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ACOUSTIC PERFORMANCE OF INLET MULTIPLE-PURE-TONE SUPPRESSORS INSTALLED ON NASA QUIET ENGINE "C"

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Abstract

The purpose of the experimental program reported herein was to define the length of multiple pure tone (MPT) treatment required to reasonably suppress the MPT's produced by a supersonic tip speed fan and also to determine what other suppression, broadband, and blade passing frequency (BPF), might be accomplished. The experimental results are presented in terms of both far-field and duct acoustic data. Front quadrant sound power level reduction in the far field is shown to agree with duct measurements over the range of treatment lengths. Detailed one-third octave and narrow band spectra at the maximum forward noise angle are presented. Some detailed analyses of one-third-octave band amplitudes are shown as a function of far-field angle. An approximate spinning mode duct propagation analysis is then introduced which predicts the acoustic suppression by the treatment on the multiple pure tones. A 91.5-cm length (L/D = 0.53) of inlet MPT treatment provided maximum forward noise suppression of 5 PNdB at 90 percent rated fan speed measured on a 305-m sideline. Treatment lengths of 61 and 30.5 cm provided approximately 4 and 1 PNdB, respectively, at the same measurement station. The treatment, which was designed for a center frequency of 630 Hz, also provided some fan BPF and broadband suppression over the range of fan speeds tested.

Introduction

Modern high-bypass-ratio turbofan engines with supersonic tip speed fans generate annoying "buzz-saw" tones. These so-called "multiple pure tones" (MPT's) occur at multiples of shaft frequency and peak at lower frequencies that require very thick acoustic treatment (based on conventional Helmholtz resonator theory) for absorption. This noise is discussed in several recent papers.[1-4] From the standpoint of initial cost and engine weight it would be well to minimize the amount of such treatment.

The purpose of the experimental program reported herein was to define the length of MPT treatment required to reasonably suppress the MPT's and also to determine what other suppression, broadband, and blade passing frequency (BPF), might be accomplished. In addition, an analytical approach to prediction of suppression based on references 5 and 6 is introduced and results are compared with the experimental findings.

NASA's Quiet Engine "C" was selected for tests which employed up to 91.5 cm in length of 7.2-cm-thick acoustic treatment in the 174.2-cm inside diameter duct. The treatment was designed by NASA early in the contracted Quiet Engine Program with the goal of suppressing the MPT's without the use of inlet splitters. The basis of the design was a cylindrical duct propagation analysis which used a plane wave as a noise input function. The design center frequency of 630 Hz was near the peak of the MPT's which covered a range of frequencies from approximately 400 Hz to blade passing frequency.

Engine "C" was equipped with a massive aft fan noise suppressor so that the inlet suppressor results could be clearly delineated. Previous tests of this MPT suppressor material installed on Quiet Engine "C" had been accomplished using other material in concert but the effect of the MPT treatment alone was not determined. These overall treatment results are reported in reference 7. The tests reported herein were conducted at the Engine Noise Test Facility of the NASA Lewis Research Center. The suppressor configurations were tested over a range of engine power conditions from ground idle to takeoff. The far-field acoustic data were obtained, analyzed, and compared to data obtained with a baseline hardwall inlet. In addition, inlet acoustic probe data were obtained for each suppression length and the baseline, and comparisons of these data are made with the far-field results.

Apparatus and Procedure

Facility Description

The test program was performed at the Engine Noise Test Facility located at Lewis Research Center adjacent to, but sufficiently far from the Flight Research Building so that accurate measurements could be obtained. The facility is shown schematically in figure 1.

The 17 far-field microphones were at the same height as the engine centerline, 3.96 m (13 ft), on a 45.7-m (150-ft) radius spaced every 10° from the inlet axis to 160°. The reflecting plane was hard pavement. Ground microphones were installed at 30°, 40°, 50°, and 60° from the inlet axis.

A photograph showing the installation of Quiet Engine "C" at the Engine Noise Test Facility is presented in figure 2. Engine operation was controlled from the Flight Research Building where the noise instrumentation and analysis equipment were located.

Engine Description

The NASA Quiet Engine "C", a low noise technology turbofan demonstrator, was designed, built, and acoustically evaluated under the NASA/GE Experimental Quiet Engine Program. The 96 900-N- (22 000-lb-) thrust class turbofan engine incorporated a newly developed, high tip speed, single-stage fan. It was designed for the altitude cruise condition with a corrected tip speed of 472 m/sec (1550 ft/sec) at a bypass pressure ratio of 1.6, and with a corrected fan flow of 415 kg/sec (915 lb/sec). The fan had 26 unshrouded rotor blades and 60 outlet guide vanes. Further details are presented in reference 7.

MPT Suppressor Configurations

A sketch of Quiet Engine "C" showing the locations of the three MPT treatment configurations is

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presented in figure 3. The lengths of 91.5, 61, and 30.5 cm of treatment corresponded to design length to diameter ratios (L/D) of 0.53, 0.35, and 0.18, respectively. The 7.1-cm-thick Single Degree of Freedom (SDOF) treatment had a porosity (percent open area) of 4.5 percent and a face plate thickness of 0.813 mm. The design of the treatment was based on a cylindrical duct sound propagation theory which used a plane wave as a noise input function. The design was aimed at suppression centered around a frequency of 630 Hz and was based on methods of references 8 to 10.

Shown also in figure 3 is the location of the acoustic probe and the massive aft fan suppressor used in the program.

Experimental Methods

Aerodynamic and acoustic data were obtained over a range of corrected fan speeds from 43 to 90 percent of design for all three MPT suppressor lengths and the hardwall baseline configuration.

The acoustic instrumentation and data recording system had a flat response over the frequency range of interest (50 to 20 000 Hz). Data signals were FM recorded from all channels simultaneously on magnetic tape. Each of three samples for a given corrected fan speed was reduced separately by using a one-third-octave-band analyzer. The resulting sound pressure levels were arithmetically averaged, adjusted to standard day atmospheric conditions, and side-line perceived noise levels were calculated using the standardized procedures presented in reference 11. The narrow band data reported herein are given as measured without any correction.

In-duct acoustic data were obtained using traversing probes at station 2.0 (fig. 3) upstream of the treatment. These area-weighted data were subtracted from similar acoustic probe data obtained from the baseline configuration (with no acoustic treatment) to yield an in-duct estimate of sound power level (PWL) reduction in each one-third-octave band.

Results and Discussion

The experimental results are presented in terms of both far-field and duct noise data. Detailed one-third-octave spectra at the maximum forward noise angle are presented. Some detailed analyses of one-third-octave-band data at or near design center frequency are then exhibited as a function of far-field angle. Front quadrant acoustic power reduction is displayed as a function of treatment length. Perceived Noise Levels (PNL's) at a 305-m sideline are shown as functions of directivity and fan speed. In-duct acoustic data is then explained. Forward quadrant sound power level reductions in the far field are then compared to duct measurements over the range of treatment lengths. Narrow band spectra are explained. An analysis which predicts the acoustic suppression by the treatment on the multiple pure tones is compared with the experimental results.

Results from Analysis of Far-Field Acoustic Data

In order to provide a better basis for the comparison of treatment length effectiveness, three sets of baseline configuration data were run on three separate run days under varying ambient conditions. An example of the results of these tests is shown on a one-third-octave basis for the 60° microphone in figure 4. The high reading, the low reading, and the average of the three sound pressure levels (SPL's) are plotted as a function of frequency. Very little data scatter exists except at a frequency of 250 Hz where the spread amounts to about 5 dB. The average value of the three baselines was used throughout the program to compute the sound reduction of the three lengths of treatment. Other analyses of the data were made in order to ensure its quality. For example, single day run to run variations were studied; acoustic sample times of integration were investigated for narrow bands and one-third-octave data; ground microphone data were compared to pole microphone data. The procedures adopted as a result of these analyses were as follows: an average of three single runs was taken for final data; an acoustic sample time of 32 sec was used for one-third-octave band data; 128 samples were used for narrow band data; and pole microphone data were chosen because they were more consistent than ground microphone data.

The guidelines established in these analyses were used to determine the one-third-octave-band sound pressure levels of the three treatment lengths. These data for 90 and 50 percent rated fan speed and the 60° pole microphone are presented in figure 5. At 90 percent fan speed (fig. 5(a)) 91.5 cm of treatment provided 9 dB of suppression for the design one-third-octave center frequency of 630 Hz; 61 and 30.5 cm of treatment provided 6.5 and 2 dB, respectively. The 91.5 cm of treatment appears to be effective over the bands from 250 to 6300 Hz. At 50 percent rated fan speed (fig. 5(b)) the shape of the baseline spectrum is quite different than at 90 percent fan speed. There are no MPT's present and the blade passing frequency (BPF) (1250-Hz band) dominates the spectrum. Nevertheless, the treatment is effective over a range of frequencies from 315 to 5000 Hz. A length of 91.5 cm provided 11 dB of suppression at the BPF, while 61 and 30.5 cm of treatment provided 11 and 5 dB, respectively.

Shown in figure 6 are the directivities of the one-third-octave bands at 630 Hz (design center frequency) and its two adjacent bands, 500 and 800 Hz for the baseline and the three treatment lengths. These data at 90 percent rated fan speed show that the treatment is effective in suppressing front quadrant MPT's and that increasing the amount of MPT treatment from 61 to 91.5 cm shows improvement in noise reduction. In fact, suppression by the treatment is evident at angles to 120°. Displayed in figure 7 is the effect of treatment length or length-to-diameter ratio (L/D) on front quadrant sound power reduction at the 630-Hz one-third-octave-band design center frequency. The variation of sound power reduction with treatment length is linear in accord with theoretical expectation for a signal consisting of a single mode. The far-field PNL directivity data on a 305-m sideline are presented in figure 8 for 90 percent rated (takeoff power) fan speed. The effect of treated length can be readily compared to the baseline data. Maximum forward noise is reduced 5 PNdB by 91.5 cm of treatment; 61 and 30.5 cm of treatment reduce maximum forward PNL by 4 and 1 PNdB, respectively. Even the aft quadrant PNL is reduced somewhat as was shown previously in figure 6. At

120°, 91.5 cm of treatment reduces the PNL by 2 PNdB.

Shown in figure 9 is a comparison of maximum forward PNL values extrapolated to a 305-m sideline for the baseline and three treated lengths as a function of corrected fan speed. The trends of the data shown previously at takeoff power are confirmed by the rest of the data points from 43 to 85 percent rated fan speed. The maximum suppression at 70 to 85 percent rated fan speed approximately equals the suppression at 90 percent rated fan speed while the suppression at 43 and 50 percent rated fan speed is approximately one-half of that at the higher fan speeds. This occurs because the MPT's are present at the higher range of speeds and not at the lower speeds.

In-Duct Acoustic Results

Displayed in figure 10 are OASPL data obtained in the inlet duct for the baseline hard-wall configuration at 70 and 90 percent rated fan speeds. These data were obtained by two different methods. The data points shown were obtained at quasi-steady-state conditions, while the probe was stopped at ten incremental steps across the inlet passage. The line described by the crosshatched bands on the figure represent the OASPL data which were obtained while the probe was continuously traversed across the passage from the outside in and back to the outer wall over a time period of about 2 minutes. The outside limits of the shaded area encompass a signal variation of about 3 dB during the traverses. The ten incremental data points generally agree with the limits of the traverse data. Reasons for some of the disagreement can be attributed to fan speed and ambient wind variations during setting of the ten quasi-steady-state data points which were typically 1 minute long with a 3- to 5-minute pause between data recordings.

The general trend of the data for both speeds indicates a higher sound pressure level at the outside wall than in the center of the inlet. This is attributed to the spinning mode generated with higher amplitude near the wall where rotor velocity is highest. The data for 90 percent fan speed have a steeper slope than the 70 percent fan speed data because of the shocks formed on the rotor blades which generate the MPT's at the outer spanwise locations where rotor tip relative Mach numbers are greater than 1. At 70 percent fan speed this Mach number has just exceeded 1.

Comparison of Far-Field and In-Duct Results

The reductions in front quadrant sound power level (ΔPWL) measured in the far-field are compared to the in-duct reductions in figure 11. As can be seen, the in-duct acoustic probe data (solid symbols) are in fair agreement with reductions measured in the far field in the front quadrant.

Analysis of Narrow Band Data

Typical narrow band spectra are presented in figure 12 for the baseline configuration for 90 percent rated fan speed. Shown in figure 12(a) is the output of the duct microphone at a position 1.9 cm from the wall where the multiple-pure-tone amplitudes would be expected to be large. The fan blade passing frequency (BPF) occurs at a frequency of about 2000 Hz. The multiple pure tone spikes are numbered 1 to 25 corresponding to multiples of shaft frequency. The 26 fan blades running at supersonic tip speed result in this classical pattern. Because of the manufacturing variations from blade to blade, the amplitude of the shocks formed on the rotor blade leading edges vary. As the shocks propagate forward, stronger shocks overtake and coalesce with weaker shocks resulting in an irregular pattern rotating with the fan; the spectral analysis of which results in the series of tones of varying amplitude at multiples of the shaft rotation frequency. Tones 4 to 9 and 12 and 14 are the dominant ones measured by this microphone at a level of about 150 dB.

Shown in figure 12(b) is the spectrum measured by the 160° far-field microphone. Tones 5 to 9 and 14 are still dominant at an average level of about 104. Tone 12 is about 9 dB below that level. Tones 19 and 21 have decreased in amplitude with respect to the dominant tones and the BPF harmonic has faded indistinguishably into the sawtooth pattern of the MPT's.

Typical narrow band spectra for the configuration with 91.5 cm of treatment are presented in figure 13 for 90 percent rated fan speed. Shown in figure 13(a) is the output of the duct microphone at a position 1.9 cm from the wall. A comparison of this spectrum with figure 12(a) reveals that the sound pressure level is down approximately 9 dB. The average level of the dominant MPT's (tones 3, 5 to 9 and 14) is about 141 dB.

Shown in figure 13(b) is the spectrum of the 60° far-field microphone for the configuration with 91.5 cm of treatment. Comparing this spectrum with that of the baseline configuration (fig. 12(b)), the same tones are dominant: tones 5 to 9 and 14. However, the average amplitude of these tones is down about 4 dB.

The intent of this section has been to acquaint the reader with the typical noise generation and dispersion of the spinning waves as they propagate from the inlet into the far field. Treated in the next section is an approximate analysis which is compared to attenuations measured from narrow bands.

Comparison of Narrow Band Data Attenuation with the Approximate Theory

More narrow band spectra similar to figures 12(b) and 13(b) were used for all the configurations to calculate sound power attenuation for each MPT for the forward quadrant. In figure 14 these data are compared to the theoretical attenuation calculated by the method of references 5 and 6. The input used for the approximate theory is described in the appendix. The dashed curves in figure 14 represent the results of this calculation for 91.5, 61, and 30.5 cm of treatment. The calculated attenuation is proportional to L/D. As can be seen, the forward quadrant sound power measured in the far field compared favorable with the theory for each tone from the third to the tenth. The deviation of the points for the third tone could be due to the varying test conditions affecting the ground reflection corrections, which is greatest at that frequency for the microphone pole height (4.1 m) used during the test. From the tenth tone through the twenty-sixth (fan BPF) the theory generally overpredicts the measured attenuation. This over-prediction as well as the erratic behavior of the measured attenuation in figure 14 cannot be explained with confidence at the present time.

Generally speaking, however, the approximate theory is a promising start on the understanding of the attenuation of MPT's. We would expect that a liner designed according to this theory would be substantially better than the present liner which, as was pointed out, was designed several years ago from theoretical considerations that are much less applicable to MPT's than the present theory.

Summary of Important Conclusions

The important conclusions derived in this paper are the following:

1. The treatment, which was designed for a center frequency of 630 Hz, also provided fan BPF and some broadband suppression over the range of fan speeds tested.

2. At the maximum forward noise angle, 91½ cm of MPT treatment provided 9 dB of suppression for the design one-third-octave center frequency of 630 Hz; 61 and 30.5 cm of treatment provided 6.5 and 2 dB, respectively, at the same position.

3. Far-field insertion loss data agreed fairly well with that measured with an acoustic probe in the inlet duct.

4. Using narrow band data results in the suppression of the forward PWL calculated for each shaft order tone up to the tenth being predicted reasonably well by the approximate spinning mode attenuation theory.(5,6)

5. A length of 91.5 cm of inlet MPT treatment provided maximum forward noise suppression of 5 PNdB at 90 percent rated fan speed measured on a 305-m sideline. At the same measurement station 61 and 30.5 cm of treatment provided approximately 4 and 1 PNdB, respectively.

Appendix

The generalized approximate equation of reference 6 for duct lining sound attenuation is based on the specification of two parameters; the maximum possible attenuation and the optimum wall acoustic impedance which completely determine the sound attenuation for any acoustic mode at any selected wall impedance. The equation is based on the nearly circular shape of the attenuation contours in the wall acoustic impedance plane. For impedances far from the optimum, the equation reduces to Morse's approximate expression. In addition, the mode circumferential lobe number needed for the calculations was obtained by assuming a rotor locked pattern. The optimum impedances for these modes were calculated based on the fact that the modes were near cutoff.

The equations in references 5 and 6 are for well propagating modes so that a change in the optimum wall impedance equation was required to accommodate modes near cutoff. Reference 5 contains equation (31) which specifies an approximate value for

$$Q = \frac{1}{1 + M}$$

which is a multiplier on the impedance equation which accounts for the flow Mach number effects, where M is uniform steady flow Mach number. The change in the equation for Q which is used in this paper for modes near cutoff is

$$Q = \frac{1}{1 - M^2}$$

Using this modification and calculating the optimum specific acoustic resistance θ_m and the optimum acoustic reactance X_m results in a variation with frequency shown in figure 15. In addition the specific acoustic resistance θ and the specific acoustic reactance X are presented as calculated for the MPT treatment design tested. As can be seen, the specific acoustic reactance crosses the optimum line at 700 Hz and then diverges rapidly as frequency increases. The specific acoustic resistance is a constant value of 5.3 and the optimum curve starts to approach it as frequency is increased from 230 Hz but then the optimum levels off at a value of about 2.25 as frequency goes above 2000 Hz.

If the resistance and reactance are known, the damping ratio β is calculated from equation (64) of reference 6, where β is defined as the ratio of the maximum possible attenuation ΔdB_m to the actual attenuation ΔdB. Figure 5 in reference 5 gives ΔdB_m as a function of frequency and lobe number.

The shape of the theoretical damping curves of figure 14 are highly dependent on the resistance and reactance curves of figure 15. The fact that the optimum resistance and the calculated liner resistance continue to approach each other at frequencies above the reactance match at 700 Hz causes the calculated attenuation to continue to rise at frequencies above 700 Hz. When the calculated liner reactance finally starts to diverge rapidly from the optimum reactance at frequencies above 1200 Hz, the calculated attenuation peaks out and falls rapidly.

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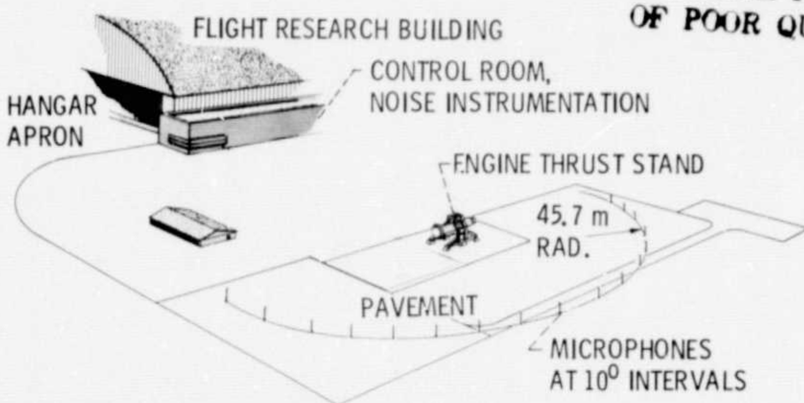

Figure 1. - Engine Noise Test Facility plot plan showing thrust stand, microphone array, control and noise instrumentation rooms.

Figure 2. - Quiet Engine "C" installed at the Engine Noise Test Facility of the NASA Lewis Research Center.

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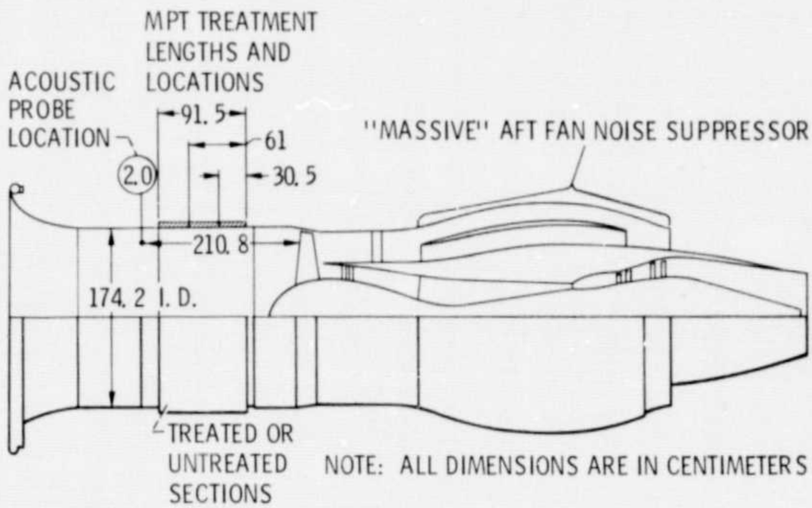

Figure 3. - Sketch of Quiet Engine "C" showing locations of MPT treatment employed and location of acoustic probe.

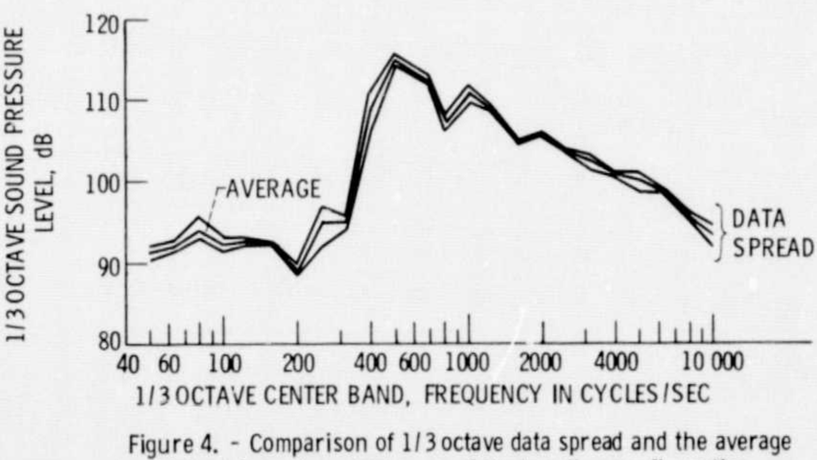

Figure 4. - Comparison of 1/3 octave data spread and the average obtained from three test runs of the baseline configuration. Data shown at 90 percent rated fan speed and 60^{0} forward angle at 30.5 meter radius.

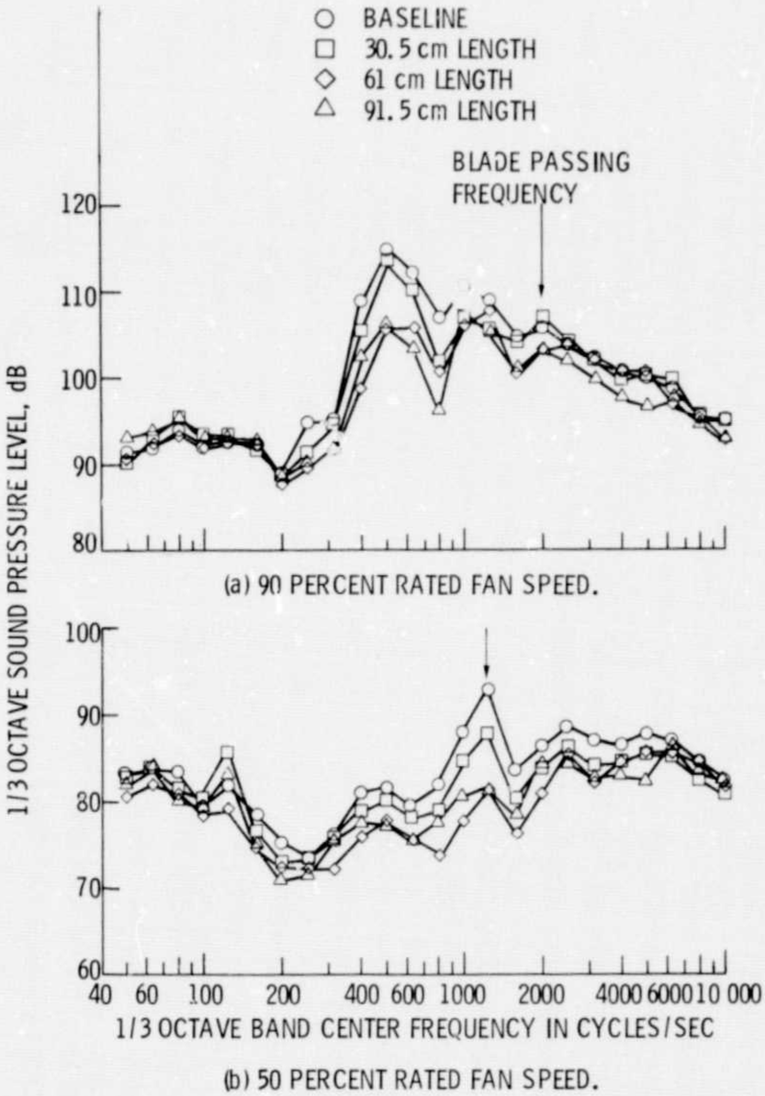

Figure 5. - Treated length effect on maximum forward angle (60^0) 1/3 octave band noise characteristics. 30.5 meter radius.

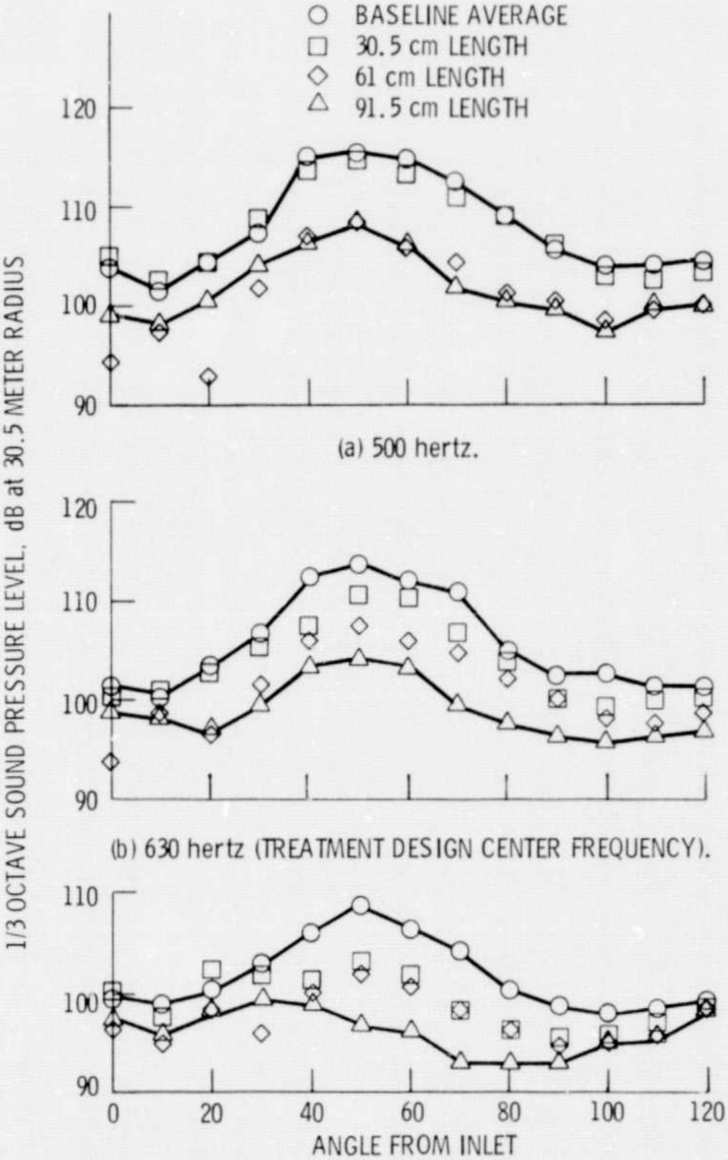

Figure 6. - Directivity of noise at various 1/3 octave bands at and near design center frequency of treatment. 90 percent rated fan speed.

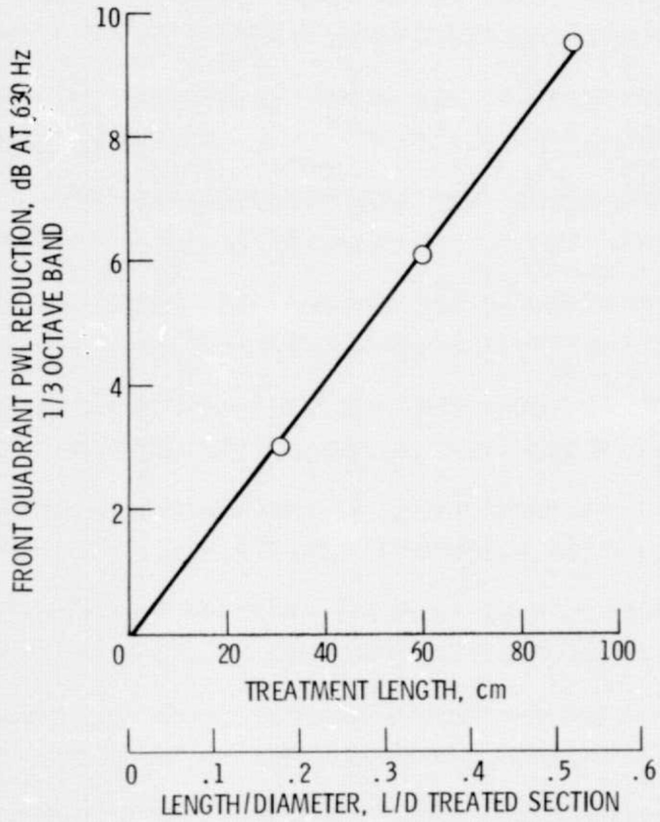

Figure 7. - Front quadrant PWL reduction at the design center frequency of the treatment (630 Hz) as a function of treated length.

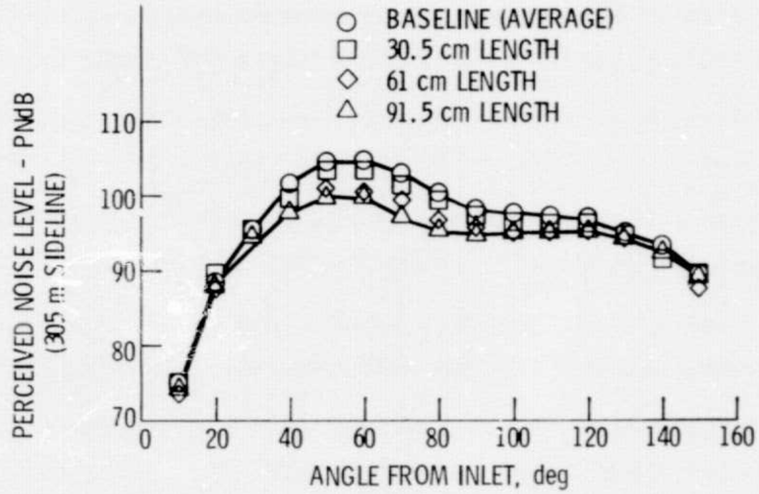

Figure 8. - Treated length effect on directivity of perceived noise level at 305 m sideline. 90 percent rated fan speed.

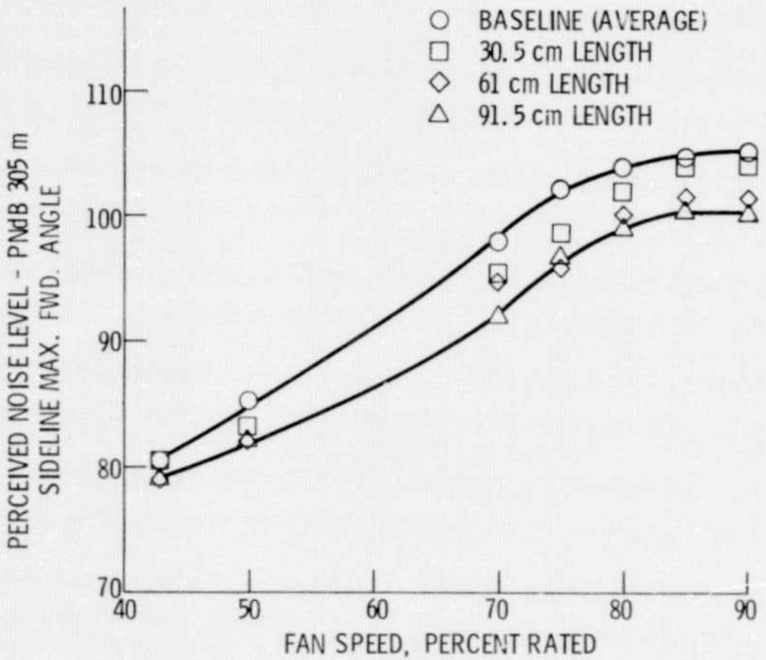

Figure 9. - Treated length effect on maximum forward angle perceived noise level as a function of fan speed.

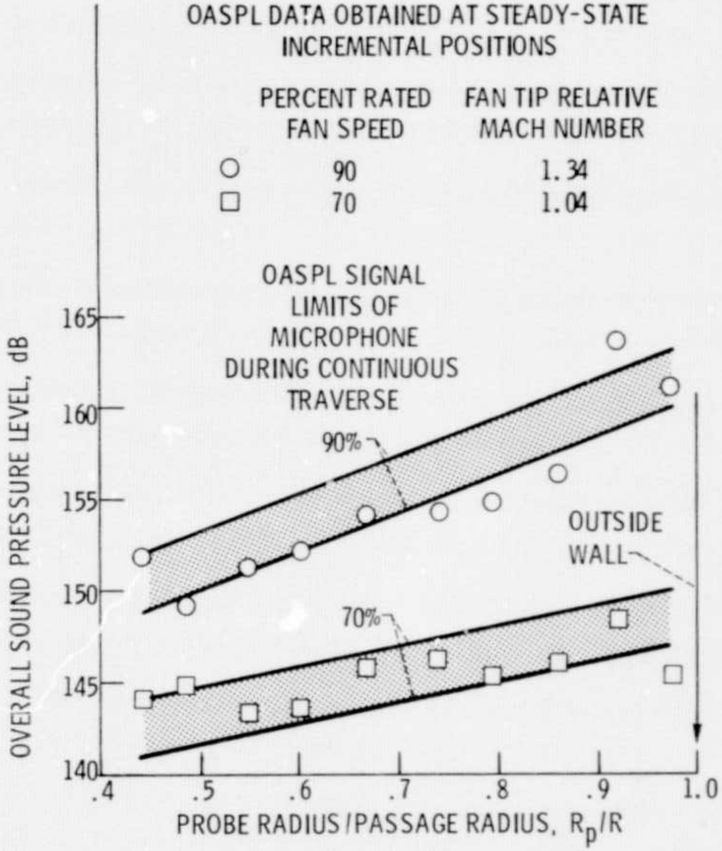

Figure 10. - Comparison of OASPL data obtained during a continuous traverse with data obtained during 10 steady-state incremental positions across the inlet. Baseline hardwall configuration.

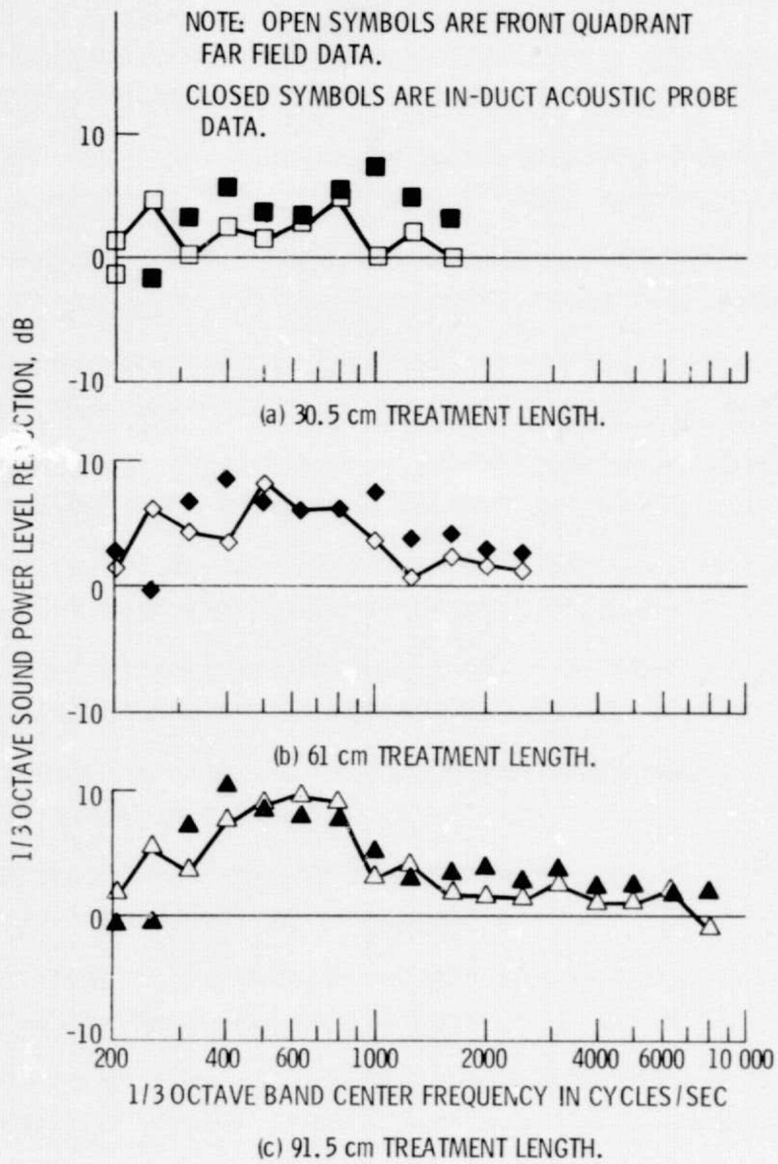

Figure 11. - Comparison of 1/3 octave front quadrant sound level reduction to the reduction obtained in the inlet.

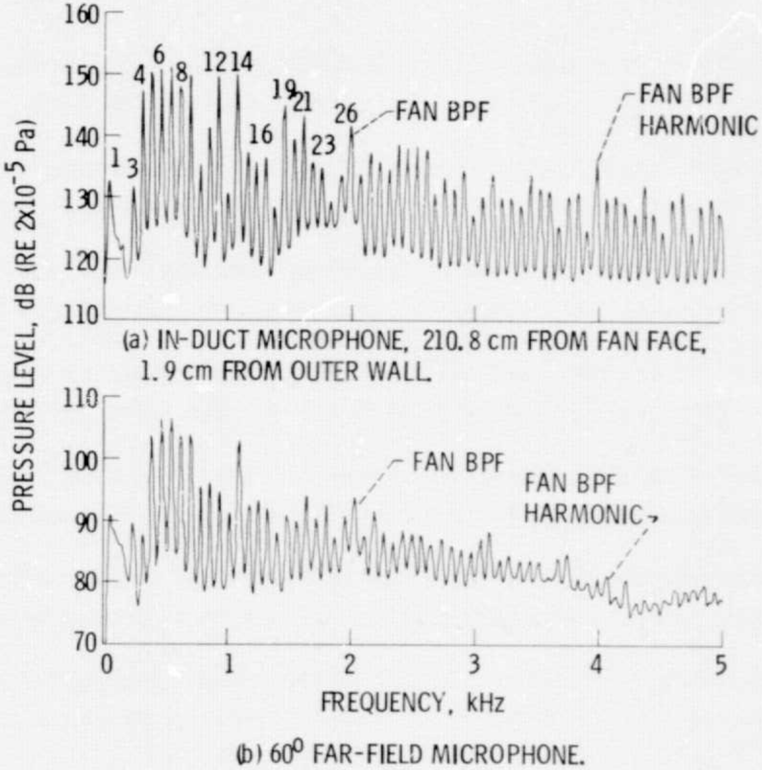

Figure 12. - Typical narrowband spectra for baseline configuration. 90 percent rated fan speed. Bandwidth 15 Hz.

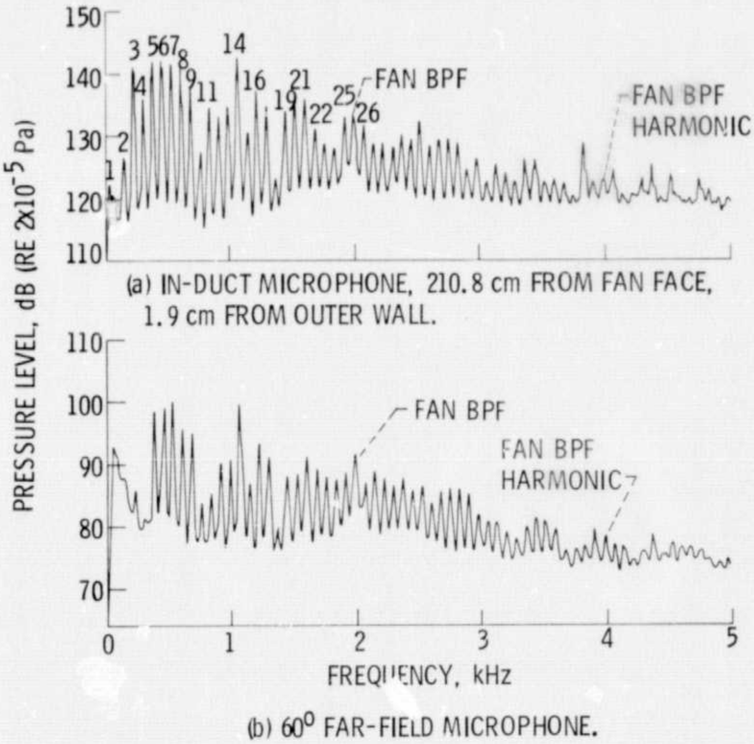

Figure 13. - Typical narrowband specira for configuration with 91.5 centimeters of treatment. 90 percent rated fan speed. Bandwidth 15 Hz.

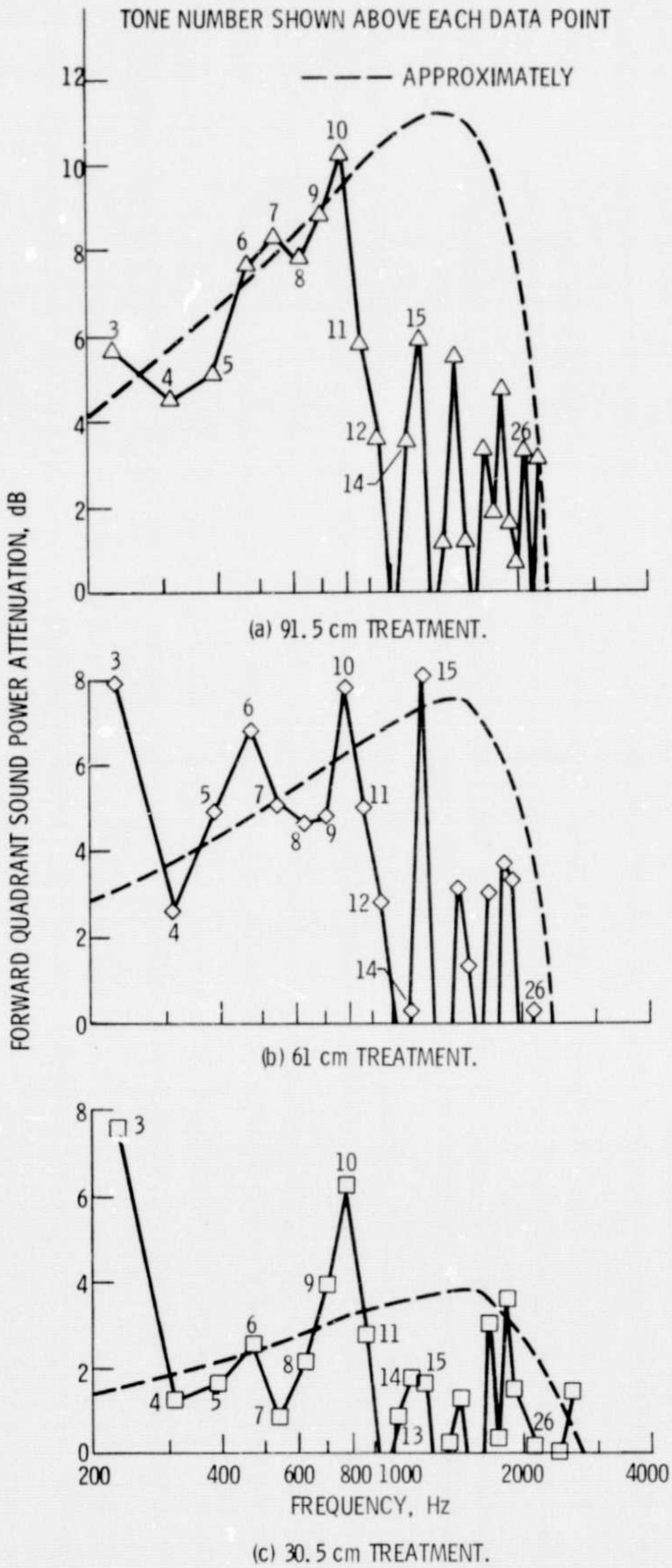

Figure 14. - Comparison of approximate theory with data.

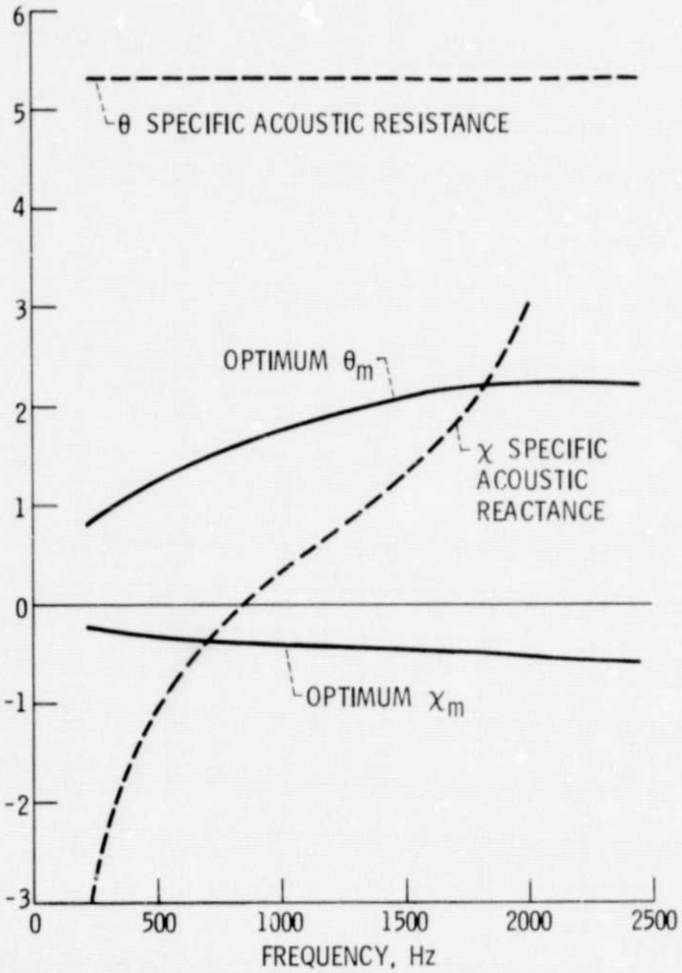

Figure 15. - Liner design variables as a function of frequency.