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ADVANCED INLET DUCT NOISE REDUCTION CONCEPTS

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SUMMARY

This paper is a progress report on the implications of inlet noise reduction on aircraft direct operating costs (DOC). It considers treated inlet rings, various other inlet noise reduction concepts, and forward-speed effects. The paper has been limited to relatively well-established approaches to inlet noise reduction, such as acoustic liners and fixed-geometry/high-subsonic-speed inlets which are the focus of considerable current research activity. All of the concepts discussed will be of a "passive" nature, i.e., no moving parts or electrical feedback systems. More futuristic approaches may include variable inlet geometry, inlet sprays, and in-duct cancellation. These "active" approaches may be applied at some future time after the passive approaches have been more fully exploited.

INTRODUCTION

Inlet noise is a contributor to the total noise signature of commercial jet transport aircraft that must be controlled to achieve community acceptability and to meet current and future federal noise regulations. Efforts to control inlet noise are either at the source through proper design of the rotating components so as to minimize the generation of noise or by appropriate modifications within the inlet duct so as to inhibit the radiation of turbomachinery noise from the inlet face. The last decade has witnessed efforts by the universities, the government, and private industry to identify, develop, and implement a variety of methods for inlet noise control. An imaginative research effort continues to improve on established methods and to produce new ideas.

The purpose of this paper is to present a progress report on current efforts by describing various approaches to noise control within the inlet which show promise for future applications. Included in the discussion are treated inlet rings, refracting inlets, variable impedance liners, hybrid inlets, and forward-speed effects. Not included in this paper are the more futuristic approaches to inlet noise reduction which would involve variable geometry, inlet sprays, in-duct cancellation, and the like. A summary of these concepts is given in reference 1.

As a reminder of the nature of the problem, a schematic example of a fan noise narrowband spectrum that may occur within an inlet is shown in figure 1. Superimposed upon a background of broadband noise are pure tones occurring at multiples of the blade passage frequency. Among the more important sources of these tones are the interaction of rotating blades and stationary vanes with upstream generated wakes, atmospheric turbulence and ground vortices, wall boundary layers, and inflow distortion resulting from crosswinds and angle of attack. On occasion combination tones can be observed which occur at the sums and differences of the harmonics of tones from multistage devices. When the relative Mach number into the fan blades becomes supersonic, shock waves created at the blade leading edges spiral down the duct to form "multiple pure tones" (MPT). This fundamental MPT occurs at the shaft speed, and there may be higher harmonics which create a very ragged sound spectrum and have a "buzz-saw" sound. In-duct levels of broadband noise on the order of 120 to 130 dB have been measured. Tones may extend 10 to 15 dB above these levels. Overall noise levels near the fan of 150 to 160 dB are not unusual. In this paper, methods of reducing fan noise within the inlet duct are described, whereas methods of reducing the noise at the source by modifications to the fan itself are not considered.

SYMBOLS AND ABBREVIATIONS

c	speed of sound
D	inlet diameter
f	frequency
l	length of acoustic treatment
m	spinning mode number
M	Mach number
BPF	blade passing frequency
DOC	direct operating cost
EPNdB	unit of effective perceived noise level
PNdB	unit of perceived noise level
PNLT	tone-corrected perceived noise level
SPL	sound pressure level

QUIET ENGINE PROGRAM

Several years ago Lewis Research Center completed the Quiet Engine Program. One of the program objectives had to do with the exploration of inlet splitter rings for noise suppression. A photograph of one of these engines with three inlet rings is shown in figure 2. At that time the state of the art indicated that inlet rings were required to substantially reduce inlet noise below the standards of Federal Aviation Regulation Part 36 (FAR 36; ref. 2). This belief was based in a large part on the results from duct theory and experiments being used for noise reduction prediction. Figure 3 (ref. 3) depicts some results from this inlet ring study. Perceived noise level is plotted as a function of azimuth angle measured from the inlet axis. There was a significant reduction in noise at all angles for the wall-only treatment. The inlet with splitter rings yielded noticeable additional reductions between 10° and 50° only. A conclusion that may be drawn from these results is that adding the complexity of inlet splitter rings produced small additional noise reductions. This result may have been due to the fact that the wall treatment performed much better than expected or that perhaps a noise floor was encountered at the level reached by the wall-only treatment, thereby preventing further reduction by the rings.

Using 1972 acoustic technology from the Lewis Quiet Engine Program, acoustic and economic trade-offs were calculated by the General Electric Company as shown in figure 4 (ref. 4). The curve indicates the trade-off between DOC and noise reduction achieved by the use of acoustic treatment. This curve is based on the experience with the low fan tip speed used on Quiet Engine "A." The initial point on the curve is for the untreated engine configuration. Subsequent points are for incremental additions of acoustic treatment with the final point representing a three-ring inlet and a two-ring exhaust duct.

A result from this analysis is the penalty on DOC incurred through the use of 1972 acoustic treatment technology to achieve noise levels 10 dB or more below the standards of FAR 36. The curve indicates that the economic cost of reaching this noise level is too high. This paper will attempt to show that the slope of this curve is being changed by current research. The exact change is not known but definite improvements are indicated. Another Quiet Engine Program may be appropriate in the future to determine more precisely the new acoustic and economic trade-offs.

Figure 5 (ref. 4) shows predicted attenuation of sound power as a function of frequency based on 1972 noise source assumptions allowing only axisymmetric modes. The amount of attenuation obtainable simply depended upon the amount of treatment that could be put in an inlet, and for higher frequencies large amounts of treatment would be required to produce only modest amounts of noise reduction. The data points above this curve indicate acoustic measurements with the quiet engine, two fans, and a JT8D engine. The noise reduction results were much better than predicted. The discrepancies between the predictions and the measurements caused a re-evaluation of the duct theory assumptions. A probable explanation for the overly conservative prediction is the noise-source assumption. Figure 6 indicates schematically the actual acoustic pressure pattern generated by rotor-stator interaction or a supersonic-tip speed rotor. When these spinning mode patterns are accounted for in the theory, the maximum possible sound attenuation is increased. Figure 7 (ref. 5) shows the effect of the presence of spinning modes in the source on maximum sound power attenuation as a function of frequency. The lowest curve represents the axisymmetric source assumption that was made with the previous theory. The same experimental data has been plotted on the curves showing that this sound description can account for the level of experimental data. When it becomes possible to measure the noise sources inside of these turbomachines it may become apparent how good these new theoretical assumptions are. Work is currently underway to measure these noise sources statically and hopefully, in the future, in a flight environment.

ADVANCED LINER CONCEPTS

In this section consideration will be given to progress made on advanced duct liner concepts for improving the sound absorption efficiency of nacelle acoustic treatment. The goals of this work are to broaden the bandwidth of absorption, to improve low-frequency absorption characteristics, and to achieve more absorption with less weight and volume of treatment. An extensive review of duct acoustics and duct liner concepts is given in reference 6. More recent advances are contained in references 1 and 7.

Refracting Inlet

A relatively new noise reduction concept termed a "refracting inlet" has been proposed in reference 8. The basic phenomenon to be exploited in this inlet is illustrated in the sketch at the upper left of figure 8. In the experiment depicted, a sound wave traveling upstream in the narrow portion of the duct is seen to be refracted toward the lower wall after passing through the throat. It is believed that this refraction is caused by the velocity gradients present near the throat, particularly near the lower wall. The amount of refraction is a function of sound wavelength and flow speed. This experimental result suggests that it may be possible to use controlled refraction of sound waves to reduce inlet noise as shown in figure 9. The data of figure 9 are based on recent laboratory tests. By suitably tailoring the gradients in the inlet flow, noise propagating within the inlet is redirected towards wall acoustic treatment. In another case the radiated noise could be directed away from the ground. By directing more sound energy onto a liner, the efficiency of acoustic treatment might be significantly enhanced. Research is currently underway to explore more fully the performance and practicality of the refracting inlet concept.

Variable Impedance

One approach to increasing liner absorption is the variable impedance concept illustrated schematically in figure 10. In its simplest form, segments of liners having different impedances are placed axially along, or circumferentially around, the inlet. One can conceive of combining these two discrete patterns and smoothing over abrupt changes in liner properties to produce a continuous variation in impedance. The carefully designed change in impedance is believed to break up the orderly modal structure found in a uniformly lined duct and may redistribute some of the [illegible] energy into cutoff modes. The axially segmented liners have been studied theoretically and experimentally because it is an arrangement which is relatively easy to set up in a laboratory or to examine theoretically. The continuous variation of impedance may emerge as a useful concept when more sophisticated fabrication techniques and design procedures become available. In particular bulk absorbing materials are re-emerging as candidates for engine inlets because of new material availability. Bulk materials could be made to have continuously varying impedance tailored for a particular noise source.

Data on three axially segmented liners, obtained using the 30.48-cm-diameter (12 inch) research compressor in the Langley anechoic noise facility, are shown in figure 11. By placing various combinations of segmented treatment in the compressor inlet, a parametric study of segmented liner configurations was conducted in cooperation with the General Electric Company. The spectra in the figure are for a hard wall inlet, a uniform liner, and one of the acoustically better three-segment liners. It can be seen that the three-segment liner produces greater noise reduction than the uniform liner in the low- and mid-frequency range, as would be expected because of the two thicker treatment sections. Moreover, the high-frequency attenuation is maintained with the segmented liner even though a smaller amount of high-frequency treatment is present. One of the aims of current research is to expand to higher values the frequency range over which segmented treatment produces significant additional noise reduction. Data such as these suggest that multisegment liners may be superior to uniform liners and that the concept deserves further careful investigation. Probably the most urgent need at the moment is for well-controlled tests of multisegment and uniform liners optimized and tested for a known noise source in order to get a true comparison of their relative merits. It will take special care to do this statically in view of what is now known about the effects of inlet turbulence on turbomachinery noise generation.

Hybrid Inlets

In a hybrid inlet both acoustic treatment and high subsonic velocity airflow are combined to reduce noise. By operating at average throat Mach numbers somewhat less than 1.0, the aerodynamic performance penalties associated with the sonic inlet are minimized. Figure 12 (ref. 9) shows a comparison between a near-sonic inlet and a hybrid inlet for the NASA QCSEE engine. This figure indicates a relatively small reduction in total pressure recovery after treatment was added. In this case the noise reduction achieved as a result of the high subsonic speed airflow is augmented by sound absorption at the acoustically lined walls. These acoustic characteristics of the hybrid inlet are indicated in figure 13 which shows data for an experimental hybrid inlet compared with data for a hard-wall baseline or high subsonic Mach number inlet. In this case, the baseline inlet was found to produce SPL noise reductions of up to 20 dB at an average throat Mach number of 0.85. With the addition of wall treatment, additional noise reduction was obtained throughout the operating range as indicated by the upper curve. The full potential of the hybrid inlet concept remains to be explored. There are several directions for further research using the hybrid inlet concept, such as the combined use of segmented acoustic treatment to improve sound attenuation, and wind tunnel or flight testing to optimize aerodynamic and acoustic performance in the presence of forward speed.

Liner Design

This discussion would not be complete without mention of the many novel liner designs of L. Wirt of the Lockheed-California Company (ref. 10). Wirt's inventiveness has produced a number of unique geometrical variations of the Helmholtz resonator which are being considered as candidates for inlet treatment. Among these are Permobllque, Schizophonium, and Can-a-bel. These names refer to the geometrical design of the backing cavities. They have been found to have excellent low-frequency noise reduction qualities.

FORWARD-SPEED EFFECTS

The flight noise data presented were measured by the Douglas Aircraft Company (ref. 3). The measuring technique employed included a series of ground microphones and sophisticated techniques for tracking the aircraft flight path, including the airplane position and speed relative to the observation point. Engine corrected speed was carefully controlled and atmospheric weather conditions were monitored.

The static noise data were measured on an engine test stand with far-field microphones. In order to compare static data with flight data, it was necessary to project the static data to flight conditions. The procedures used accounted for the number of engines, aircraft flight path, air speed and altitude, atmospheric absorption, Doppler shift, and acoustic path length. Appropriate corrections were also applied to the jet noise component of the spectra to account for the effect of relative velocity on this noise component.

Flight data on a CF6-6 engine were obtained on a DC-10 installation where the nacelles have fixed geometry inlets and acoustic treatment on the cowl walls. A comparison of flight and projected static PNLT time histories is shown in figure 14. For this engine, the flight data are 3 to 12 PNdB less than the static projection depending on the time or position at which the comparison is made. Figure 15 shows a spectral comparison of these data at an inlet angle of about 70°, corresponding to the peak inlet fan noise. While the static data clearly reveal the presence of the fan fundamental tone, it is absent in the flight data. At frequencies higher than the fan fundamental frequency, the projections from the static data remain higher than the flight data.

The trends of figure 15 were also observed when the spectra were compared at the maximum PNLT values. The maximum values correspond to aft-radiated noise for this engine. Thus, a major difference between flight and static data is the absence of the fan fundamental tone in the flight data. The absence of this tone probably accounts for a significant part of the reduction in flight PNLT values relative to the static projections.

The presence of the fan fundamental in the static data suggests that it had to be produced by a different noise source during static testing that was absent during flight tests. The source is thought to be inflow distortion or atmospheric turbulence.

Aside from the disturbing conclusion that static fan or engine data are to some degree unreliable because of unsteady inflows, the important conclusions from flight data are that these unsteady inflows are minimized and that acoustic "cutoff" can be realized to yield noise levels substantially less in flight than would be expected from projection of the static data to flight.

Research is currently underway (ref. 11) to explain static noise results. The product of this work will, hopefully, improve the quality of future fan and engine static tests.

CONCLUDING REMARKS

This paper has presented an overview of certain passive, advanced concepts for the suppression of noise within the inlets of gas turbine engines. A status report of research on inlet acoustic liners and high subsonic Mach number inlets has been given. Some directions for improving these suppression methods have been pointed out and certain research and operating problems have been highlighted. Attention has been drawn to several ideas which may find practical application in the future and some optimism has been shown regarding minimizing operating losses for engine noise reduction concepts. These concepts can be expected to improve the relationship between noise reduction and direct operating cost.

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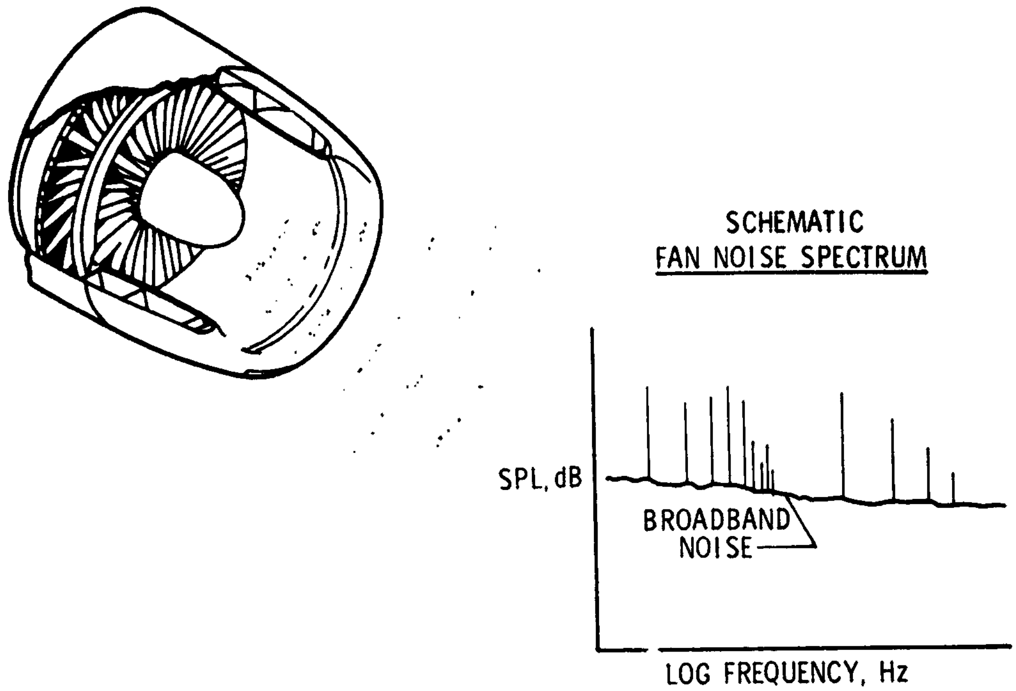

Figure 1.- Fan inlet noise.

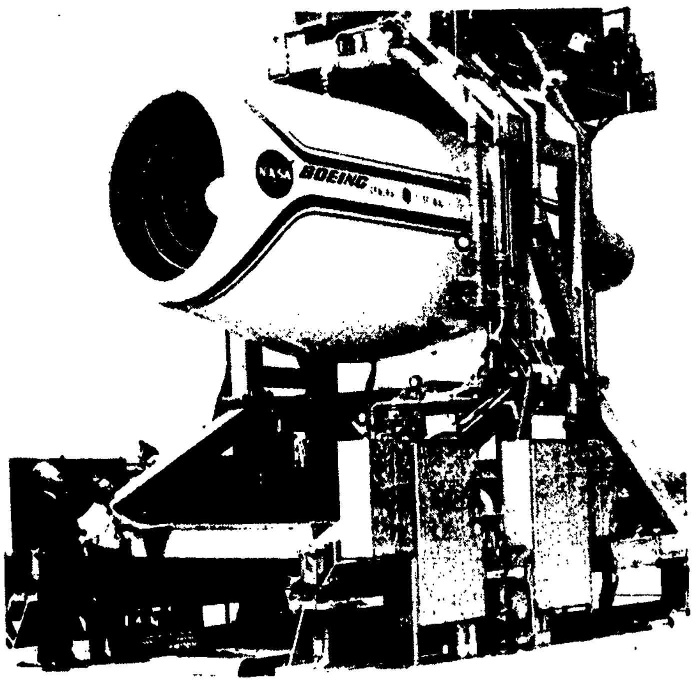

Figure 2.- NASA Quiet Engine with inlet rings.

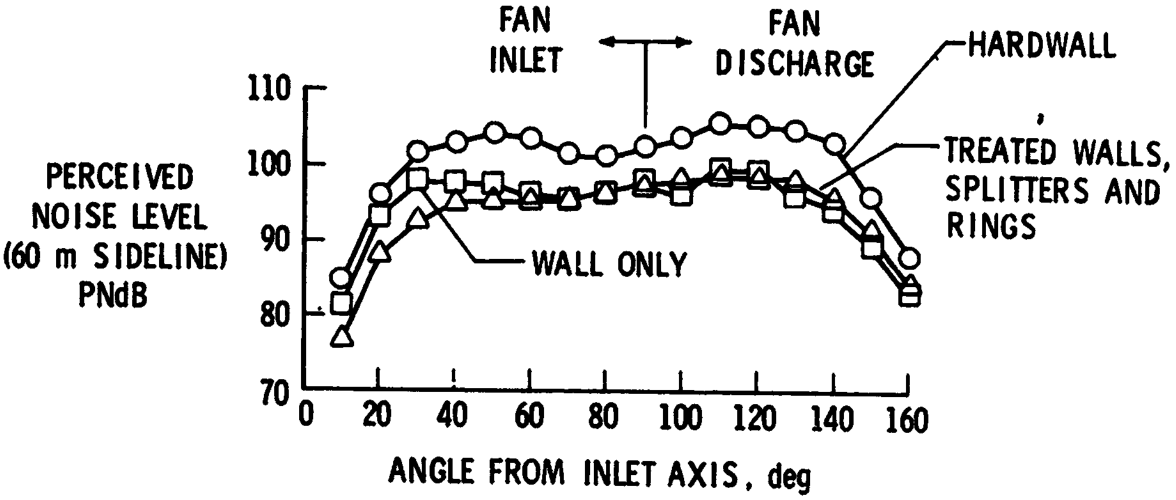

Figure 3.- Effect of inlet suppressor configuration from Quiet Engine Program.

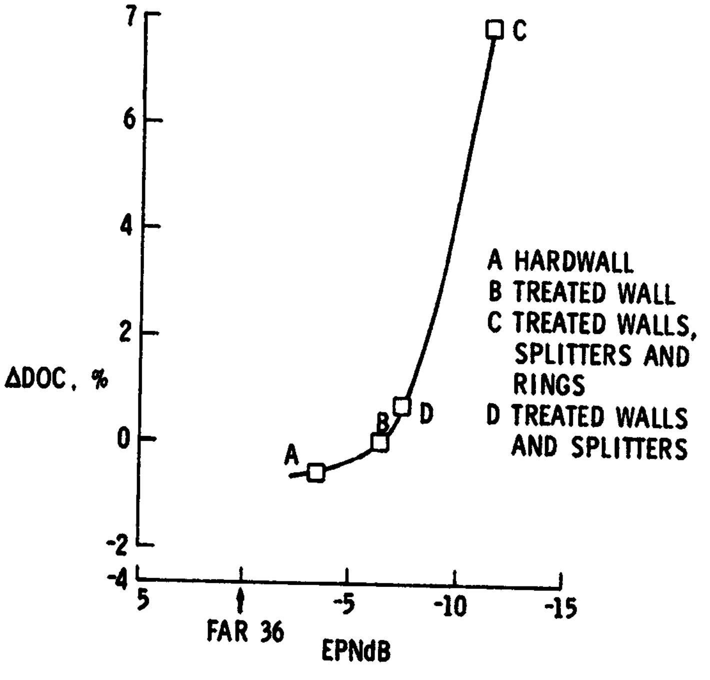

Figure 4.- 1972 relationship between estimated perceived noise level and direct operating costs from the Quiet Engine Program.

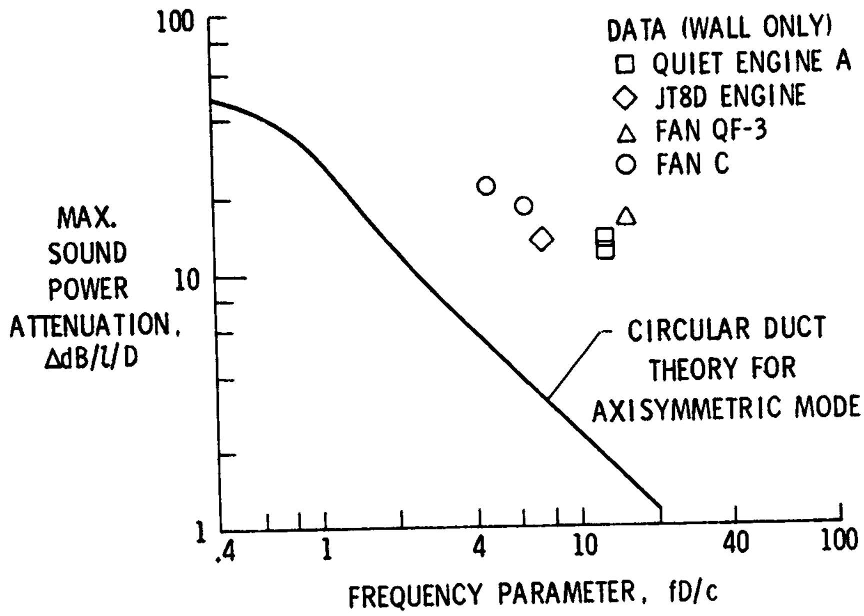

Figure 5.- Comparison of suppressor theory with data.

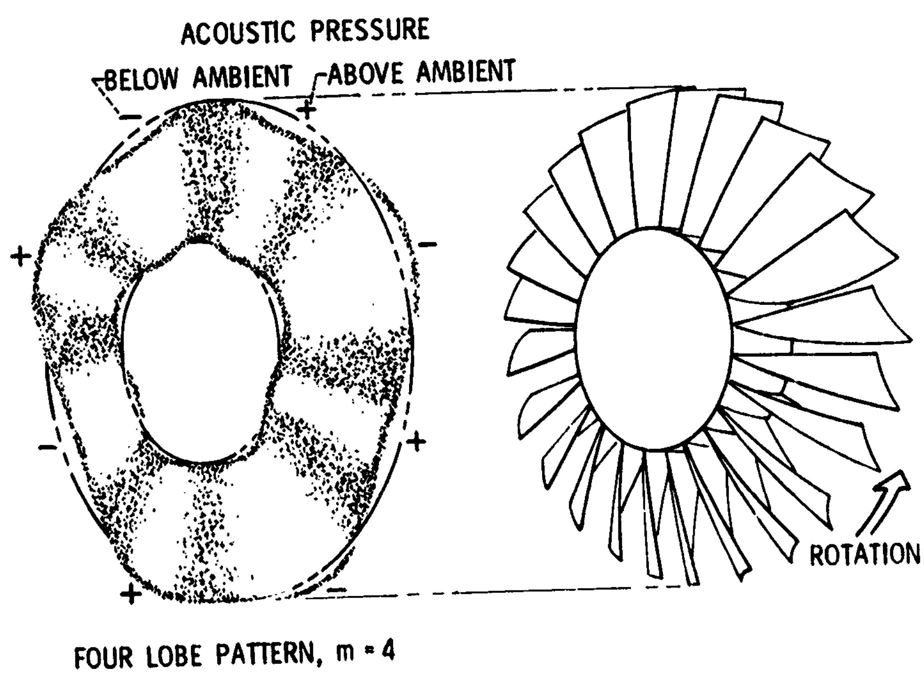

Figure 6.- Spinning lobe or mode pattern.

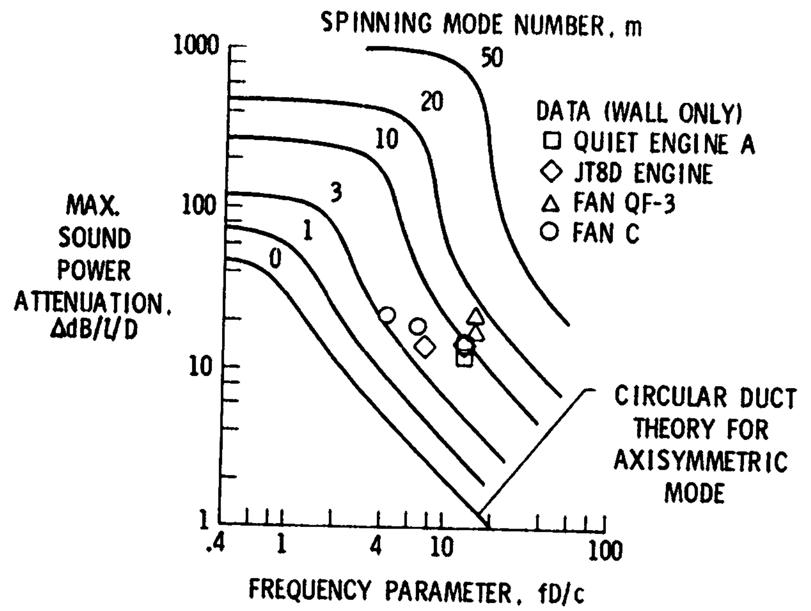

Figure 7.- Effect of spinning mode number on theoretical maximum sound attenuation.

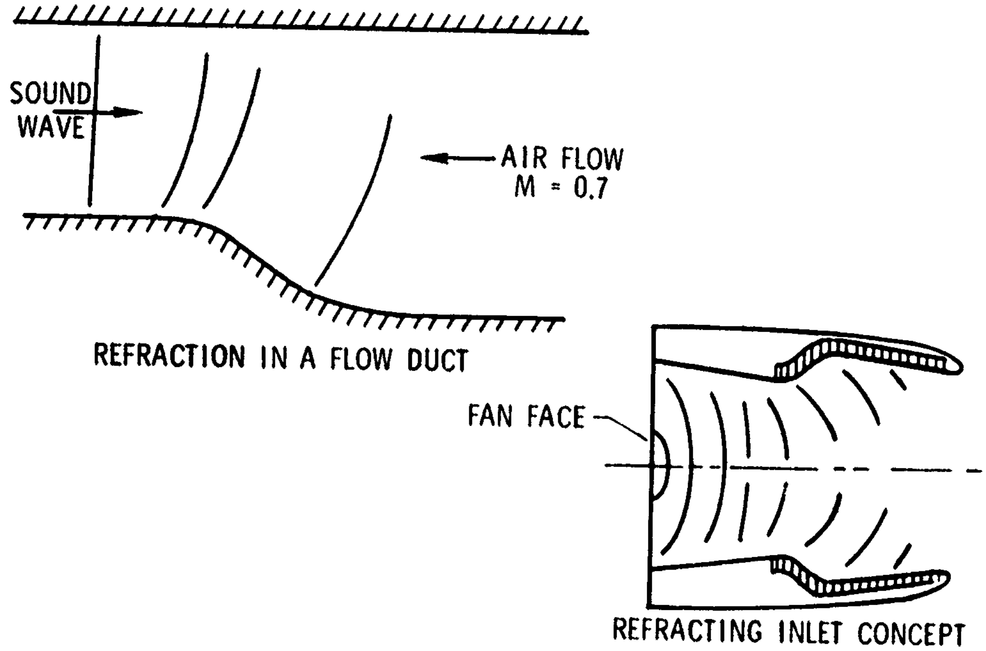

Figure 8.- Wave refraction by velocity gradients.

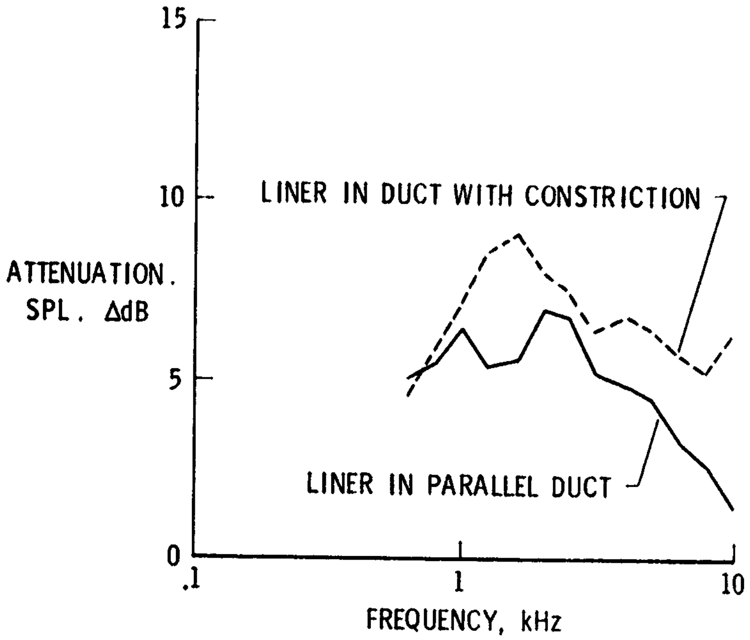

Figure 9.- Improvement of linear effectiveness by refraction; M = 0.35.

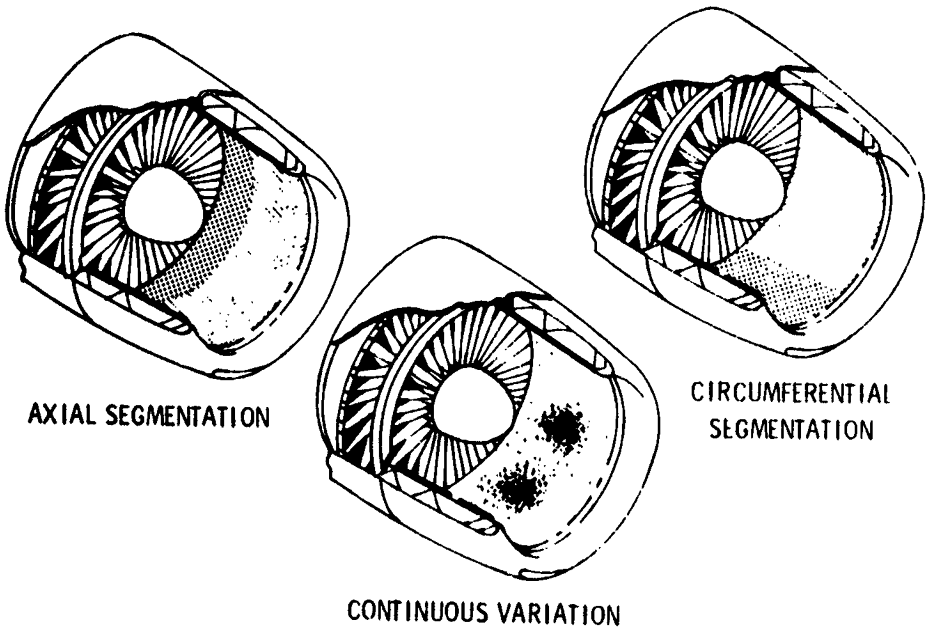

Figure 10.- Variable impedance liner concepts.

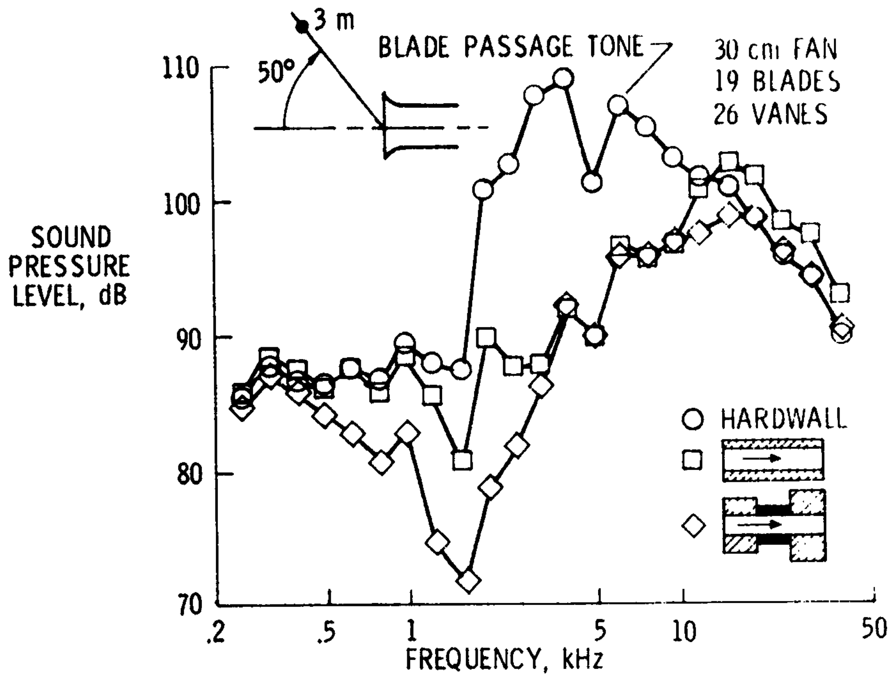

Figure 11.- Segmented liner spectra comparisons.

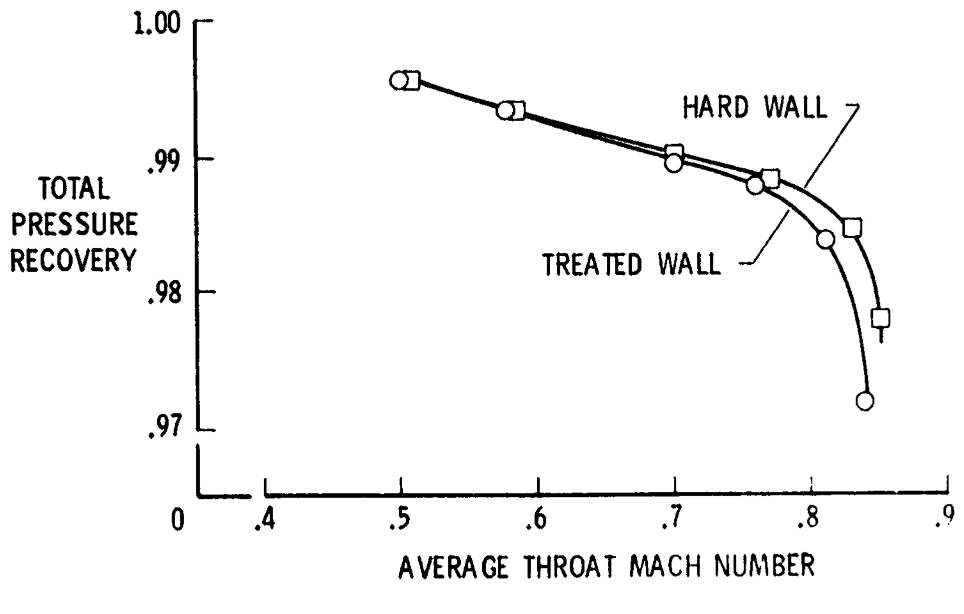

Figure 12.- Hybrid inlet aerodynamic performance for QCSEE engine.

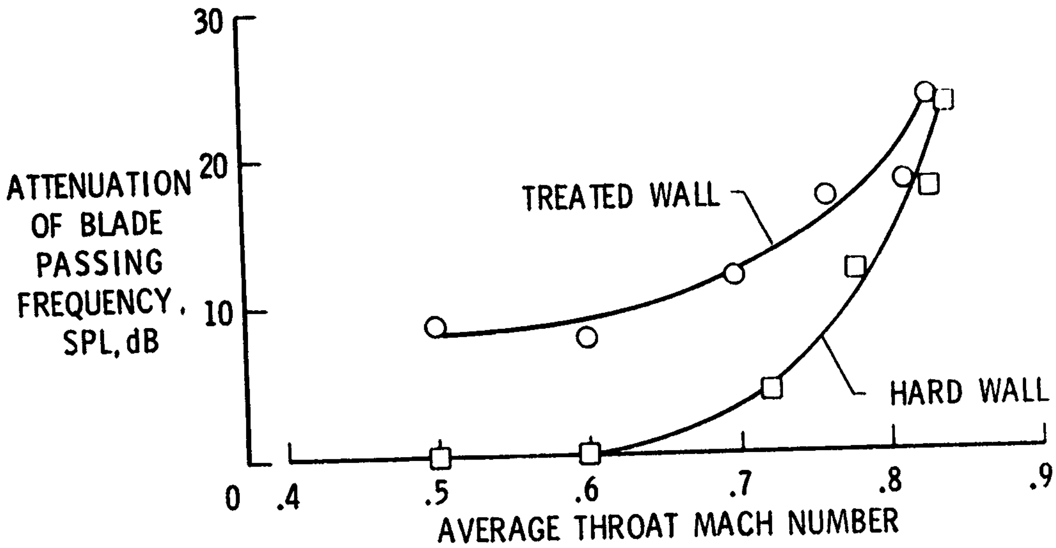

Figure 13.- Hybrid inlet acoustic performance for QCSEE engine.

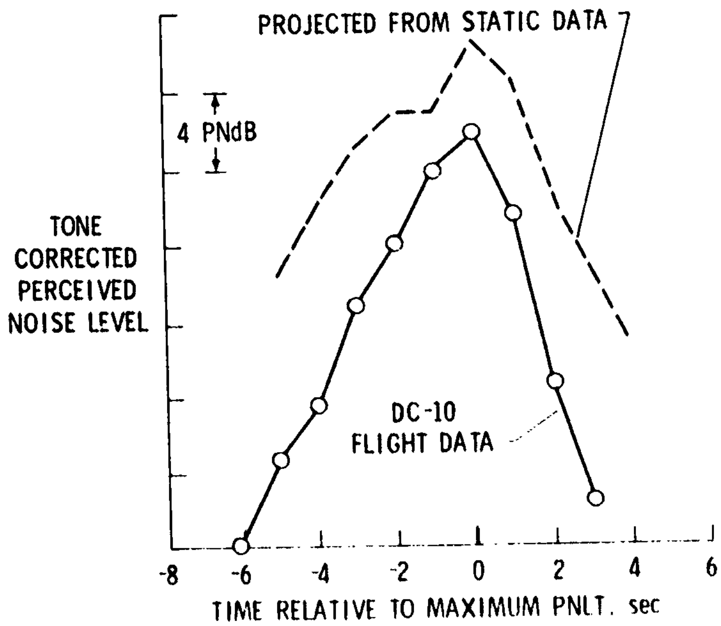

Figure 14.- Comparison of flight and projected static noise histories for CF6-6 engine.

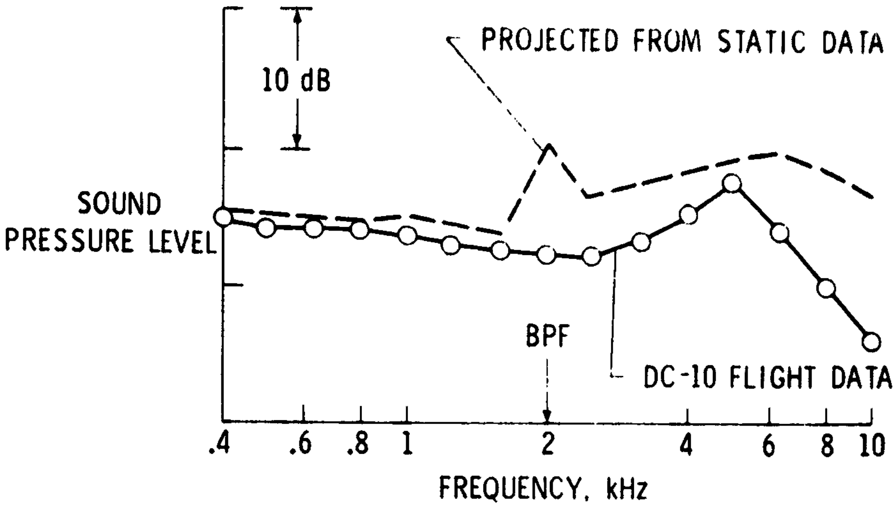

Figure 15.- Comparison of flight and projected static inlet sound pressure spectra for CF6-6 engine.