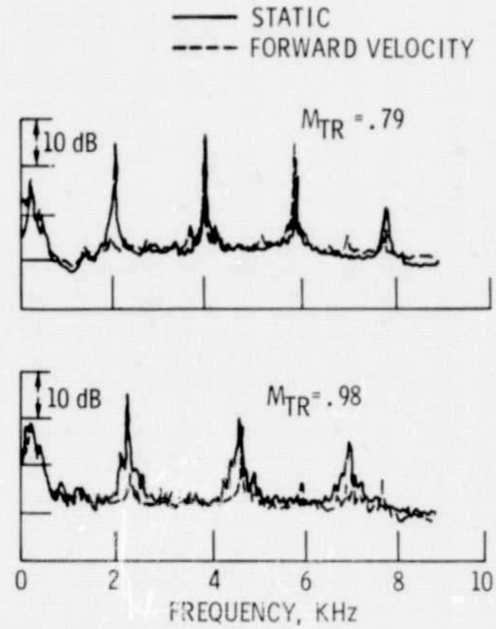


Figure 3. - Far-field spectra in 9x15 wind tunnel - rotor 55 (ref. 7).

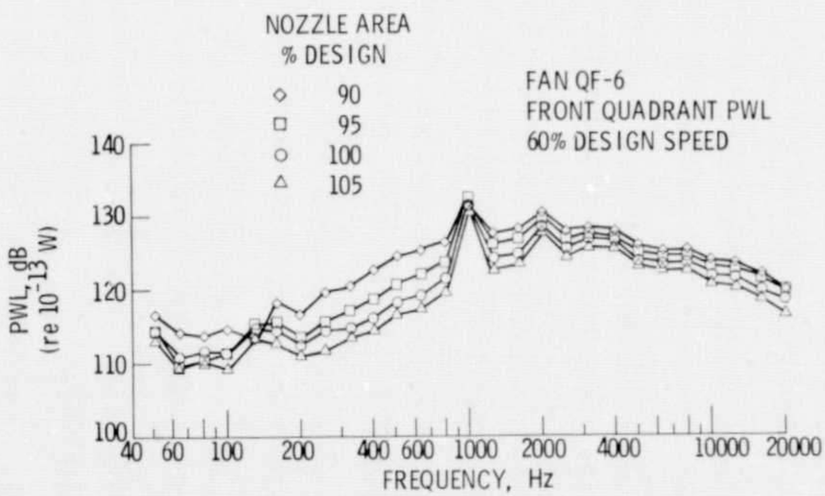
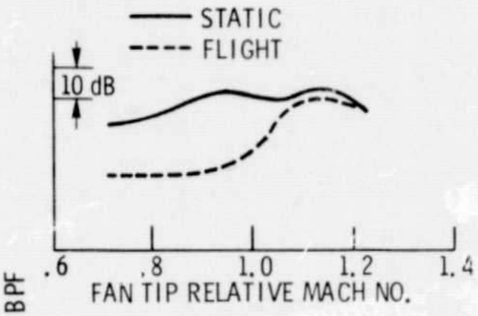
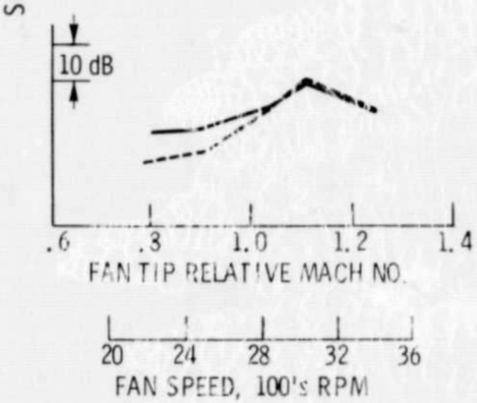


Figure 4. - Effect of operating line on fan noise.

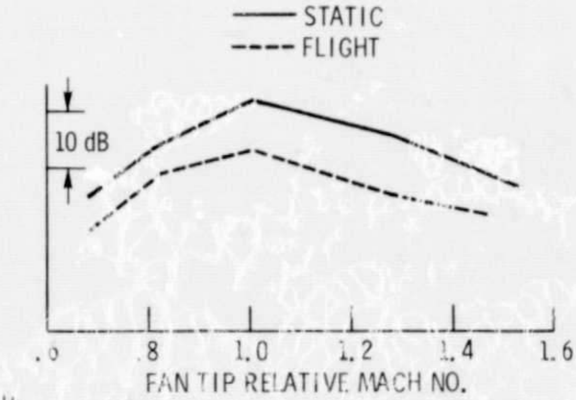


(a) RB211 (REF. 2).

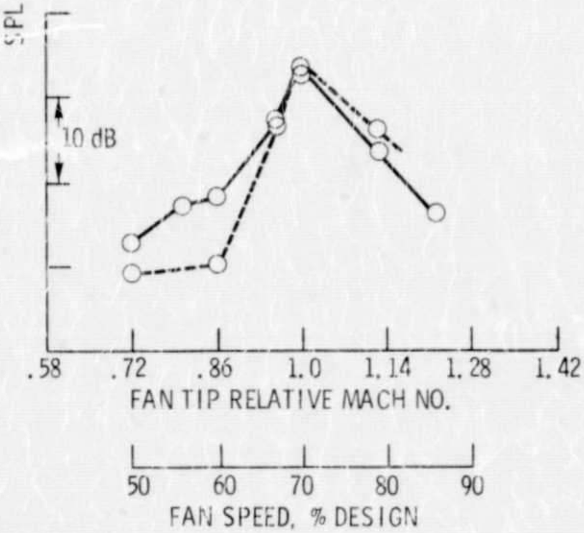


(b) CF6-6 (REF. 5).

Figure 5. - Effect of flight on blade passing tone in inlet duct.



(c) CF6-50 (REF. 6).



(d) JT8D REFAN.

Figure 5. - Concluded.

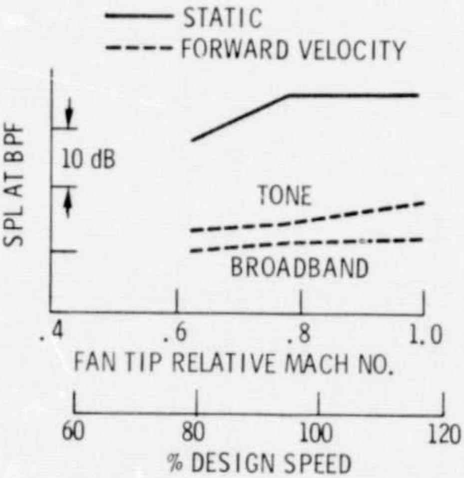


Figure 6. - Effect of forward velocity on far field blade passing tone in 9x15 wind tunnel - rotor 55 (ref. 8).

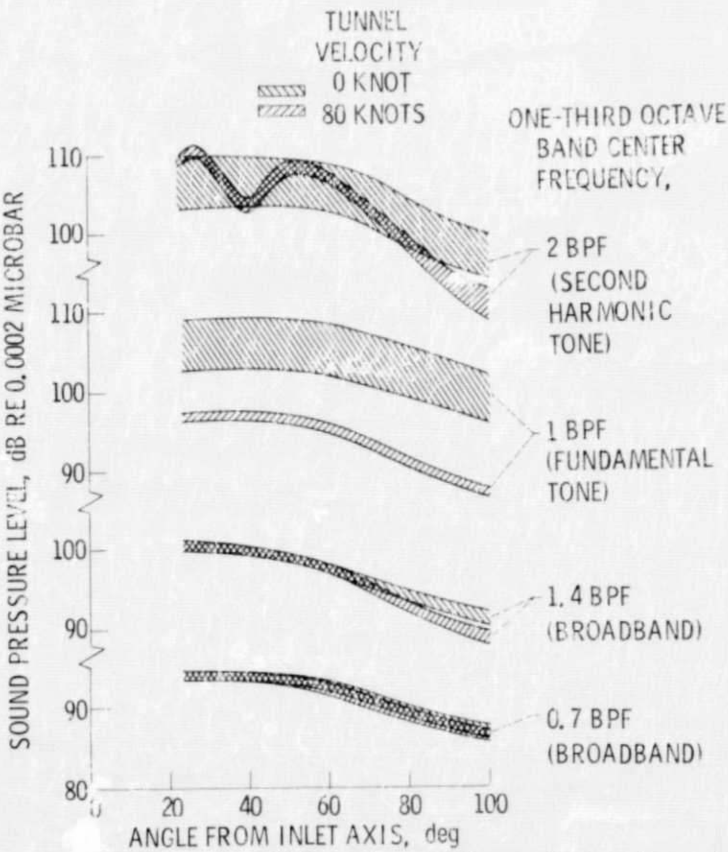


Figure 7. - Directivity and unsteadiness effects of forward velocity (ref. 7).

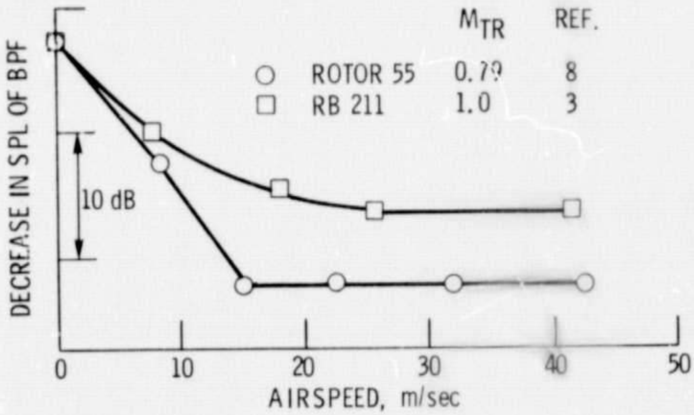


Figure 8. - Effect of forward velocity on blade passing tone. Narrowband data.

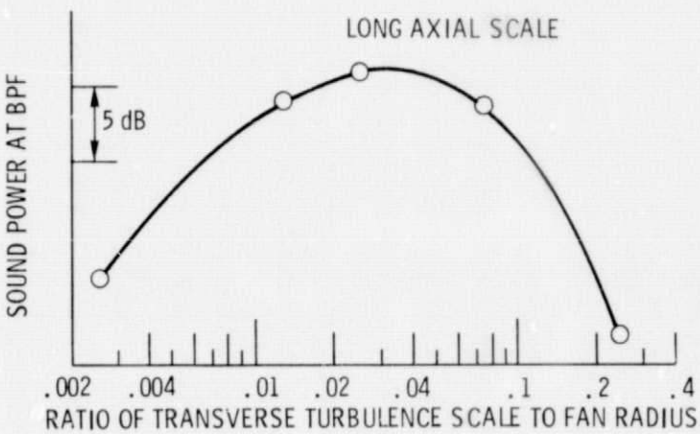


Figure 9. - Effect of transverse turbulence scale on forward radiated tone noise (ref. 22).

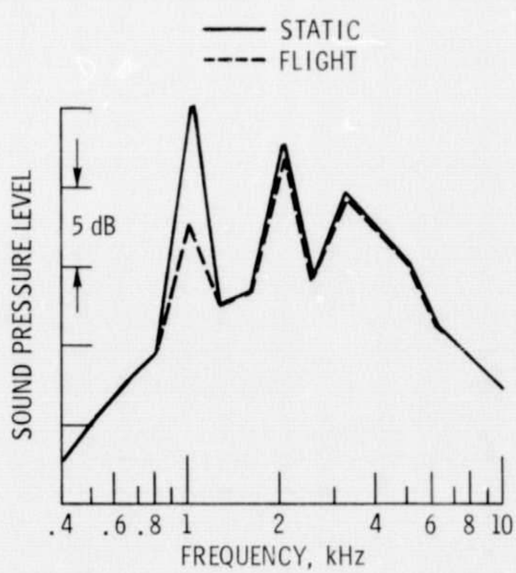


Figure 10. - Spectra used in perceived noise exercise.

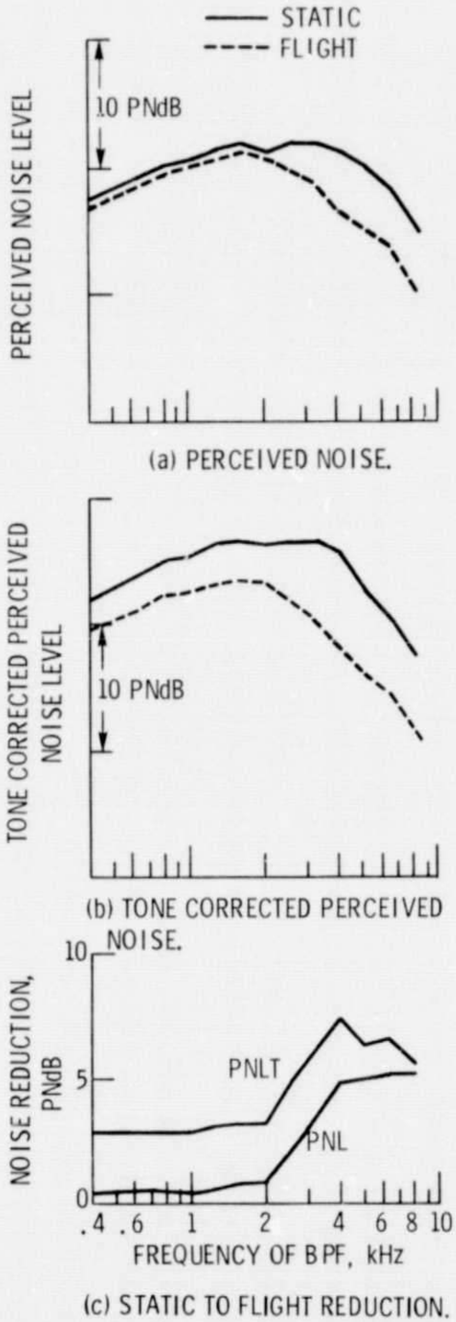


Figure 11. - Calculated effect of flight and spectral content on perceived noise.

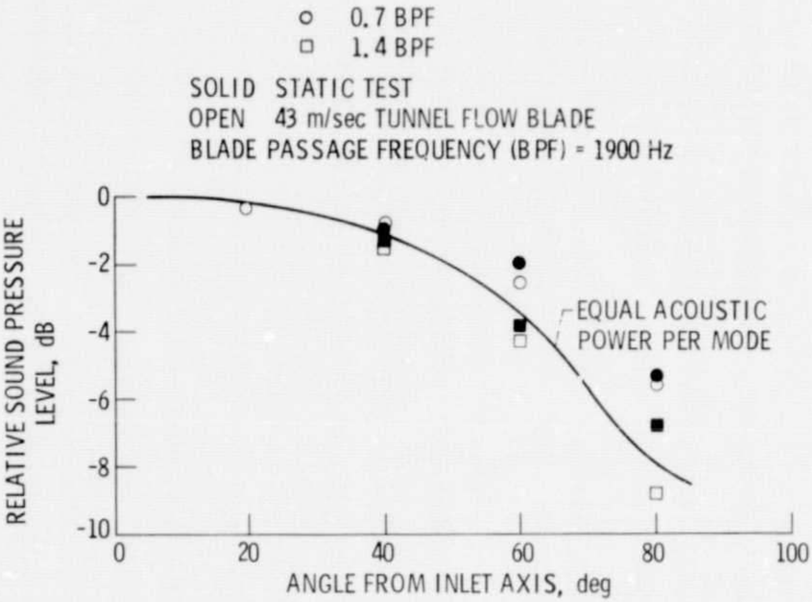


Figure 12. - Comparison of measured broadband directivity to predicted directivity for equal power per mode (ref. 26).