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Flight Noise Simulation in an Anechoic Chamber

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A widely recognized problem in the jet engine industry is the discrepancy between inflight measurements of fan noise as compared to static tests. This discrepancy consists of blade passing frequency tones, caused by ingested turbulence and flow distortions that appear in the static tests but do not appear in flight. An intensive effort has been carried out to devise means by which an anechoic chamber could be employed to yield fan noise data of the type that one obtains in flight. To reduce flow distortions and turbulence caused by wakes, a streamlined inlet is used to quiet the air entering the fan. Inlet casing suction surfaces are incorporated to allow removal of the turbulent boundary layer. Reduction of the midstream turbulence and flow distortion is accomplished by means of a honeycomb and screen combination. This effort has succeeded in reducing the ingested turbulence, to the point where reductions in the acoustic power at blade passing frequency are as high as 18 dB for subsonic tip speeds. Turbulence mapping of the inlet has confirmed that the tone reductions are due to a reduction in turbulence, as the low frequency (large scale) streamwise and transverse turbulent velocities have been reduced by up to four times and ten times, respectively.

Introduction

STATIC facilities for jet engine fan noise testing have consistently shown enhanced blade passing noise in comparison to flight data. Given the difficulties of flight tests, it is important to resolve the sources of this excess noise and affect reductions so that static facilities can accurately simulate the inflight fan noise emissions. This excess noise has been generally attributed to rotor-turbulence interaction. The noise generation due to turbulence impinging on axial fans was first mentioned in the literature by Sofrin and McCann[1] and Filluel.[2] Temporal variations of both amplitude and phase of the blade passing frequency (BPF) signal were observed by Sofrin and McCann. Filluel reduced the blade passing frequency sound pressure level by 5-6 dB by using a smooth bellmouth inlet rather than a sharp-edged cowl ring. Sofrin and McCann also noted that when inlet guide vanes were used, the BPF noise decreased with rotor-guide vane spacing only up to a certain point. Only when the guide vanes were removed did the noise drop to a lower level. Both of the effects were attributed to a reduction of inlet turbulence. The investigators had not, however, addressed the question of static-to-flight noise comparisons. One of the earliest investigators to establish the importance of turbulence on rotor noise and relate this to the flight-static noise discrepancy was Hanson.[3]

From a theoretical viewpoint, the turbulence interaction noise can be divided into two types: the first due to fluctuating lift on the rotor blades (dipole) and, second, the interaction of the turbulent eddies with the rotor-locked potential field (quadrupole). Mani[4] and Pickett[5] have made theoretical predictions of the noise due to fluctuating lift from lightly loaded subsonic rotors. Pickett extended Mani's analysis to include transverse turbulent length scales different from the axial length scale. Pickett was then able to show that the turbulent noise peaked at an intermediate transverse scale. For more highly loaded rotors, Mani,[6] in a more recent analysis, has included the quadrupole contributions. The existence of this quadrupole sound field was first pointed out by Ffowcs Williams and Hawkins.[7]

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Attempts to control the rotor-turbulence noise from axial fans date back to Filluel's work, where the placement of radiators made up of honeycomb-like sections in front of the fan reduced the BPF noise. In an unreported experiment in 1973, Wells[8] used a single fine meshed screen in a nearly spherical form to cover a conventional bellmouth. This screen produced a maximum reduction of 3 dB in the power level of the BPF tone. Boundary-layer suction ahead of the rotor has been tried by Cumpsty and Lowrie,[9] Moore,[10] and Kazin et al.[11] In all of these suction cases, a slot was used to remove the boundary-layer. Generally with no bleed flow, the BPF tone was enhanced. Application of suction did produce a reduced BPF tone level but the reduction was not sufficient to reduce the BPF tone (at subsonic tip speeds) to the broadband level. Considerable progress in tone noise reduction was reported by Lowrie.[12] A combination of boundary-layer suction (via a slot) and a single hemispherical screen was used. Unfortunately, a high degree of variability of tone level occurred with suction, and at no suction the BPF tone level was increased. In a further effort, reported by Lowrie and Newby[13] and Cocking and Ginder,[14] a hemispherical structure of self-supporting honeycomb was used to condition the flow to a subsonic rotor. Cocking and Ginder concluded that even though the reduction in the BPF tone protrusion above the broadband level was significant (up to 10 dB), further reductions of the tone were necessary. The peak angle BPF tones were still protruding about 10 dB above the adjacent broadband level. Two other experimental studies have also been reported. Shaw et al.[15] and Woodward et al.[16] both used a nearly spherical flow conditioner consisting of an outer layer of honeycomb with a fine screen attached on the inner edge of the honeycomb. One study[15] tested a fan in a wind tunnel while the other[16] measured the fan noise in an anechoic chamber. Shaw found that the flow conditioner reduces the BPF tone by about 10 dB but the reduced level was still about 9 dB above what was obtained when the wind tunnel was used to simulate the flight condition. Likewise, Woodward found nearly identical results with a 10 dB reduction in the BPF tone being realized but the tone was not reduced to near broadband levels as had been observed in some flight measurements. As these prior investigations had not reduced the BPF tones of a subsonic rotor to near the broadband levels, a major effort was made in this program to identify and eliminate all the sources of ingested turbulence.

As a result of this effort, three inlet clean up methods were found to be effective and are described in this paper. A flared reverse cone inlet is used to eliminate wakes from the fan casings and/or probe supports. Boundary-layer suction is employed ahead of the fan rotor and on the outer flare of the cone to reduce the boundary-layer turbulence and remove any residual wakes. To reduce the midstream turbulent intensity and length scales, a turbulence control structure, constructed with both a layer of honeycomb and a fine mesh screen, is also used.

To quantify the effects of these clean up methods, the far-field noise is measured in an anechoic chamber, using a high speed fan (50 cm diam) of the current high bypass type. The changes in the turbulent field impinging on this rotor are quantified by mapping the streamwise and transverse turbulent properties (spectra, intensity, and length scale) with crossed hot-film probes. For the sake of brevity, only a limited amount of the turbulence data will be presented; more detail can be found elsewhere.[17,18] These tests are carried out at the General Electric Corporate Research and Development aeroacoustic facility in Schenectady, New York.

Experiments

Experimental Facility

The test vehicle used in this investigation was a 0.504 m (20 in.) diam fan model. The fan design characteristics are given in Table 1. The anechoic chamber was designed to simulate a free-field acoustic arena and provide adequate aerodynamic operation. To achieve the lowest possible amount of inlet distortion and turbulence, the sidewalls, ceiling, and floor are porous. It has been demonstrated in a prior program[19] that such an aspirating chamber arrangement reduces in-flow distortion to the fan.

Test Hardware

To reduce inlet distortion, a flared reverse cone inlet, as shown in Fig. 1, was designed and fabricated. The reverse cone inlet acts as a shroud covering all of the "upstream" hardware associated with the inlet and other test instrumentation. This hardware has, in the past, been identified as a major source of inlet distortion.[19] Along with the addition of the reverse cone inlet, great care was taken to aerodynamically clean up the chamber and remove all objects that protrude into the inlet flowfield, and therefore possibly generate flow distortions and turbulence. For example, the chamber back wall near the inlet was covered with smooth foam panels and the work platform was made removable. To further eliminate flow distortions and turbulence that reside in the boundary layer, the reverse cone inlet was equipped with both internal and external surface suction. The external suction surface is covered with metallic tape when only internal suction is used.

Table 1 Test fan stage design characteristics

Rotor inlet tip diameter	0.50 m (19.84 in.)
Pressure ratio	1.574 (1.37 at DV = 0)
Rotor blade number	44
Stator vane number	86
Vane/blade ratio	1.95
Inlet guide vanes	None
Rotor inlet hub/tip radius ratio	0.50
Rotor-stator tip spacing	1.27 rotor chords
Rotor rotative speed	16,100 rpm
Rotor tip speed	424.9 m/s (1394 ft/s)
Rotor tip inlet relative Mach no.	1.394
Rotor chord (midspan)	4.62 cm (1.817 in.)
Stator chord (midspan)	4.06 cm (1.597 in.)
Rotor aspect ratio	2.5
Stator aspect ratio	2.3
Rotor tip solidity	1.298
Stator tip solidity	1.270
Corrected inlet weight flow	29.5 kg/s (65 lb/s)
Adiabatic efficiency	85.5% (80.9% measured)

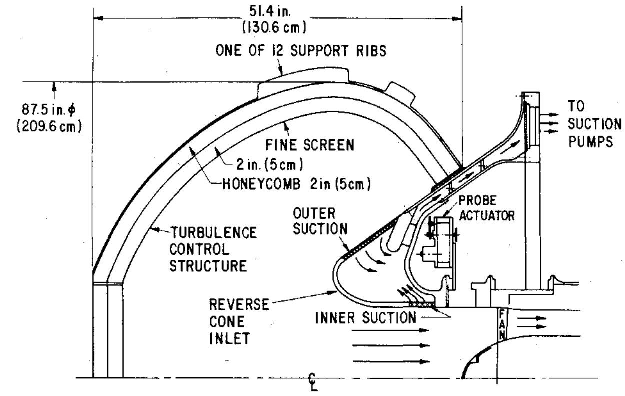

Fig. 1 Assembly sketch of reverse cone inlet and turbulence control structure.

The third inlet clean up element consists of a turbulence control structure (TCS) to condition the inlet flow, also shown in Fig. 1. The TCS used for this program is very similar in size and shape to that used in the earlier work of Shaw et al.[15] and Woodward et al.[16] The major difference is that in this current design, the inner fine screen is displaced 5 cm (2 in.) downstream of the trailing edge of the honeycomb. The design of the TCS and its performance are discussed in a paper by Ho et al.[20] The complete structure was built and installed in such a way as to minimize the wakes from the support structure and, therefore, offer minimal flow distortion and self-generated turbulence.

Experimental Methods

The acoustic measurements were made in the anechoic chamber with an array of 12 microphones. The microphones (B&K Model 4135) were located every 10 deg from 0 (fan centerline) to 110 deg at an arc radius of 5.2 m (17 ft), as measured from the center of the inlet and one rotor diameter upstream from the rotor face (see Fig. 1). The microphones were calibrated by a piston-phone (B&K Model 4220) prior to each run and measured spectra were also corrected for the individual microphone frequency response. The electrostatic actuator method was used for the frequency response measurements. Atmospheric absorption is accounted for via the SAE Specification No. ARP866. No other acoustic corrections were applied to these data.

Circumferential inlet flow mapping was done at several radial immersions and at two speeds. Mean and unsteady components of both the streamwise and transverse velocities were measured via two crossed wire hot-film probes mounted in the inlet just upstream of the rotor. The furthest upstream (movable) probe was mounted in a rotary actuator which was remotely controlled through a 180 deg arc within an accuracy of ±1 deg. By rotating the entire mechanism 180 deg, a full 360 deg inlet survey was provided. With data established in a velocity and temperature calibration, it was possible to adjust each of the hot film's overheat temperatures to compensate for actual test temperature conditions.

All acoustic and hot-film data were recorded on a 28 channel FM tape recorder. Post test data reduction included turbulence spectrum and turbulent scales' via the auto and space-time cross correlations, that are reported elsewhere.[17,18] During the inlet mapping tests, on-line circumferential plots were made of the mean and turbulent velocities.

Acoustic Results

Two basic inlet configurations were tested: 1) reverse cone inlet, and 2) reverse cone inlet with turbulence control structure. Both configurations were tested without any suction and with inside suction. Suction mass flow rates were set as a percentage of fan mass flow and ranged from 5 to 10%. Two types of suction surface liners were used: 1) metal for hardwall or no suction, and 2) feltmetal. Acoustic data were taken at seven corrected speeds (54, 60, 69, 74, 80, 86, and 100%) and one discharge valve setting. At 100% corrected speed, this discharge valve setting (DV = 0) produces a pressure ratio of 1.37.

Flared Reverse Cone Inlet

With the reverse cone inlet installed, the test series included far-field acoustic measurements, inlet turbulence, and mean velocity traverses. Our attention will be concentrated first on the acoustic results and the flow measurements will be taken up later in this paper.

To clarify further discussion, let us digress for the moment and explain what the expected noise characteristics of this fan would be on an idealized basis. For this rotor-stator set operating with a completely turbulence-free inlet flow, there would be two noise source mechanisms. These would be the rotor-stator interaction noise and the rotor-alone noise. The rotor-stator interaction would be caused by the potential field interaction between the rotor and stator and by the rotor wakes impinging on the stator. The blade passing frequency (BPF) noise due to this rotor-stator interaction will not propagate in the inlet duct below a certain rotor speed; this speed is dependent on the rotor blade and stator vane numbers. For this particular rotor and stator, this phenomenon, called cutoff, occurs at about 74% speed. Likewise, the BPF noise caused by the supersonic rotor itself is also governed by the same type of cutoff phenomenon only at a slightly higher rotational speed, about 77% speed. Therefore, it would be expected that with a completely turbulence-free inlet flow this fan would have very low BPF noise below 74% speed. Above 74% speed, the rotor-stator interaction noise and the supersonic rotor-alone noise would cut on and produce high levels of BPF noise. In a nonideal flow, that is one with large scale inlet turbulence, the BPF noise at high speed, above cutoff, would not be significantly affected due to the dominance of the rotor-stator and rotor-alone noise. However, with a turbulent flow, the BPF noise at low speed below cutoff, would be greatly increased above the low levels of BPF noise with a nonturbulent inlet flow.

The first tests were without suction flow and with hard walls replacing the suction surfaces. In this condition, the flared reverse cone produced a 1 dB reduction in the acoustic power level (PWL) at 69% speed and lower, when compared to the standard bellmouth configuration.

To determine the acoustic benefits of a thinner boundary layer, the inner suction surface was used to remove the boundary layer. Comparing these results to those obtained with a standard bellmouth, a maximum BPF tone reduction of about 5 dB is seen at the lower speeds for a 10% inner suction rate. This result indicates that the rotor-turbulence interaction noise is only slightly reduced. At higher speeds, the BPF tone reduction decreases to about 1 dB as would be expected, since in this speed range the rotor-alone and rotor-stator interaction noise are cut on and dominant. In summary then, the combination of a flared reverse cone inlet and a suction rate of 10% of the main flow will result in only a modest 5 dB reduction in BPF tone for this subsonic cutoff fan. This level of reduction is not enough to achieve flight simulation and, therefore, a turbulence control structure (TCS) must be employed.

Flared Reverse Cone Inlet with Turbulence Control Structure

The TCS used to condition the inlet flow is shown in Fig. 1 in its installed position. The effect of the TCS on BPF tone is dramatically illustrated in Fig. 2. Not only are the BPF tones greatly reduced below cutoff (about 74% N) but at supersonic rotor Mach numbers well above cutoff, the BPF noise is not greatly affected by the TCS as one would hope. This indicates that the TCS is not greatly attenuating the fan noise, and that agrees with the calibration of the TCS as given in Ho et al.[20] To briefly summarize the results given in that paper, it may be stated that on a power level basis, the attenuation is less than 1 dB for frequencies less than 16,000 Hz. Above 16,000 Hz, the power level is attenuated by about 1½ dB. The sound pressure level shows a somewhat greater attenuation at the shallow angles, between 20 to 50 deg from the inlet centerline. At the fundamental (3150 Hz) and fifth harmonic (16,000 Hz) of the one-half wavelength resonance of the honeycomb, attenuation levels of 3 dB are reached at 30 deg to the inlet centerline. Most important is that at BPF, the acoustic power level would be attenuated by less than 1 dB by the TCS.

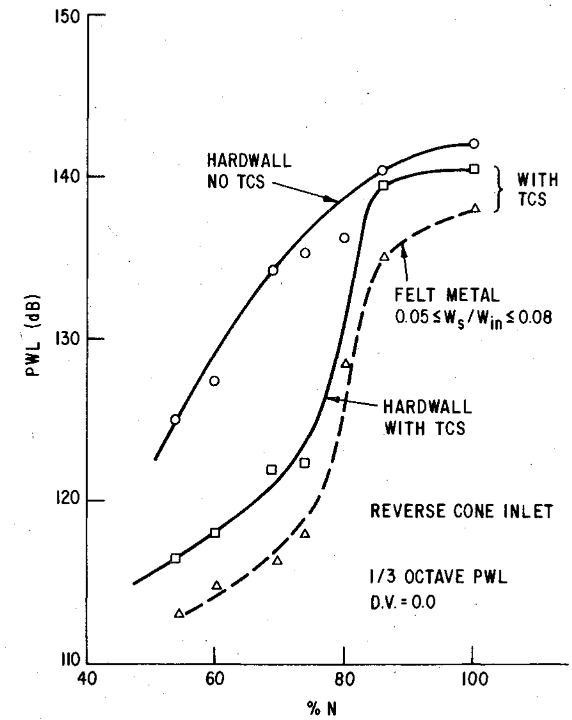

Fig. 2 Effect of TCS and suction on PWL at BPF vs fan speed.

These results give good confidence that the TCS has reduced the inlet turbulence, and hence the rotor turbulence interaction noise generation, and not just suppressed the overall noise emission. The BPF tone reduction due to the TCS is as high as 12 dB at 69% speed. This large reduction in BPF tones due to the TCS compared to the effect of boundary layer suction points to the existence of disturbed flow that is well outside the boundary layer. However, the boundary layer reforms downstream of the TCS and it is possible to bleed off this developed boundary layer to gain a further reduction in BPF tone levels. This effect is also shown in Fig. 2 where an additional 4-5 dB reduction, at rotor speeds below cutoff, is achieved with 5-8% suction using the feltmetal inner suction surface. When compared to the standard bellmouth results (1 dB higher than the hardwall reverse cone inlet), the maximum BPF tone reductions in PWL range from 12 dB at 54% speed to almost 18 dB at 69% speed. Further evidence that these BPF noise reductions are due to rotor turbulence noise source reductions and not any acoustic attenuation due to TCS is provided by the acoustic power spectra data.

The acoustic power spectra shown in Figs. 3 and 4 illustrate the comparative effects of the TCS on the flared reverse cone inlet and the effect of inner suction in conjunction with the TCS. To study the change in acoustic emission, the power spectra is used as it will not be affected by any redirection of the acoustic waves that might be caused by the TCS. For the lowest speed (below cutoff, Fig. 3), the installation of the TCS produces a substantial reduction in the BPF tone while a smaller reduction is seen in the second harmonic of BPF. This is reasonable as the second harmonic is cut on at these low fan speeds and any potential interaction of the rotor and stator can then produce a tonal sound. When suction is applied, it produces an additional reduction in the BPF tone protrusion.

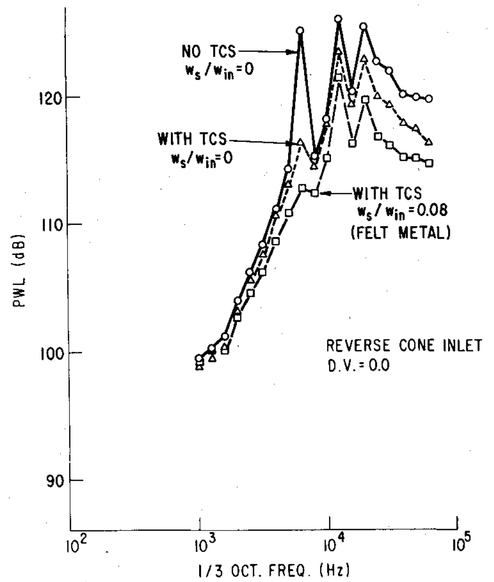

Fig. 3 Acoustic power spectra, effect of TCS and suction, 54% speed.

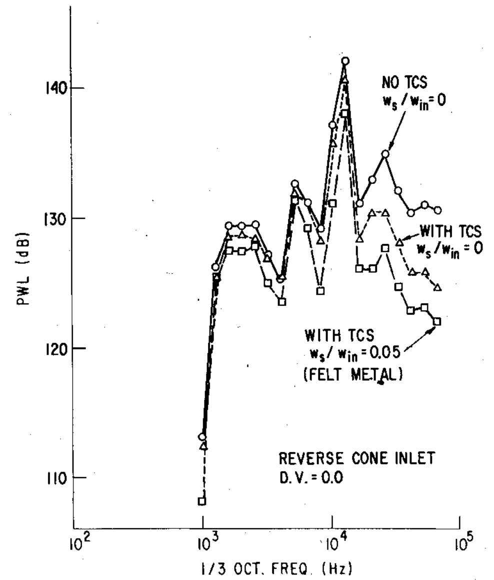

Fig. 4 Acoustic power spectra, effect of TCS and suction, 100% speed.

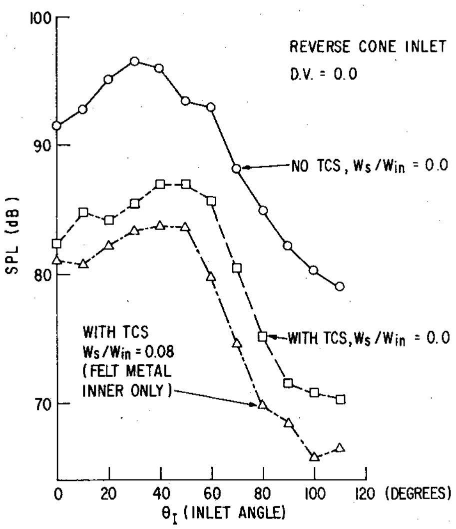

Fig. 5 One-third octave SPL directivity at blade passing frequency, 54% speed.

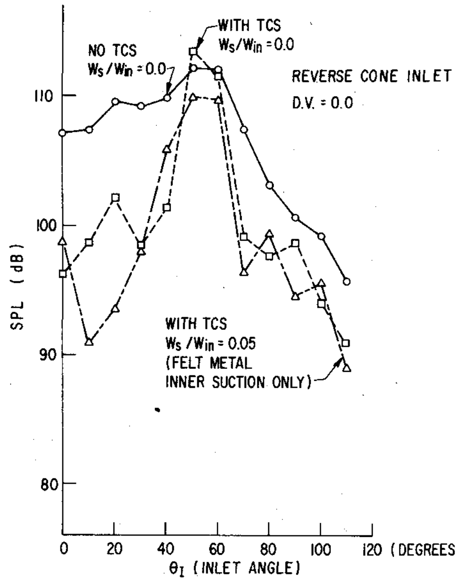

Fig. 6 One-third octave SPL directivity at blade passing frequency, 100% speed.

At the higher speed, 100%, the fundamental BPF tone due to rotor-alone and rotor-stator interaction noise dominates, as one would expect. The effect of the TCS and suction have a lesser effect as speed increases, until at 100% speed only a 1.5 dB reduction occurs with the use of the TCS. This is a very gratifying result as the supersonic rotor-alone noise should dominate at these speeds and should not be affected by inlet turbulence and, hopefully, not attenuated by the TCS.

The change in the random content of the BPF noise with use of the TCS and suction can be seen by studying the SPL directivity. In that study, we will restrict our attention to two of the speeds where the BPF tone is centered in a one-third octave band. Figures 5 and 6 display the SPL at BPF for 54 and 100% speed. At the lower speed, the BPF level is dominated by the narrow band random noise caused by rotor turbulence interaction and exhibits a rather smooth directivity pattern. Employing the TCS and suction cause nearly uniform reductions in SPL at all angles at BPF. At this low speed this is due to the random noise content of the BPF signal and is quite independent of whether it is narrow band (without TCS) or wide band (with TCS) random noise. At the higher speed, application of the TCS and suction again cause changes in the SPL directivity patterns; however, now the SPL levels at $\theta_i = 50$ and 60 deg, where θ is the inlet angle between the far-field microphone and the fan centerline, are practically unaffected by the TCS or suction. This indicates that the peak angle BPF level is dominated by the cut-on spinning modes due to rotor-alone and rotor-stator interaction noise. When suction and the TCS are applied, the net result is sharply lobed BPF directivity patterns as one would expect from a fan that is producing relatively coherent pure tone noise.

Flight-to-Static Noise Comparison

As stated in the introduction, the goal of this effort was to simulate flight noise in a static facility. To measure how well this has been done, let us summarize the general affects of flight on the measured noise signal. One of the most subjective parts of this comparison is what has been removed from the measured flight noise to account for all the other engine and airframe-related noise sources. The intent here is not to provide an exhaustive review of this comparison as that falls well outside of the scope of this paper but rather to use readily available flight-to-static noise comparisons. Perhaps

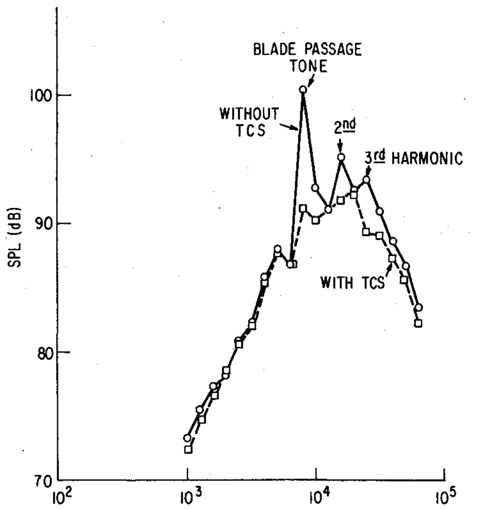

Fig. 7 Sound pressure spectra at $\theta = 70$ deg, effect of TCS at DV = 1.27, 74% speed.

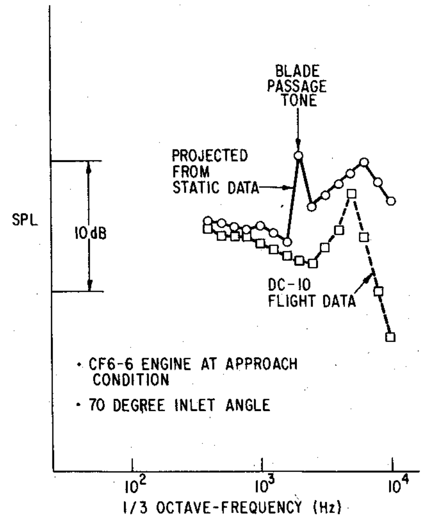

Fig. 8 Noise comparison, flight to static.

one of the most complete studies in this area is that published by Blankenship.[21] Of the data presented in that paper, we will concentrate only on the forward arc noise from a fan running at subsonic cutoff conditions. This is necessary to avoid turbine tones that appear in the sideline noise and cut-on rotor-alone and rotor-stator interaction noise. Restricted to these measurements, the fundamental BPF tone reductions, in going from static to flight data, as reported by Blankenship for the DC-10-10 airplane with the CF6-6D engine, are 7.5 dB at 60 deg from the inlet centerline, at about a rotor tip Mach number of 0.73. For the same rotor Mach number and emission angle, the second harmonic is also reduced by 5 dB. The higher harmonics are likewise reduced, for example, at a slightly higher rotor tip Mach number of 0.83, the third and fourth harmonics were reduced by 3.5 and 5.5 dB, respectively. Unfortunately, Blankenship[21] did not include the higher harmonic tone reductions at the lower rotor Mach number (0.73); however, the second harmonic tone reduction went from 5 dB to 2.5 dB when the rotor tip Mach number increased from 0.73 to 0.83, indicating that the other higher harmonics may have behaved in the same manner and shown lower flight reductions at a higher tip Mach number. Similar reductions in the fundamental BPF tone and its harmonics in flight data with respect to static data, as reported by Blankenship, have been reported by Lowrie[12] (for the Rolls-Royce RB211) and by Feiler and Merriman[22] (for the General Electric CF6-6). These flight measurements seem, then, in general agreement, in that the fundamental of the blade passing tone of subsonic cutoff fans is barely visible (0-2 dB) above the surrounding broadband level and the higher harmonics also protrude only slightly (2-3 dB) above the surrounding levels. This is observed only in the forward arc and with one-third octave band filtering.

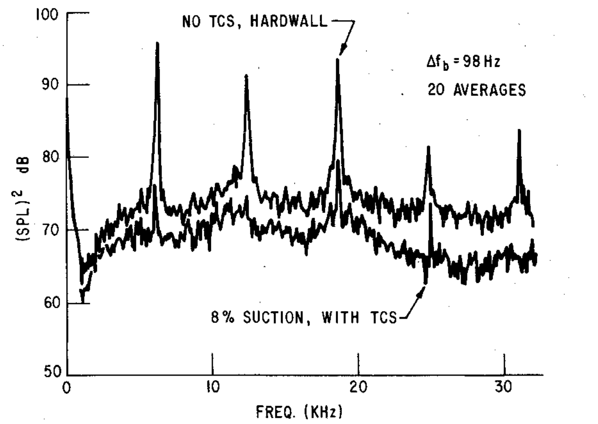

Fig. 9 Narrow band $(SPL)^2$ spectrum at $\theta = 60$ deg, outer hardwall, 54% speed.

Has simulation of in-flight fan noise data been achieved in this facility? With respect to the protrusion of BPF fundamental tones, it would appear so. For the higher harmonics of BPF, the evidence is not as conclusive. However, it is informative to compare results from this effort, Fig. 7, with the previously reported static-flight comparisons of Feiler and Merriman,[22] Fig. 8. At the harmonics of BPF, there is reasonable agreement of magnitude of tone reductions. For the in-flight data shown on Fig. 8, it appears that a turbine blade passage tone harmonic is appearing at 5 kHz, midway between the fan second and third BPF harmonic. This turbine noise is pointed out by Blankenship[21] and indeed comparing to Fig. 24a of Blankenship's paper will reveal a remarkable similarity to the results shown on Fig. 8.

Narrow Band Spectra

To quantify further the reduction in tonal content of the far-field acoustic signal, a series of sound pressure squared $(SPL)^2$, narrow band spectra are presented in Figs. 9 and 10. Two different test conditions are shown in this set of figures: first a hardwall inlet without the TCS and, second, the feltmetal suction inlet with the TCS. For each fan speed, the narrow band spectra for both the inlet configurations are overlaid; for the high speed case, a 20 dB separation is necessary for clarity. In Fig. 9, where neither the TCS nor suction are employed, strong tones at BPF and multiples of BPF are seen for subsonic tip speed conditions. These tones are reduced when the TCS is employed along with an 8% inner suction rate, as seen in Fig. 9. At 54% speed, the total reduction in the BPF tone is 19 dB while the surrounding broadband is reduced only 5 dB. Approximately 1-2 dB of this broadband reduction is probably due to treatment effect of the suction liner. This remaining 3-4 dB is most likely due to the thinning of the boundary layer and subsequent reduction in the wide band noise of the rotor tip interacting with the small scale turbulence in the boundary-layer flow.

Substantial reductions of the other harmonics of BPF also occur when the TCS and inner suction are employed. For the supersonic tip speeds 80% and above, the supersonic rotor-alone noise dominates and the tone levels are increasingly independent of the presence of the TCS and suction as the rotor approaches 100% speed. This can be seen in Fig. 10. The main effect of the TCS and suction is to reduce the noise in wide frequency bands without significantly reducing the

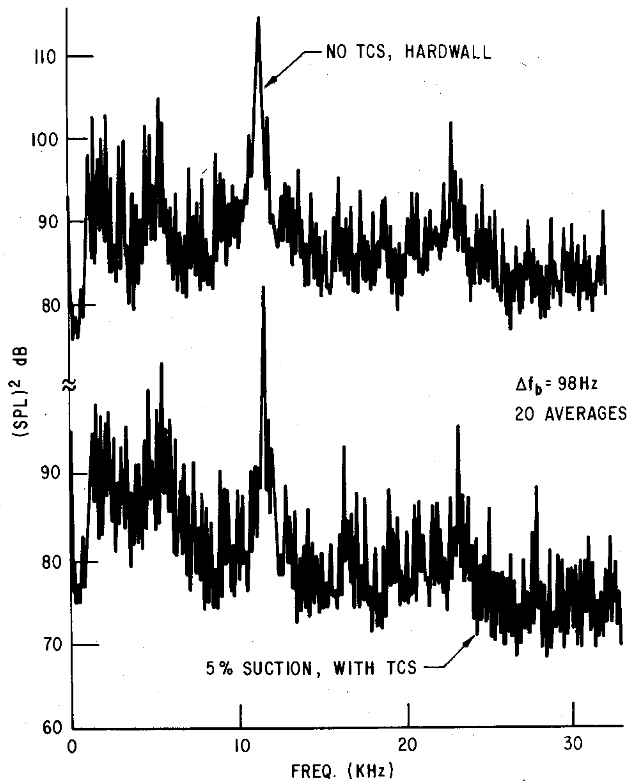

Fig. 10 Narrow band $(\mathrm{SPL})^2$ spectrum at $\theta = 60$ deg, outer hardwall, 100% speed.

BPF tone and its second harmonic. At 100% speed, the broadband level near the fundamental of BPF is reduced by some 8 dB and near the higher harmonics the noise reduction is about 10 dB. This decrease in wide band noise with frequency is probably due to the increased attenuation of TCS at these high frequencies.

These high-speed results are in complete agreement with the viewpoint that with a supersonic rotor tip speed, the tonal content is governed by the rotor bow shock pattern and its subsequent upstream distortion and the broadband content is primarily due to the interaction of the rotor tip with the turbulent boundary layer. The fact that this inlet clean up method greatly reduces the tonal content below cutoff and does not substantially alter it above cutoff proves that the flight quality fan noise data can be simulated in a static test facility.

Hot-Film Results

In order to determine the state of the flow impinging on the rotor, hot-film surveys of the inlet were taken. A rotary actuator was used to traverse a crossed film probe around the circumference at a given radial immersion. The fan speed was restricted to the lowest speed, 54% of corrected design speed. There are three reasons for this. The first is that the higher level acoustic signals at the high speeds could cause acoustic contamination of the turbulence measurements and, second, that probe life decreases dramatically at high velocity. Third, since in this effort we are trying to characterize the turbulent state of air ingested by the fan, it was felt that fan speed should not have a large effect on the turbulent intensity and length scales. However, the effects of the TCS and the boundary-layer removal on the turbulent condition of the inlet flow are of very definite interest.

The outer suction surface was covered with metallic tape and only the inner feltmetal suction surface was employed. Two crossed hot-film sensors, at an immersion of $\Delta r/R_0 = 0.25$, were used so that the circumferential length scales could be determined. A 12 min time record was taken to allow spectral resolution below 1 Hz and determination of large eddy sizes. When data were taken, on-line plots of the circumferential distributions of the mean and fluctuating velocities for both the streamwise and transverse directions were recorded. For these real time x-y plots, a 4 kHz low-pass filter was used to suppress any BPF acoustic perturbations and probe vibrational effects that might show up on these plots. For the analog tape recording to be used in the off-line spectral and correlation measurements, this low-pass filter was not used.

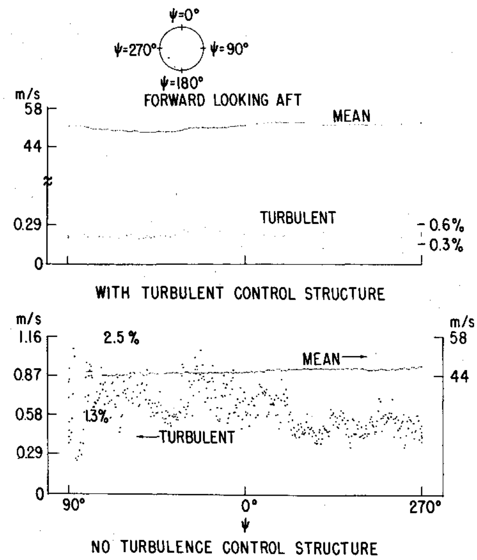

Fig. 11 Circumferential distribution of mean and fluctuating axial velocities, 54% speed, $\Delta r/R = 0.25$, no suction.

A discussion of the on-line measurements will be presented before going into the length scale data; again more details are available elsewhere.[17,18]

This paper will consider only the case of midstream turbulence, $\Delta r/R = 0.25$. As a starting point, let us consider the case when the TCS was not used. The flow, in this situation, is characterized by very uneven, but repeatable, distribution of the streamwise turbulent intensities, as seen in the lower half of Fig. 11. These intensity distributions are "locked" to the inlet casing and do not change with time. The peak levels of turbulent intensity are the major concern as they are the major sources of rotor-turbulence interaction noise. With the addition of suction ($w_s/w_{in} = 8\%$ using the inner surface only), a very small (5-10%) decrease in the turbulent intensity was noted. While suction had only a minimal effect on the freestream ($\Delta r/R_0 = 0.25$) turbulence, the use of the TCS produces major changes, as seen in the top half of Fig. 11. When the TCS is used, a very dramatic change is seen. Indeed now the turbulent intensities are very uniform and of low level. The turbulence levels are so low that the small wakes due to the TCS support structure can be seen in the transverse turbulence plots.[17] It is interesting to note that the axial velocity defect, between $\Psi = 0$ and 90 deg, persists even in the presence of the TCS (Fig. 11). With the TCS in place, removing the boundary layer with the inner feltmetal suction surface had almost no measurable effect on these intensity measurements, at this freestream location of $\Delta r/R_0 = 0.25$.

In summary, the combination of the TCS and the reverse cone inlet can produce an inlet flow that contains average levels of turbulent intensities on the order of 0.5% or less. The effect of these controls on the length scales will be taken up next.

Turbulent Length Scales

Two crossed film sensors with an angular separation were used to measure the transverse cross correlation of the transverse velocities. These measurements were made at an immersion of $\Delta r/R_0 = 0.25$ and at the same time as the on-line

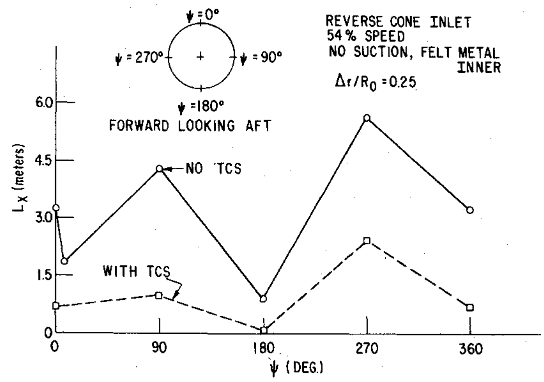

Fig. 12 Streamwise turbulent length scale.

intensity plots. Two locations of the reference sensor, $\Psi_f = 157.5$ and 337.5 deg, were used and produced essentially equivalent results. The data were fitted to functional relations and integrated to yield a transverse integral length scale of 1.2 cm. Measurements were also made with the TCS in place but due to the extremely small transverse scale, discernible levels of cross correlation were not possible even at the smallest probe separation of $\Delta\Psi = 5$ deg. Probe separations of much less than 5 deg can cause the downstream probe to be in the wake of the movable upstream probe and therefore were not attempted.

In order to determine the streamwise or axial length scales, the autocorrelation of a single cross film sensor was integrated over time and eddy convection assumed to be equal to the streamwise velocity. Figure 12 illustrates the distribution of the axial length scales around the inlet circumference. With the reverse cone inlet only, no TCS, the axial length scales are on the same order as measured previously in this facility.[19] The acoustic results confirm this fact as only about a 1 dB reduction in the BPF tone occurs with the reverse cone inlet, as compared to the standard bellmouth as used in Ref. 19. When the TCS is in place, a rather large reduction in the length of the eddies occurs. This reduction does not, however, appear to be as large as occurs in the transverse scale. The most interesting result is that,in spite of the substantial streamwise turbulent length scales, up to 2.5 m, the TCS produces a large reduction in the BPF tones. This can be explained by briefly reviewing the theoretical aspects of rotor-turbulence interaction noise.

To generate significant tone noise, the ingested turbulence has to have certain characteristics. A long axial integral scale is necessary to allow the rotor to cut the eddy many times, as pointed out by Ffowcs Williams and Hawkins.[7] For the range of axial scales measured here, without the TCS (1.5-6 m) the rotor blades will chop the typical eddy from 200 to 800 times as it passes through the rotor. Even with the TCS, the typical eddy will be chopped from 20 to 300 times; clearly the eddies are sufficiently long.

The transverse scale also has an effect on the noise generation, as pointed out by Mani.[4] In particular, the ratio of the integral transverse length scale to the transverse blade spacing is very important. For large values (above 2), the turbulence acts like a low lobe number inlet distortion that produces relatively coherent interactions that are spinning too slowly to propagate effectively. As the scale to spacing ratio goes down, the spectra broadens and the resulting higher-order modes propagate more effectively. For very low transverse scale to spacing ratios, below 0.5, the spectral peak is no longer apparent and the signal at BPF drops with a decreasing scale. The overall acoustic power level increases, however, but now is of a broadband nature. Pickett has given an example of this effect on the noise centered around the BPF signal and found that the noise was a maximum at a ratio of transverse scale to fan radius of 0.025. For Pickett's fan (1.2 m diam with 46 blades), this translates to a ratio of transverse scale to blade tip spacing of about 0.2. This same ratio for the experiments reported herein, without the TCS, is 0.33. This is quite close to the point of maximum turbulence rotor interaction noise generation as predicted by Pickett.

Conclusions

The research program described in this paper has been very successful in demonstrating the type of inlet turbulence control techniques that are necessary to obtain "flight" quality data from a static fan anechoic test facility. A flared reverse cone inlet that eliminates wakes from probe supports and actuators is used along with a turbulence control structure to condition the inlet flow. Both items are apparently necessary as prior research[12-16] with other turbulence control structures has met with only limited success. With this inlet configuration for a subsonic, cut-off fan, blade passing frequency tone reductions as high as 12 dB were obtained. By applying boundary-layer suction ahead of the rotor, further tone reductions of 4-5 dB, for the subsonic rotor tip speeds, are realized. These reductions in PWL at BPF (in one-third octave bands) then range from 12 to 18 dB for this subsonic tip speed range. Equally important is the observed steep rise in the BPF acoustic power as the rotor tip speed becomes supersonic and the first spinning modes cut on. At supersonic speeds, the fan BPF noise levels become nearly independent of the TCS and boundary-layer suction indicating that the TCS is not merely an attenuator of the fan noise, but can reduce the subsonic noise generation and yet not substantially alter the supersonic rotor-alone noise.

Turbulence mapping of the inlet confirmed the conclusions from the far-field acoustic data. In the freestream at an immersion of a quarter of the fan radius, the employment of the TCS reduced the low frequency streamwise velocity by as much as a factor of four, and the transverse turbulent velocity was reduced by a factor of ten.[17] The streamwise and transverse turbulent length scales were also reduced.

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