PROPULSION SYSTEMS NOISE TECHNOLOGY

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SUMMARY

Recent turbofan engine noise research relevant to conventional aircraft is discussed. In the area of fan noise, static to flight noise differences are discussed and data are presented for two different ways of simulating flight behavior. These results show that simulation of flight behavior should be possible in ground-based facilities. Experimental results from a swept-rotor fan design are presented which show that this concept has potential for reducing the multiple-pure-tone or buzz-saw noise related to the shock waves on a fan operating at supersonic tip speeds. Acoustic suppressor research objectives have centered recently around the effect of the wave system generated by the fan stage that is the input to the treatment. A simplifying and unifying parameter, mode cutoff ratio is described. This parameter appears to correlate all aspects of the propagation and attenuation of sound in acoustically treated ducts and its radiation to the far field. Results are presented which show that suppressor performance can be improved if the input wave is more precisely described. In jet noise, calculated results showing the potential noise reduction from the use of internal mixer nozzles rather than separate-flow nozzles are presented. Finally, estimates of the noise of aircraft using E^3 engines are shown relative to the present FAR Part 36 noise regulations.

INTRODUCTION

This paper summarizes some of the recent research into turbofan engine noise at Lewis Research Center. Progress in noise abatement can be illustrated by reference to FAA Noise Certification Levels and estimated levels for commercial aircraft and to the FAR Part 36 Noise Regulations. These are displayed in figures 1(a) and (b) for the takeoff and approach measuring points (refs. 1 to 4). Flyover noise levels are shown for narrow-bodied aircraft with low-bypass engines and for the newer wide-bodied aircraft with high-bypass engines. Also shown in the figures is the first FAA Noise Regulation (the top curve in each figure), which became a certification standard in 1969. The narrow-bodied aircraft with their low-bypass engines generally exceeded the 1969 noise standard at both takeoff and approach. Their noise levels are dominated by jet noise at takeoff and fan noise at approach. The wide-bodied aircraft with their high-bypass engines generally are quieter than the 1969 noise rules at both takeoff and approach. This is a consequence of the lower jet noise of the high bypass engine, of fan noise reduction design features, and of the use of acoustic treatment. These noise reductions were obtained even though aircraft size was about doubled.

The figures also show the more stringent 1977 noise certification standards. The figures also show data from two research programs directed toward lowering the noise of the low-bypass engines used on the narrow-bodied aircraft. These programs are the Quiet Nacelle program and the Refan Engine program. The former sought to reduce engine noise through the extensive use of acoustic treatment in the engine nacelle, and the latter involved an engine modification that included a new single-stage fan with quieting features, an increase in engine bypass ratio, and extensive acoustic treatment in the nacelle. Both programs demonstrated lower noise technology for the bypass engines. Retrofit programs for existing aircraft have not emerged; however, the McDonnell Douglas DC-9 Super 80 aircraft using Pratt & Whitney JT8D-209 refanned engines has been introduced.

It is clear that substantial reductions in aircraft noise have been achieved since the introduction of the jet-powered fleet. But, as the louder component noise sources are quieted, further reductions become more difficult because the number of component sources contributing increases and measurable change in the noise level requires that all sources be reduced together. In the presence of multiple sources, little reduction in the noise an observer hears occurs if only one source is reduced or even completely eliminated. Thus, for several years, aircraft noise reduction research has proceeded along a broad front, addressing several different noise sources that involve very different technical disciplines. Some of this research will be discussed in this paper, and some estimates of the noise levels for aircraft powered with engines from the NASA Energy Efficient Engine Program will be given.

TURBOFAN NOISE SOURCES

Figure 2 shows, as a memory refresher, the often-used turbofan engine schematic outlining the major engine noise sources. For the high bypass engines being considered today for lower noise and greater fuel economy, these are the important noise sources. The present paper will discuss fan noise research and reduction concepts, acoustic suppressor research, and, briefly, jet noise and the concept of internal mixer nozzles.

JET NOISE

The most effective means of controlling jet noise is through engine cycle selection. Basically this involves keeping the jet exhaust velocities as low as possible. In practice, for turbofan engines this results in higher engine bypass ratios. The basic dependence of jet noise on bypass ratio is shown in figure 3.

The upper curve, for coaxial nozzles, was calculated by the interim prediction method for jet-noise reported in reference 5. The points are calculated for current engines and have been normalized to the same engine thrust.

The lower curve is the calculated noise, according to reference 5, for the same engines operating with an ideal mixer nozzle. This calculation assumed perfect mixing of the core and bypass fan jets without any generation of noise due to mixing. The mixer nozzle concept has received some attention recently as a means of increasing engine fuel economy and reducing jet noise. Comparison of the coaxial and mixer nozzle curves suggests that under ideal circumstances the mixer nozzle may reduce jet noise up to 5 or 6 PNdB. In practice the reduction will be less than this because of imperfect mixing and the generation of internal mixing noise that will radiate to the farfield.

A single data point is shown from a study program sponsored by the FAA (ref. 6). This point, for an engine bypass ratio near unity, shows an experimental noise reduction relative to the coaxial nozzle of 3 to 4 PNdB. The use of mixer nozzles may be most important for growth versions of an engine whose jet noise would increase as the engine bypass ratio is reduced. The mixer nozzle might then be used to reduce the jet noise level to near that of the original engine cycle.

FAN NOISE

Forward Velocity Effects

Over the last year or two the chief emphasis in fan noise has been on the differences between static test and flight test results. (See ref. 7.) The differences are illustrated in figure 4 by the spectra from inlet-wall microphones taken during the static and flight operation of several engines. The data are shown at two fan tip speeds, one approximating takeoff speed and one approximating approach speed. Generalized behavior patterns are difficult to define, but it can be seen that the fan fundamental tone is lower for all the engines operating at the lower speed. In some cases reductions in the broadband occurred over a range of frequencies.

The reason for these results is represented in figure 5, which suggests that the differences in fan noise between static and flight operation are due to the presence and ingestion of flow disturbances into the inflow during static operation. In static testing, because of the effectively large inflow contraction, atmospheric turbulence is elongated by the contraction. The resulting long turbulence eddies, along with possible ground vortices and wakes from adjacent engine support structure and other hardware, are seen by the fan blades as variations in upwash or incidence angle. Depending on the length or time duration of such local disturbances, the fan generates tone or broadband noise.

During flight, on the other hand, the overall inflow is considerably more uniform and the effective contraction ratio is considerably lower, resulting in lower noise. The importance of this is the realization that, in many cases, the noise of a fan stage during static testing is due to a source mechanism either not present or of diminished importance during flight. Two consequences are that flight noise tends to be overpredicted by static test data and that source noise reduction concepts, generally related to the rotor-stator interaction noise source, prove to be ineffective in static experiments because they are masked by the noise due to inflow disturbances.

These considerations have led to a search for methods and techniques of static testing that simulate the flight behavior of fan noise. One successful tool is the anechoic wind tunnel. Figure 6 shows the Lewis 9- by 15-foot low-speed, anechoic wind tunnel with a 51-cm (20-in.) model fan stage in a nacelle. A description of this tunnel is given in reference 8.

Another tool is a flow-straightening, turbulence-damping structure. A schematic representation of such a device is shown in figure 7 as it has been employed in an anechoic chamber. This structure approximates a hemisphere and consists of flexible core aluminum honeycomb supported by a coarse mesh screen. The honeycomb cell's effective length to diameter ratio was about eight. The honeycomb cell walls were approximately parallel to the flow streamlines. A second smaller mesh screen is used between the honeycomb and the coarse screen to further control the turbulence. This control structure has been tested on a fan in the 9- by 15-foot anechoic wind tunnel (ref. 9) and in an anechoic chamber (ref. 10). A photograph of the structure mounted on the fan inlet in the Lewis anechoic test chamber is shown in figure 8.

A series of experiments has been performed in the anechoic wind tunnel in which fan-inlet noise was measured for a clean, unobstructed inlet both statically and with forward velocity and for two variations of the inflow control structure. These experiments are described in detail in reference 9; the fan stage and other aeroacoustic results are described in references 11 to 14. The fan stage had a design tip speed of 213 m/sec and a design pressure ratio of 1.2.

Figure 9 shows far-field narrowband sound spectra for each of the inflow conditions. Just as for the engine data of figure 4, these data show that forward velocity substantially lowered the fan fundamental tone. In fact for this particular fan stage the tone was reduced essentially to the broadband level. The use of the inflow control structure also reduced the fan fundamental tone, but not to the extent that forward velocity did. An interesting clue to part of the tone-causing disturbance is shown by the data with the inflow control structure when the aft portion was covered to prevent flow in the reverse direction over the exterior of the inlet. Preventing this flow from entering the inlet was beneficial in reducing the tone compared with the case when the aft portion was open to pass flow. This suggests that flow over the nacelle exterior, where there are probes and other obstructions that can generate flow disturbances, may be one of the tone noise sources. It may be also that the flow around the inlet highlight would be more disturbance free if the reverse flow over the nacelle, which is turned 180°, is minimized.

In any case, the results are encouraging and show that a properly designed inflow control structure can produce data more like those in flight. This area is receiving considerable attention under a joint program among the NASA Langley, Lewis, and Ames Research Centers.

Fan Noise-Reduction Concepts

The primary objective in fan noise research is to understand the sources and mechanisms of noise sufficiently well that low-noise designs can be developed. A photograph of a fan stage that uses two noise-reduction concepts is shown in figure 10. This fan design was proposed by the firm of Bolt, Beranek, and Newman in response to a Lewis request (refs. 15 and 16). One of the noise-reduction concepts is intended to reduce the shock-related multiple pure tone or buzz-saw noise that the fan will generate at its design tip speed of 488 m/sec. The concept is to sweep the rotor leading edge so that the velocity normal to the blade is subsonic, thereby eliminating the shock-wave system. This idea is the same one used in swept-wing supersonic aircraft. In the design sweep reversal midway along the span avoids the structural problems that might result from having the blades cantilevered too far forward or backward. The other noise-reduction concept, intended to reduce rotor-stator interaction noise, is to sweep the stator vanes back axially from hub to tip.

This fan stage was tested recently in the Lewis anechoic chamber. The results are shown in figure 11 where inlet sound power spectrum of the swept rotor fan stage is compared with spectra from two earlier supersonic-tip-speed fans. These fans are engine C of the NASA-GE Quiet Engine program and the ATT fan tested under the NASA-GE Advanced Transport Technology program (ref. 17). The swept-rotor fan stage produced about 10 decibels less noise than the earlier fans did in the spectral region below the blade passing frequency. The sound in this frequency range is associated with the shock-related noise and thus the swept-rotor concept did work. Some smaller benefits are also apparent at frequencies higher than the blade passing frequency. It should be noted that the swept-rotor data and ATT fan data were scaled to the engine C data. Sound power was scaled proportional to fan diameter squared and frequency inversely proportional to fan diameter. This scaling procedure may not be exact but is adequate for comparison. Fortunately the three fans do not differ greatly in tip speed and pressure ratio. The aerodynamic efficiency of the swept rotor fan stage was about 77 percent compared with a design value of about 86 percent. Although the performance was low, it is perhaps not too surprising in view of the unusual features of the fan design.

ACOUSTIC SUPPRESSION

Acoustic suppression research has been one of the more active areas recently. The elements of the acoustic suppressor problem are illustrated in figure 12. The problem is focussed on the propagation and attenuation of a sound field as it traverses through an inlet or exhaust duct whose walls have been treated acoustically. One of the needed inputs to suppressor analysis and design is a description of the sound field generated by the fan stage at the entrance to the treated duct. An exact description of this field is very difficult to obtain and has not been measured for fan stages operating in realistic engine tests. Thus, the input wave was often assumed to be a plane pressure wave or a wave consisting of only the least attenuated mode, on the ground that these would yield conservative estimates for suppressor design. Indeed, these assumptions proved to be far too conservative when used to estimate the acoustic performance of inlet-wall-only suppressors although they are adequate for annular ducts or ducts with splitter rings (ref. 18). It is clear today that correct description of the input sound source field is necessary to design and to predict the performance of acoustic suppressors.

The spatial pattern of the sound field generated by a fan at a plane axially removed from the fan is described in terms of circumferential and radial coordinates. The pattern in the circumferential direction consists of an integral number of lobes and it has been shown that this pattern rotates or spins in the duct (ref. 19). There is a similar periodicity of the spatial pattern in the radial direction. Each of the discrete patterns consisting of an integral number of lobes both radially and circumferentially is termed a mode. It is this modal pattern, generated by the fan stage, that the sound suppressor must attenuate and that finally radiates in modified form from the duct termination to the far-field, where it determines the far-field sound pattern or directivity. Thus, all of the events relating to the sound field, including the design of the acoustic treatment and its performance, depend on the modes that are present in the pressure pattern and on the sound frequency. At any given sound frequency the duct can and does sustain many modes, which the fan generates. The number of modes increases with sound frequency.

The sound-field description, as just outlined, is a three-parameter representation determined by the sound frequency and the circumferential and radial mode numbers. A recent advance in duct acoustics theory was the observation by Rice that these three parameters could be replaced by a single simplifying and unifying parameter, called cutoff ratio (refs. 20 and 21). This parameter correlates the optimum wall impedance of suppressors, the associated sound attenuation, the effect of the duct termination, and the far-field radiation pattern (refs. 22 and 23). The cutoff ratio is not easily depicted in a circular duct, but it can be clearly shown in a two-dimensional duct (fig. 13). In figure 13 a wave front is represented by a line that, in general, propagates with some angle ψ to the duct axis. The cutoff ratio is given in this simple geometry by the reciprocal of the sine of the propagation angle. Figure 13 also illustrates the two extremes of propagation. An infinite cutoff ratio is shown for a plane wave that always propagates if present, and a cutoff ratio of one is shown for a transverse wave that does not propagate axially at all. The cutoff ratio thus describes, in this simple case, the propagation direction of the sound wave relative to the duct axis.

For simple situations where the number of modes is limited, the sound input wave can be experimentally determined directly from an array of pressure sensors located around the duct wall. In general, radial measurements are also required; however, the introduction of a radial probe into the duct will affect the sound field generated by the fan (as discussed in the preceding section). Theoretical models of fan source noise also yield the input wave; however, these depend on the adequacy of the description of the unsteady aerodynamics and the flow disturbances that are present but not usually known. A third method is to infer the input wave from the far-field directivity of a fan stage. In this case, the effects of factors such as the duct termination, atmospheric scattering, and convective flow field into the inlet should be included. Some success with this method has been reported (ref. 24).

When more accurate descriptions of the input wave are used to design suppressors, their performance can be improved. Figure 14 shows the experimental results from suppressors for multiple-pure-tone noise that were tested on the AVCO-Lycoming YF-102 engine and on the NASA GE engine C at Lewis. The data plotted are the sound-power attenuations in the one-third-octave band containing the peak multiple-pure-tone levels. A single suppressor length was tested on the YF-102 engine; it yielded a sound power suppression of about 48 dB per unit of suppressor L/D. This result is compared with an earlier result from the NASA-GE engine C suppressor tests. The suppressor on engine C was designed in accordance with the then current plane-wave sound-input theory. Clearly, the more recent theory represents a significant improvement in suppressor performance. Current experiments are further exploring the benefits of incorporating these advances in suppressor concepts and theories.

CONCLUDING REMARKS

Engine noise research has progressed in a broad range of disciplines involving all of the noise sources. Progress is reflected by improved understanding of the sources and by the demonstration of concepts that have lead to lower noise. Cycle selection remains the best control of jet noise, with the use of mixer nozzles showing some promise for further reductions. In fan noise the effects of flight are the subject of considerable attention, and promising means of simulating flight were shown. A new fan design concept, the swept rotor is effective in reducing the source levels of multiple-pure-tone or buzz-saw noise. In acoustic suppressors a more accurate discription of the input source wave allows designers to improve suppressor performance. A simple parameter unifying all aspects of duct propagation, including optimum wall impedance, attenuation, and radiation was described. The parameter, cutoff ratio, is the focal point of further exploration of suppressor behavior.

The data and noise certification standards shown in figure 1 are shown again in figure 15 with noise estimates from the NASA Energy Efficient Engine Program added as an illustration of possibilities in aircraft noise. The E^3 program is not aimed at noise, per se, and the noise goals of the program are the FAR Part 36, 1977, certification standards. Nevertheless, the estimates for three and four engine aircraft predict noise levels 3 to 4 decibels below the FAR Part 36, 1977, noise standards at both takeoff and approach. The approach estimates are nearing the levels for airframe noise (ref. 25) shown in the figure. As the title of reference 24 indicates, "airframe" noise is a barrier that may require reduction if the overall aircraft noise levels are reduced much further. The outlook for success in exceeding the FAR 36 - 1977 noise standards is good.

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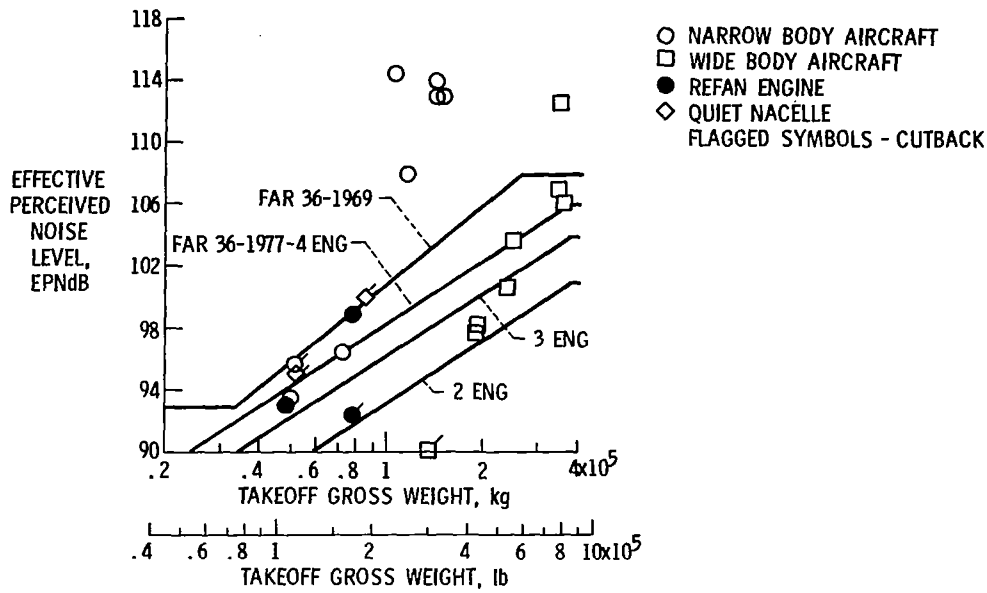
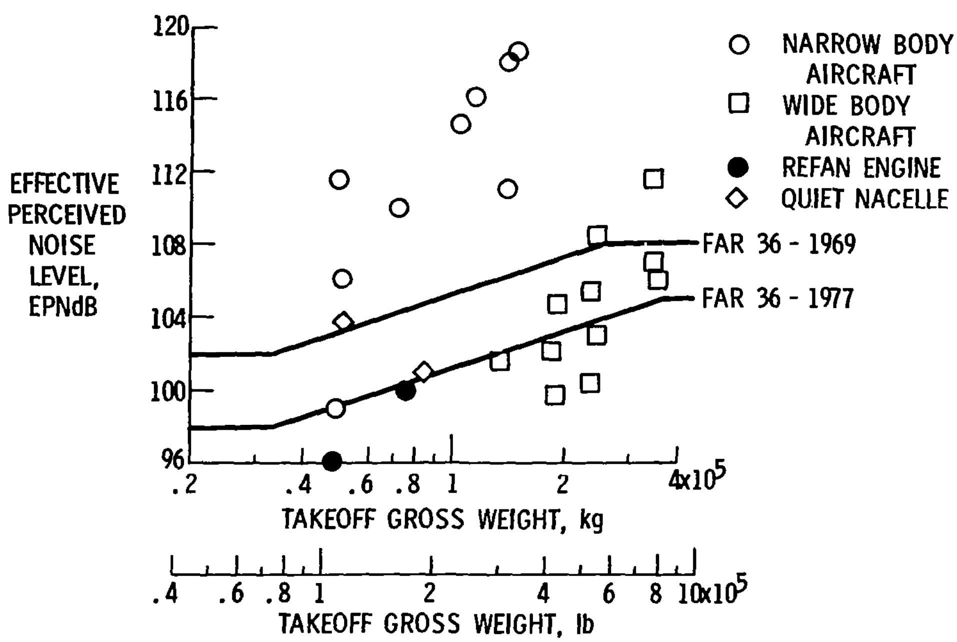


(a) Takeoff noise levels.



(b) Approach noise levels.

Figure 1.- Aircraft noise certification levels and regulations.

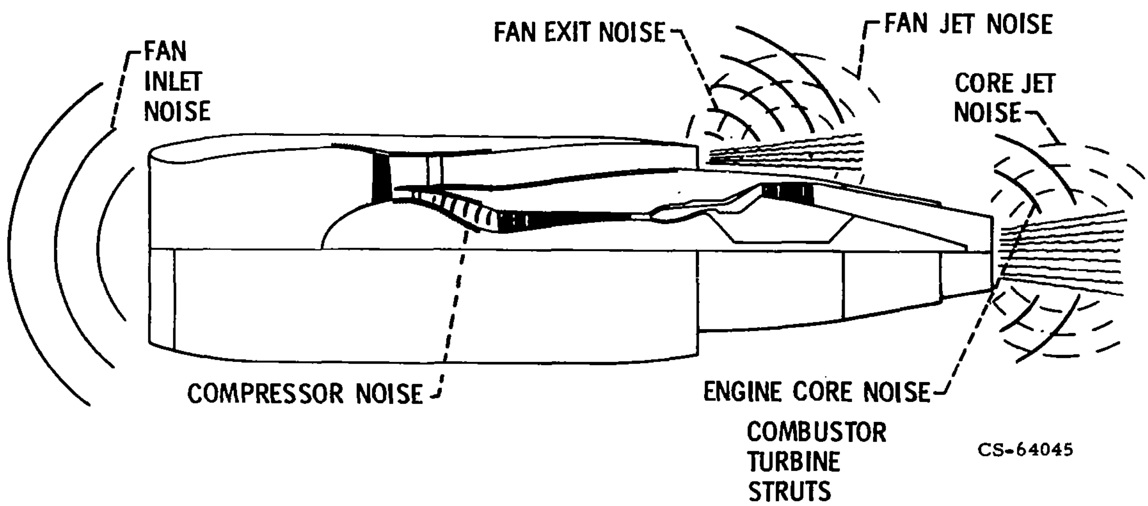


Figure 2.- Turbofan engine noise sources.

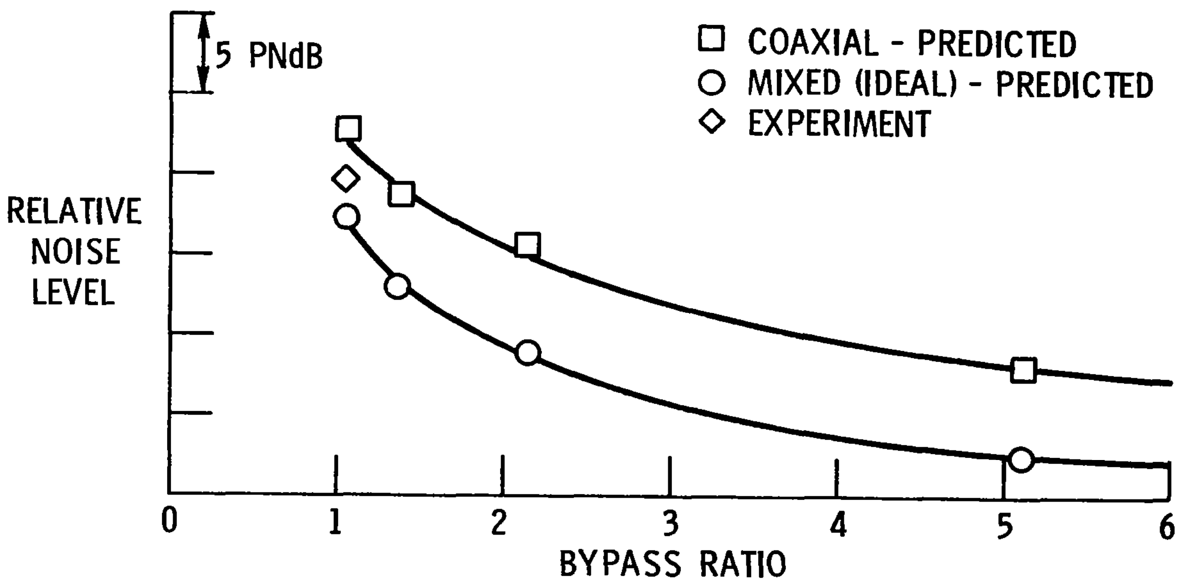


Figure 3.- Jet noise variation with engine bypass ratio for coaxial- and mixed-flow nozzles.

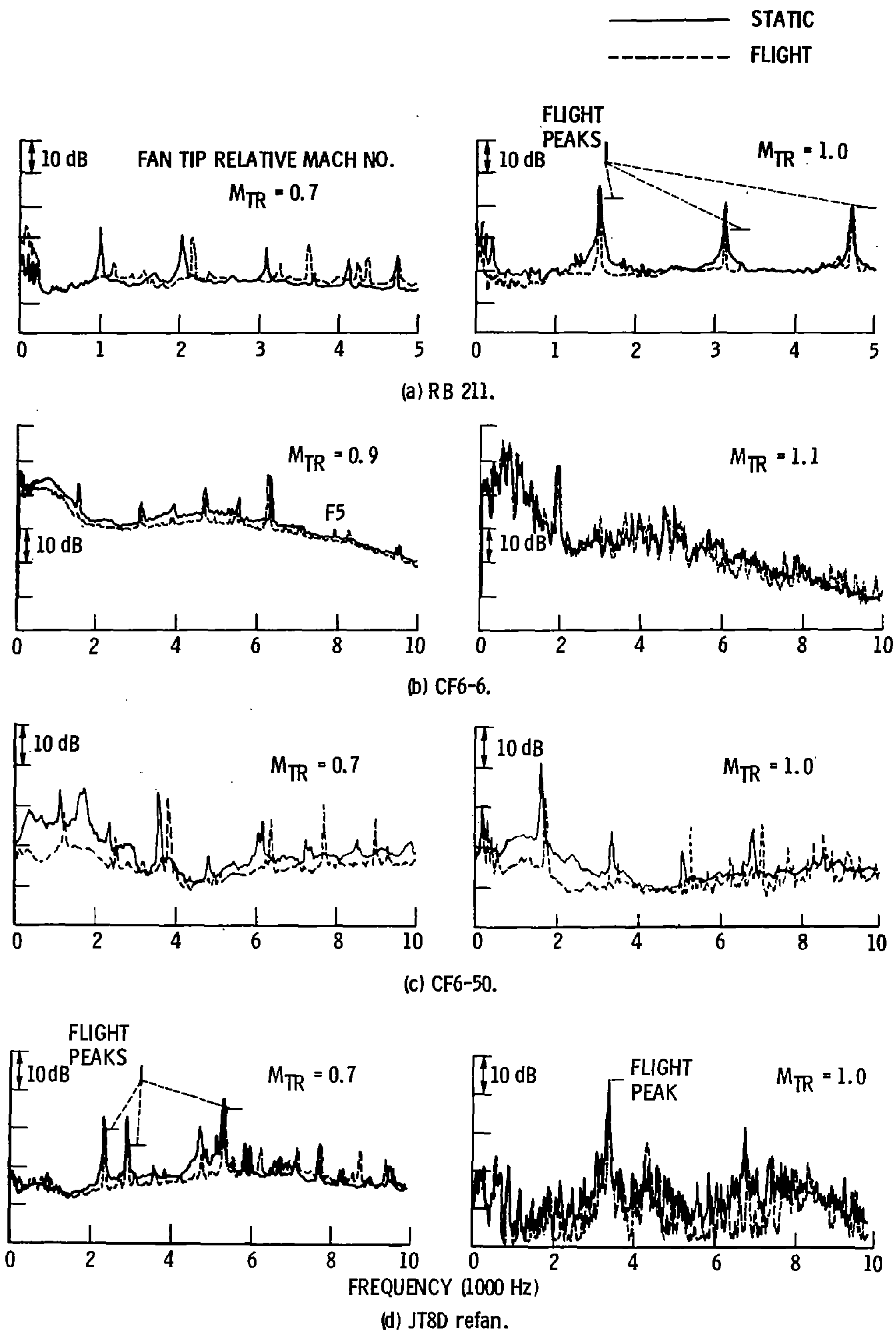


Figure 4.- Effect of flight on fan-inlet noise.

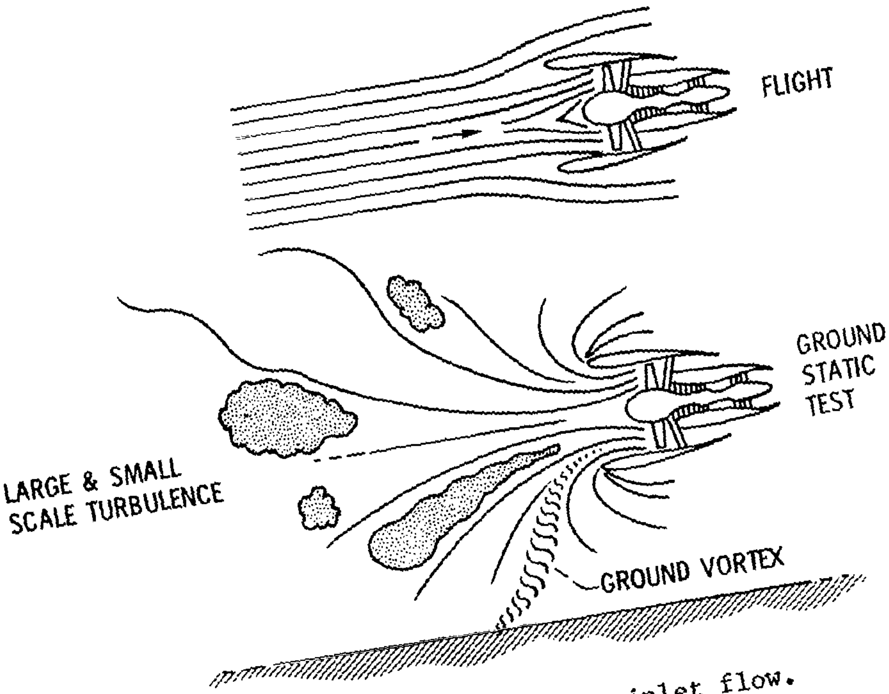


Figure 5.- Effect of flight on inlet flow.

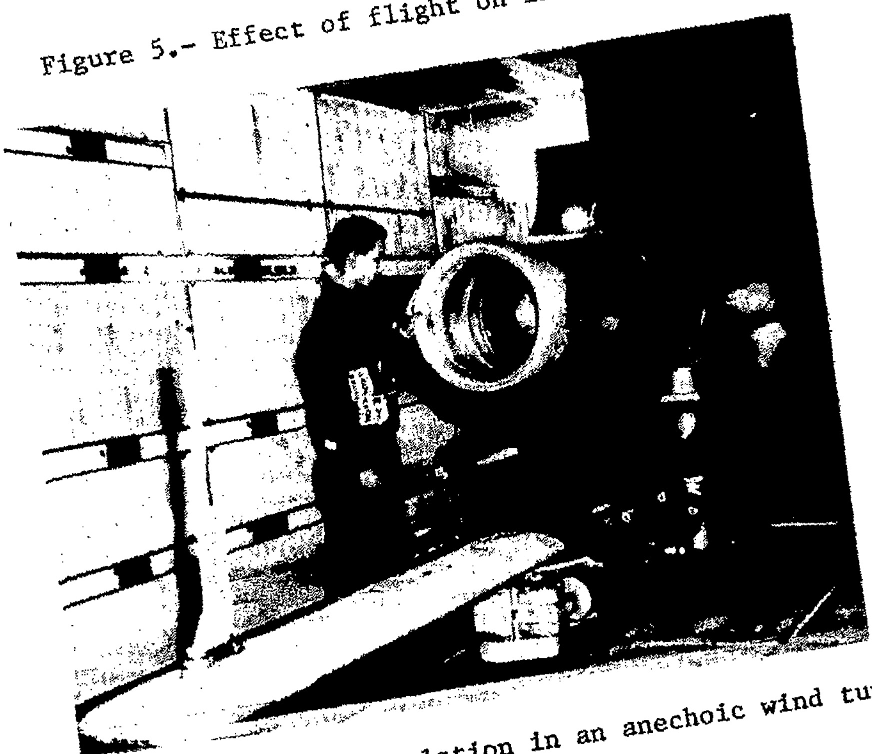


Figure 6.- Flight test simulation in an anechoic wind tunnel.

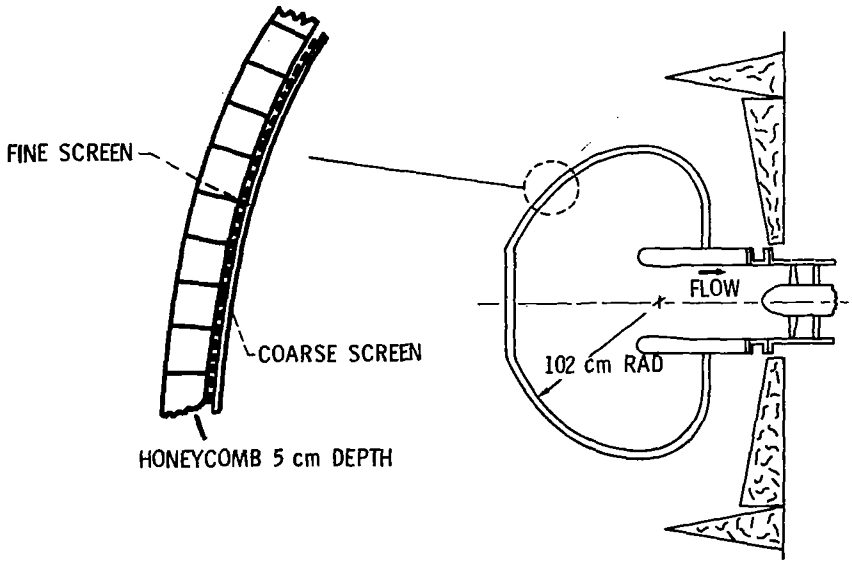


Figure 7.- Inflow-control structure schematic.

Figure 8.- Inflow-control structure mounted over fan inlet in anechoic chamber.

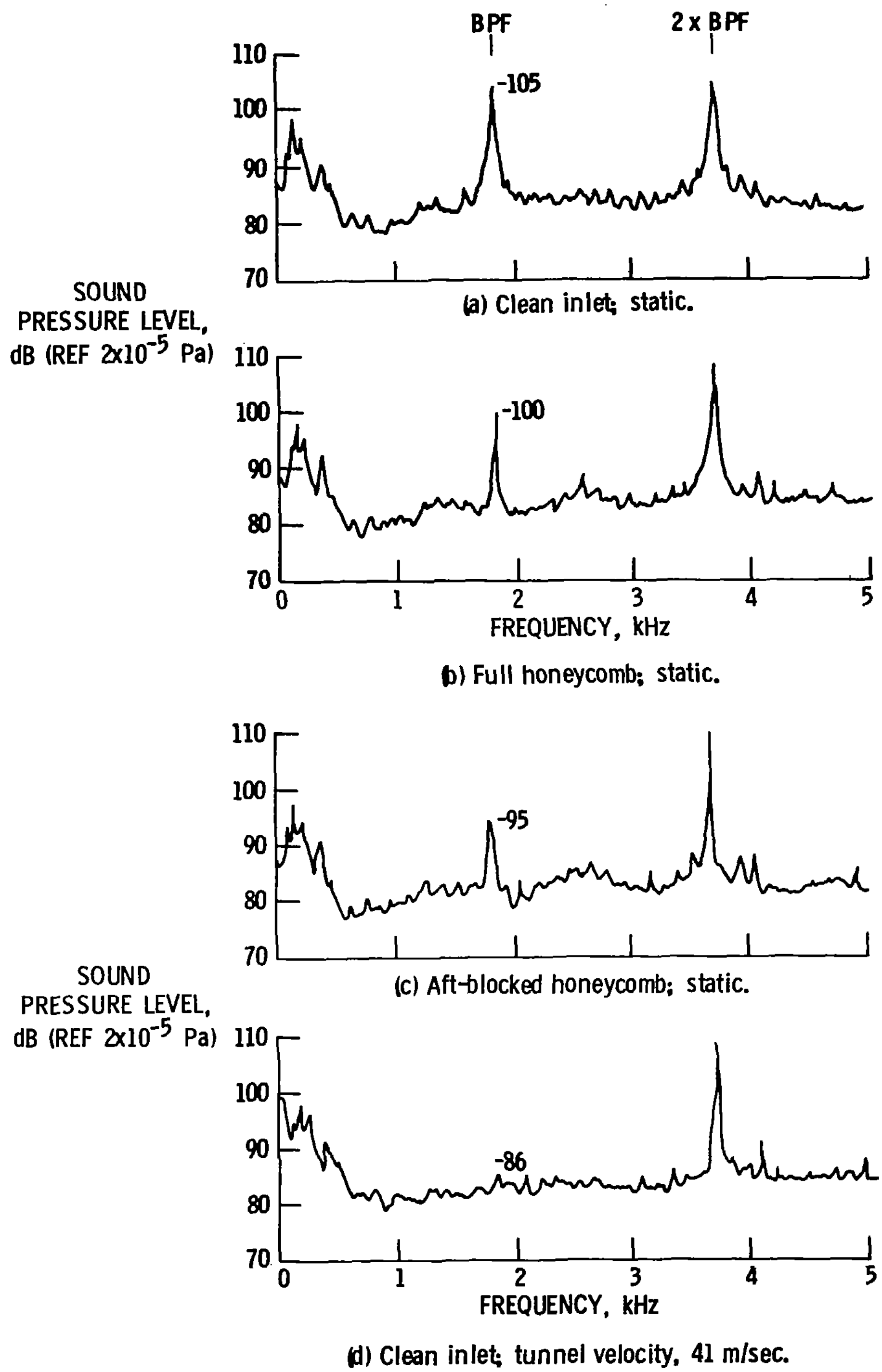


Figure 9.- Inlet fan noise variation with different approaches to inflow control.

Figure 10.- Swept-rotor fan concept.

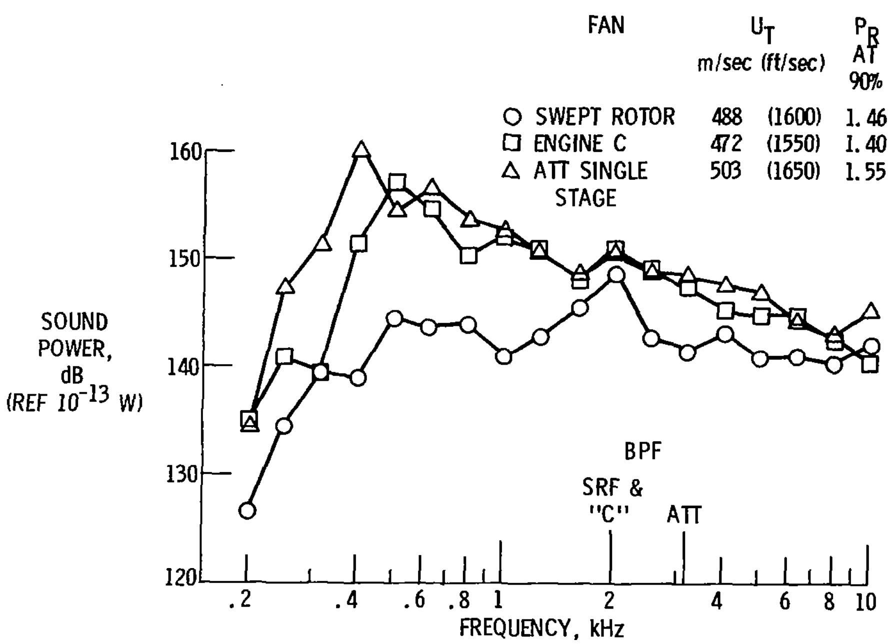


Figure 11.- Comparison of swept-rotor fan inlet noise with noise from earlier supersonic fans. Fan speed, 90% of design; full scale.

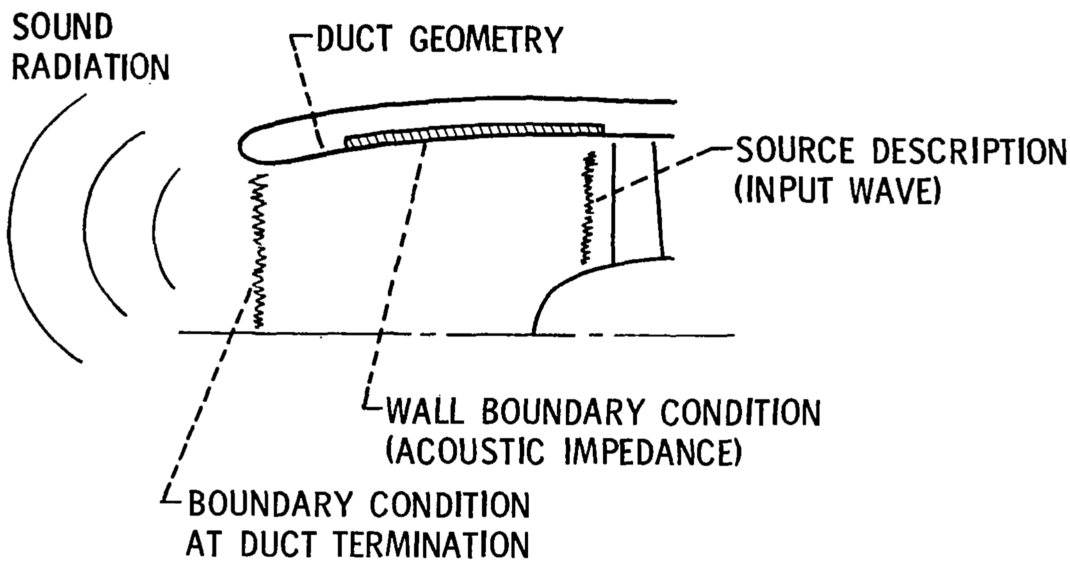


Figure 12.- Elements of the acoustic suppressor problem.

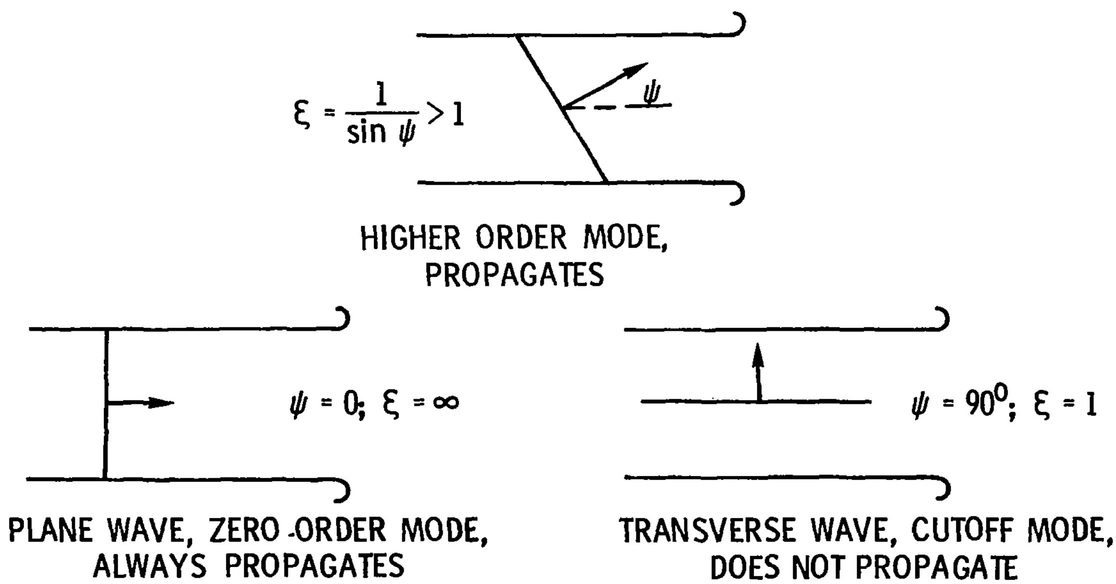


Figure 13.- Sound propagation in a two-dimensional duct illustrating mode cutoff ratio.

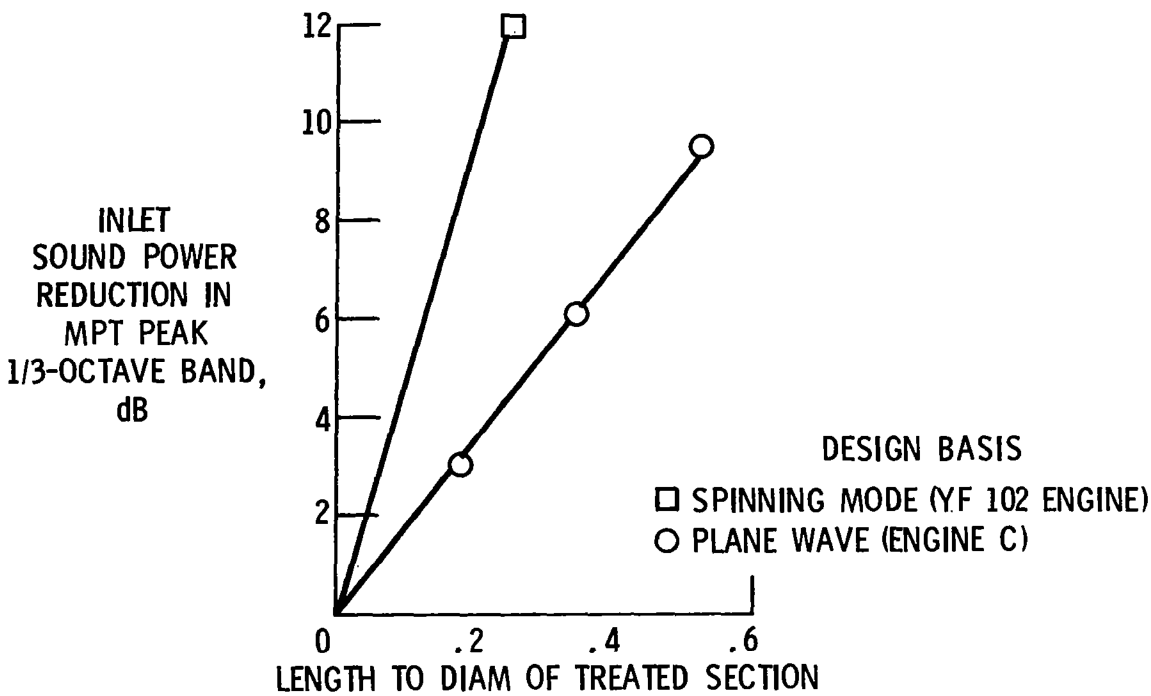
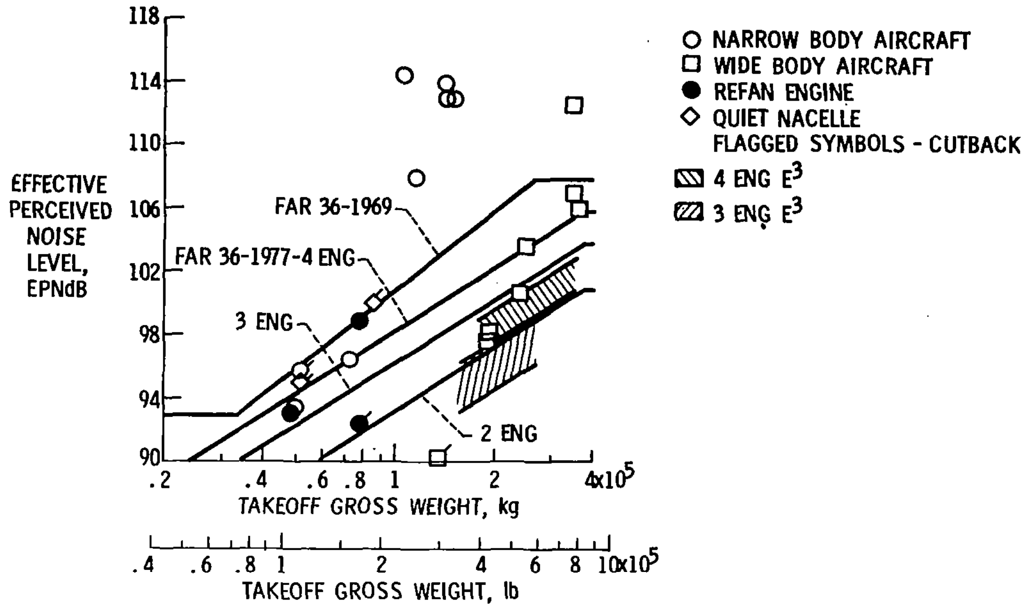
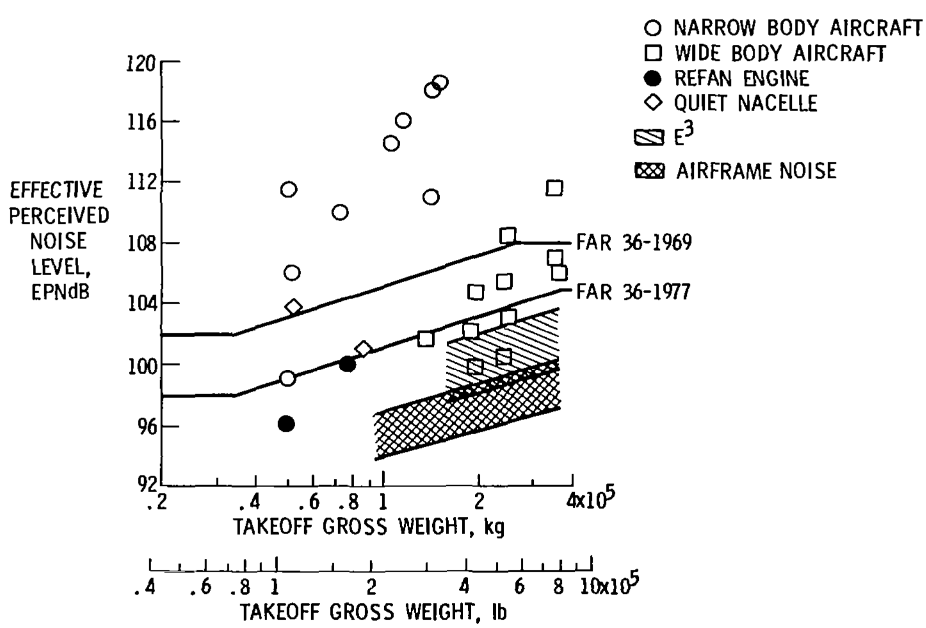


Figure 14.- Performance of suppressors based on spinning mode and plane wave designs.



(a) Takeoff noise.



(b) Approach noise.

Figure 15.- Estimated noise levels of aircraft powered by E^3 engines.