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STATE-OF-THE-ART OF TURBOFAN ENGINE NOISE CONTROL

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INTRODUCTION

Over the past several years considerable progress has been made in turbofan engine noise reduction. This progress is primarily due to the joint efforts of both the aircraft industry and the government working together to advance the understanding of noise generation and suppression in these engines. This paper attempts to highlight some of the recent advances in the technology of turbofan engine noise reduction including discussions covering: 1) turbomachinery noise sources, 2) new fans for low noise, 3) fan and core noise suppression, and 4) a new program for improving static noise testing of fans and engines. The references cited are by no means inclusive of all related work. The intent was to indicate work which is representative of current approaches to developing ways of quieting particular components of engine noise.

With the advent of the high bypass turbofan engines such as the CF-6, JT9D and RB211 the problem of jet noise has been substantially reduced by the lower jet velocities produced by these engines. The now dominant noise source of these engines is produced by the turbomachinery. The turbomachinery noise sources consist of the fan stage, compressor and turbine. Of these sources the fan stage is currently dominant. The compressor and turbine noise may also require attention once the fan noise has been suppressed. Since the fan stage is the primary source of turbomachinery noise it has received the major research emphasis, for example.[1,2] The noise reduction technology developed for the fan, however, in many cases is applicable to the other turbomachinery noise sources.

In addition to turbomachinery noise, jet noise, jet/flap interaction noise and combustor noise have been identified as other sources that can be major contributors depending upon the turbofan propulsion system operational mode and the aircraft type application.

IDENTIFICATION OF TURBOMACHINERY NOISE SOURCES

Fan Noise. Most modern high bypass fans are designed, from aerodynamic performance considerations, to operate at supersonic blade tip Mach numbers when the engine is at takeoff power. For the approach power condition the fan blade tip speed is generally subsonic. The spectral characteristics at these two operating conditions are shown in figure 1. The upper part of the figure illustrates the fan noise spectrum for subsonic operation. The subsonic spectrum is dominated by tones of the blade passing frequency (BPF), i.e. the frequency at which the fan blade pass a given point, and its harmonics. Underlying the BPF tones is a spectrum of noise characterized as broadband in nature. The supersonic tip speed fan stage spectrum is illustrated in the lower half of the figure. This spectrum is dominated by a multiplicity of tones called multiple pure tones (MPT). These tones which are radiated from the inlet occur at multiples of shaft rotational frequency. The blade passing frequency again seen here is also a tone occurring at a multiple of shaft rotational frequency and has a frequency equal to the number of fan blades multiplied by the shaft rotational frequency.

These two spectra explain the reasons for the characteristics whine (BPF) of the engine during approach and landing with the fan operating at subsonic tip speed and the buzz-saw sound (multiple pure tones) occurring during takeoff with the fan operating at supersonic tip speed.

Turbine Noise. The spectral characteristics of turbine noise are illustrated in figure 2 at frequencies above 6 kHz. These data were obtained from NASA Quiet Engine "C", for the approach power condition.[3] The engine for these tests was equipped with a highly noise-suppressed fan which allowed the blade-passing frequency tones for both the first stage and second stage low pressure turbine to be clearly identifiable for the baseline unsuppressed core exhaust duct case. The spectrum for the takeoff power case is shown in figure 3. The emergence of fan and jet noise at the higher power condition is illustrated here.

Combustor Noise. Although combustor noise has not heretofore been directly identified as a major turbofan engine noise source, some recent work of Karchmer and Reshotko[4,5] has identified combustor noise as a strong contributor to aft radiated low frequency noise at the approach engine power condition. Figure 4 illustrates data from a YF-102 (7500 lb thrust, bypass ratio 6 engine) acoustic test at Lewis Research Center. Low frequency sound power level is shown plotted against effective exhaust jet velocity. By use of cross correlation techniques the authors have determined that the aft quadrant far field low frequency noise (for effective jet exhaust velocities below 150 m/sec) is predominately combustor noise. Other experimenters[6-8] have studied combustor noise from full scale engines and generally have concluded that for the approach engine power the low frequency content of the far field noise was originating from the combustor.

Jet Noise. As has already been mentioned, the advent of the high bypass turbofan engine with lower jet velocities has resulted in substantially reduced jet noise levels. Figure 5 shows the overall sound pressure level as a function of average jet velocity. The older JT3D and JT8D engines have jet velocities that are near supersonic and consequently produce very high jet noise during takeoff. The newer high bypass CF-6, JT9D, and RB211 class engines operate at much lower jet velocities and jet noise levels. The Quiet Clean Short-Haul Experimental Engine (QCSEE) has even higher bypass ratio and lower jet velocities and jet noise levels than the CTOL high bypass engines.

DESIGNS FOR LOW FAN NOISE

Noise reduction concepts used in current state of the art fan designs utilize: 1) elimination of inlet guide vanes, 2) wide axial spacing between rotor and stator, and 3) selection of the ratio of the number of rotor to stator blades to provide acoustic cutoff of blade passage tones cuased by rotor-stator interaction.[9] These features are all intended to reduct noise by reducing blade vane interaction. At the higher supersonic tip speeds typical of takeoff, the rotor-alone source in the form of multiple-pure tones becomes dominant. Two exploratory fan design concepts specifically directed to reducing high tip speed noise generation are being pursued.

The first is based on the concept of rotor blade sweep.[10] The rotor blade leading edges are swept such that the component of flow normal to the leading edge is subsonic. Such flow conditions result in a shockless leading edge and, presumably, reduced multiple pure tone noise. An experimental fan stage incorporating blade sweep is shown in the two views in figure 6. For mechanical design reasons the leading edge sweep is compound; the leading edge sweeps forward from the hub to a reversal point and then sweeps rearward to the tip. The stage also incorporates stator sweep designed to reduce noise produced by rotor wakes interacting with the stators. Figure 7 shows a sketch of an actual rotor blade as constructed. Discontinuities at the sweep reversal point and at the rotor tip are expected to produce weak conical shocks with the remainder of the span being shock free. This fan stage will be tested in the NASA Lewis anechoic chamber.

A second exploratory concept being pursued is a fan designed with high specific inflow (flow rate per unit fan area) and, therefore, high Mach numbers at the inlet face of the rotor. This is an alternate noise reduction approach to a high Mach number inlet, also discussed in this paper, where the high Mach number inflow inhibiting upstream noise propagation occurs at the engine nacelle inlet throat.

Preliminary inlet noise measurements made on a stage having high specific inflow are compared to similar measurements on a lower flow conventional design in figure 8. The more rapid decrease in tone level for the high specific flow design as speed is increased toward design indicates a phenomenon worth investigating.

An experimental high flow fan has been designed and is being fabricated.[11] The fan has an average rotor inlet axial Mach number of 0.71, and variable tandem stators and nozzle area such that both approach and takeoff thrusts can be attained while running at design speed. This fan will also be evaluated acoustically in the NASA Lewis anechoic chamber.

FAN NOISE SUPPRESSION

Suppressor Design by Spinning Mode Theory. Early acoustic treatment designs for fan inlet ducts were based on sound propagation theories for either plane or axisymmetric acoutic waves. These designs usually resulted in multi splitter rings with all surfaces of the rings and adjacent duct wall acoustically treated. More recent inlet duct treatment designs rely on sound propagation theory for spinning acoustic modes.[12-14] The theoretical maximum attenuation for wall-only treatment designed on the basis of spinning mode theory is considerably greater than indicated by the previous plane wave theory. An example of the results from two suppressor experiments designed by plane wave and spinning mode theory is shown in figure 9. The circled data points are from a suppressor experiment on NASA Quiet Engine "C" using a suppressor design based on plane wave theory. This suppressor was designed for peak suppression at 630 Hz (center of MPT band). The single data point at an $L/D = 0.25$ represents the suppression obtained on another experimental suppressor designed using spinning mode theory. This suppressor was run on a YF-102 engine and was also designed to suppress MPT (1600 Hz for YF-102 engine). The amount of suppression obtained on the spinning mode design was 11.7 dB (for $L/D = 0.25$) or between 3 and 4 times that obtained with the plane wave design. These results are an indication of the greater potential of wall-only treatment when designed on the basis of spinning mode theory. Treatment designs based on plane wave theory are still used successfully for inlet ducts with splitter rings.

Bulk Absorber Suppressor. A recent experimental program was conducted at Lewis using the YF-102 engine to investigate the suppression characteristics of bulk absorber linings. The bulk absorber material used was Kevlar fiber, a nonwicking material with a potential for flight rating. Figure 10 compares the suppression characteristics at the design frequency of 5 kHz for both the bulk absorber and for single degree of freedom (SDOF) honeycomb structure designed using spinning mode theory. The data from these experiments indicate very similar suppression characteristics on the basis of directionality at the design frequency. Figure 11 compares the bulk absorber with the SDOF liner on the basis of bandwidth suppression. At the design frequency of 5 kHz the two liners have essentially the same suppression. For frequencies both above and below the design point, however, the bulk absorber exhibits better suppression. These suppression bandwidth advantages of bulk absorber materials relative to Helmholts resonators have been recognized for some time.

High Mach Number Inlets. One of the concepts of engine fan inlet noise suppression that has received considerable attention is the High Mach Number (sonic or near-sonic) inlet. The noise reduction potential of such an inlet is well known. Figure 12 shows some typical data obtained from a fan test at NASA Lewis[15] where noise reduction is plotted against inlet throat Mach number. As Mach number was increased from about 0.7 noise attenuation increased from 0 to about 35 dB where a noise floor was reached.

To achieve inlet noise reductions on turbofan engines, many types of sonic and near-sonic variable geometry inlet configurations have been proposed. From a Lewis sponsored contractor study, one type, the contracting cowl configuration, was considered to have advantages over other types from the standpoint of mechanical, aerodynamic, and acoustic design potential. An experimental program was conducted at Lewis on NASA's Quiet Engine "C" using a variable geometry type contracting cowl configuration.[16] A photo of the inlet installed on Quiet Engine "C" is shown in figure 13. A plot of the spectral characteristics is shown in figure 14. The data indicate that both the MPT and BPF noise have been significantly suppressed by the high Mach inlet. The total pressure recovery for this inlet was above 0.98 for all operating conditions.

Although the acoustic suppression and the aerodynamic performance of the variable area contracting cowl design necessary for CTOL operation were impressive the problems of weight, mechanical complexity, and aerodynamic performance may result in unacceptable penalties for commercial airline use.

The operational characteristics of the short-haul powered lift aircraft are such as to not require a high Mach inlet with variable-area capability. An example of the acoustic suppression for a fixed area high Mach inlet designed for the QCSEE engines is shown in figure 15.[17] This high Mach inlet also incorporated treatment and is also referred to as sonic/hybrid inlet. The data are from 20-inch model tests run in an anechoic chamber. At the design average throat Mach number of 0.79 the suppression obtained was about 12 PNdB, of which about 5 PNdB was due to the treatment and 7 PNdB due to the high Mach number effect.

CORE ENGINE NOISE SUPPRESSION

As previously discussed, considerable progress has been made toward reduction of jet and fan noise. As these two sources of engine noise are brought down, additional internal noise sources become important. These noise sources are classified as "core noise" and consist of combustor noise, turbine noise, and internal strut noise. Figure 16 illustrates how core noise contributes to the total engine noise for a suppressed fan case. With decreasing jet velocity, the total engine noise decreases, and the core noise begins to emerge as a new noise floor.

Recent tests to investigate the suppression of core noise were conducted on NASA Quiet Engine "C".[3] The configuration tested are shown in figure 17. The suppression designs consisted of duct wall treatment with and without a treated splitter. Figure 18 shows 1/3-octave-band sound pressure level for the two suppressed configurations tested. Although the treated splitter configuration provided the best overall suppression, the wall-only treated configuration did almost as well at all frequencies except the highest.

TURBOFAN GROUND STATIC TESTING TECHNIQUES FOR FLIGHT NOISE SIMULATION

Forward velocity effects on turbofan engine noise have been determined through flight tests performed on commercial jet aircraft. A comparison of the JT3D static and in-flight noise signatures obtained from a DC-8 aircraft, is shown in figure 19.[18] The presence of the dominant BPF in both the static and flight data suggests that the controlling source mechanisms were the same in both flight and static testing. Since the JT3D fan was not designed for acoustic cut-off of BPF, the existence of the dominant BPF tone in both static and flight data would be expected to be caused by rotor-stator interaction.

The newer high bypass turbofan engines now being used by the wide body commercial jets incorporate low noise design features such as wide spacing between fan rotor and stator (2 or more fan blade chords), and the ratio of the number of fan blades to stator vanes needed for acoustical cut-off of BPF due to rotor stator interaction. Figure 20 compares projected static-to-flight data and actual flight data from a DC-10 aircraft with CF6-6 engines. The absence of the BPF tone in the flight data suggests that acoustic cut-off is a real phenomenon in engines as well as in simpler more controlled situations such as flow ducts. The static data however, contains the BPF tone. This result suggests the existence of engine inlet turbulence or distortion effects that for ground static test conditions can cause rotor alone noise even for a fan designed for cut-off. These ground static effects have been observed in all ground static test data. Recent tests of a cut-off designed fan, run in the Lewis Research Center low-speed 9 x 15 foot wind tunnel, demonstrated the cut-off effect with tunnel forward velocity.[19,20] This effect is shown in figure 21 where the BPF tone is shown as a function of tunnel velocity. Both the level and the amplitude fluctuation of the BPF tone were reduced by the tunnel forward velocity.

An explanation for this forward velocity effect is given with the aid of figure 22 for a fan design in which the BPF due to rotor-stator interaction is cut-off. The static inflow diagram illustrates how ground level turbulence is stretched into long sausage-like disturbances as the flow is accelerated into the inlet. These disturbances are then chopped by the rotating fan blades and can produce BPF tone.[21] In contrast, for the forward velocity case much less stretching occurs and the rotor alone BPF tone is greatly reduced.

In order to simulate in-flight noise effects in ground static testing of turbofan engines, it is evident that a means must be devised to eliminate the introduction of the sausage-like disturbances in the inlet of the engine during ground static tests. Figures 23 and 24 illustrates an inflow control device which has been tested on the same fan used in the forward velocity testing in the

9 x 15 Anechoic Wind Tunnel.[19] The effect on inlet blade passing tone levels is compared to levels measured statically and with forward velocity in figure 25.[22] Levels with the flow control device are reduced indicating improved inflow but do not match the large reductions accompanying forward velocity. One difficulty associated with such devices is designing and building a structure to support honeycomb and screen materials without introducing flow disturbances due to the structure itself. While such devices show some promise for in-flight noise simulation, considerable developmental work remains.

A NASA intercenter and contractor Flight Noise Simulation program is currently underway with the objective of developing methods of ground static testing of turbofan engines to provide valid acoustic data for the prediction of in-flight fan noise. This program will utilize a modified JT15D engine for flight tests, ground static tests, and wind tunnel tests. A JT15D fan and modified stator set will also be tested in the Lewis anechoic facility where inflow effects on fan generated noise will be determined. These inflow conditions will be controlled by use of turbulence control devices similar to those which will be developed for outdoor static engine testing.

An important aspect of this overall flight simulation program will be that the same fan stage will be used for the flight tests, the outdoor ground static tests, the ground static anechoic chamber tests, and for the wind tunnel tests. By using the same fan stage for all facilities and for the flight tests a comprehensive evaluation of the applicability of the facility acoustic data to predict inflight fan noise will be made.

CONCLUDING REMARKS

This paper has reviewed the current state of the art of turbofan noise control. The fan stage of the current high bypass engines was identified as the dominant noise source. Existing and new methods of reducing fan source noise as well as suppression by acoustical treatment were discussed. Some experimental results of suppressors designed by new spinning mode theory methods and a bulk absorber design were compared. These results indicate that the new designs are considerably more effective in suppressing fan noise than previous designs. Another method of inlet fan noise suppression is the high Mach inlet. The suppression potential for this concept was shown to be very high, however the complication, weight, and performance penalty for the variable area type required for CTOL may make it undesirable for commercial airline use. The fixed area high Mach inlet used on the QCSEE engines for short-haul aircraft, however, shows considerable promise for substantial fan inlet noise suppression.

Noise sources other than fan noise were also identified and discussed. Suppression of the higher frequency components of the core engine noise sources was described and some experimental data given from engine tests.

Problems in flight simulation of fan noise by ground static testing have been identified and research programs to solve their problems are discussed. These efforts are primarily directed toward the control of inlet turbulence by use of honeycomb/screen structures at the inlets of the engine and fan test rigs.

REFERENCES

1. "Aeronautical Propulsion," NASA SP-381 (1975).
2. "Aircraft Engine Noise Reduction," NASA SP-311 (1972).
3. H. E. Bloomer, "Aero-Acoustic Performance Comparison of Core Engine Noise Suppressors on Quiet Engine "C"," NASA TM X-73662 (1977).
4. M. Reshotko, "Core Noise Measurements on a YF-102 Turbofan Engine," NASA TM X-73587 (1977).
5. A. Karchmer and M. Reshotko, "Core Noise Source Diagnostics on a Turbofan Engine Using Correlation and Coherence Techniques," NASA TM X-73535 (1976).
6. E. A. Burdsall, F. P. Brocher, and V. M. Scaramella, "Results of Acoustic Testing of the JT8D-109 Refan Engines," Rep. PWA-5298, Pratt and Whitney Aircraft, NASA CR-134875 (1975).
7. R. K. Matta, G. T. Sandusky, and V. L. Doyle, "Core Engine Noise Investigation - Low Emission Engines," FAA RD-77-4, Federal Aviation Administration (1977).
8. D. C. Mathews, N. F. Rekos, and R. T. Nagel, "Combustor Noise Investigation," FAA RD-77-3, Federal Aviation Administration. (1977).
9. J. M. Tyler and T. G. Sofrin, "Axial Flow Compressor Noise Studies," SAE Trans. 70, 309-332 (1962).
10. D. B. Bliss, et al., "Design Considerations for a Novel Low Source Noise Transonic Fan Stage," AIAA Paper 76-577, Palo Alto, Calif. (1976).
11. J. D. Sottau, et al., "Detailed Design of a Quiet High Flow Fan," Rep. EDR-9071, Detroit Diesel Allison, NASA CR-135126 (1977).
12. E. J. Rice, "Spinning Mode Sound Propagation in Ducts with Acoustic Treatment," NASA TN D-7913 (1975).
13. E. J. Rice, "Attenuation of Sound in Ducts with Acoustic Treatment - A Generalized Approximate Equation," NASA TM X-71830 (1975).
14. K. R. Bilwakesh and A. Clemons: "Acoustic Tests on a 20-Inch Diameter Scale Model Fan and Inlet for the Under-the-Wing Engine," (QCSEE) General Electric Company, CR-135117 (1975).
15. B. A. Miller, "Experimentally Determined Aero-Acoustic Performance and Control of Several Sonic Inlets," AIAA Paper 75-1184, Anaheim, Calif. (1975).

16. H. E. Bloomer and J. W. Schaefer, "Aerodynamic and Acoustic Performance of a Contracting Cowl High Throat Mach Number Inlet Installed on NASA Quiet Engine "C"," AIAA Paper 76-540, Palo Alto, Calif. (1976).

17. K. R. Bilwakesh and A. Clemons, "Acoustic Tests of a 20-Inch Diameter Scale Model (1:3.5) Fan and Inlet for the Under-the-Wing Engine," I, NASA CR-135117 (1977).

18. C. E. Feiler and J. E. Merriman, "Effects of Forward Velocity and Acoustic Treatment on Inlet Fan Noise," AIAA Paper 74-946, Los Angeles, Calif. (1974).

19. M. F. Heidmann, and D. A. Dietrich, "Simulation of Flight-Type Engine Fan Noise in the NASA-Lewis 9 x 15 Anechoic Wind Tunnel," NASA TM X-73540 (1976).

20. D. A. Dietrich and M. F. Heidmann, "Acoustic Signatures of a Model Fan in the NASA-Lewis Anechoic Wind Tunnel," NASA TM X-73560 (1977).

21. D. B. Hanson, "Spectrum of Rotor Noise Caused by Atmospheric Turbulence," J. Acoust. Soc. Am. 56, S3 (1974).

22. Loretta M. Shaw, Richard P. Woodward, Frederick W. Glaser, and Benjamin J. Dastoli, "Inlet Turbulence and Fan Noise Measured in an Anechoic Wind Tunnel and Statically with an Inlet Flow Control Device," to be presented at AIAA 4th Aero-Acoustic Conference, Atlanta, Ga. (1977).

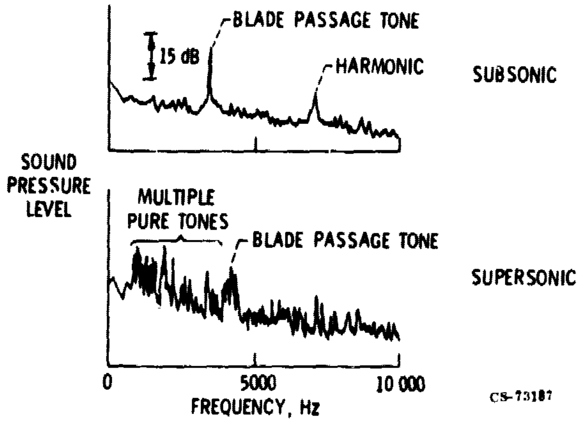

Figure 1. - Fan inlet noise spectra at low and high tip speeds.

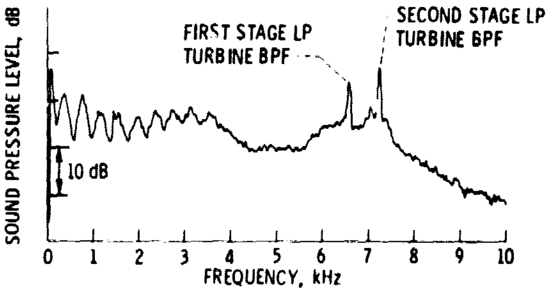

Figure 2. - Approach power narrowband turbine noise spectra.

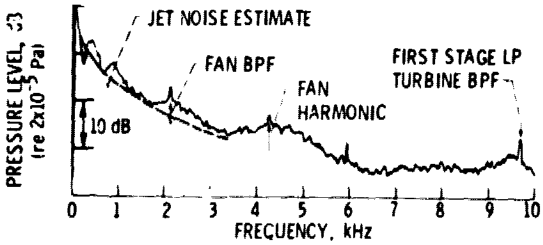

Figure 3. - Take-off power narrowband spectra.

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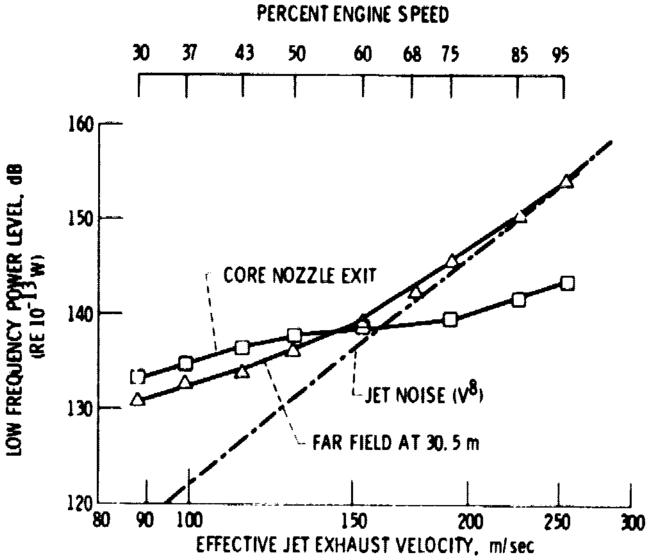

Figure 4. - YF-102 low frequency acoustic power. Frequency range, 50 to 2000 Hz.

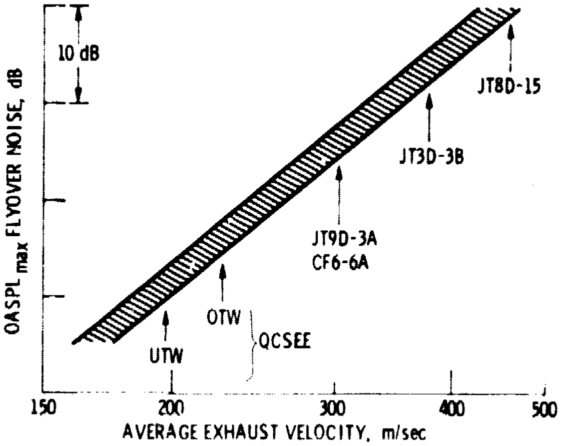

Figure 5. - Jet noise of several turbofan engines.

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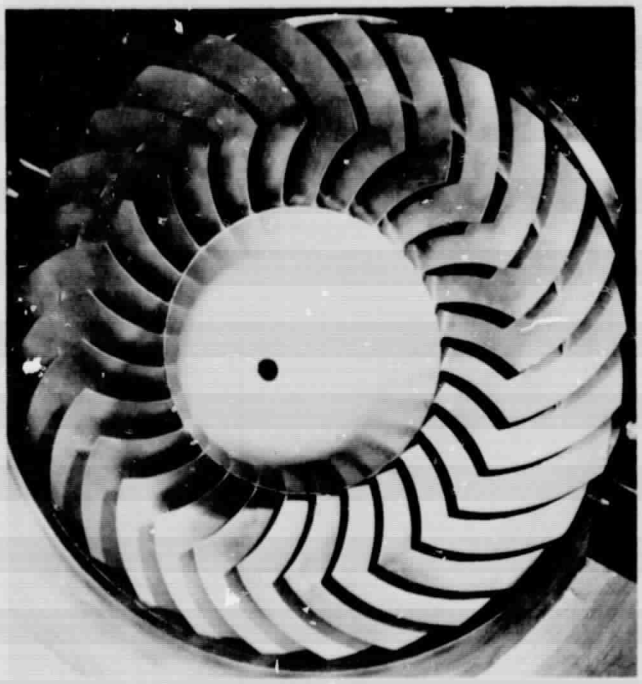
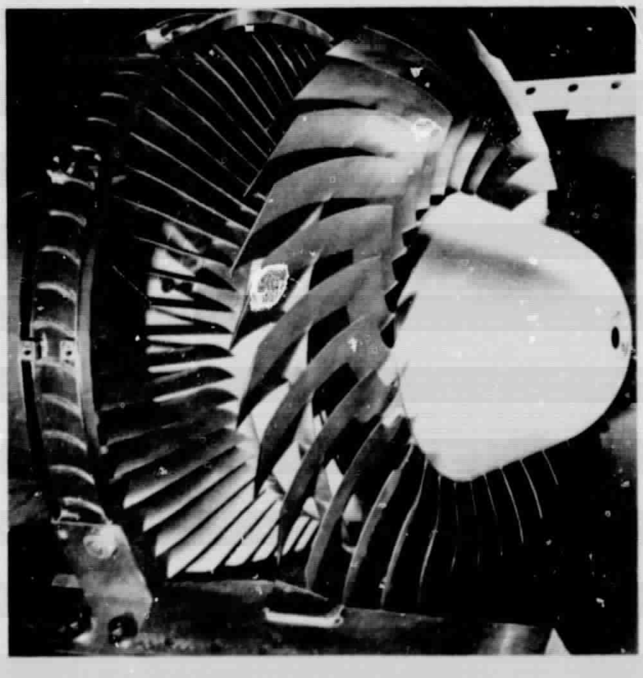


(a) FRONT VIEW.



(b) SIDE VIEW.

Figure 6. - Low noise experimental fan stage incorporating blade sweep.

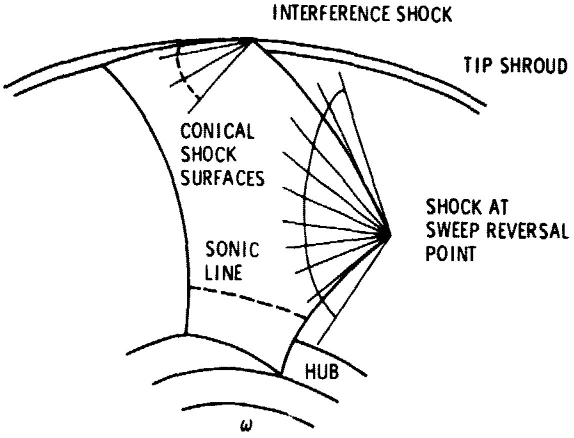


Figure 7. - Rotor blade with a compound sweep leading edge.

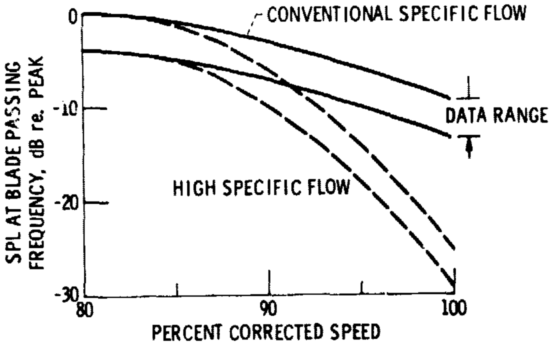


Figure 8. - Comparison of blade passing tone trend with rotor speed for high and conventional specific flow compressors.

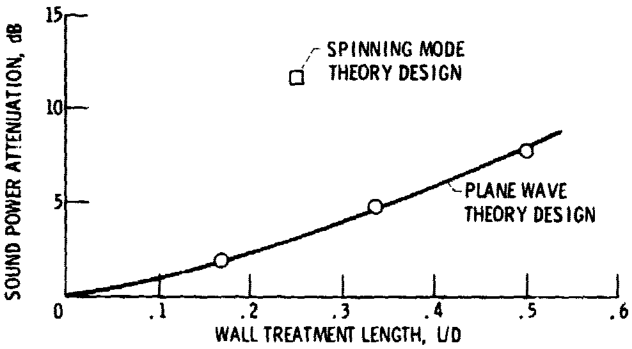


Figure 9. - MPT Fan suppressor design experimental results.

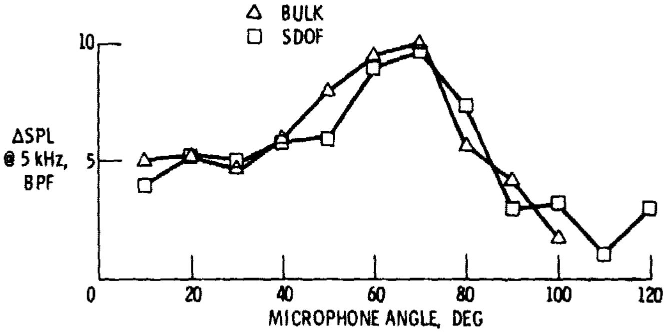


Figure 10. - Attenuation of bulk absorber and single degree of freedom liners.

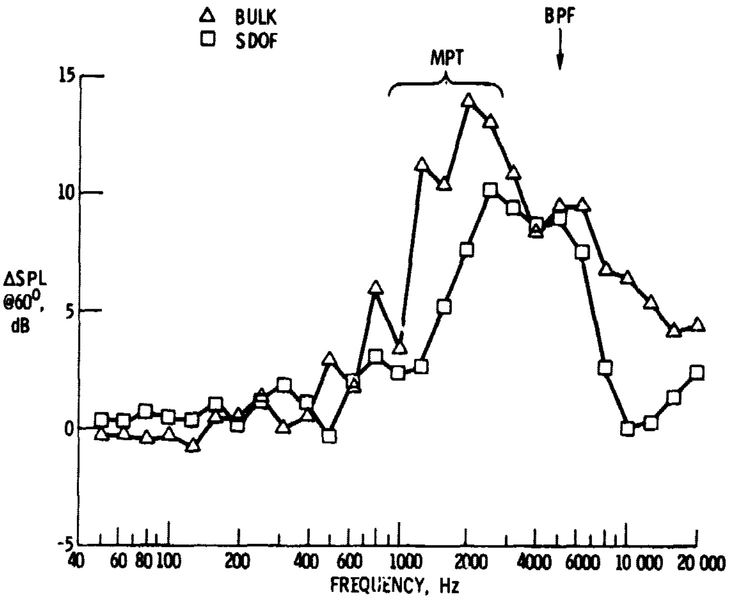


Figure 11. Comparison of bulk and single degree of freedom liner attenuation spectra.

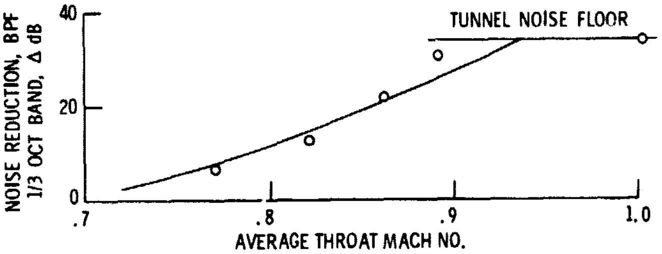


Figure 12. - Sonic inlet acoustic performance.

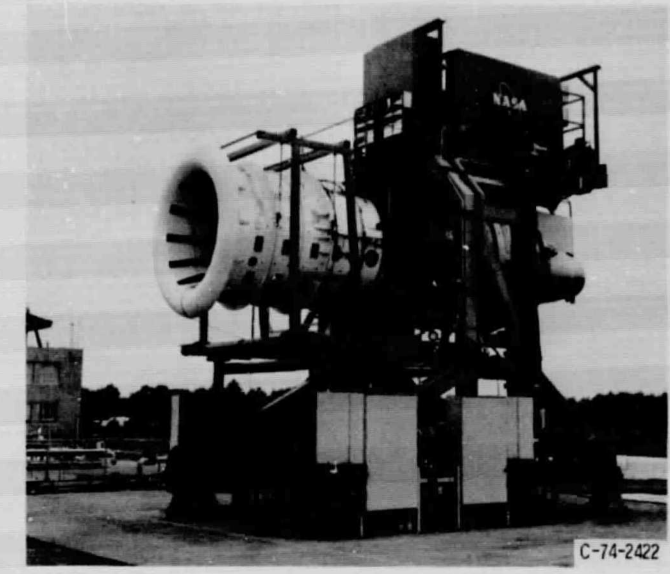


Figure 13. - Sonic inlet installed on Quiet Engine "C".

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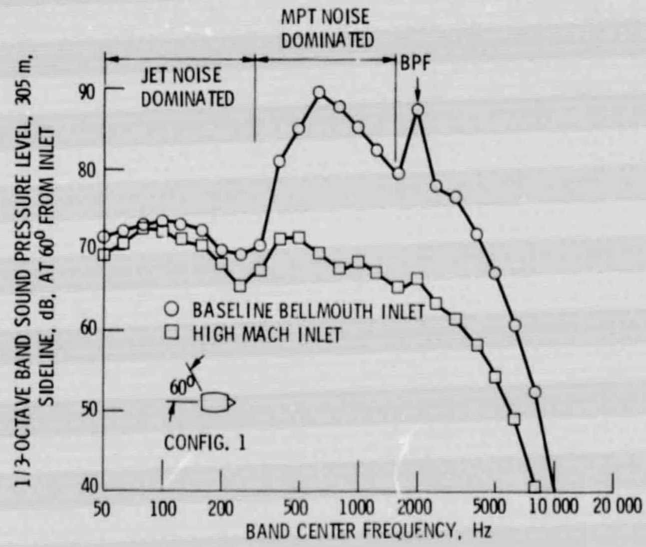

Figure 14. - Comparison of SPL spectra for baseline bellmouth and takeoff high Mach inlet.

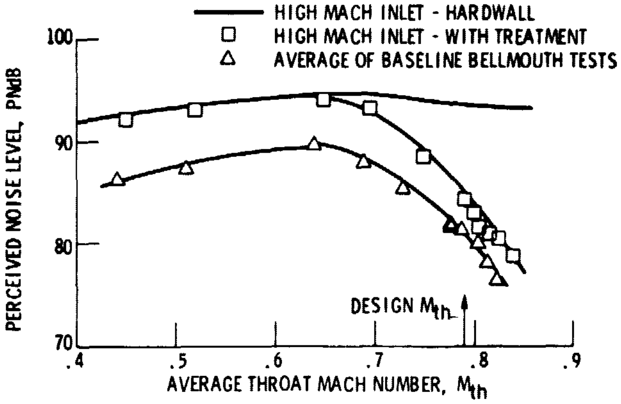

Figure 15. - QCSEE 20 inch fan, high Mach inlet, acoustic performance.

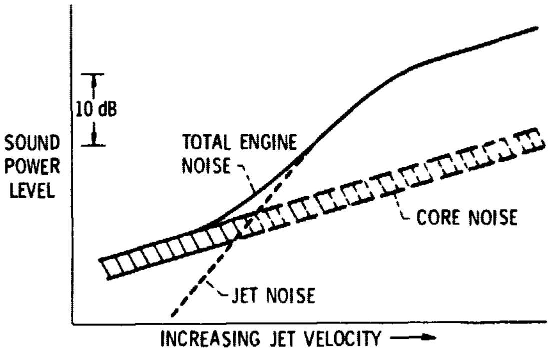

Figure 16. - Engine noise (fan noise suppressed).

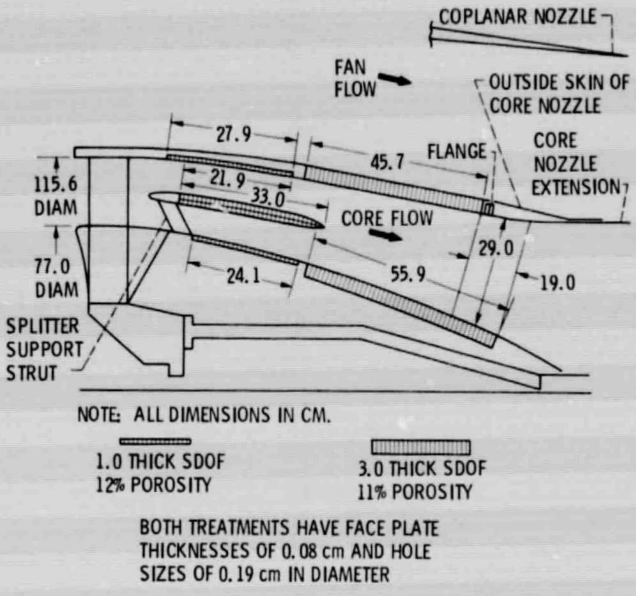

Figure 17. - Quiet Engine "C" core exhaust suppressors. Configurations 1 and 2 (configuration 2 without splitter).

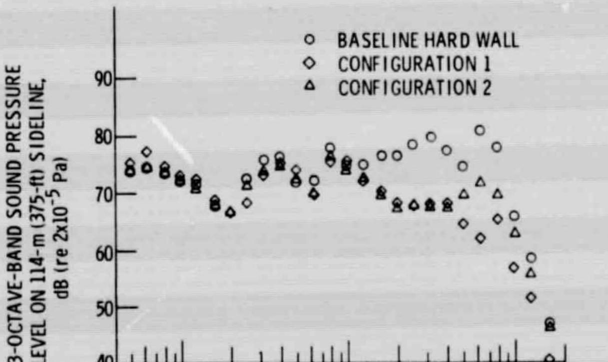

Figure 18. - Comparison of 1/3-octave spectra for Quiet Engine core exhaust suppressors, approach power.

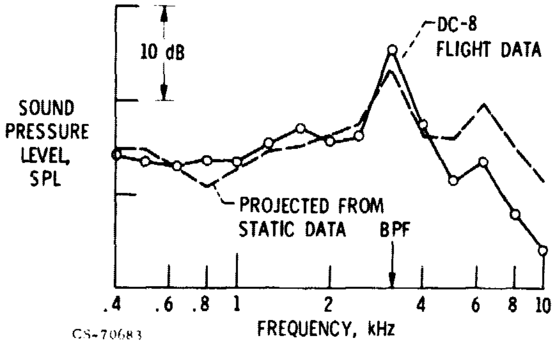

Figure 19. - Comparison of flight and projected static inlet sound pressure spectra for JT3D-3B engine at approach condition (4696 rpm; 75° inlet angle.

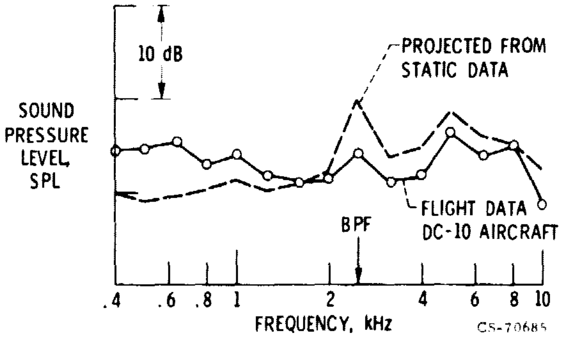

Figure 20. - Comparison of flight and projected static inlet sound pressure spectra for Jt9D-20 engine at approach condition (2666 rpm; 60° inlet angle.

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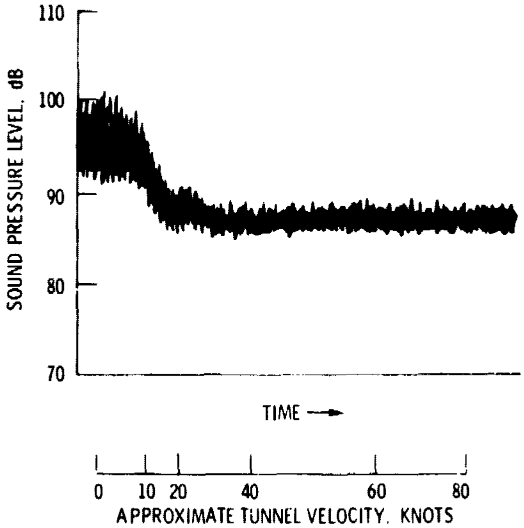

Figure 21. - Change in blade passage frequency tone level during tunnel start transient. One-third octave frequency level at 60° from inlet axis. Fan speed 96% of design.

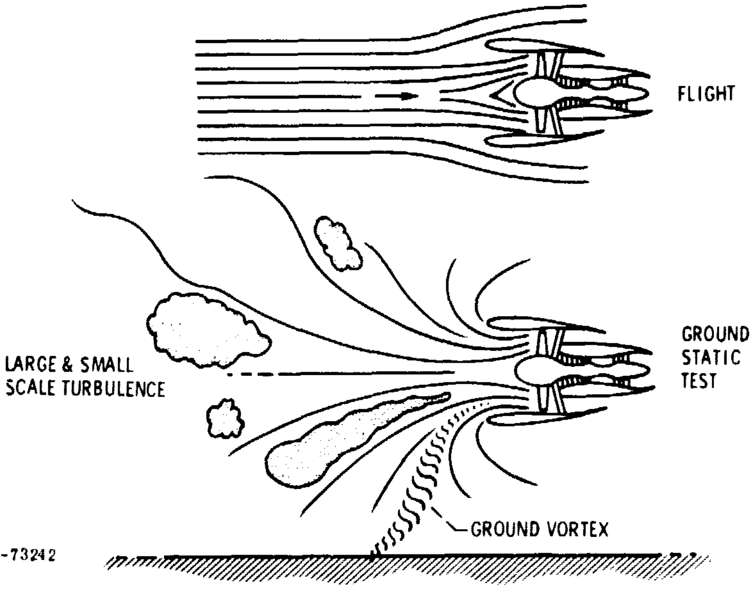

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Figure 22. - Effect of flight on inlet flow.

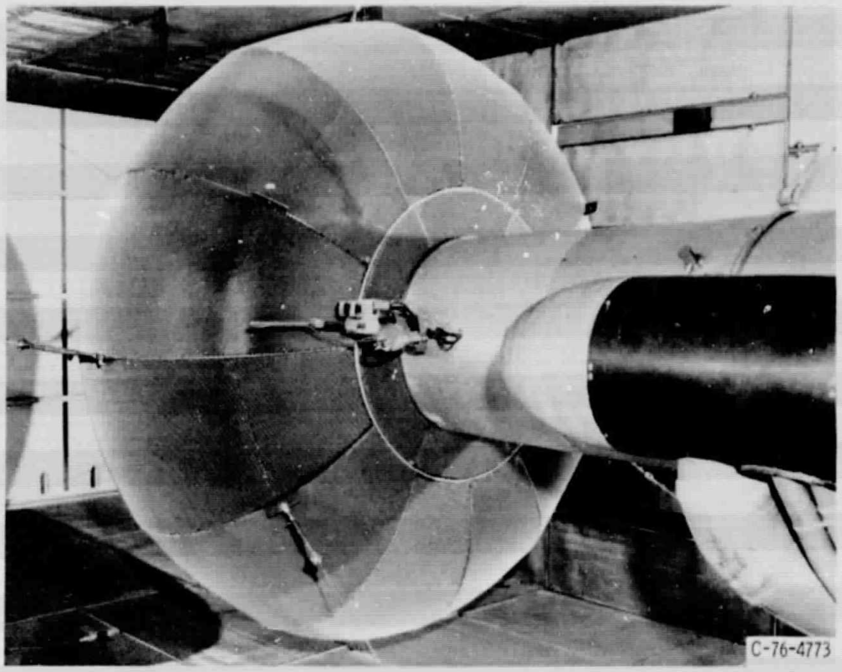

Figure 23. - Turbulence control device installed on 20 inch fan in Lewis 9- by-15 ft wind tunnel.

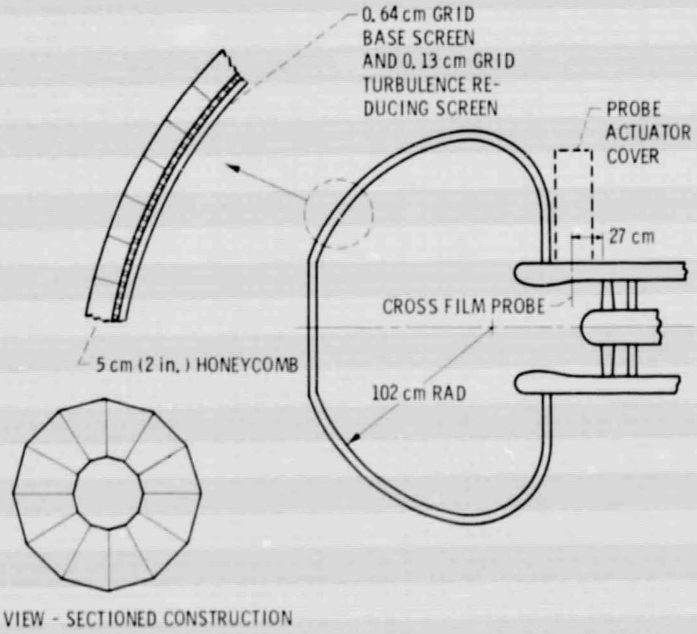

Figure 24. - Schematic diagram of turbulence control device mounted on fan rig.

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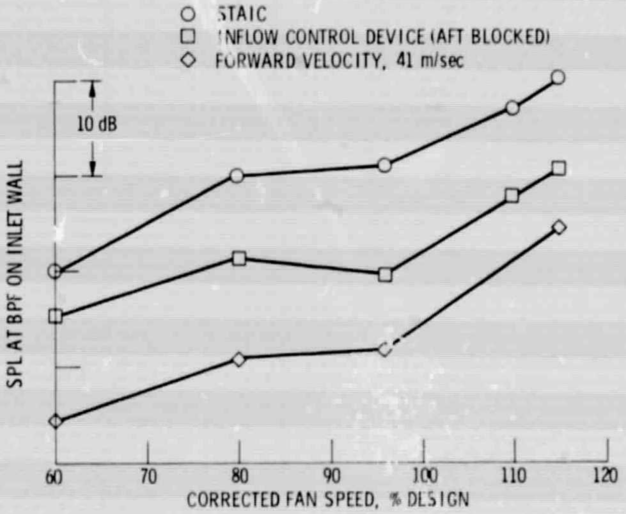

Figure 25. - Effect of inflow control and forward velocity on narrowband inlet blade passing tone levels.

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