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# SIMULATION OF FLIGHT-TYPE ENGINE FAN NOISE IN THE NASA-LEWIS 9 X 15 ANECHOIC WIND TUNNEL

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## ABSTRACT

A major problem in the measurement of aircraft engine fan noise is the difficulty of simulating, in a ground-based facility, the noise that occurs during flight. Flight-type noise as contrasted to the usual ground-static test noise exhibits substantial reductions in both (1) the time unsteadiness of tone noise and (2) the mean level of tones calculated to be nonpropagating or cut-off. A model fan designed with cut-off of the fundamental tone was acoustically tested in the anechoic wind tunnel under both static and tunnel flow conditions. The properties that characterize flight-type noise were progressively simulated with increasing tunnel flow. The distinctly lobed directivity pattern of propagating rotor/stator interaction modes was also observed. The results imply that the excess noise attributed to the ingestion of the flow disturbances that prevail near most static test facilities was substantially reduced with tunnel flow. The anechoic wind tunnel appears to be a useful facility for applied research on aircraft engine fan noise under conditions of simulated flight.

## INTRODUCTION

Significant quiet aircraft engine research and development effort in the past decade has been directed toward reducing the noise of the bypass fan in turbofan engines.(1, 2) The fan has received particular attention because it becomes a dominant noise source at high bypass ratios such as those employed in the newer JT9D and CF6 class of en-

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gines. Further increases in bypass ratio and continued dominance of fan noise is projected for short-haul and energy conservative aircraft applications. Several quiet design features for the fans of high bypass ratio engines have proven successful in actual flight applications as attested to by the comparatively quiet 747, DC10, and L 1011 class of aircraft. Unfortunately, less success has been experienced in the evaluation of quiet design features in ground-static testing of engines and fans. This lack of success is attributed to the failure to simulate in ground based test facilities the noise that occurs during flight. The commonly-used ground-static tests usually exhibit extraneous noises that are not present during flight. This excess noise can mask the benefits of quiet design features in ground-static tests. It has therefore been difficult to methodically exploit the usual systematic and progressive research and developmental approach to reduce fan noise.

Ground-static acoustical tests of fans frequently show little impact of quiet design features on unsuppressed noise levels. For example, the substantial changes in measured noise levels expected from increases in rotor/stator blade spacing only occur when spacing is varied from a very small fraction of a chord length to several chords. The effect of other design features that should more subtly affect noise generation often require detailed data analyses to be identified.[3-5] Frequently, quiet features, firmly based on acoustic theory, have exhibited no effect on fan noise as measured in ground test facilities. This insensitivity of fan noise to design differences is such that at NASA-Lewis a family of full-scale low-speed quiet fans gave static test noise levels that could be effectively correlated on the basis of fan thrust and pressure rise alone regardless of other design features.[6] Quiet design features, however, can be strongly evident during flight.[7-10] Most notably, the tone cut-off phenomena prescribed by Tyler and Sofrin[11] is often observed in flight noise but difficult to detect in static tests. The situation implies that quiet fan design technology has not been fully exploited because of the insensitivity and often misleading results of ground-static tests.

Identity of the excess noise problem in ground-static testing has slowly evolved since the advent of such testing. Ground vortices (often visible during proper humidity conditions) trailing into the fan inlet have always been suspected to cause excess blade passage frequency noise. The ingestion of disturbances and wakes from fan-induced flow over the structures used to mount and drive the fan or engines were also known to influence measured noise levels.[12] Recently, however, the problem has been identified by Hanson[13, 14] to be much more complex than anticipated.

According to Hanson the excess noise in ground-static tests is not completely eliminated when ground vortices are eliminated and supporting structures are streamlined. An additional source of the excess noise can be much more subtle than that. It can be shown from potential flow considerations that the inlet flow undergoes a large area contraction that extends far afield. "Packets" of atmospheric inhomogeneities in the far field can be captured by this flow process. The axial length scale of such a captured "packet" is greatly increased at the expense of its lateral scale during the contracting flow process. The simultaneous ingestion of a multiplicity of such elongated inflow disturbances is a source of excess tone-like and broadband rotor noise. The noise can be generated by the rotor either by direct interaction with the disturbance or indirectly by interaction with boundary layer instabilities in the inlet flow triggered by the disturbance.[15] It is postulated these later two sources of noise are substantially reduced or eliminated during flight. In flight both the stream tube area contraction causing the elongation and the prevalence of inhomogeneities are greatly reduced.

Methods to eliminate the excess noise in ground based facilities have been analyzed and tried by various investigators.[9, 15-18] In general the results have tended to further identify rather than solve the problem. There has been limited success with turbulence screens and similar flow modifying devices either on the air entering the test chamber or entering directly into the inlet duct. The problems with such inlet devices involve (1) interference with far field noise propagation, and (2) the introduction of additional wakes in the inlet flow by structural supports needed for the screens.

A promising approach for eliminating excess noise in a ground based facility appears to be motion of either the vehicle or the air supplying the fan.[(15)] Acoustic tests with a turbofan engine mounted on a moving platform has been proposed. Far field noise measurements, however, pose a problem when the test vehicle is moving. Promising results have also been obtained by operating the fan in an airstream generated by an auxiliary fan.[(15)] Similarly, excess noise has been influenced by tunnel flow in tests at NASA-Ames.[(16)] Further testing and documentation, however, is needed to confirm that flight-type noise can properly be simulated and measured with either vehicle motion or a flowing air stream.

The purpose of this paper is to report the noise behavior observed in a preliminary analysis of the data for a 50.8 centimeter (20-in.) diameter fan stage tested in the NASA-Lewis 9 × 15 foot anechoic wind tunnel. The tunnel walls were acoustically treated to achieve free-field acoustic behavior over a useful frequency range. Far-field noise measurements were made both statically and for a range of tunnel velocities. The fan stage tested was a subsonic tip speed fan designed for cut-off of the fundamental blade passage tone. Test results are presented and discussed within the context of the prominent characteristics distinguishing flight-type noise from ground-static noise.

## PROMINENT STATIC/FLIGHT NOISE DIFFERENCES

In this preliminary report of wind tunnel results the prominent differences that distinguish flight-type noise from ground-static noise will be used as qualitative indicators to determine if flight-type noise was simulated. Three distinguishing properties that contrast flight noise from static noise will be considered. These are (1) a substantial reduction in the time variations or unsteadiness in tone noise levels, (2) a significant reduction in the noise level of a tone designed to be cut-off, and (3) a distinctively lobed far field directivity pattern of a tone for which only a few rotor/stator interaction modes propagate.

A reduction in the time variations or unsteadiness in tone noise levels during flight or with a reduction of inflow distortions has been reported by various investigators.[7, 9, 10, 15] The results obtained from an analysis of data acquired during aircraft tests in the NASA JT8D Refan Program[19] shown in figure 1 are typical of the differences between flight and ground-static results. Time variations in the blade passage tone level in the inlet duct are shown for static and flight conditions for several fan speeds. These inlet duct measurements show that flight conditions reduce the amplitude of the variations from about 10 to 15 dB to 1 or 2 dB. This behavior is consistent with a generation model where excess noise in a static test is caused by the random ingestion of a multiplicity of elongated flow disturbances. Changes in tone unsteadiness in the far field are expected to be of the same magnitude as that observed in the inlet duct. Unsteadiness of tone levels is observed in the far field during static tests. The steadiness in flight has also been noted in fuselage mounted microphone signals.[10] Tone unsteadiness in the far field, has also been shown to vary in experiments where inflow disturbances are altered.[15, 17]

The observance of tone cut-off during flight but not in ground static tests is probably the most publicized difference between flight and ground-static noise. Figure 2 shows the reported[7, 9] behavior of the JT9D and CF6 engines in the 747 and DC10 aircraft, respectively. The blade passage tone should be cut-off for both engines for the conditions shown. Cut-off occurs as predicted during flight for the CF6 engine and a significant reduction is evident for the JT9D engine. Figure 2 also shows a lower noise level at high frequencies during flight than during ground static tests for the CF6 engine but not the

JT9D engine. Differences such as this are now considered to be largely caused by an inability to properly project the source noise to the ground because of shear layers, atmospheric attenuation and engine placement rather than a source noise change. Broadband noise changes are anticipated by some investigators during flight. The changes, however, have not yet been identified as prominent features distinguishing flight and ground-static fan noise.

The directivity pattern of tone noise observed during flight has received little attention with regard to its detailed properties. A distinctively lobed directivity pattern, however, is predicted from acoustic theory for propagating rotor/stator interaction modes when the number of propagating modes is not too large. In static tests, however, any distinctive directivity pattern of rotor/stator modes can be masked by the high level and unsteadiness of the excess tone noise due to inflow disturbances. The time average directivity in typical ground-static tests does not exhibit a distinctively lobed pattern. The pattern has been shown to be comparatively smooth and relatively independent of fan design and operating condition.[20] The measured and calculated directivity patterns, typical of tone noise in static tests, are shown in figure 3(a). The multiplicity of modes that inflow disturbances can generate are used to give the relatively smooth calculated directivity pattern. With the elimination of excess noise during flight, however, the distinctive pattern or rotor/stator interaction noise should be revealed. Figure 3(b)[11] illustrates the calculated and measured directivity patterns for a fan when a single rotor/stator interaction mode is made to dominate the far field tone noise by close rotor-stator spacing. The emergence of such a lobed pattern with wide spacing can be indicative that flight-type noise has been simulated or approached.

## WIND TUNNEL

The NASA-Lewis $9 \times 15$ wind tunnel test section is located in the return loop of the Lewis 8 × 6 supersonic wind tunnel (fig. 4). The 9 × 15 test section has a relatively long history of aerodynamic experiments and many of its properties have been previously reported.[21] The acoustic treatment of the tunnel walls used to achieve anechoic properties, however, is a relatively recent addition. These additions and the capabilities of this facility for acoustic tests of model fans are described in reference 22. A description of the tunnel properties will be limited to a brief discussion of those properties considered significant to the simulation of flight noise. They are (1) anechoic or free-field behavior, (2) control of the airflow, and (3) installation features of the fan.

The acoustically-treated test section of the tunnel (with fan installed) is shown in figure 5. The acoustic treatment design, installation and evaluation was performed under contract by the Bolt, Bernek, and Newman Company.[23] Details of the wall treatment are shown in figure 6. The acoustic treatment consists of fiberglass form board with fiberglass cloth and wire screen facing A summary figure of the acoustic calibration without flow for a broadband source located at the fan inlet location is shown in figure 7. It shows that anechoic or free-field properties are exhibited for frequencies above about 1000 hertz. It is above 1000 hertz where the flight-type properties of a scale model fan would be identified.

The airflow in the 9 × 15 test section is varied by control of both the tunnel drive motor speed and the diversion of flow along a bypass path. Airflow velocities in the range of 25 to 125 knots are established and maintained in this manner. The effect of velocities below 25 knots on fan noise were also explored in this study. The starting transient of the tunnel was used for this purpose in some tests. Low airflow velocities were also established by the use of auxiliary tunnel fans that normally are used for air circulation during air drying operations.

The 20-inch diameter fan in itself is relatively small for a 9 × 15 test section, however, figure 5 shows that the required auxiliary equipment is quite prominent. The fan was driven by a shaft powered by an acoustically-isolated high pressure air turbine located to the rear of the fan. The exhausts of both the turbine and the test fan were diverted by a closed duct through the tunnel wall rather than being exhausted into the airstream. The stack-like structure shown in figure 5 contains the exhaust system. The fan installation also includes a pivotable mount used in other studies to vary inlet angle of attack.

The fan nacelle inlet, protruding ahead of the auxiliary structure, is exposed to undisturbed flow under normal tunnel velocities. It is possible, however, that the supporting structure could affect the fan inflow during static and extremely low velocity tests because of fan-induced reverse flow along the inlet nacelle. The problem, however, is typical of the ground-static conditions that such tests attempted to simulate.

Other features of the tunnel tests section include the aerodynamic and acoustic instrumentation that are described in reference 22. Figure 5 shows several microphones. Of significance in this preliminary report of results is the rotatable boom microphone that provided the primary source of acoustic data. The microphone traversed in the plane of the fan axis along a circumferential path centered at the fan inlet. The radial distance from the inlet highlight plane to the microphone was 3.6 fan diameters. The traverse was limited from $20^{\circ}$ to about $120^{\circ}$ of the inlet axis. The minimum proximity of the microphone to the tunnel wall was about 1/2 meter. The microphone was mounted in weather-vane fashion to maintain orientation with the airflow direction. The mechanism used for traversing the microphone consisted of a boom located near the tunnel floor with the elevated microphone at its terminus.

## FAN PROPERTIES

The fan stage used in the tests consisted of Rotor-55, previously tested,[(24)] and a specially-designed set of stator vanes. Rotor-55 is a scale model of the rotor for the full-scale QF-9 fan stage tested at NASA-Lewis.[(25)] The stators were designed to simulate fan stage properties of interest in the NASA-Lewis Quiet Clean Short-Haul Experimental Engine Program.[26] Some of the design properties of this fan are listed in Table I. Of significance to this study are the tone cut-off properties prescribed by Tyler and Sofrin.[11] The cut-off theory predicts that with a configuration of 15 rotor blades and 25 stator vanes the fundamental or first harmonic of the blade passage tone due to rotor/stator interactions will not propagate below the design speed. The second harmonic of this tone will propagate at all speeds above 40 percent of design speed. Propagation of the second harmonic, however, is restricted to the lower radial orders of a five-lobed spinning mode. Because of the few propagating modes present the directivity of the second harmonic tone due to rotor/stator interactions may be expected to exhibit a distinctively-lobed pattern when the noise caused by inflow disturbance is not present.

Aerodynamic performance of the fan measured in $9 \times 15$ tunnel tests was comparable to that measured with the fan in other facilities. The fan is considered to be representative of a good low tip-speed design.

## TEST PROCEDURE

The test results to be reported are a part of an extensive program of tests with the modified Rotor-55 fan stage. For this preliminary study attention is focused on test results taken at a fan speed of 96 percent of design with static and 80 knot tunnel conditions and at zero inlet angle of attack. These conditions are considered adequate to establish whether the features distinguishing flight and ground-static noise are simulated. Some data at a fan speed of 80 percent of design are used to substantiate the behavior noted at the higher speed. The progressive effect of tunnel flow on fan noise is also illustrated by test results taken during a starting transient of the tunnel and at low tunnel velocities.

The acoustic measurements consist of noise levels from both boom microphone traverses and with the boom fixed at $60^{\circ}$ from the fan inlet axis. The fixed-position signals were tape recorded for later analysis. On-line graphical displays of noise levels were used at all times and the boom traverse results were limited to such records. The on-line graphing basically consisted of an x-y plotter coupled to a variable 1/3-octave filter, appropriate amplifiers and a logarithmic converter. The x-axis of the plotter was either activated by a boom position sensor or used in the time-scan mode depending on the type of data taken. One-third octave noise levels were plotted for center frequencies adjusted to 0.7, 1.0, 1.4, and 2.0 times the blade passage frequency. Records of broadband and first and second harmonic tone level directivities were thus obtained on-line.

## RESULTS AND DISCUSSION

The simulation of flight-type noise in the 9 × 15 wind tunnel is qualitatively indicated by the tunnel starting transient record shown in figure 8. The 1/3-octave filtered blade passage tone level at $60^{\circ}$ from the inlet is shown as a function of the transient tunnel velocity. The velocity scale shown in figure 8 is not precise because a manual read-and-record method was used to establish velocity conditions in this time transient record. Figure 8, however, dramatically displays that two of the features distinguishing flight noise from ground-static noise are progressively simulated with an increase in tunnel velocity. Both the time variations of tone level and the mean level of the tone are substantially reduced. These reductions appear to be initiated at a tunnel velocity of somewhat less than 10 knots and completed at about 25 knots. This simulation of flight-type noise shown in figure 8 can be more quantitatively supported in the subsequent fixed tunnel velocity results.

The tone and broadband noise at 96 percent fan speed are shown in figure 9 for static and 80 knot tunnel conditions. Figures 9(a) and (b) show directivity plots recorded on-line for the one-third octave noise levels centered at 0.7, 1.0, 1.4, and 2.0 times the blade passage frequency (BPF). Figure 9(c) is a schematic composite that overlays the results with and without tunnel flow. At static conditions (fig. 9(a)) both the first and second harmonic tones (1.0 and 2.0 time BPF) exhibit tone level variations of 7 to 10 dB. These variations decrease to 2 or 3 dB over most of the angles at the 80 knot condition - figure 9(b). The broadband noise levels (0.7 and 1.4 times BPF) do not exhibit this change. The time variations in broadband levels are several dB for both static and 80 knot conditions. The result implies that the random ingestion of inflow disturbances that can cause unsteadiness in tone noise had been substantially altered by tunnel flow. The broadband noise appears to be insensitive to the changes in these disturbances.

The mean level of the fundamental tone is shown in figure 9(c) to be about 10 dB lower at 80 knots than at static conditions. The decrease is relatively uniform over the range of angles. The fundamental tone is predicted to be cut-off at this fan speed. The decrease in tone level is similar to that experienced by cut-off fans in flight. The experimental result implies that inflow disturbances that generate the tone at static conditions are absent or substantially altered at the 80 knot condition.

As expected, since the second harmonic is not cut-off, the harmonic tone in figure 9(c) does not exhibit a uniform decrease in mean level with the 80 knot tunnel flow. Rather, a lobed directivity pattern is observed. The tone level at the peak of the lobes approaches or slightly exceeds that for static conditions. Between the lobes and in a direction normal to the fan axis the tone level reductions are 5 to 7 dB. The lobed directivity pattern at 80 knots indicates that the tone energy is limited to a small number of propagating acoustic modes. As stated previously, only lower radial orders of the five lobed spinning pattern due to rotor/stator interactions are predicted to propagate at this fan speed. The observed result at 80 knots implies the elimination or substantial reduction of the noise related to in flow disturbance that interferred with the rotor/stator interaction noise under ground-static conditions.

The level and directivity of the broadband noise is shown in figure 9(c) to be relatively unaffected by tunnel velocity. The result is consistent with the implications stated regarding time variations in broadband level. That is, the broadband noise is insensitive to the flow disturbances that substantially affect the tone noise.

One-third octave spectra are shown in figure 10 for a variety of conditions for measurements taken at the $60^{\circ}$ inlet angle location. Figure 10(a) shows the static and 80 knot spectra corresponding to the 96 percent fan speed data displayed in figure 9. The effects of tunnel velocity on the fundamental tone, second harmonic tone and broadband noise levels are essentially the same as that observed in figure 9. The third harmonic tone level, however, is shown to be higher at 80 knots than it is statically.

The progressive effect of tunnel velocity on tone levels is shown in figure 10(b). The figure is identical to figure 10(a) but contains one-third octave level data points at some intermediate tunnel velocities. The reduction in the fundamental tone level is shown to be relatively complete at 25 knots. There is essentially no change in the second harmonic level for any tunnel velocity at the $60^{\circ}$ angle position. Changes, however, occurred at other angles as shown by figure 9(c).

The third harmonic level is shown in figure 10(b) to progressively increase with an increase in tunnel velocity. The reason for the increase in the third harmonic level is not known. Directivity must be examined to be assured that the increase was not a unique behavior at one location. The scale and intensity of the turbulence in the tunnel flow may also require attention. The increase in the third harmonic level, however, does not appear to be a general result as indicated by figure 10(c) where the spectra at a fan speed of 80 percent of design are shown. The third harmonic tone level does not show an increase with tunnel flow at this fan speed. Figure 10(c), however, tends to confirm the generality of a substantial reduction in the fundamental tone level and the smaller changes in the second harmonic and broadband levels with tunnel flow at the $60^{\circ}$ angular position.

It is possible that the effects of tunnel flow on harmonic tone levels may be somewhat unique to the fan tested. It can be noted in figure 10 that the second harmonic is the dominant tone under static test condition whereas a dominant fundamental tone is a more typical fan spectral property. Test results from other fans are needed before any generality regarding the effect of tunnel flow in harmonic tone levels can be established.

Whether or not fundamental tone reductions, due to cut-off in flight, results in perceived noise level reductions depends on the strength and frequencies of the tone and its harmonics. If the spectra in figure 10 are adjusted to full-scale by reducing the tone frequencies by a factor of 2 or 3 the second harmonic would control the perceived noise because this dominant tone occurs at a high annoyance frequency. The perceived noise of the full scale fan would be relatively insensitive to fundamental tone cut-off during flight. It appears that larger reductions in perceived noise could be expected from a fan configuration where the fundamental tone frequency occurs near the upper limit of the high annoyance frequency region of about 4000 hertz. In such a fan the fundamental tone level would be more heavily weighted than that of its harmonics regarding annoyance and thus increase the sensitivity of perceived noise to cut-off during flight.

## CONCLUSIONS

A model fan, designed for blade passage tone cut-off, was tested both statically and with tunnel flow (simulating forward velocity) in the NASA-Lewis 9 × 15 Anechoic Wind Tunnel. Three prominent characteristics that distinguish flight-type fan noise from ground-static test noise were, at least to a larger degree, simulated by tunnel velocities above about 25 knots. The flight-type characteristics simulated are:

1. The blade passage tone level was reduced with tunnel flow to about 10 dB below the static test level.

2. The time variations in tone levels were substantially reduced with tunnel flow from those observed statically.

3. The directivity pattern for the second harmonic tone with tunnel flow showed lobes of the type expected for propagating rotor/stator interaction tones.

The anechoic wind tunnel appears to be a useful facility for applied research on aircraft engine fan noise under conditions of simulated flight.

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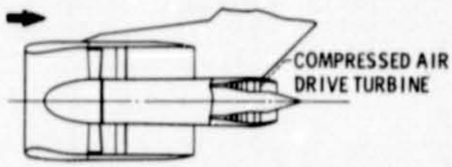
TABLE I. - FAN DESIGN PARAMETERS




| | |
|---|---|
| FAN DIAMETER . . . . . . . . | 20 IN. (50.8 CM) |
| PRESSURE RATIO . . . . . . | 1.2 |
| ROTOR TIP SPEED . . . . . . | 700 FT/SEC (213 m/s) |
| HUB/TIP RATIO . . . . . . . | 0.46 |
| ROTOR TIP SOLIDITY. . . . . | 0.9 |
| ROTOR/STATOR SPACING . . | 1 CHORD (NOMINAL) |
| ROTOR BLADES. . . . . . . . | 15 |
| STATOR VANES. . . . . . . . | 25 |
| VANE/BLADE RATIO. . . . . . | 1.67 |

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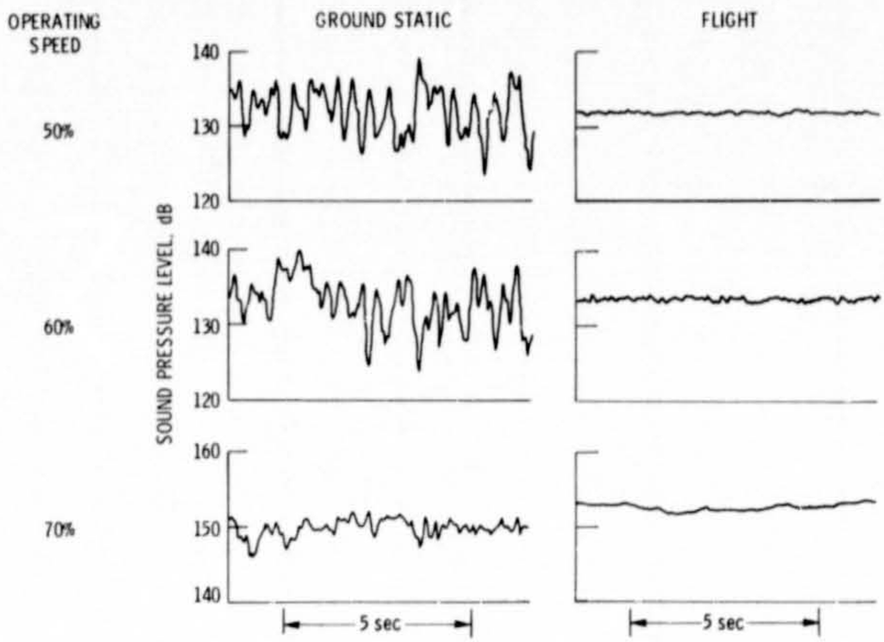
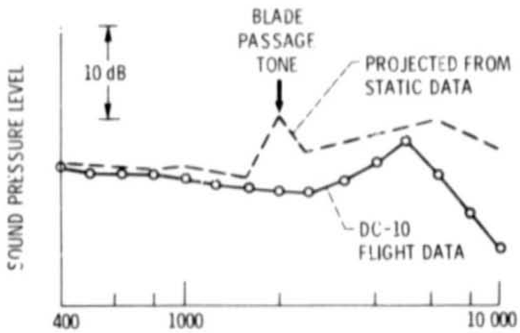
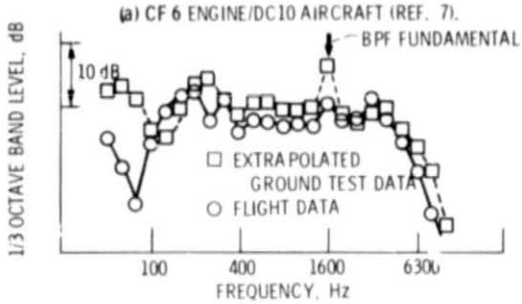



Figure 1. - Time variations in blade passage frequency tone levels in inlet duct of JT8D Refan engine on DC-9 aircraft. Resolution bandwidth, 50 hertz.

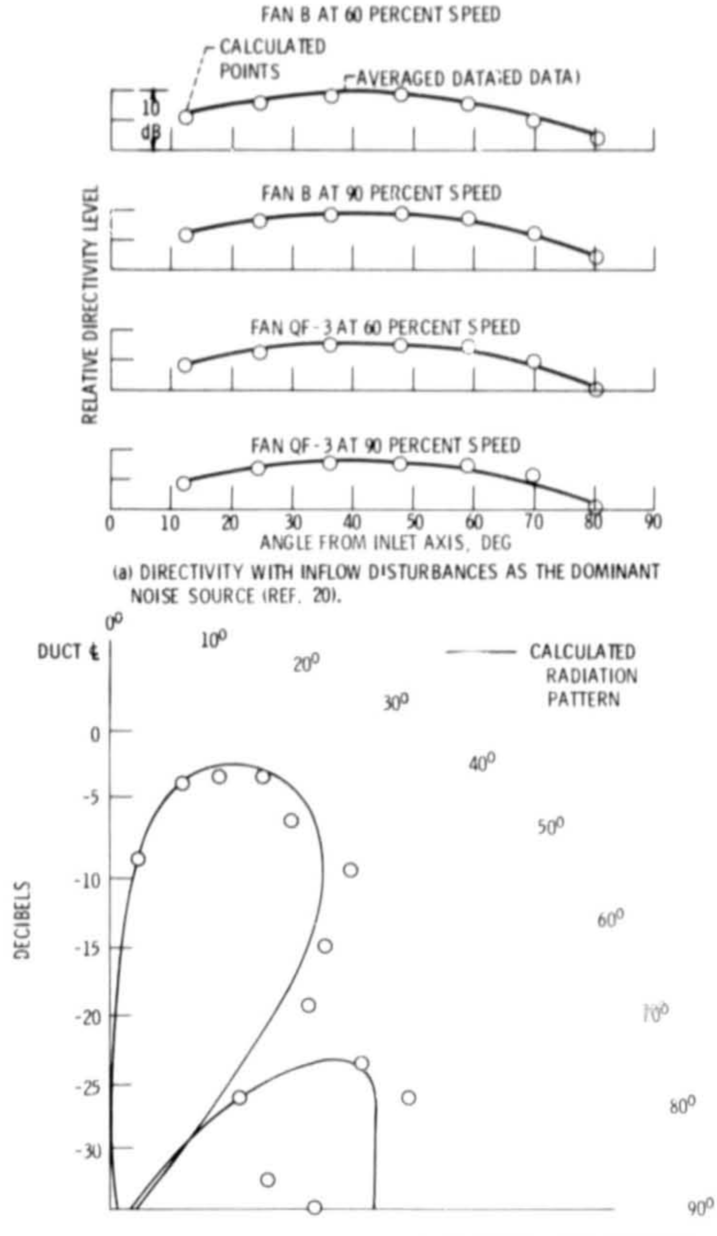



(a) CF 6 ENGINE/DC10 AIRCRAFT (REF. 7).




(b) JT9D ENGINE/747 AIRCRAFT (REF. 9).

Figure 2. - Comparison of flight and ground-static engine noise spectra.




(a) DIRECTIVITY WITH INFLOW DISTURBANCES AS THE DOMINANT NOISE SOURCE (REF. 20).



(b) DIRECTIVITY WITH ROTOR-STATOR INTERACTIONS AS DOMINANT NOISE SOURCE. ONE-LOBE SPINNING PATTERN (REF. 11).

Figure 3. - Experimental and calculated directivity patterns for blade passage frequency tone noise in static tests.

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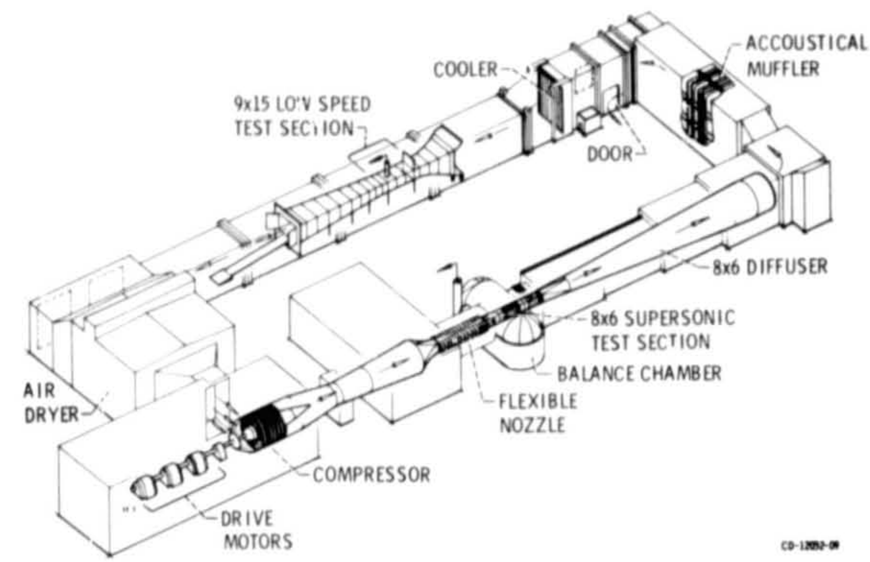



Figure 4. - 9x15-Foot wind tunnel test section in 8x6-foot wind tunnel facility.

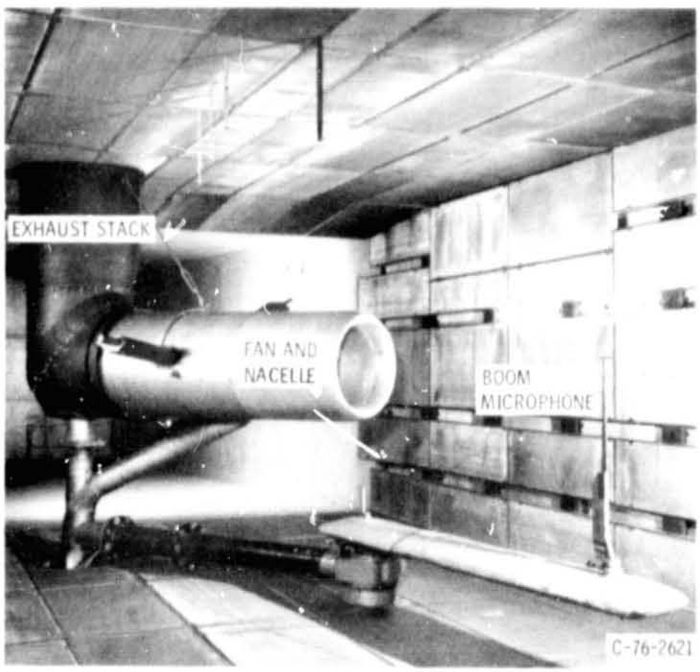



Figure 5. - Fan installed in 9 x 15 anechoic wind tunnel.

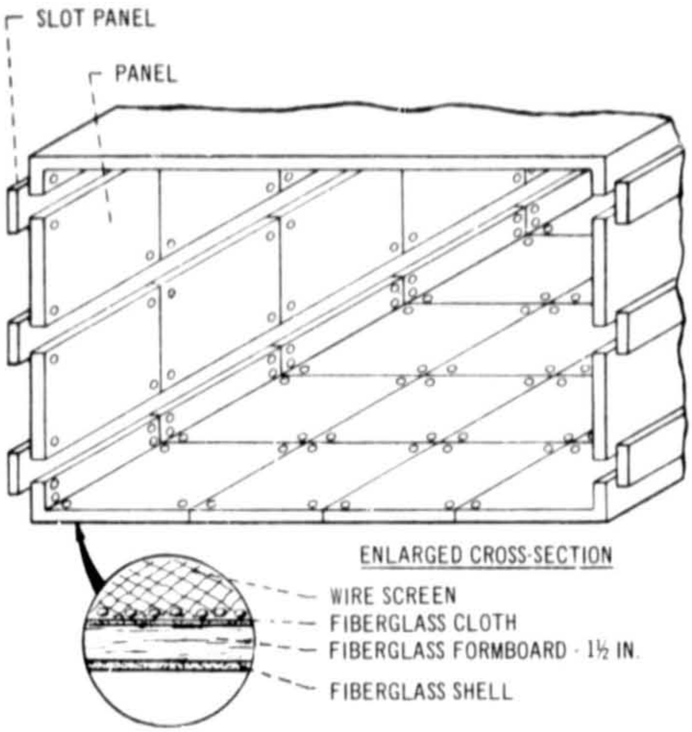



Figure 6. - Acoustic panel installation in the LeRC 9- by 15-foot wind tunnel.

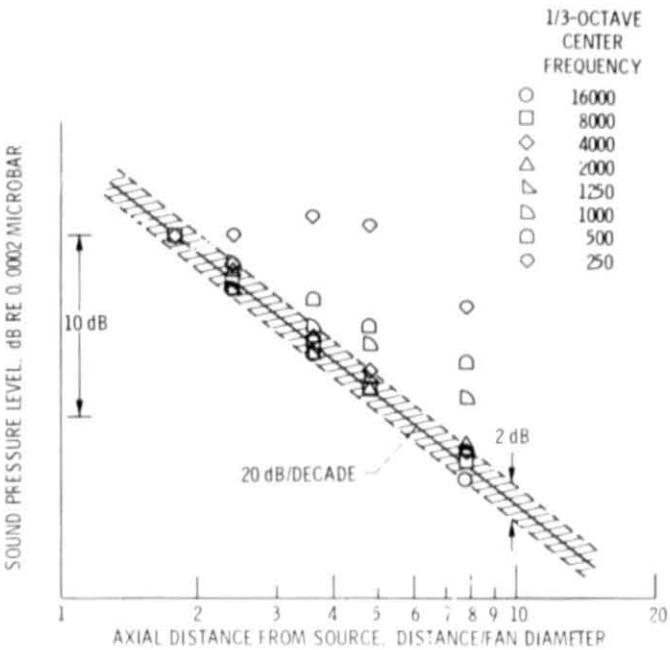



Figure - Anechoic or free field properties of the 9x15 test section from acoustic evaluation tests for a broadband noise source without tunnel flow.

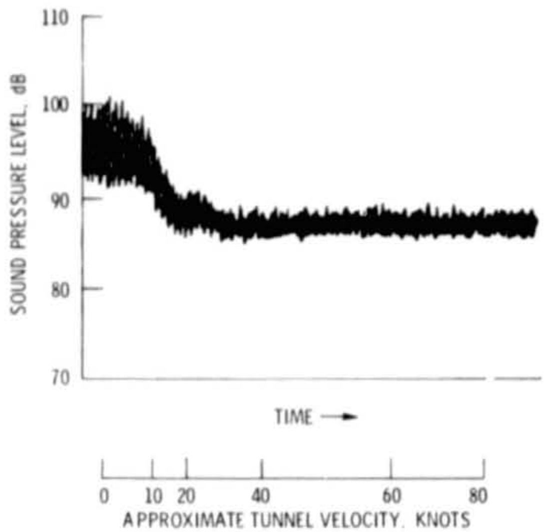



Figure 8. - Change in blade passage frequency tone level during tunnel start transient. One-third octave frequency level at 60$^0$ from inlet axis. Fan speed 96% of design.

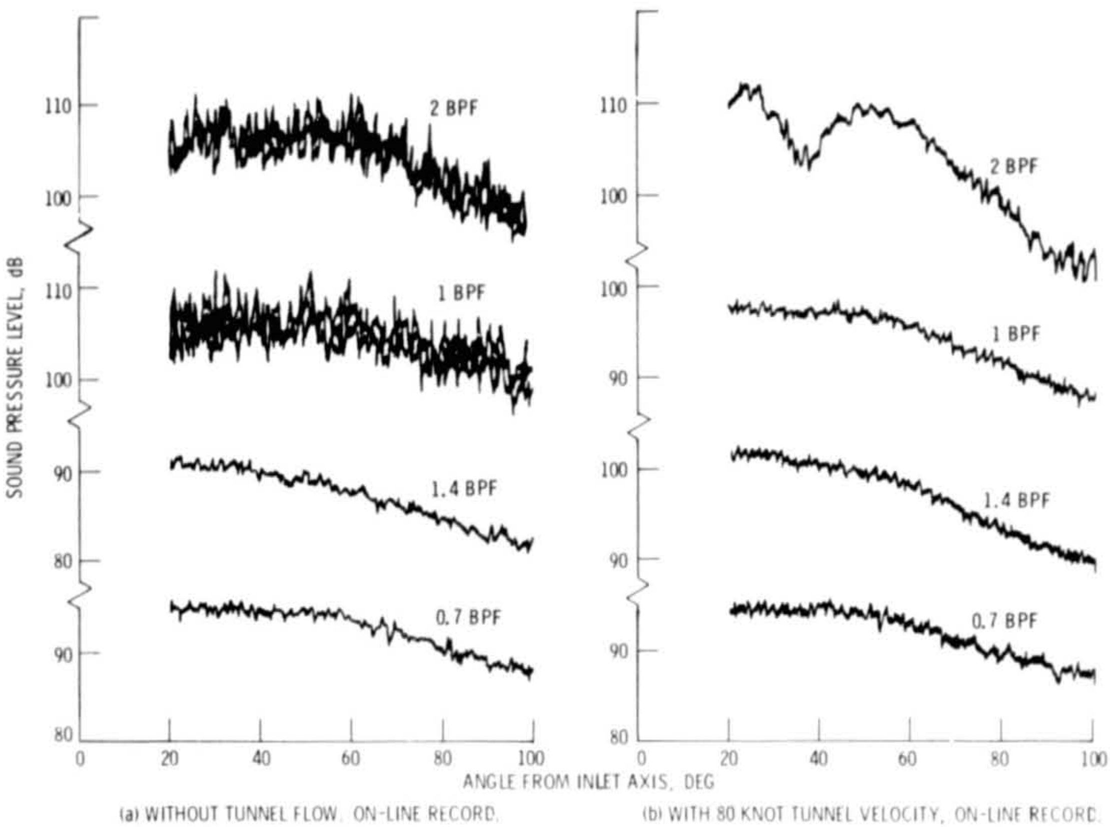
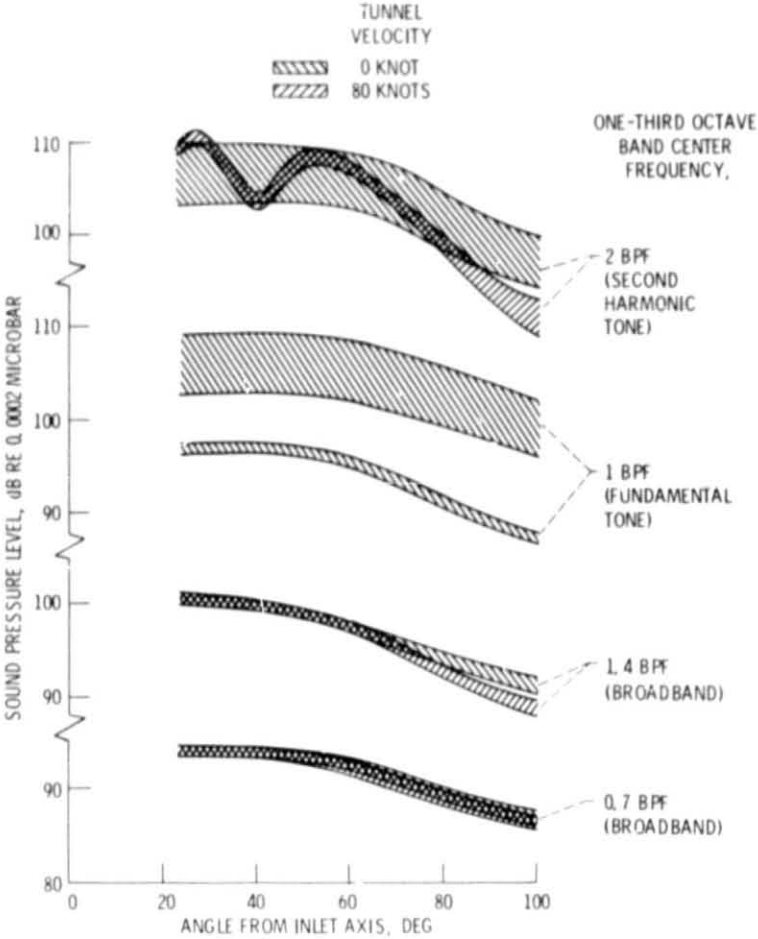



Figure 9. - Directivity of tone and broadband noise with and without tunnel flow. Fan speed, 96% of design.




(c) WITH AND WITHOUT TUNNEL FLOW, SCHEMATIC COMPOSITE.

Figure 9. - Concluded.

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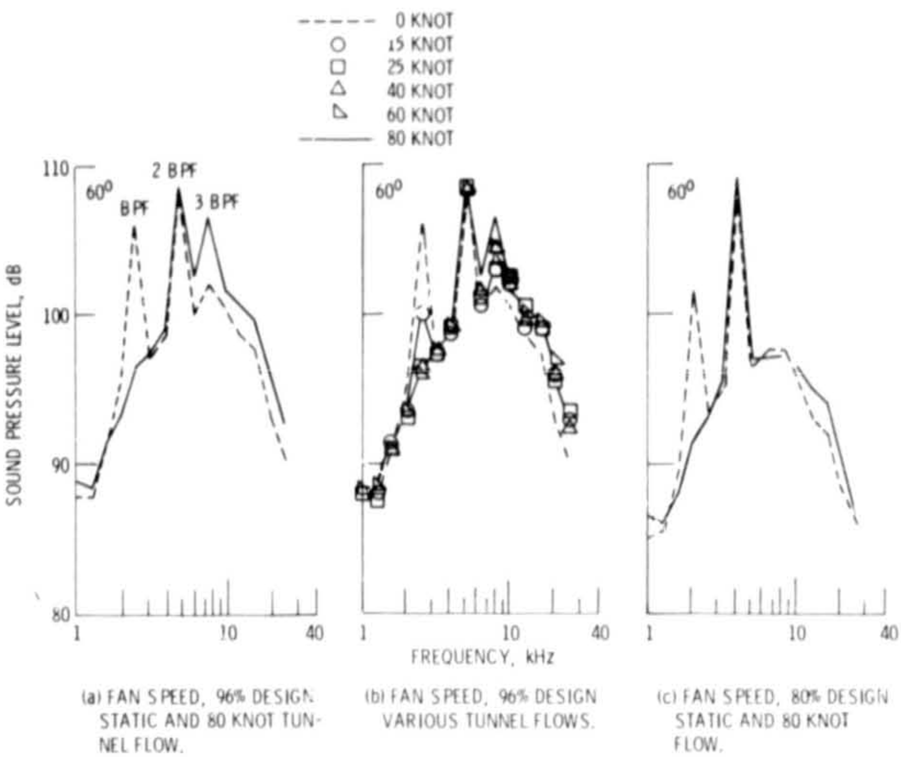


Figure 10. - One-third octave spectra showing effect of tunnel velocity.