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Abstract

Acoustic testing of the AVCO-Lycoming YF-102 turbofan engine was done on a static test stand at Lewis Research Center in support of the Quiet Short-Haul Research Aircraft (QSRA) acoustic design. Overall noise levels are dominated by the fan noise emanating from the exhaust duct, except at high power settings when combination tones are generated in the fan inlet. Component noise levels, calculated by noise prediction methods developed at Lewis Research Center for the ANOP program, are in reasonable agreement with the measured results. Far-field microphones placed at ground level were found superior to those at engine centerline height, even at high frequencies.

Introduction

The propulsion system for the Quiet Short-Haul Research Aircraft (QSRA) consists of four AVCO-Lycoming YF-102 turbofan engines. To aid in the design of the suppression required for this aircraft to meet its noise impact goals, extensive acoustic as well as aerodynamic performance tests were undertaken with a YF-102 engine on a static test stand at Lewis Research Center. The acoustic tests included both near-field and far-field microphone measurements in several unsuppressed configurations. Tests of fan tone characteristics and core noise identification have been reported earlier.[1,2]

These tests are also part of a program to study the effects of flight on various noise sources. As part of the flight research program of the QSRA, extensive acoustic tests are planned, both near-field and far-field.[3] It will then be possible to evaluate installation and flight effects on the noise sources, using the static test data as the basis for comparisons.

The YF-102 turbofan engine is a high bypass ratio engine (6:1) with low exhaust velocities. Although the engine was developed for an earlier application, it incorporates such low noise features as ample fan rotor/stator spacing and fan tone cut-off design. The engine was tested with a bellmouth inlet and with a confluent flow exhaust nozzle.

The acoustic data obtained in this program also afford an opportunity to compare the noise of an AVCO-Lycoming engine with noise source predictions developed at Lewis Research Center in support of the Aircraft Noise Prediction (ANOP) program.[4-8] These were developed without data input from any AVCO-Lycoming engine; hence, comparisons with the data test the applicability of the noise prediction procedures to a low-noise turbofan engine designed by a different manufacturer.

Test Hardware and Analysis

Engine and Stand

The AVCO-Lycoming YF-102 turbofan is a prototype engine designed and built for an earlier aircraft program. Five engines were refurbished and made available to the Quiet Short-Haul Research Aircraft (QSRA) program. One of these engines was tested at Lewis Research Center in the Vertical Lift Test Facility (Fig. 1).

The YF-102 engine (Fig. 2) has a nominal thrust of 33 360 N (7500 lb), 1.5 fan pressure ratio, and 6:1 bypass ratio. The single fan stage has 40 blades and 85 vanes with a rotor/stator spacing (axial spacing to projected chord) of 275 percent. The engine core is fed by a supercharger stage having 90 rotor blades located just behind the hub region of the fan. The engine inlet consists of a 1.17 m long bellmouth section adapted from an earlier program, a 0.47 m transition section, and a 0.29 m cylindrical section as shown in Fig. 3. The engine was tested without a nacelle.

The confluent flow nozzle (Fig. 3) produces a partially-mixed (approx. 15 percent) stream, with a core exhaust terminating 0.915 m upstream of the fan nozzle exit. This round nozzle configuration was designed with the same effective flow areas as the over-the-wing "D" nozzle for the QSRA airplane.

The engine was supported by a fairly massive test stand (Fig. 1) at a 2.74 m centerline height. Although the bellmouth lip was well ahead of the support stand, it is probable that flow over the test stand structure into the inlet resulted in inlet distortion. No inlet flow control structure was used to minimize these distortions or turbulent eddies from the surrounding air.

Acoustics

The test arena is paved with concrete and asphalt to about 1 m beyond the 30.5 m microphone circle (Fig. 4). The asphalt surface is painted white to minimize solar heating. There are no acoustically reflecting surfaces nearby, except the test stand structure and the ground plane. There is a wooded ravine in the direction of the engine exhaust.

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Sixteen 12.7 mm (1/2 in.) condenser microphones were placed at ground level every 10° on a 30.5 m radius, pointed at the engine for normal sound incidence. A thin hardboard square was placed under each microphone to minimize effects of local roughness. Four additional microphones were mounted at engine centerline height on the same radius, at 40°, 60°, 90°, and 120° from the inlet axis. Results from the two sets of microphones are compared in Appendix A. Microphone outputs were preamplified and transmitted through 152 m cables for standard amplification to nominal 1 V levels for tape recording and analysis. The entire microphone system was calibrated by pistonphone before and after each day of running.

Most of the 1/3-octave spectrum analyses were performed on-line during the test. The remainder and all of the narrow band analyses were made from standard FM magnetic tape playback at 152.4 cm/s (60 ips). The total averaging time for 1/3-octave levels was 12 seconds; narrow band levels were determined from 126 ensembles, for a total averaging time of 3.2 seconds.

Digitized 1/3-octave spectra were read into the computer for calculation of lossless levels at 30.5 m radius (with all atmospheric attenuation corrected out), acoustic power, and standard day levels at 152.4 m sideline, together with perceived noise levels (PNL) and tone corrected PNL (PNLT). Lossless data are calculated with 6 dB subtracted from the ground microphone data to give free-field data. Sideline noise calculations assume a flat 3 dB addition to the free-field data to account for ground reflection.

Results and Discussion

1/3 Octave Spectra

In general, the AVCO-Lycoming YF102 turbofan unsuppressed noise levels on a 152.4 m (500 ft) sideline (Fig. 5) are fan exhaust noise dominated and vary from about 85 to 107 PNdB as engine power increases from ground idle to maximum. At the maximum power condition, the engine becomes inlet-noise dominated, which will later be shown to be due to the appearance of combination (or multiple-pure) tones from the fan. Fig. 6 shows that along a 500-ft sideline the maximum inlet noise occurs at 40° to 50° from the inlet centerline, and maximum exhaust noise at 120° to 130°. Again, the loudest contribution is in the aft quadrant, except at maximum engine power (30.5 kN thrust).

In Fig. 7, 40° and 120° are chosen as representative for the maximum noise points. One-third-octave spectra measured at a 30.5 m (100 ft) radius at these angles are shown for three thrust levels. Note the prominence of peaks (which show as tones in later narrow-band plots) at the fan blade passing frequency, BPF_F, and its harmonics. Combination (or multiple-pure) tones are apparent in the inlet direction at high engine power. There are also peaks between 10 000 and 12 500 Hz in the inlet direction at low power settings, which may originate in the supercharger stage feeding the compressor. In the exhaust spectrum at low power there is a peak at 6300 Hz, which corresponds to the last-stage turbine BPF.

Further indication of the probable sources of noise contributing to these spectra can be obtained from the comparisons shown in Fig. 8. Measured spectra at each microphone are summed with area weighting to obtain acoustic power spectra. These spectra are then compared to the power spectra for the total noise calculated from predicted fan, jet, core (combustor), and turbine noise sources. Predictions were made using a computerized noise prediction program written at Lewis Research Center, and based upon documents[4-8] submitted in support of the NASA Aircraft Noise Prediction (ANOP) program.

Detailed examination of Fig. 8 indicates that the jet noise (low frequency) prediction is too low except at 17.7 kN thrust. This jet noise (solid curve) is predicated on fully mixed core and fan streams leaving the confluent nozzle. It is certain that the degree of mixing is much less, perhaps only 15 percent. Calculations of jet noise based on coaxial unmixed jets (dashed curve) predict levels 5 to 8 dB higher than for fully mixed jet streams, but the peak frequency is about one octave too high. The total noise curve includes jet noise predicted for a fully mixed stream. Core (combustor) noise appears to be predicted several dB too high. Turbine tone level predictions seem to reasonably match the appropriate data peaks at the low thrust level, where the turbine tone can be discerned. The predicted fan BPF and second harmonic tone levels agree with the data peaks except at 17.7 kN thrust, where they are over-predicted. At maximum power, the combination tones are predicted considerably too high. At low power there are unpredicted peaks in the high frequency region which may arise as sums of fan and supercharger BPF tones.

In general, the prediction procedure gives a reasonable agreement with the noise levels and trends for this engine. The low-frequency broadband portion of the spectra arises from a combination of jet and core noise sources. Fan and turbine (and supercharger) tone and broadband sources combine to generate the high-frequency portion of the spectra. At maximum thrust, combination tone levels are not as severe as predicted, but still represent an important contribution to the sideline PNdB levels.

Fig. 9 shows the measured and predicted trends of the overall and BPF tone acoustic power levels to be close. Note that the measured data shows a change in slope of the curve for the fan BPF second harmonic and that this change of slope also occurs in the predicted curve. The narrowband spectra presented later show that the one-third octave band of the fan second harmonic also contains a tone from the supercharger blade passing fundamental. However, this tone is present only in the inlet direction and is several dB below the fan second harmonic level, except at the lowest fan speeds. Hence, in the integrated form of acoustic power, the fan second harmonic dominates the third-octave band level, except possibly at the lowest fan speeds. In Fig. 10, the directivity of the fan BPF tone matches the predicted directivity fairly well. In the measured data the contribution from the inlet drops off with angle somewhat faster than predicted.

From these comparisons of the static acoustic test results with predictions, it appears that the prediction procedures can be used (with perhaps some small adjustments) to give a reliable prediction of YF-102 ground test noise. For the QSRA airplane noise impact in flight, suitable static-to-flight corrections and installation effect corrections and predictions for other noise sources, such as flap noise, must be added. The comparisons also indicate that the noise sources for this engine are fairly similar to those for other recent high-bypass subsonic fan engines.

Narrow-Band Noise Spectra. The tonal content of the YF-102 acoustic spectrum is apparent in Fig. 11. Two engine power settings are adequate to show the principal features: at 5700 rpm (17.7 kN thrust) the relative tip speed of the fan rotor is near sonic ($M_{tip} = 0.98$); at 7100 rpm (30.5 kN thrust) the tip speed is supersonic ($M_{tip} = 1.24$). Tone contributions due to the fan, inlet supercharger, turbine (third stage), and multiple pure tones can be identified. Various sum and difference frequencies are also tagged in Fig. 11(a), where they are easily distinguishable. Only the fan tone harmonics remain prominent at 7100 rpm (Fig. 11(b)). Note that at this speed shaft tone multiples should appear every 118 Hz, but are incompletely resolved by the 60-Hz bandwidth filtering. What appeared as high-frequency broad-band noise in the 1/3-octave data shown earlier is actually dominated by fan and supercharger harmonics (at 5700 rpm) and by shaft tone harmonics (at 7100 rpm). The many combination tones exceeding 100 dB in the inlet noise (40°) at the 7100 rpm condition result in the inle noise becoming dominant over the aft-end noise, as was mentioned earlier.

Conclusions

The unsuppressed YF102 turbofan engine produces noise of broadband and tonal content which is typical for this type of engine. At low frequencies, particularly in the rear quadrant, the major contributors are jet noise and some core (combustor) noise. As shown by narrow-band analysis high frequency tones from the fan, supercharger and turbine dominate the higher frequency portion of the spectrum. As the relative fan tip speed becomes supersonic, shaft-order combination tones appear. At high speed the engine noise on a sideline becomes inlet dominated, rather than aft dominated.

When compared with the engine noise spectra, existing component noise predictions developed at Lewis Research Center give a reasonable approximation of the measured spectra and trends with engine speed.

Appendix A

Ground-Level Microphones for Noise Measurements Up To 20 000 Hz

Controversy still surrounds the question of microphone placement with respect to the ground for the most reliable acoustic data. In some cases involving high frequencies and rather complex sources, the source and microphones can be situated well above the ground, since on a small radius, the reflected signal will be considerably weaker (6-8 dB) than the direct signal. In other acoustic arenas, a sound absorbing material has been successfully used to blanket the ground between the source and microphones, and thus to minimize the ground reflector problem. In both of these approaches, the measured signal approximates "free-field" conditions with no ground plane.

In many cases, including the YF-102 engine tests of this report, test conditions do not permit the above measures. For many years the author and others have advocated the use of microphones placed as near as possible to a hard ground surface, so that reflected and direct sound waves arrive simultaneously, add in pressure, and give a measured signal 6 dB above "free field." In most experimental acoustic areas this procedure eliminates vagaries due to ground reflections, particularly in the low frequencies.

In the present engine tests the 17 ground-level microphones were laid on square pads on the ground, pointed at the source. Details were described under Instrumentation and in Fig. 2. The asphalt surface between the microphones and source was painted white to minimize surface heating during the day. Four additional microphones were located at engine centerline height at 40°, 60°, 90°, and 120° from the inlet direction. Comparison of the output from these microphones with the corresponding ground microphones recorded simultaneously is used to show the superiority of the ground microphone system.

Figure A1 shows a comparison of 1/3-octave spectra obtained simultaneously from microphones at ground level and at centerline height. The centerline microphones show a predictable dip in each spectrum due to destructive interference by the wave reflected from the ground. In the exhaust direction the cancellations occur at a lower frequency than in the inlet direction, perhaps due to the distributed nature of the jet noise source. In the inlet direction the high frequency bands show more than the 3 dB difference between microphone readings that would be expected for either randomly related tones or broadband noise.

In Fig. A2 the level differences of Fig. A1 are plotted for a wider range of conditions. Note that as engine speed is changed the ΔSPL spectra are nearly independent of the concomitant frequency and sound level changes. Except for a few stray points, the ground microphones register a higher noise level than the centerline microphones, even at high frequencies. This is contrary to the often-heard caution that ground microphones may read low at high frequencies due to refraction by velocity and temperature gradients near the ground.

Simultaneous narrow-band analyses of the microphone outputs show some striking contrasts in tone levels (Fig. A3). Some of the tones in the centerline microphones register 11 dB lower than at the ground microphones. The discrepancies are especially large in the inlet directions. There is no predictable relation in these tone levels except that the ground microphones almost always give the higher readings.

No tests have been made to determine the acoustic impedance of the paved area around the microphones. It is possible that at high frequencies the real part of the impedance is well below infinite, and strongly dependent on the grazing angle. The grazing angle for the centerline microphones is about twice that for the ground microphones. This could explain part of the difference between the microphone readings for both tones and broadband noise, but at most only 6 dB.

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In summary, it is difficult to explain how ground microphones could read more than 6 dB above free field values in this open arena. However, several factors may be combining to cause the centerline microphones to read much lower than ground microphones, even at high frequencies. These factors may include tone cancellations and the influence of grazing angle on the complex impedance of the ground at high frequencies. Hence, with some care to avoid thermal and wind gradients near the ground, microphones on the ground are found to be far superior to centerline height microphones for reliable measurements of far-field noise at high as well as low frequencies.

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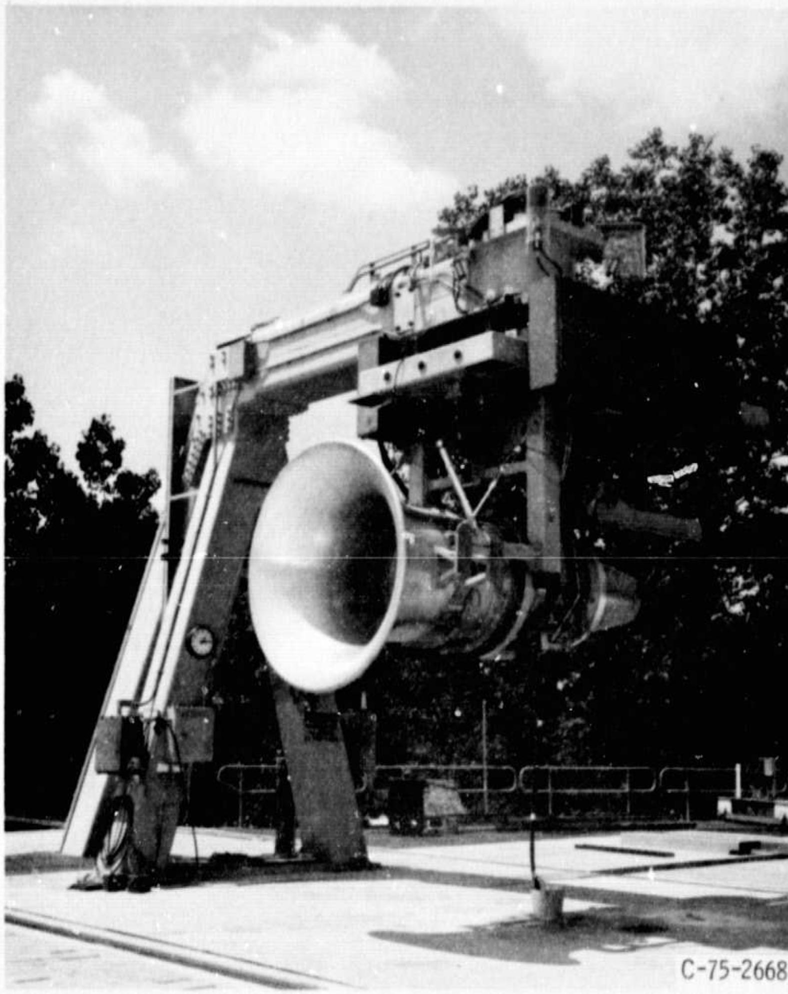

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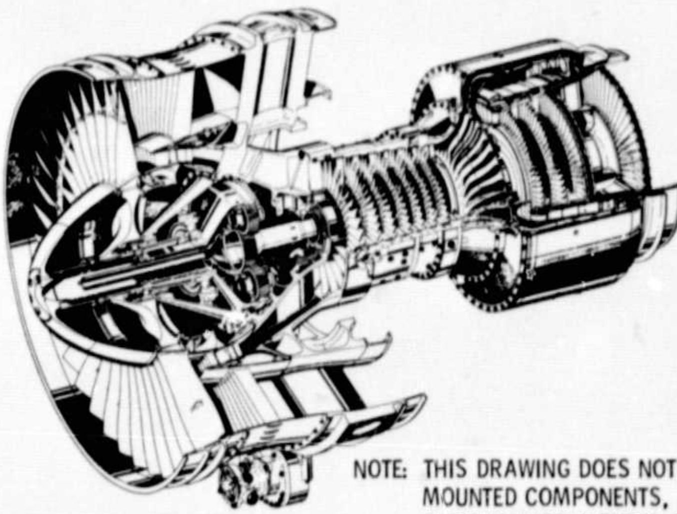
Figure 1. - Avco-Lycoming YF-102 turbofan engine on test stand.



NOTE: THIS DRAWING DOES NOT SHOW THE ENGINE MOUNTED COMPONENTS, OR THE CORE AIR-BLEED MANIFOLD FITTED ON THE COMBUSTOR HOUSING OF THE LeRC TEST ENGINE.

Figure 2. - Illustrative sketch of Avco-Lycoming YF-102 turbofan engine.

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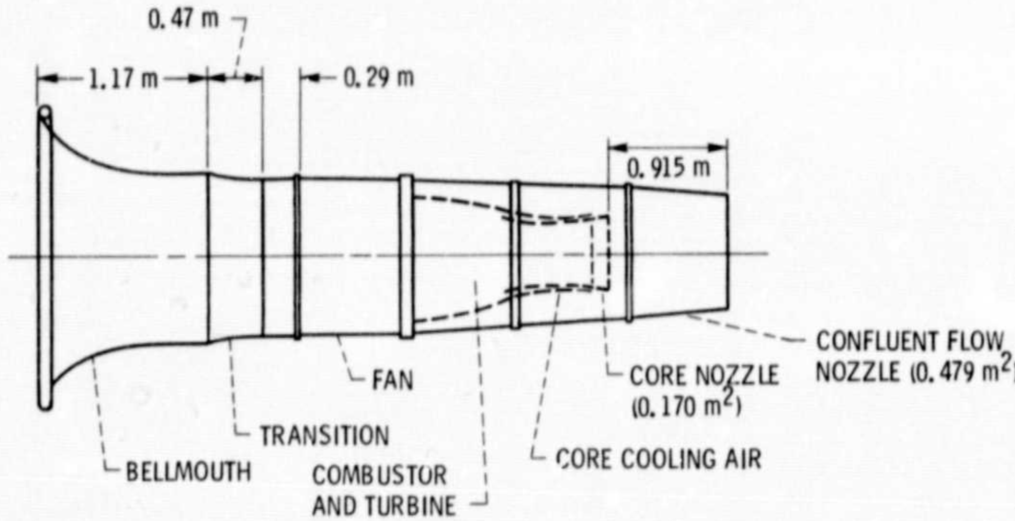

Figure 3. - YF-102 engine inlet and confluent flow exhaust nozzle configuration.

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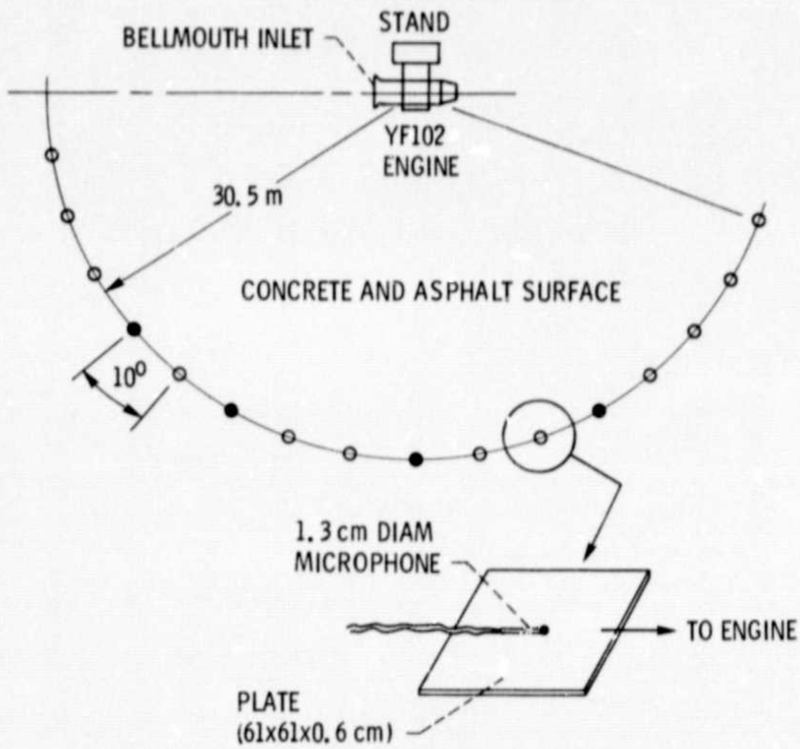

Figure 4. - Far-field microphone array. Solid symbols refer to locations for added microphones at engine centerline height.

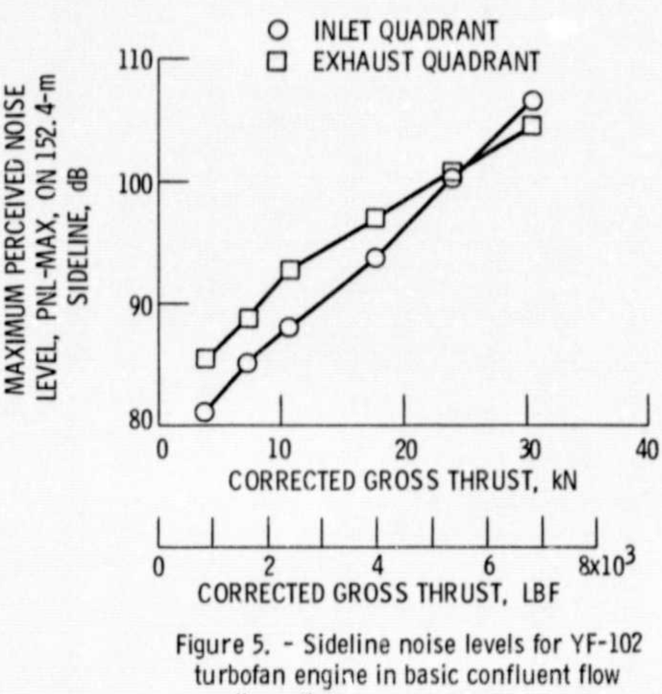

Figure 5. - Sideline noise levels for YF-102 turbofan engine in basic confluent flow configuration.

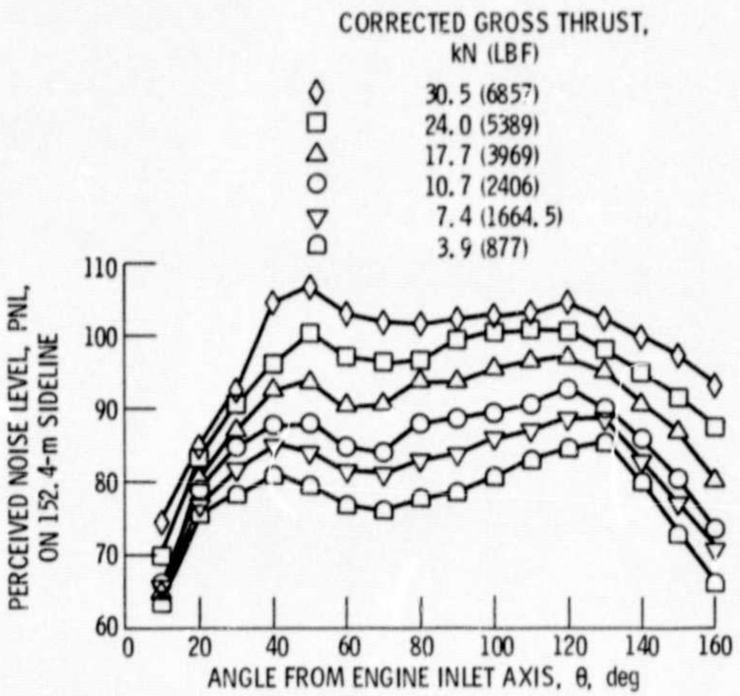

Figure 6. - Sideline directivity of YF-102 turbofan engine noise, in basic confluent flow configuration.

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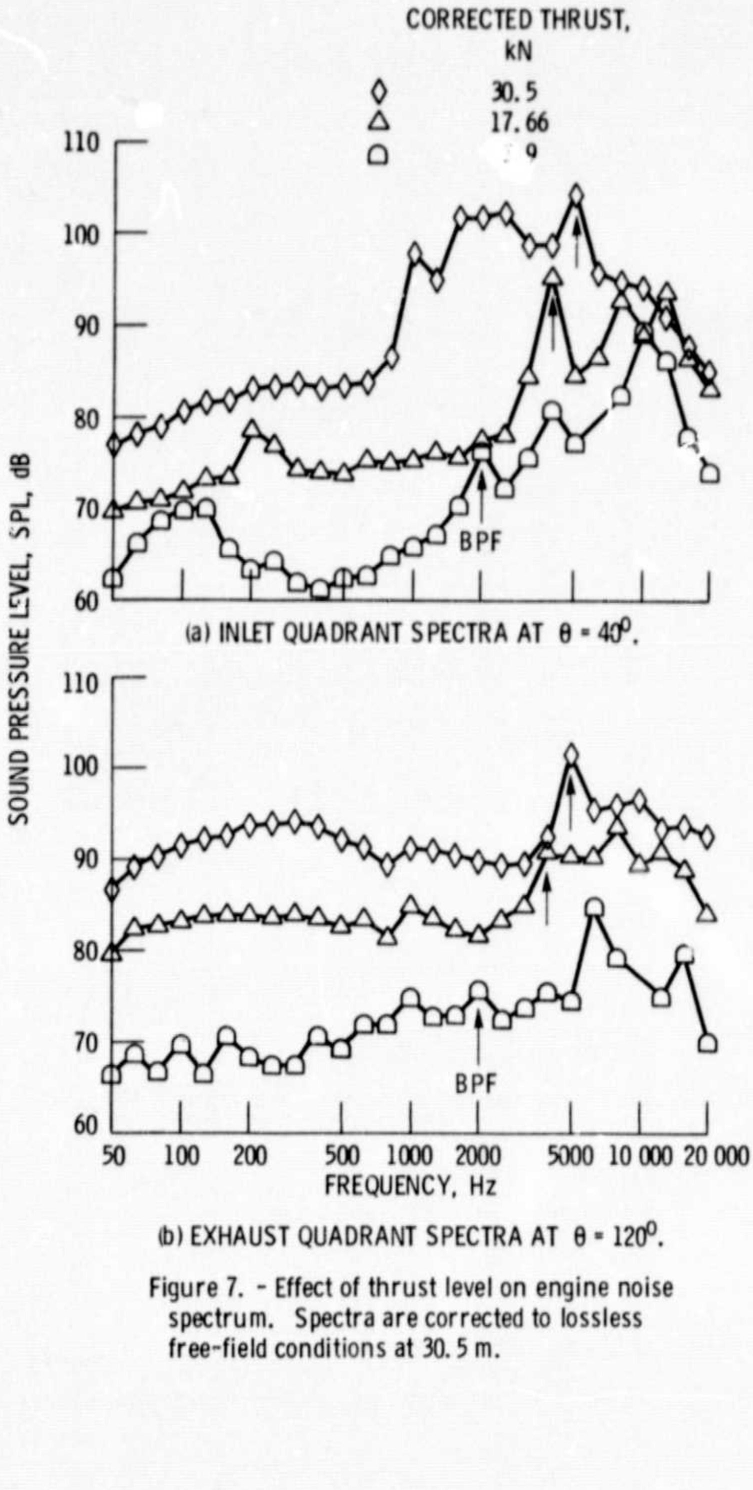
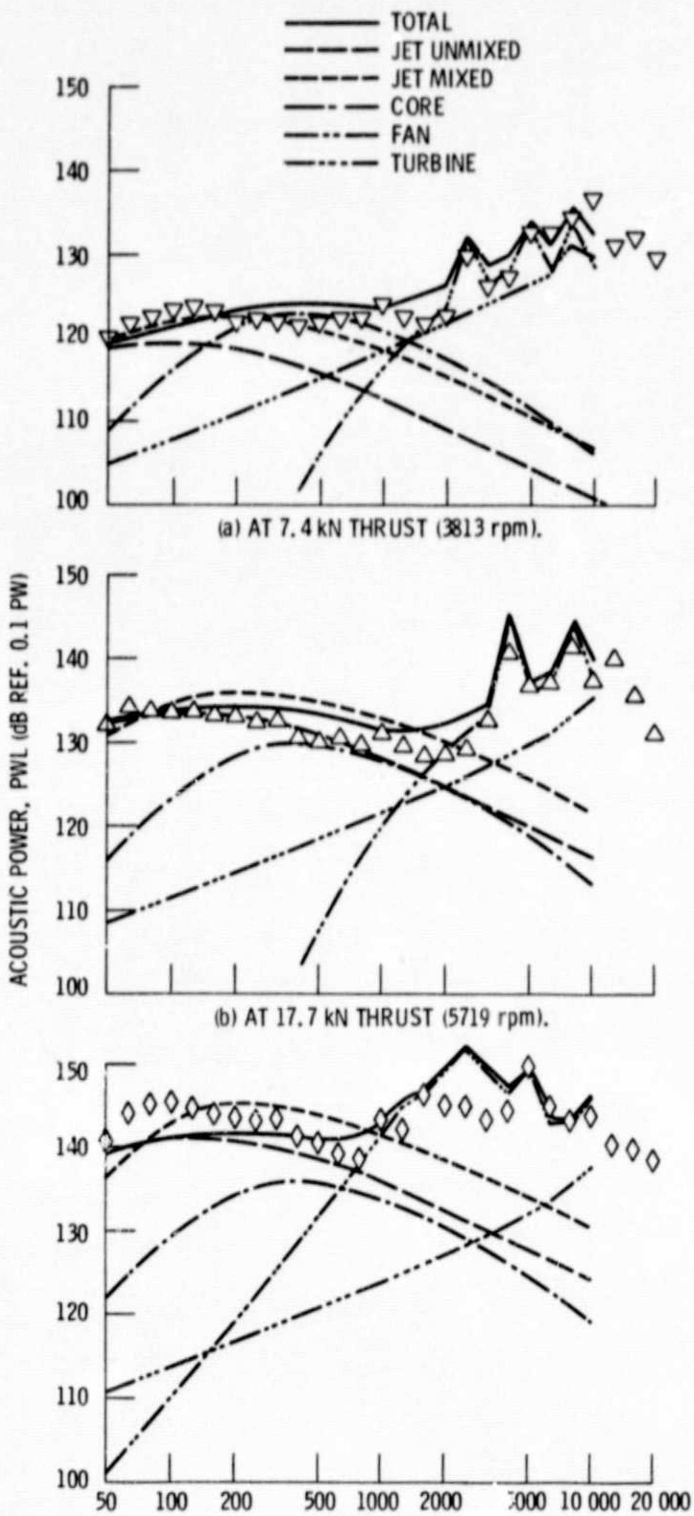
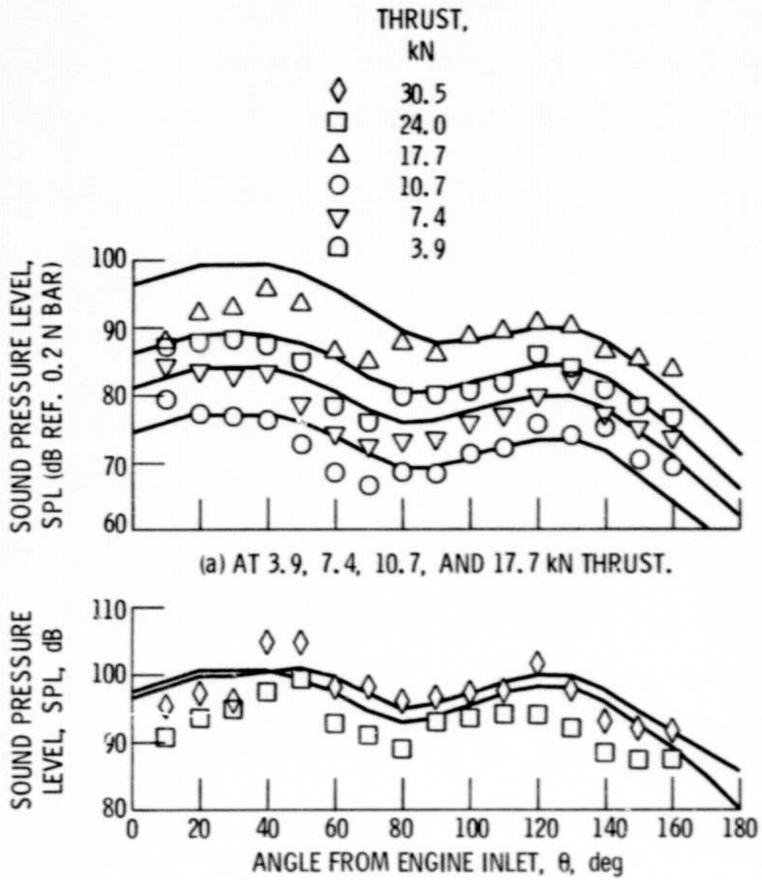


Figure 7. - Effect of thrust level on engine noise spectrum. Spectra are corrected to lossless free-field conditions at 30.5 m.



(c) AT 30.5 kN THRUST (7154 rpm).

Figure 8. - Comparison of predicted acoustic power with measured engine acoustic power. Jet noise calculated for both mixed and unmixed core and fan flows.



(a) AT 3.9, 7.4, 10.7, AND 17.7 kN THRUST.

(b) AT 24.0 AND 30.5 kN THRUST.

Figure 10. - Comparison of measured and predicted blade-passing tone levels for YF-102 engine. SPL data are corrected for free-field and lossless conditions. Symbols refer to measured data.

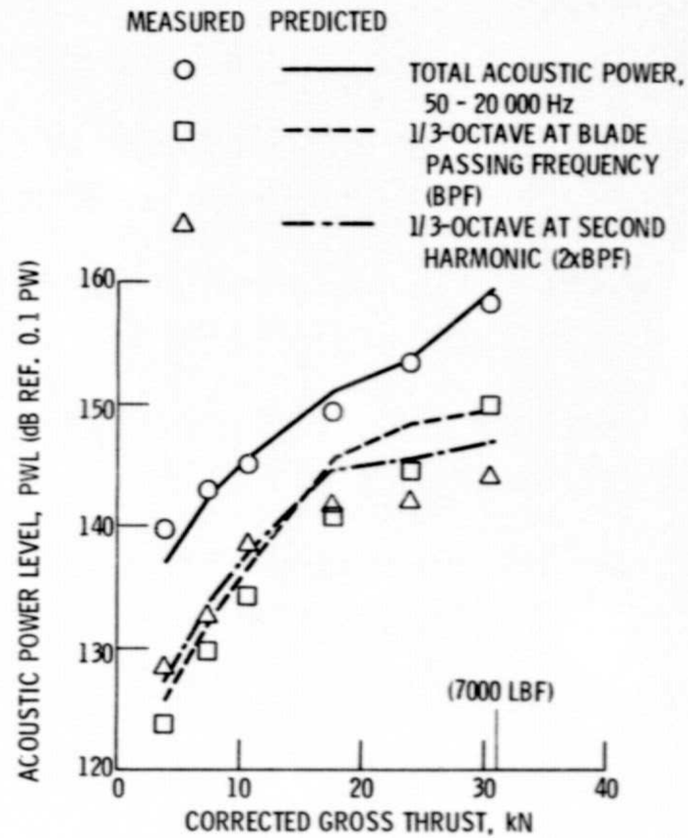
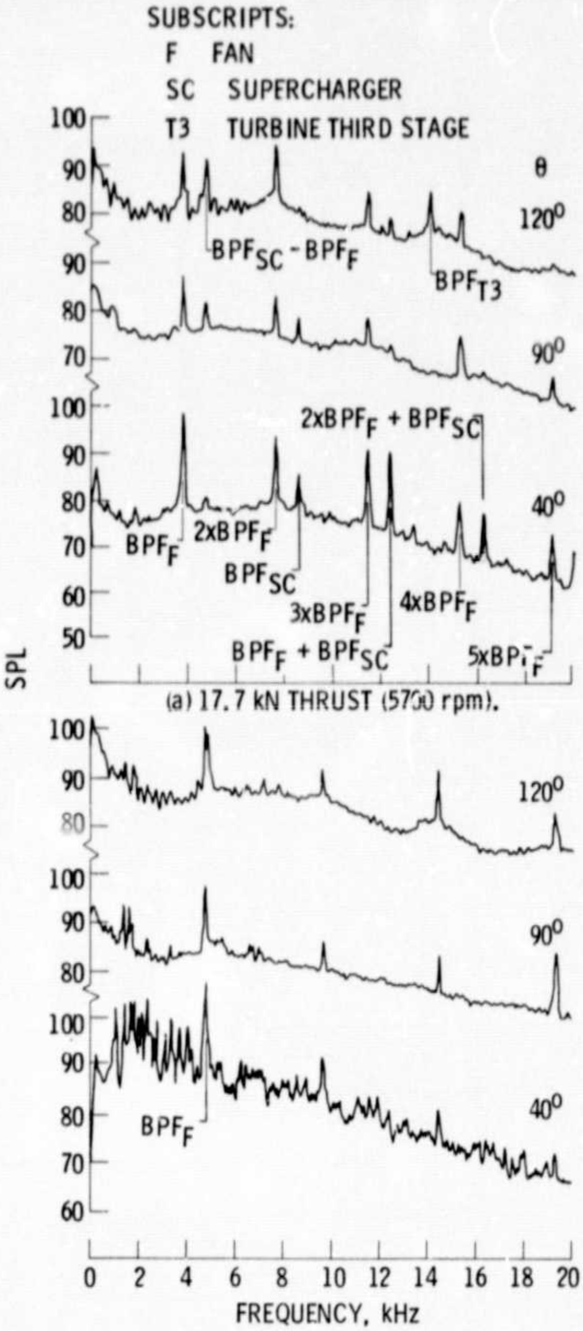
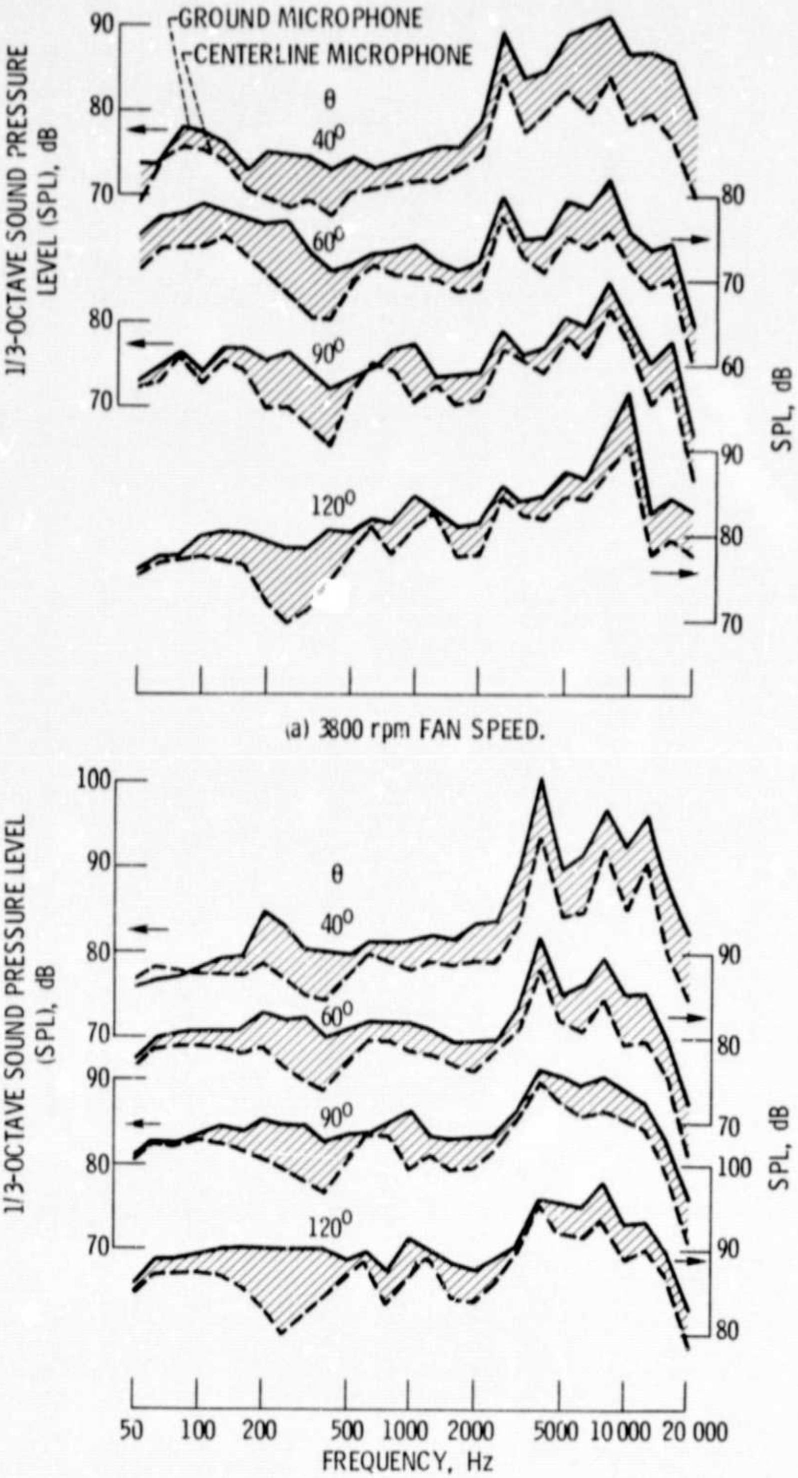


Figure 9. - Acoustic power levels of the unsuppressed YF-102 turbofan engine in the "basic" confluent flow configuration.



(b) 30.5 kN THRUST (7100 rpm).

Figure 11. - Narrowband analysis (60 Hz bandwidth) of far-field microphone signals, basic confluent flow configuration.



(a) 3800 rpm FAN SPEED.

(b) 5700 rpm FAN SPEED.

Figure A1. - Comparison of sound spectra from ground-level and centerline height microphones, confluent flow nozzle.

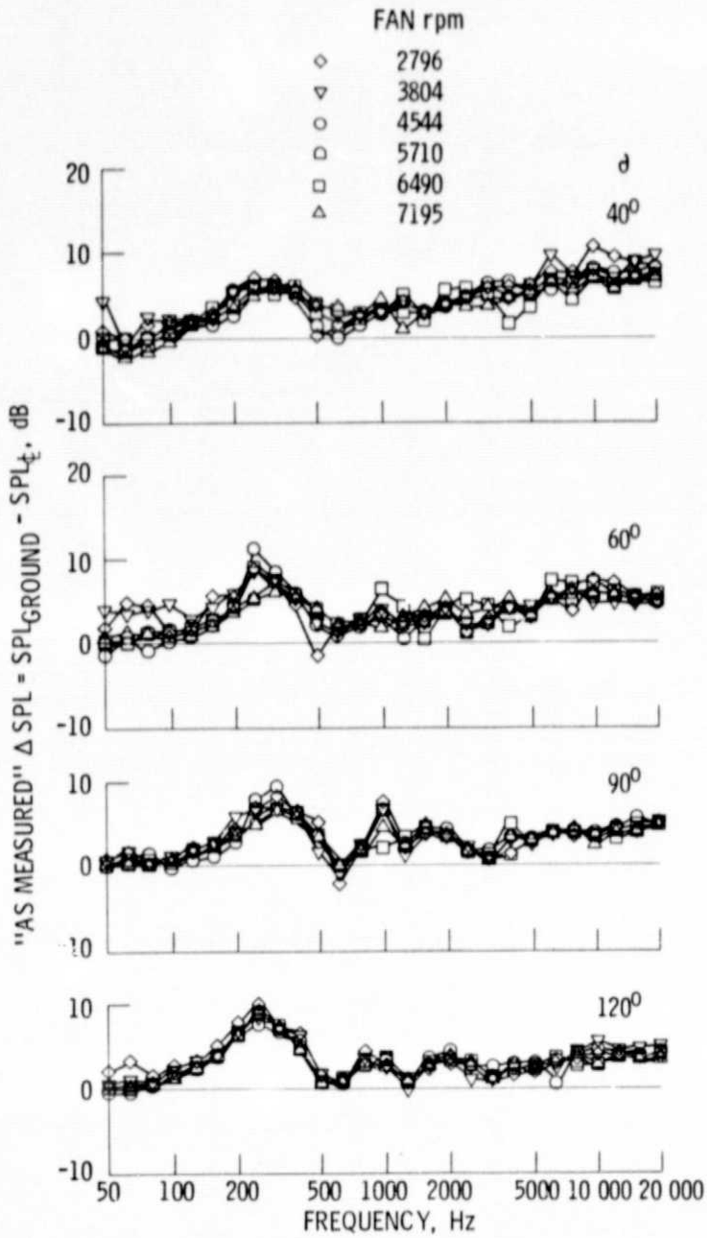
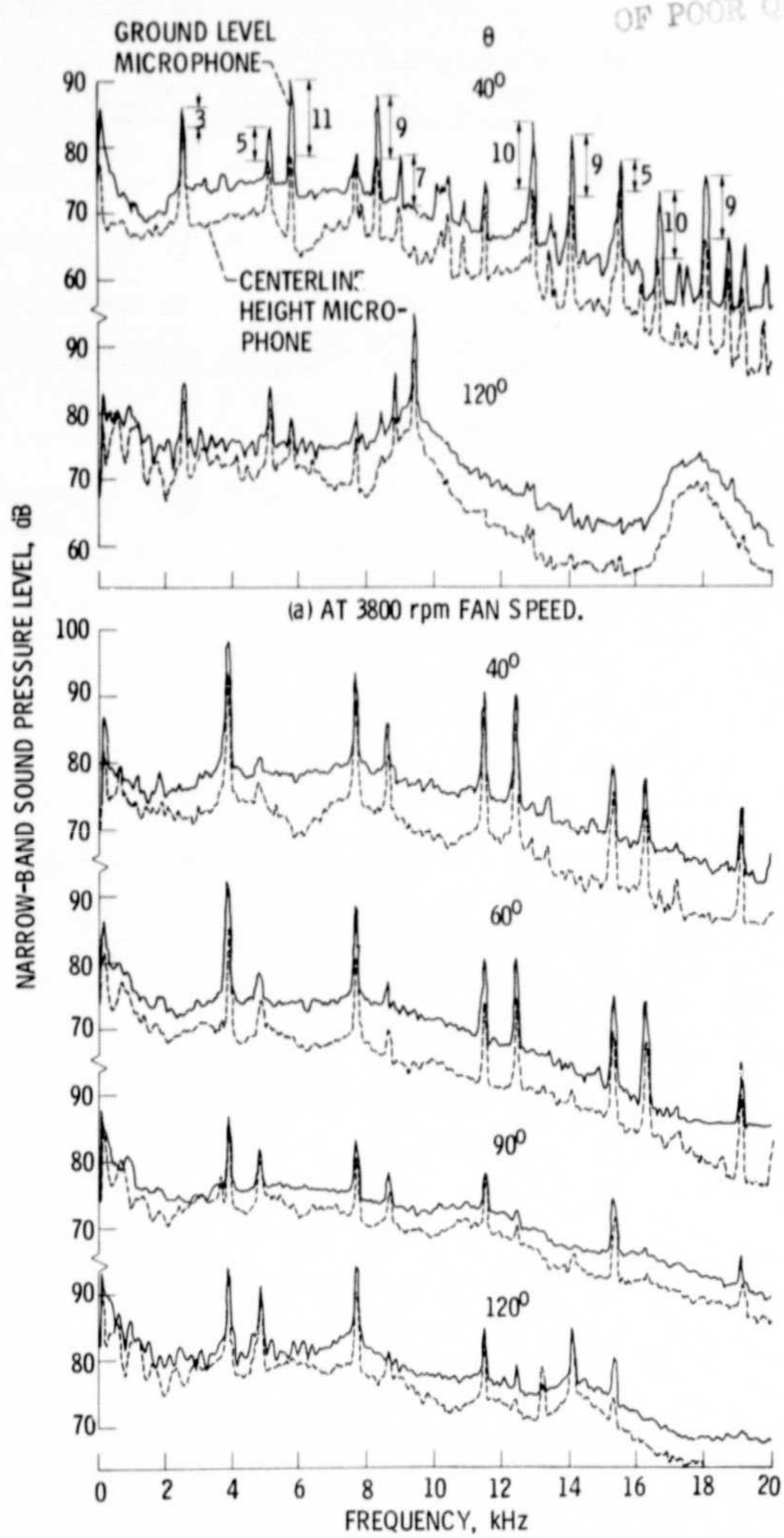


Figure A2. - Comparison of ground level and center-line height (℄) microphone readings for several angles at various engine geometries and speeds, confluent flow nozzle, unsuppressed.



(b) AT 5700 rpm FAN SPEED.

Figure A3. - Comparison of narrow-band spectra (60 Hz bandwidth) from ground level and engine centerline height microphones at various angles θ from engine inlet.