RECENT DEVELOPMENTS IN AIRCRAFT ENGINE NOISE REDUCTION TECHNOLOGY

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SUMMARY

This paper reviews some of the more important developments and progress in jet and fan noise reduction and flight effects made in the past several years. Experiments are reported which show that nonaxisymmetric coannular nozzles have the potential to reduce jet noise for conventional and inverted velocity profiles. It now appears that an improved understanding of suppressive liner behavior, coupled with the new understanding of fan source noise, will soon allow the joint optimization of acoustic liner and fan design for low noise. It is also shown that fan noise source reduction concepts are applicable to advanced turboprops. Advances in inflow control device design are reviewed that appear to offer an adequate approach to the ground simulation of in-flight fan noise. This approach will be assessed by flight experiments currently being conducted on a JT15D engine in a joint program of the Lewis, Langley, and Ames Research Centers. Also in regard to flight effects, it is shown that static jet engine exhaust noise can be projected to flight with reasonable accuracy on an absolute basis.

INTRODUCTION

Aircraft noise has been a major environmental concern for many years. One indication of the public pressure to reduce noise is the number of airports around the world that have noise restrictions such as curfews on nighttime operations, flight routing and operating restrictions, and use of preferential runways. Some data on noise restraints at major world airports are shown in figure 1 for the years 1968, 1973, and 1978 (ref. 1). It can be seen that in 10 years the number of airports with restrictions has doubled. This has happened even though during this time the Federal Aviation Administration (FAA) has issued increasingly stringent noise certification standards that are critical design constraints on new aircraft. To alleviate this noise problem, which is a major constraint to the growth of the civil aviation industry, NASA is conducting research and technology studies to advance the state of the art. The Lewis Research Center has concentrated primarily on propulsion noise reduction technology.

Propulsion noise research is focused on understanding the noise-producing processes, or sources, so that noise can be reduced in efficient and economical ways that do not penalize the engine performance or weight significantly. An additional objective is to develop prediction procedures for each noise source that will allow aircraft noise to be estimated accurately. This paper deals primarily with high-bypass-ratio turbofan engines, although the application of this technology to advanced turboprops is also discussed. Recent advances in supersonic cruise noise technology are not dealt with specifically in this paper but are reported in reference 2.

The noise sources for a turbofan engine are illustrated in figure 2. The sources are both internal and external to the engine. The internal sources are the fan, the compressor, the combustor, the turbine, and the flow over the support struts. The last three sources have usually been considered collectively as engine core noise. Sound from the internal sources must propagate through the engine ducts and nozzles, where it can be reduced by acoustic treatment. Thus acoustic treatment and sound propagation in ducts are very important elements in engine noise reduction. The external sources are the high-velocity jet exhausts mixing with each other and with the ambient air. An important aspect of the engine noise problem is the effects of flight on the various noise sources. As is shown, the effects of flight, or forward velocity, differ for the several noise sources.

SYMBOLS

(S. I. Units unless noted)

D	diameter of nozzle
f	frequency
H	annular height of nozzle
M_0	flight Mach number
OASPL	overall sound pressure level, dB re 20 $\mu N/m^2$
PNL	perceived noise level, PNdB
PR_i	inner-stream-total- to ambient-pressure ratio
PR_o	outer-stream-total- to ambient-pressure ratio
SPL	sound pressure level, dB re 20 $\mu N/m^2$
T_j	jet total temperature
T_s	shielding stream total temperature
V_j	jet velocity
V_s	shielding stream velocity
V_0	flight velocity

θ polar directivity angle referred to inlet, deg

φ azimuthal angle, deg

φ_s azimuthal angular extent of shielding stream, deg

FAN NOISE

The fan is a dominant noise source in current high-bypass-ratio turbofan engines, particularly during landing approach. Furthermore advanced turbofan design studies, such as those associated with the Energy Efficient Engine program, indicate that the fan will continue to be a dominant noise source in future high-bypass-ratio engines (ref. 3). The ultimate goals of fan noise research are to develop noise-reducing design features that are compatible with good aerodynamic performance and to confirm experimentally the acoustic effectiveness of these designs. The approaches to noise reduction include source strength reduction and unified design of the fan and liner to obtain the optimum synergistic effects. The NASA research programs are aimed at understanding the noise-generating mechanisms and describing in detail the fan source characteristics (e.g., ref. 4). Describing the source is important because propagation, liner suppression, and radiation all strongly depend on the initial conditions at the source (refs. 5 to 9). An important constraint on experimental work in static facilities is that the test environment must lead to noise levels that correctly simulate flight (ref. 10), as discussed further in a later section.

Two primary source mechanisms that are addressed in research to reduce fan noise are shown in the turbofan cross section in figure 3. Rotor-stator interactions in the form of rotor wakes and vortices impinging on the stators can be particularly important at the subsonic tip speeds that occur during landing approach. The corresponding narrowband spectrum is shown in the upper portion of figure 4. The blade passing tone and its harmonics, which are due to periodic interactions of the rotor wakes with the stator blades, are superimposed on the broadband levels that result from interactions involving random flow disturbances. Rotor-alone noise production occurs because of nonuniformities in the rotor-locked shock wave patterns that form at the leading edges at supersonic tip speeds. These patterns radiate multiple pure tones during takeoff and have a spectrum of the type shown in the lower portion of figure 4. Multiple pure tones can occur at all multiples of fan shaft rotation frequency, and some of the individual tone levels often exceed the level of the blade passing frequency and its harmonics.

One of the concepts that has been investigated to reduce shock-generated, multiple-pure-tone noise is to sweep the rotor-blade leading edges. An experimental swept-rotor fan designed to explore the acoustic performance of swept blades is shown in figure 5. The acoustic design of this fan was performed by Bolt, Beranek and Newman, Inc., and the aerodynamic and mechanical designs were developed by the Lycoming Division of AVCO Corp. (ref. 11). The blade leading edges are swept forward to midspan and then rearward to the tip in order to limit the maximum blade root stresses. These stresses would be unacceptably high if the sweep were only in one direction. The sweep is varied spanwise in such a manner that the normal component of blade leading-edge relative Mach number is subsonic over the entire span. It is this component that controls leading-edge shock formation. Thus except for blade end effects and the sweep-reversal point this design should essentially eliminate the leading-edge shock system and thereby reduce the multiple-pure-tone noise.

The swept-rotor fan shown in figure 5 was acoustically tested in the NASA Lewis Research Center anechoic chamber (ref. 12), and the major results are shown in figure 6. The multiple-pure-tone power levels for an unswept fan and the swept-rotor fan are compared as a function of fan-tip relative Mach number. Rotor sweep delayed the onset of multiple pure tones to higher relative Mach numbers, about 1.25 instead of 1.0, and reduced the levels over a large portion of the tip-speed range, including speeds representative of takeoff. The aerodynamic performance of the fan did not meet the design goals (e.g., the efficiency was 9 percent low), but this is not surprising since this was the first build of a new design concept for which there are no established design procedures. These initial results are encouraging, and refinement of the aerodynamic design may lead to further multiple-pure-tone noise reductions with more acceptable aerodynamic performance.

APPLICATION OF SWEPT-ROTOR TO ADVANCED TURBOPROPS

The swept-rotor concept, described earlier, is also being considered for advanced high-speed turboprops, which have a potential cabin noise problem at cruise due to propeller noise. Blade sweep also helps reduce aerodynamic losses caused by compressibility effects. Three basic blade planforms pictured in figure 7 were tested in the NASA Lewis 8- by 6-Foot Supersonic Wind Tunnel (ref. 13). Blade sweep angles of 0°, 30°, and 45° were used for these designs. Wall-mounted pressure transducers were used to obtain near-field acoustic data. (Further details are given in refs. 14 and 15.)

The beneficial effects of sweep on propeller noise reduction are shown in figure 8, which compares 45° sweep with no sweep. Maximum blade passing tone level is plotted against helical tip Mach number (total, including flight and rotation). The advance ratio and the power coefficient for all cases are approximately the design values. Variation in helical-tip Mach number was obtained by taking data at various free-stream Mach numbers. The plots for both the 0° and 45° swept blades exhibit a sharp noise increase with increasing helical-tip Mach number; this is then followed by a region where noise levels off. The tailored sweep of the 45° design provides noise reduction over the complete range of tip speeds. Near the cruise design tip Mach number of 1.14, the reduction is about 5 to 6 dB and appears to be even larger at the lower tip speeds tested. Data in reference 14, obtained with a 30° swept blade, support the behavior shown in figure 8.

EXHAUST NOISE

The various noise sources associated with the exhaust are considered in this section. Exhaust noise sources include jet mixing noise, jet shock-cell noise, and core noise. The aft-radiated turbomachinery noise is not included. However, noise transmission through the turbine is an important element in the core noise problem, and recent results are given in references 16 and 17. Core noise generally becomes important at low power settings, particularly in flight. Recent results of core noise investigations are reported in references 18 to 23. Jet shock-cell noise is a potentially important source for supersonic cruise aircraft but is generally not a factor for high-bypass-ratio turbofan engines. For jet-powered aircraft the most important source at takeoff is usually jet mixing noise, and so the present discussion focuses on this noise source. Considerable research has been conducted on jet mixing noise reduction, particularly for supersonic cruise application (ref. 24). Progress has also been made in developing jet noise reduction concepts applicable to subsonic aircraft. Two basic approaches that have received considerable attention are shown in figure 9.

One approach is to mix the fan and core streams; this reduces the maximum jet velocity and consequently reduces jet noise. In addition, this approach offers the potential added benefits of increasing thrust and reducing specific fuel consumption. Such internal mixers have been investigated by the industry (refs. 25 and 26), with some support from the FAA (ref. 27). NASA has also supported mixer-nozzle development studies for large and small turbofan engines (refs. 24 and 13, respectively). Model-scale research is currently being conducted at the Lewis Research Center to help develop internal mixer noise technology for high-bypass-ratio turbofan engines such as the Energy Efficient Engine.

The other approach is to use asymmetry in the jet exhaust in the form of a noise shielding concept. Two variations to this approach that have been investigated on a preliminary basis at the Lewis Research Center are discussed in the following sections.

Thermal Acoustic Shielding

Velocity and temperature profiles in the jet flow field affect noise generation and propagation (e.g., ref. 28), and these phenomena can lead to noise suppression concepts (e.g., ref. 29). It has been shown that a relatively quiet jet can shield a noisier jet (refs. 30 and 31). On the basis of these considerations the thermal acoustic shield concept, illustrated in figure 10, is receiving considerable attention.

Previous experimental studies (ref. 32) have shown that jet exhaust noise can be reduced by using a full ($\varphi_s = 360°$) annular thermal acoustic shield consisting of a high-temperature, low-velocity gas stream surrounding the high-velocity central jet exhaust. It has also been recognized for some time that even a low-temperature annular flow reduces the noise of the central jet, as in a conventional bypass engine (e.g., ref. 33). The reductions obtained with a full-annular shielding stream are believed to be limited by multiple reflections within the jet. It has been suggested that a semiannular shield (φ_s = 180°) would not be limited in this manner. Therefore an exploratory study of this concept was begun at the Lewis Research Center (ref. 34).

The semiannular thermal acoustic shield configuration was obtained by blocking the flow in half of the outer stream of a coplanar, coannular nozzle, as shown in figure 11. Typical noise spectra for a subsonic primary jet at three angles - θ = 45° (forward quadrant), θ = 90° (overhead), and θ = 135° (aft quadrant) are shown in figure 12. It can be seen that the partial shield provides high-frequency noise reduction at all angles, but the effect is most pronounced in the aft quadrant (θ = 135°). Since it is in the aft quadrant where jet noise peaks, significant peak perceived noise level (PNL) reductions should result. Perceived noise level directivities, scaled up to a nominally full-size engine, are shown in figure 13 for these same conditions. The shielding benefits can be observed at all angles, and the reduction in peak PNL is about 4 PNdB. These promising results indicate that the thermal acoustic shield should be further investigated since the present study was exploratory and the geometry by no means optimized. Lewis has recently begun a model-scale contract study of the thermal acoustic shield integrated with an annular plug nozzle. Although this study is motivated primarily by the possibility of supersonic cruise application, promising results might lead to concepts applicable to high-bypass-ratio turbofans.

Nozzle Shaping

Other means of using asymmetry in the flow field of dual-stream exhausts have been proposed to control noise. As shown in figure 14, for a conventional-velocity-profile coannular nozzle, increasing the annular height H for fixed velocities and temperatures reduces the noise. However, for the inverted-velocity-profile case, the opposite trend occurs (ref. 35). It seems reasonable then that favorable acoustic results might be obtained by proper introduction of asymmetry. Specifically, the passage height should be increased on the side toward the observer for a conventional profile, and for an inverted profile the passage height should be decreased in the direction of the observer. These trends were observed in exploratory experiments with the nozzle shown in figure 15. The outer nozzle was mounted eccentrically to produce a 70 percent reduction in passage height in one direction and a corresponding 70 percent increase in passage height in the opposite direction.

The expected type of results was obtained for the conventional-velocity-profile case, most likely to be applicable to high-bypass-ratio turbofans, and typical results (ref. 36) are shown in figure 16. Measured spectra for the concentric and eccentric nozzles are compared at a directivity angle θ of 125°, which is at or near the peak noise angle. A significant suppression is obtained with the eccentric nozzle for model-scale frequencies above 1000 Hz. For lower frequencies the effects are minimal. Also given on the abscissa is a second scale showing the corresponding frequencies for a typical full-scale engine (0.69-m diam). It is apparent that the suppression occurs in a frequency range where it would be beneficial at full scale. Similar results were obtained for the inverted-velocity-profile case and show potential for supersonic cruise application (ref. 37).

For purposes of practical application noise suppression is generally desired both in the sideline plane ($\varphi \cong 65°$) and the flyover plane ($\varphi = 0°$). The eccentric nozzle provides maximum suppression in the flyover plane, with decreasing suppression as φ increases toward 90°. However, by shaping the annulus with a constant wide width to $\varphi = 90°$, or even greater, sideline suppression should be achievable. In this procedure the annulus width must be decreased for φ values larger than the φ for the wide-width annulus. This in essence yields an asymmetric passage (fig. 17) for the present nozzle concept.

It is expected that further substantial noise suppression can be achieved with shaped nozzles by incorporating suppressor elements into the design concept. Such nozzle concepts could include either full-core stream suppressors or partial-core stream suppressors. The application of such suppressors could not only reduce the jet noise, but could also enhance the usual suppressor noise reduction of the baseline nozzles by advantageously altering the jet plume velocity profile.

FLIGHT EFFECTS

To assess the effect of aircraft noise on the environment in the vicinity of an airport, it is necessary to predict the effects of flight on the various components of engine noise. For new or proposed aircraft such predictions must often be made on the basis of only static data for the full-scale engine, since costs limit the number of configurations that can be flight tested. Therefore it is essential that methods be developed for obtaining valid static data for projection to flight as well as analytical procedures for making such projections. The general problem is complicated by the fact that the effects of flight are not the same for all the noise components. The Lewis Research Center programs focus on the different problems of inlet and exhaust noise flight effects and simulation.

Fan Inlet Noise

Modern turbofan engines exhibit less fan noise in flight than is projected from ground static tests. A major reason for this discrepancy is the apparent existence of an additional noise source in ground static tests that is not present in flight. This extraneous noise mechanism, illustrated in figure 18, is due to rotor interaction with inflow disturbances. The rotor blades cut externally produced turbulence, wakes, or vortices that are drawn into the inlet. At subsonic fan tip speeds this source often obscures or completely masks the rotor-stator interaction source expected to be dominant in flight.

The reason for the prominence of the inflow source statically and its greatly reduced importance in flight (ref. 10) are illustrated in figure 19. The nature of the fan inlet flow field for both the static and flight cases is shown on the left side of the figure, and the corresponding fan spectra are shown on the right. In the static case turbulence in the atmosphere as well as wakes and vortices from the proximity of the test stand and ground plane are drawn into the inlet through the greatly contracting stream tubes. The contraction intensifies transverse turbulent fluctuations and stretches the disturbances axially so that the rotor blades cut each intensified disturbance many times. Tone bursts are generated that appear as a strong blade passing tone and harmonics in the fan spectrum. In contrast, in the flight case the stream tubes do not contract to intensify and elongate the atmospheric turbulence, and test-stand and ground-plane disturbances are not present. Thus for fan stages that have been designed to limit the noise produced by rotor-stator interaction, the tone levels, particularly those of the fundamental tone, are greatly reduced.

Several investigators (refs. 38 to 44) have shown that honeycomb-screen structures mounted over the test inlet can reduce inflow disturbances and the resultant tone noise. Recent tests have been conducted at the Lewis Research Center to evaluate several types of inflow control devices (ICD) similar to that shown in figure 20 (ref. 45). These tests were conducted on a JT15D engine with a massive exhaust muffler, as shown in figure 21. The ICD's ranged from 1.6 to 4 fan diameters in size and differed in shape and fabrication method. The results obtained with the ICD shown in figures 20 and 21 are summarized in figure 22. All the ICD's significantly reduced the blade passing tone in the far field, but the smallest ICD's apparently introduced propagating modes that could be identified by additional lobes in the directivity patterns. Other recent experiments on fan source noise with this type of ICD are reported in reference 46. Flight tests are being conducted by the Langley Research Center for this engine mounted on an OV-1 airplane as shown in figure 23. Thus actual flight data will be obtained that will permit an evaluation of how well the ICD's reproduce the flight type of inflow condition.

Jet Exhaust Noise

The subject of flight effects on jet exhaust noise has been a rather controversial one in recent years. Some of the terminology needed to describe flight effects is defined in figure 24. The cases considered herein are level flyovers at an airplane velocity of V_0. The observer is located at an angle θ from the engine inlet axis.

According to classical jet noise theory in-flight jet noise should follow a fairly simple relation, as the velocity arrows at the bottom of figure 24 suggest. For a given absolute jet velocity V_j (shown by the upper, longer arrow), increasing the flight velocity V_0 (shown by the lower, shorter arrow) reduces the velocity of the jet relative to the air. This reduces the shear, and therefore the noise should be less in flight.

The current interest in flight effects was greatly stimulated several years ago when Rolls-Royce (refs. 47 and 48) reported results like those shown in figure 25, where the overall sound pressure level is plotted as a function of directivity angle. The static case is shown by the solid curve, and the corresponding flight case is shown by the dash-dot and curve. The noise in the rear quadrant was reduced, as expected. However, in some cases, such as the one shown here, the noise in the forward quadrant increased in flight. Further confusing the issue is the fact that model-jet simulated flight tests indicate that in-flight noise should be reduced at all angles, as shown by the dashed curve. Studies conducted or sponsored by NASA suggest that these apparent anomalies can be resolved when the engine internal noise is considered (refs. 49 to 55). The internal noise is amplified by a sufficient amount (ref. 56) that the total in-flight noise exceeds the static level even though the jet noise is reduced.

Based on the favorable comparisons with flight data when internal noise is accounted for, a methodology has been developed for predicting in-flight exhaust noise for single-stream exhausts from static data (ref. 57). This methodology is illustrated in figure 26. The experimentally determined static total noise is compared with the jet mixing and shock-cell noise predicted from reference 58. The predicted jet noise and shock noise are antilogarithmically subtracted from the total measured noise to produce an inferred excess noise. The inferred excess noise is correlated with similar data for other angles and power settings to produce an empirical excess noise correlation. The correlated excess noise and the shock noise are then projected to flight, as shown on the right side of figure 26, with the assumption of a Doppler frequency shift and an amplification of $-40 \log (1 - M_0 \cos \theta)$. The jet mixing noise in flight is predicted from reference 58, and the total projected flight noise is obtained by antilogarithmic addition.

Typical static results are shown in figure 27 for an Orenda turbojet on an F-86 airplane at high jet velocity (596 m/sec). The results were obtained by Boeing (ref. 59) and made available to NASA. Noise spectra are shown at three angles - $\theta = 50°$ (forward quadrant), $\theta = 90°$ (overhead), and $\theta = 130°$ (peak noise, aft quadrant). It can be seen that the importance of the various noise sources varies with the different angles. Shock noise is dominant in the forward quadrant, and jet mixing noise is dominant in the aft quadrant. At lower power settings the excess noise becomes more important. The projection of these data to flight is compared with actual flyover data in figure 28. The relative importance of jet mixing noise is reduced as compared with the static case (fig. 27), and the projection agrees rather well with the experimental data. Additional comparisons are shown for the Orenda engine on the F-86 in reference 58 and for the J85 turbojet on the Bertin aerotrain in reference 60.

CONCLUDING REMARKS

This paper reviews some of the recent important developments in engine noise reduction technology. Some developments of particular interest are as follows:

1. Sweeping of the fan blades has been shown to be useful in reducing multiple-pure-tone noise. Similarly, increasing sweep has been shown to reduce the noise of advanced turboprop models.

2. Two methods of using nozzle asymmetry have been shown to reduce jet exhaust noise: nonconcentric dual-stream exhausts and the thermal acoustic shield.

3. Inlet flow control devices have been developed that appear to allow static fan noise tests to be made with inflow conditions approximating those encountered in flight. Flight tests are planned to more fully resolve the issue.

4. It is shown that static jet engine exhaust noise can be accurately projected to flight on an absolute basis.

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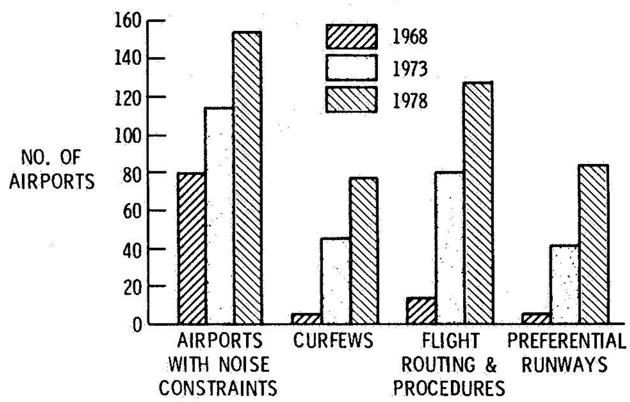

Figure 1.- Noise constraints at major world airports.

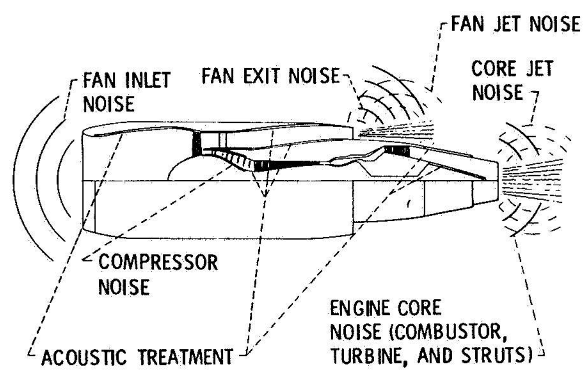

Figure 2.- Turbofan engine noise sources.

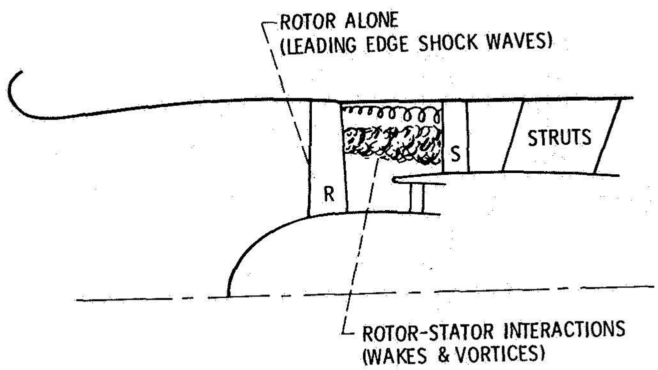

Figure 3.- Fan noise sources.

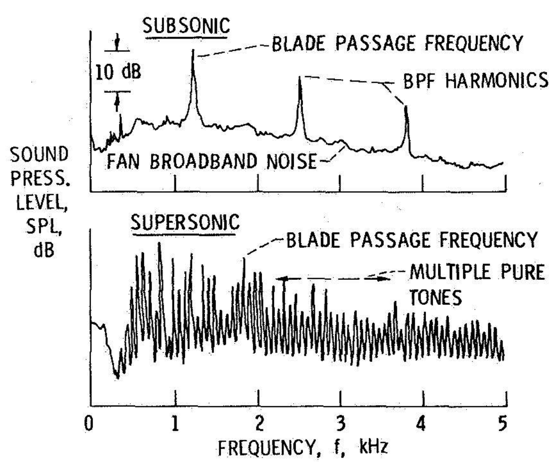

Figure 4.- Fan noise spectra at subsonic and supersonic tip speeds.

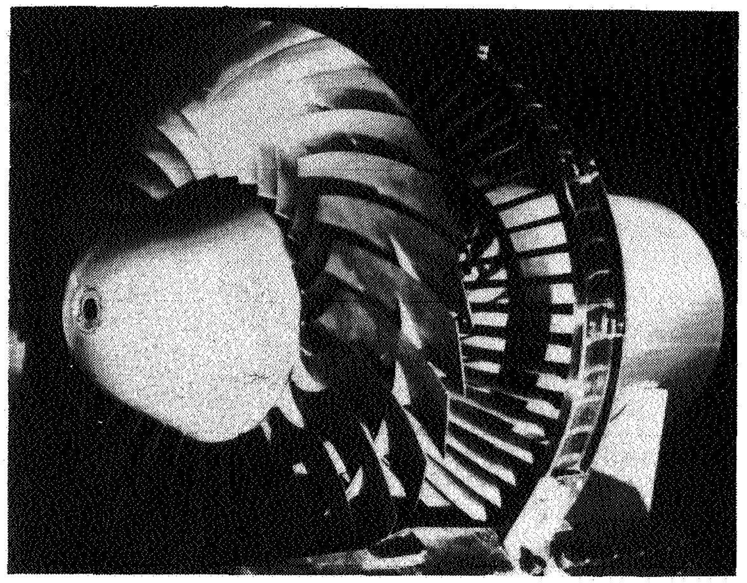

Figure 5.- Swept-rotor fan.

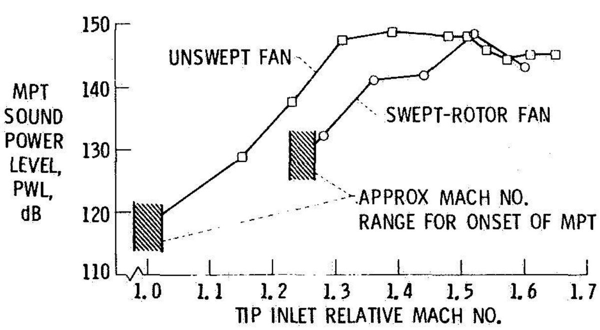

Figure 6.- Multiple-pure-tone generation of unswept- and swept-rotor fans.

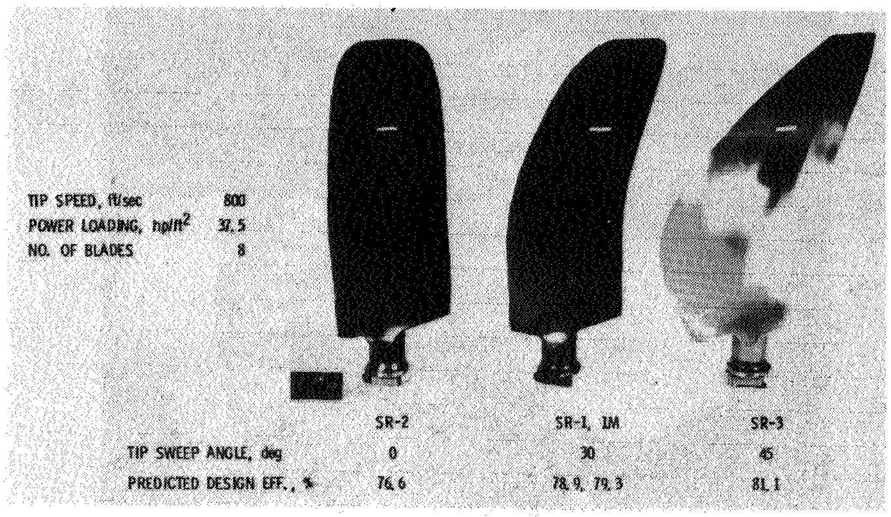

Figure 7.- Propeller model comparison. (Note: 1 ft = 0.305 m and 1 hp/ft^2 = 8018 W/m^2.)

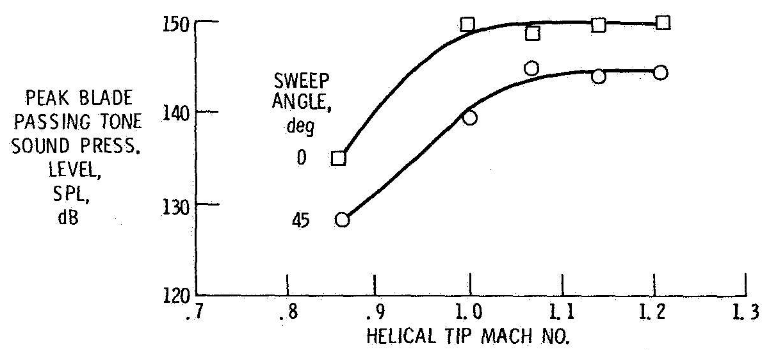

Figure 8.- Effect of tip Mach number on measured noise.

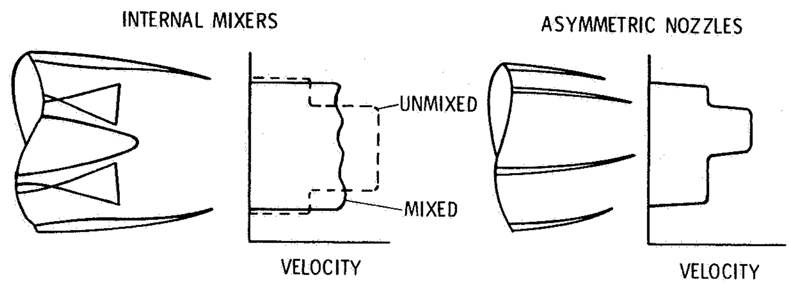

Figure 9.- Jet noise reduction concepts.

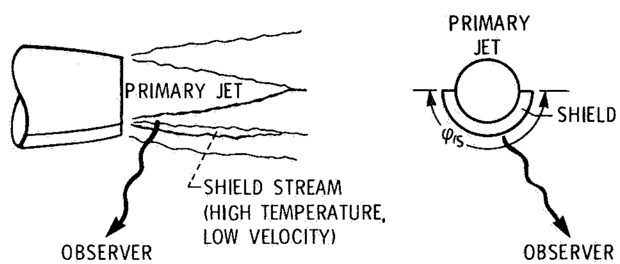

Figure 10.- Thermal acoustic shield schematic.

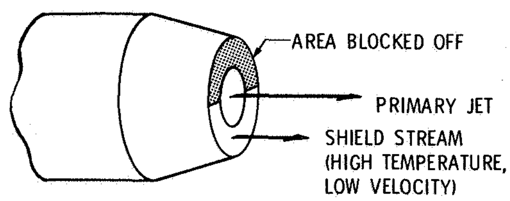

Figure 11.- Thermal acoustic shield test configuration.

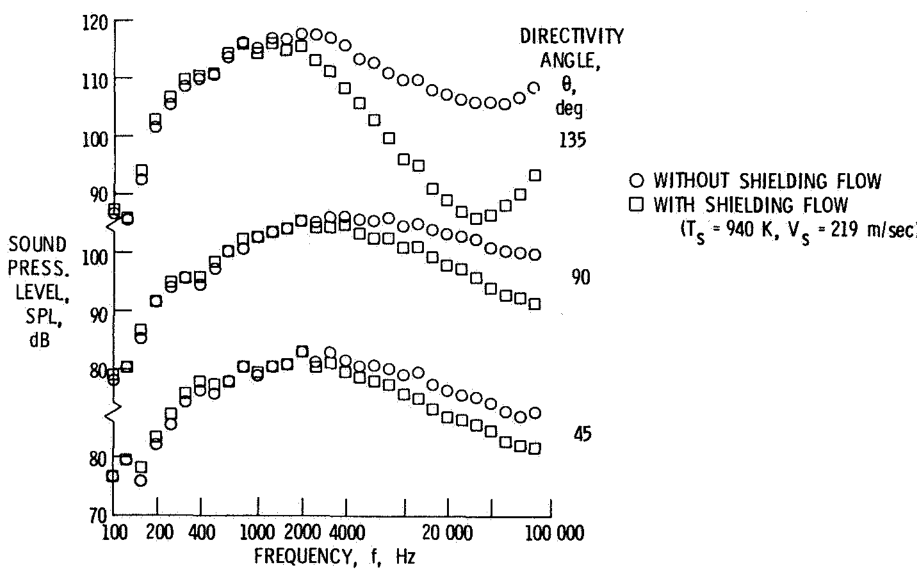

Figure 12.- Effect of shielding flow on subsonic jet noise for coplanar, coannular nozzle. Jet velocity, 575 m/sec.

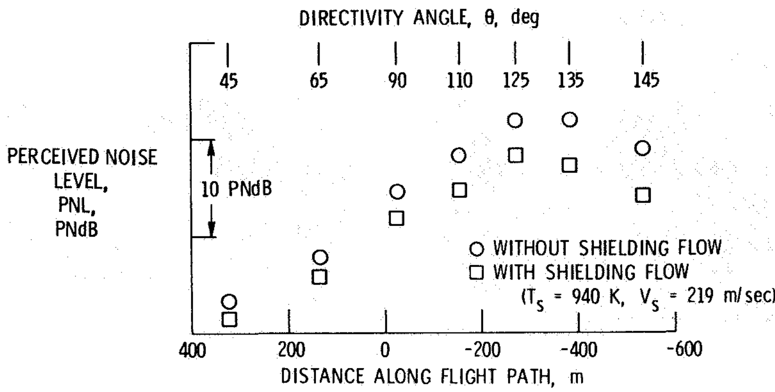

Figure 13.- Effect of shielding flow on flyover perceived noise levels for large scale conical nozzle. V_j = 575 m/sec; subsonic, flyover distance, 335 m.

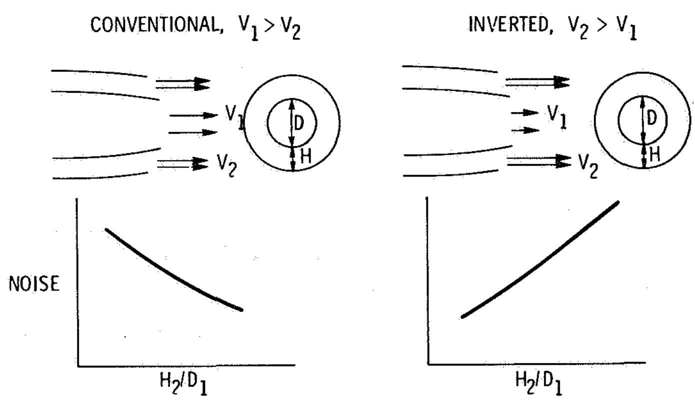

Figure 14.- Coannular nozzle geometric effects.

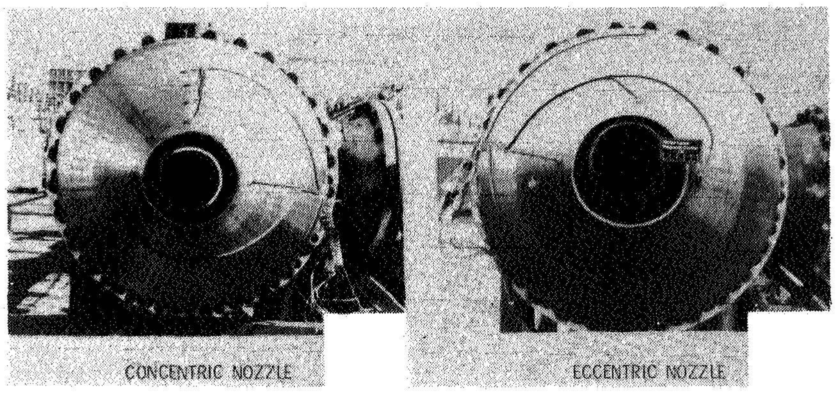

Figure 15.- Concentric and eccentric nozzles.

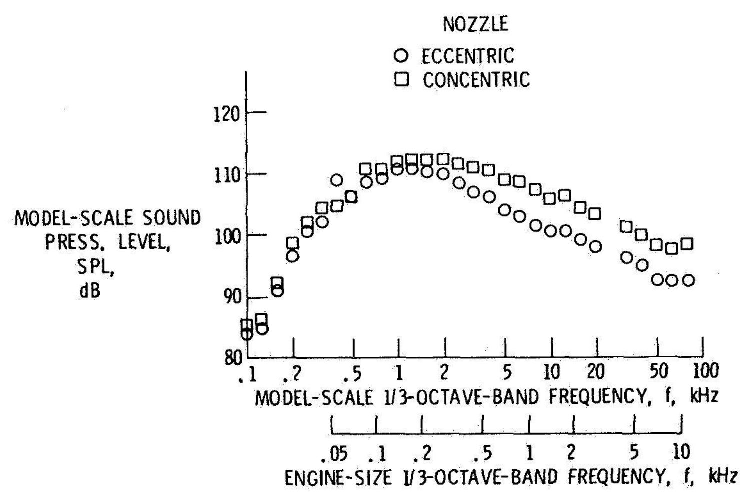

Figure 16.- Model-scale spectra. $\theta = 125^{o}$; $PR_i = 2.2$; $PR_o = 1.4$; $V_o = 496$ m/sec; $V_i = 229$ m/sec.

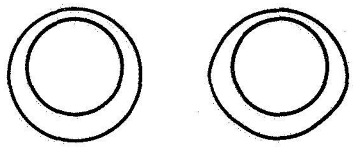

Figure 17.- Nonaxisymmetric application of suppression principle.

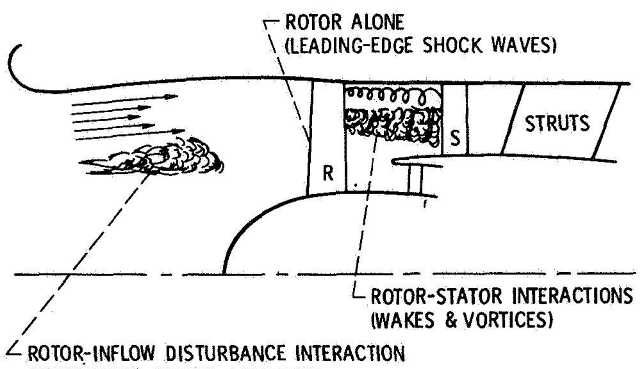

Figure 18.- Fan noise sources - effect of inflow disturbances.

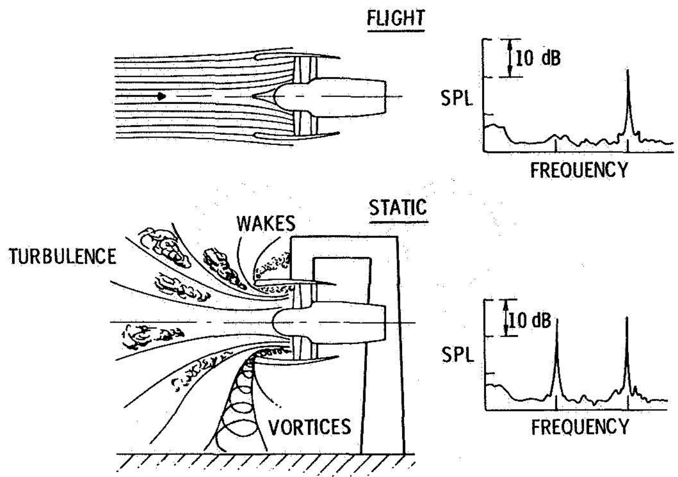

Figure 19.- Forward velocity effects on inlet flow and noise.

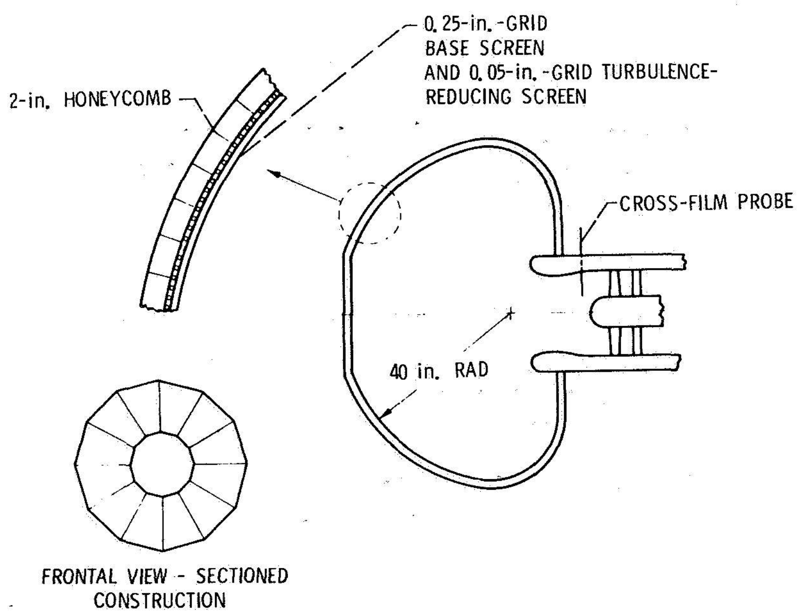

Figure 20.- Inflow control device. (Note: 1 in. = 2.54 cm.)

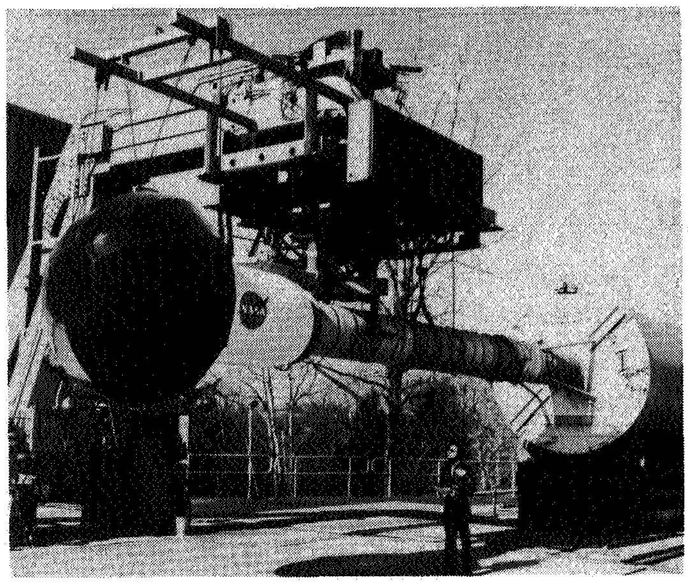

Figure 21.- JT15D engine with ICD installed.

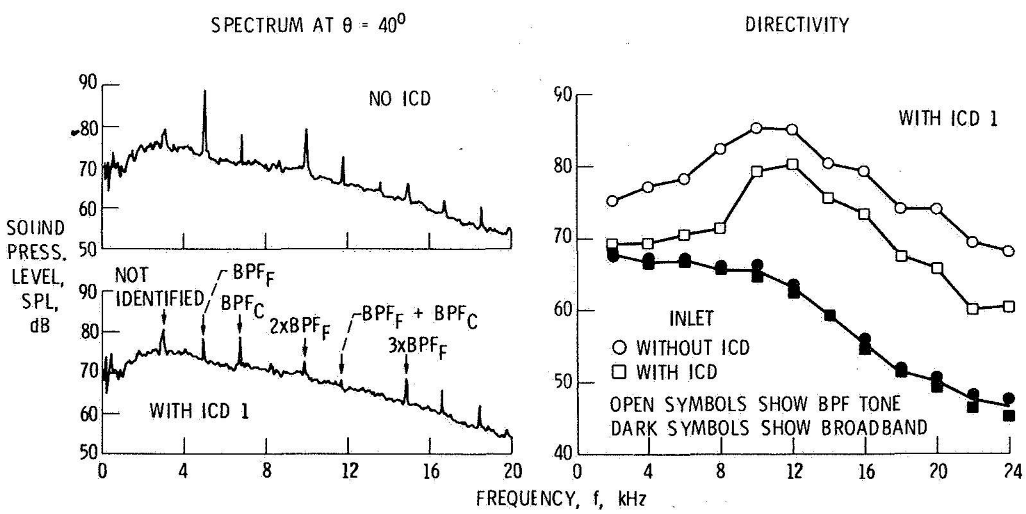

Figure 22.- Effect of inflow control device on fan noise generation.

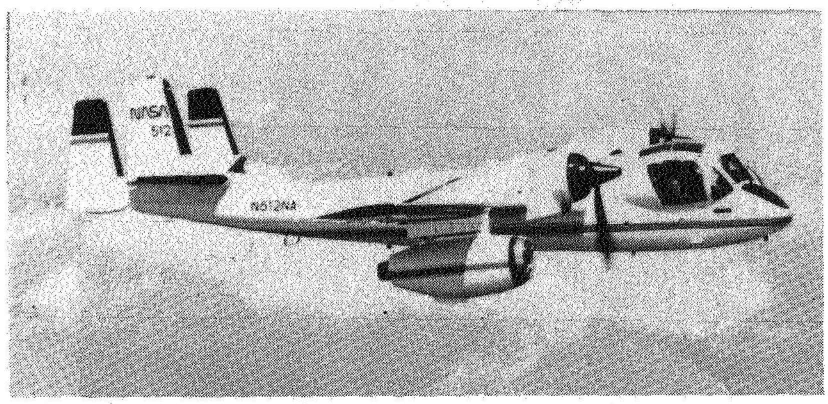

Figure 23.- OV-1 in flight with JT15D engine installed.

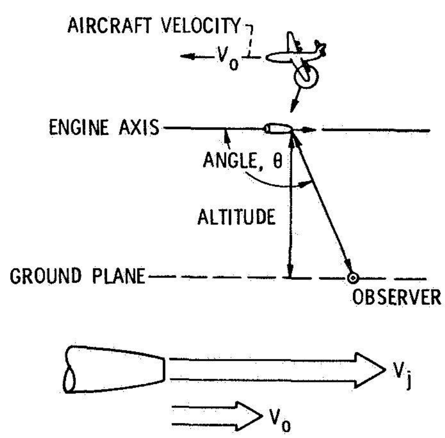

Figure 24.- Flight effects on exhaust noise.

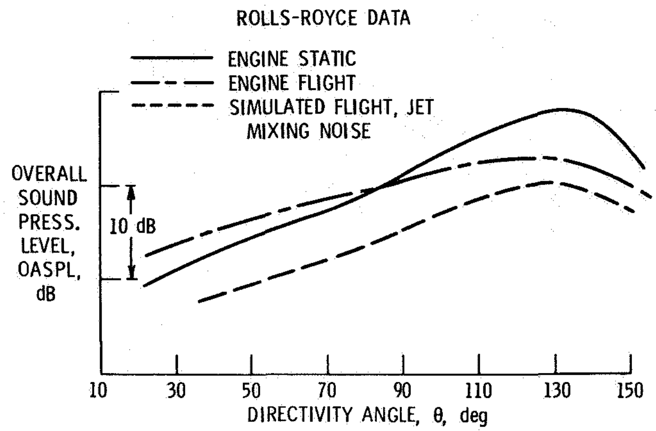

Figure 25.- Typical flight effects on exhaust noise.

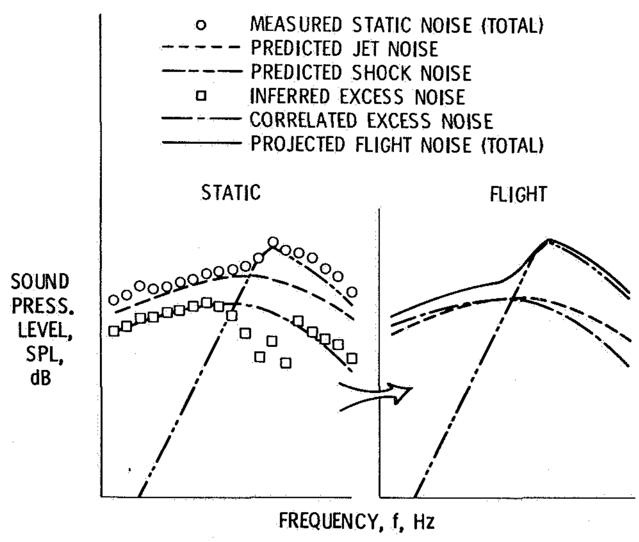

Figure 26.- Methodology for predicting in-flight noise from static data.

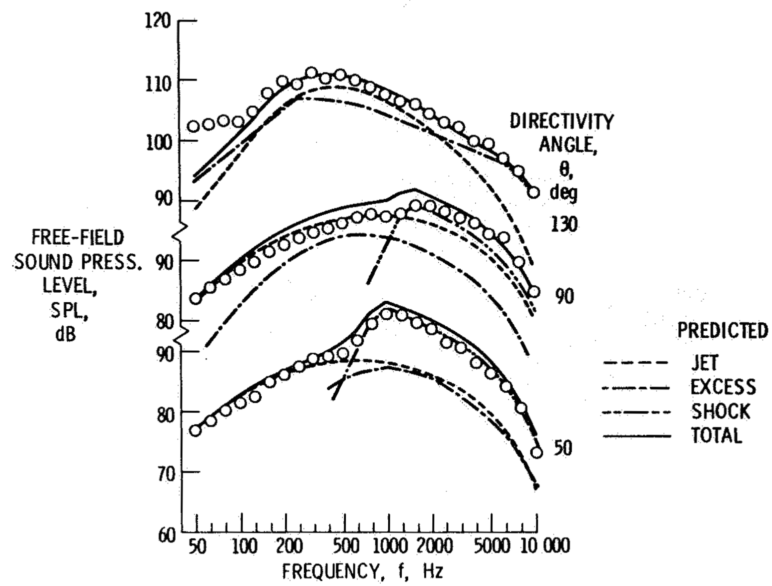

Figure 27.- Experimental and predicted static spectra for Orenda turbojet on F-86 airplane. High jet velocity (596 m/sec).

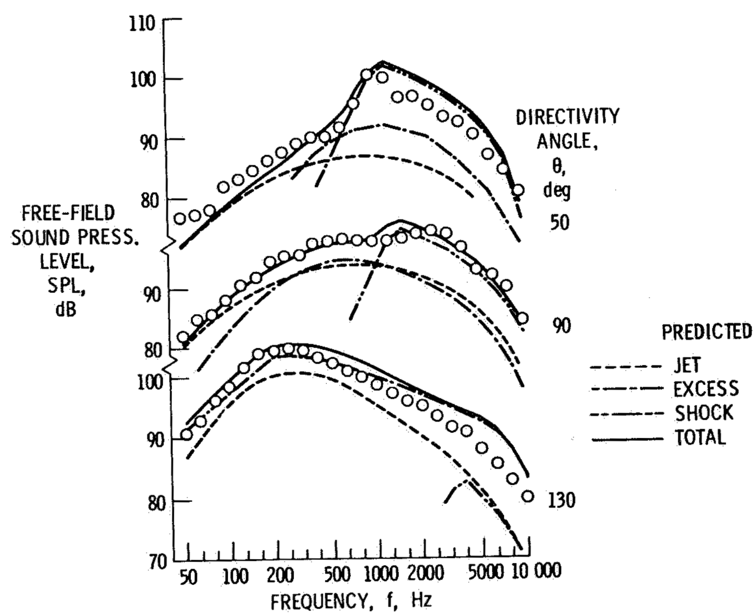

Figure 28.- Experimental and predicted flight spectra for Orenda turbojet on F-86 airplane. High jet velocity (596 m/sec).