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Measured Acoustic Properties of Variable and Low Density Bulk Absorbers

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Milo D. Dahl and Edward J. Rice
Lewis Research Center
Cleveland, Ohio

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Milo D. Dahl and Edward J. Rice
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

Experimental data were taken to determine the acoustic absorbing properties of uniform low density and layered variable density samples using a bulk absorber with a perforated plate facing to hold the material in place. In the layered variable density case, the bulk absorber was packed such that the lowest density layer began at the surface of the sample and progressed to higher density layers deeper inside. The samples were placed in a rectangular duct and measurements were taken using the two microphone method. The data were used to calculate specific acoustic impedances and normal incidence absorption coefficients. Results showed that for uniform density samples the absorption coefficient at low frequencies decreased with increasing density and resonances occurred in the absorption coefficient curve at lower densities. These results were confirmed by a model for uniform density bulk absorbers. Results from layered variable density samples showed that low frequency absorption was the highest when the lowest density possible was packed in the first layer near the exposed surface. The layers of increasing density within the sample had the effect of damping the resonances.

INTRODUCTION

The acoustic characteristics of wind tunnel test sections has become an important consideration in the measurement of aircraft propulsion system noise at subsonic Mach numbers. Under simulated flight conditions, it is desirable to measure both acoustic amplitude and directivity to help fully characterize the noise source. This is not possible if reflections from the wind tunnel walls are interfering with the direct sound. In the past, acoustic measurements have been taken in high speed wind tunnels that have test section walls that were considered acoustically hard. For instance, the NASA Lewis 8- by 6-Foot Wind Tunnel has been used to measure the cruise noise of advanced turboprops (1). Comparison between wind tunnel data and in-flight data showed good agreement in the direction where the noise reached a maximum. Dittmar (2) has stated that this ability to measure noise in a hardwall wind tunnel was due to the highly directional characteristics of the propeller noise source in combination with the high flow speed. The peak noise dominated above reflections at flows higher than Mach 0.6. At these flows, large interfering reflections were swept downstream past the measurement location for the direct sound. Thus, measurements of the peak noise amplitude and direction were available.

High speed wind tunnels have not usually been used for acoustic measurements and, consequently, few have treated test sections. At low Mach numbers of 0.2 and below, wind tunnels are available with acoustically lined test sections. The NASA Lewis 9- by 15-Foot Low Speed Wind Tunnel is one tunnel with an acoustically lined test section that permits acoustic measurements, especially directional characteristics (3). Reflections are diminished by the treatment rather than relying on highly directional sources and flow speed to minimize reflections. The 9 by 15 wind tunnel lining had been designed for measurements above 1 kHz.

It was the immediate goal of the work reported here to develop a new acoustic lining for the 9- by 15-Foot Wind Tunnel test section. The objective was to extend the low frequency measurement range down to about 250 Hz from 1 kHz for noise measurements of advanced propellers at takeoff and approach conditions. To achieve this goal, the acoustic characteristics of uniform low density and layered variable density bulk absorber linings were investigated.

A longer range goal is to make improvements on a uniform bulk absorber model and to develop a model for a bulk absorber lining having a density which increases with depth. The variable density may either be in layers or in a wedge structure. This type of lining is being considered for use in large wind tunnels, such as the proposed Lewis Altitude Wind Tunnel (4), to allow acoustic measurements to be made down to very low frequencies.

This paper considers only the use of a bulk absorber called Kevlar in the acoustic linings. Kevlar is a fibrous bulk material that is manufactured in a blanket form with the fibers primarily aligned in a two-dimensional plane. This material can withstand the severe environmental conditions which may occur in a wind tunnel test section without breaking down and dispersing in the flow. Kevlar has also been the subject of work by Hersh and Walker (5) and by Lambert (6) in analytically modeling the acoustic characteristics of a bulk absorber. The model developed by Hersh and Walker has been used to predict the optimum impedance of a uniform density absorber at a given thickness and frequency. Measurements taken on the uniform density configurations in this study were compared to their theory. The densities considered ranged from 7.4 kg/m^3 (0.46 lb/ft^3) to 18.4 kg/m^3 (1.15 lb/ft^3).

In this report, the experimental apparatus involving the two microphone transfer function method of measuring acoustic impendance is first described. Then, the measured results are given in terms of the specific acoustic impendances and the normal incidence absorption coefficients as a function of frequency. Uniform density configurations are discussed for a fixed 30.5-cm (12-in) depth and varying density. Layered variable density tests are discussed for two and four layer configurations. Changes in the density gradient are considered for the two layer configuration by changing the second layer density and holding the first layer density constant. In the four layer configuration, the first layer density is held constant and the other three layers are varied in order to change the density gradient. For both configurations, the effect of changing only the first layer density is considered.

NOMENCLATURE

c	speed of sound in air
f	frequency
H_{12}	transfer function between microphones 1 and 2
H°_{12}	transfer function between microphones 1 and 2, "original position"
H^{s}_{12}	transfer function between microphones 1 and 2, "switched position"
j	$\sqrt{-1}$
k	wavenumber = $2\pi f/c$
ℓ	distance between sample face and microphone 1
R_1	complex reflection coefficient at microphone 1
s	microphone separation distance
Z	complex acoustic impedance
α_n	normal absorption coefficient
ρ	density of air

EXPERIMENTAL APPARATUS AND CALCULATIONS

A tube or duct is usually used for the normal incidence measurements of acoustic impedance and absorption coefficient. From the many methods available to carry out these measurements, the technique chosen here is the two microphone transfer function method (7). The following paragraphs describe the apparatus and the procedure involved.

Acoustic Duct

An acoustic duct, originally described in Ref. (8), was modified for use as an impendance tube. As shown in Fig. 1, one end was closed off by a steel plate and an acoustic horn was attached to the other end. The rectangular duct had inside dimensions of 3.81 by 10.16 cm (1.5 by 4 in). The plane wave cutoff for these dimensions was 1700 Hz which set the upper frequency limit of the measurement. The top of the duct was made of removable plate sections to allow access to the interior. Material samples were placed inside through these openings and microphones were inserted through a modified plate section.

Electronics

Figure 1 also shows blocks designating the electronics involved in the setup. Broadband noise was generated and amplified to drive a 120 W compression driver acoustically coupled to the duct. Two microphones picked up acoustic signals and sent their electrical outputs to a two channel FFT analyzer which calculated the transfer function between the two signals. A computer was programmed to calculate the impedances and the absorption coefficients from the transfer function data.

Microphone Placement

Two 0.64-cm (0.25-in) condenser microphones were mounted in one of the duct plates with a 3.81-cm (1.5-in) separation. This separation distance determined frequencies that would give indeterminate results. These frequencies could occur whenever an integer number of half wavelengths equaled the separation distance. The first frequency corresponding to the above separation distance was 4.5 kHz. This was well above the plane wave cutoff of the duct and was not considered in the measurements. In addition to separation placement, these microphones were placed far enough from the sample so that reflected waves were planar; yet, close enough so that any duct attenuation was minimal and could be ignored. Data were taken with the distance from the sample face to microphone 1 equal to 23.5 cm (9.25 in).

Calculations

The two microphone transfer function method is based on the work of Chung and Blaser (7). Assuming that the microphones measure the sound at a point, their outputs are used to estimate the transfer function $H_{12}(f)$ between those two points in the duct. Once the transfer function is known, the complex reflection coefficient at microphone location 1 is given by:

$$R_1(f) = \frac{H_{12}(f) - e^{-jks}}{e^{jks} - H_{12}(f)} .$$

Then, the acoustic impedance at the sample face is calculated from the standard transmission line relationship between impedance and reflection coefficient.

$$\frac{Z}{\rho c}(f) = \frac{1 + R_1(f)e^{j2k\ell}}{1 - R_1(f)e^{j2k\ell}} .$$

Finally, the normal absorption coefficient is simply:

$$\alpha_n(f) = 1 - |R_1(f)|^2 .$$

The above calculations assume that the gain and phase relationship between microphones 1 and 2 are due only to the acoustic field. This was not the case. Gain and phase differences must be accounted for between the two microphone-amplifier systems. According to Ref. (7), this was done by switching the two microphone

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systems and repeating the measurement. This lead to the additional calculation:

$$H_{12}(f) = \left[H_{12}^{\circ}(f) * H_{12}^{s}(f)\right]^{1/2} .$$

Therefore, the compensation for the gain and phase differences between the two microphone-amplifier systems was accomplished through the complex multiplication and complex square root calculations.

TEST SAMPLES

The Kevlar samples were taken from a low density blanket where the fibers were layered and lightly needled. When ordered from the manufacturer, the Kevlar blanket was specified to have an average density of 6.4 kg/m^3 (0.4 lb/ft^3) with a nominal thickness of 2.54 cm (1 in). Thirty pieces of the material, cut to fit the 3.81- by 10.16-cm (1.5- by 4-in) duct were weighed to determine their densities. Based on the nominal 2.54-cm (1-in) thickness, the average density was 7.34±0.77 kg/m^3 (0.46±0.05 lb/ft^3). Therefore, the uncompressed Kevlar blanket was assumed to have the nominal density of 7.34 kg/m^3 (0.46 lb/ft^3) in a 2.54-cm (1-in) thickness and when compressed, the density was assumed to increase proportionally.

Uniform Density Configuration

The samples for the uniform density configuration were placed in layers starting against the hardwall duct termination and continuing to a depth of 30.5 cm (12 in). They were held in place by a 40 percent open area perforated plate. Before replacing the top plate, the samples were adjusted such that the entire depth of material appeared to have about the same compression. Uniform density configurations were tested for densities of 7.4, 11.1, 14.7, and 18.4 kg/m^3 (0.46, 0.69, 0.92, and 1.15 lb/ft^3).

Variable Density Configurations

Layered variable density tests were conducted on the two configurations shown in Fig. 2. One configuration had two layers each 15.24-cm (6-in) thick and the other configuration had four layers each 7.62-cm (3-in) thick. The layers were separated and their material held in place by a 40 percent open area perforated plate. Each layer had a uniform density. The layers were arranged such that there were step increases in density proceeding from the treatment face to the hardwall. The configurations tested for both two and four layers are listed in Table I.

DISCUSSION OF RESULTS

Effects of the Perforated Plate

Bulk absorbers need to have some means of keeping the material in place. Wire screens and fiberglass fabric which tend to be transparent to the incident sound have been used for this purpose. Thus, the acoustical properties of the absorber are mainly represented by the material. When the environment is more demanding, something more rugged than screen is necessary to cover the material. In a wind tunnel, the material must be protected from the conditions created by the air flow. A perforated plate with a 40 percent open area is considered to be a good covering to hold the absorber in place because it has enough open area to allow the sound to penetrate into the material and it has the structural integrity to hold up under flow conditions. Since the absorptive linings considered here were for potential use in a wind tunnel test section, testing of the lining included a perforated plate to hold the material in place.

Groeneweg (9) conducted an analysis of the acoustical behavior of perforated plates and Guess (10) elaborated on the theory. Using their analysis, a 40 percent open area plate, 0.16-cm (0.06-in) thick, and with holes 0.32-cm (0.13-in) in diameter had a calculated specific acoustic resistance of 0.014 at 1500 kHz. The resistance decreased for lower frequencies at a rate proportional to the square root of the frequency. Thus, the resistance of the perforated plate was small and could be ignored compared to the material's specific acoustic resistance, which was expected to be on the order of 1.0.

The perforated plate specific acoustic reactance was larger than the resistance. As shown in Fig. 3, the measured reactance had levels similar in magnitude to the theory and approximately following the theoretical increase in reactance with frequency. The predicted reactance increased faster than the measured reactance at the highest frequency. The perforated plate reactance could be a significant factor when the material reactance is small. This will be considered in the discussion on uniform density bulk absorbers comparing measured values to the theoretical model.

Uniform Density Configurations

The measured specific acoustic impedances for the 30.5-cm (12-in) thick uniform density bulk absorber configurations are shown in Fig. 4. Comparisons were made with predicted impedances based on the model of Hersh and Walker (5). There was, in general, good agreement at low frequencies. Above about 300 Hz, larger deviations from the theory were observed. However, there were some agreements in trends such as the decrease in the oscillatory behavior of the resistance and reactance curves at higher densities. This behavior was due to the acoustic resonances that existed in the treatment sample. The theoretical resistance curve for the lowest density of 7.4 kg/m^3 (0.46 lb/ft^3) showed the first peak at about 530 Hz. Measured resistance peaked at about 80 Hz lower than predicted. This deviation could be seen throughout the comparison between theoretical and measured resistance and it was also noticeable in the reactance curves. As the frequency increased above 600 Hz, the resonance levels decreased for the measured impedance compared to the theoretical impedance for the lowest density. As the density increased, both theoretical and measured impedances decreased in the levels of the resonances as they were damped out with the increased density. There was good agreement at low frequencies, but deviations were seen at frequencies above 300 Hz.

Another trend was that both the theoretical and the measured resistance and reactance increased in absolute value at higher densities. The resistance at low frequencies increased from about 0.7 at 7.4 kg/m^3 (0.46 lb/ft^3) to about 1.62 at 18.4 kg/m^3 (1.15 lb/ft^3). As the frequency increased, the resistance for the four densities tended to converge toward 1.0. The reactance also moved further away from zero at low frequencies when the density increased. The lowest density reactance was -0.8 and the highest density reactance was -1.2. For the higher frequencies, the reactance converged toward 0.0.

The model of Hersh and Walker was derived based on the idealization that the fibers were placed parallel and normal to the incident sound direction. There were also various constants empirically derived from measurements of material pressure drops and propagation constants. From data collected on materials with higher densities than measured in this study, correlations were made to determine the constants. As used for comparison here, the model included both the normal and the parallel fiber parameters for the viscous loss term. The applicability of this form of the model was unexpected since the Kevlar blanket was thought to be dominated by fibers normal to the incident sound direction. Good agreement was seen between measured and predicted impedances using the model with both parallel and normal fiber parameters. Differences could be due to the perforated plate. The reactance of the perforated plate was shown to be large enough to have some effect, but its resistance was too small to account for the differences seen in Fig. 4. Therefore, it is suggested that modifications in the model are necessary to reconcile the differences between the measured and predicted impedance of uniform, low density bulk absorbers. The exact nature of these modifications are the subject of future studies.

Since the absorption coefficient is calculated from the impedance, the model also predicts the material's absorption coefficient. Comparison between measurement and prediction is shown in Fig. 5. As expected from the impedance, there was good agreement at low frequencies and larger deviations from the model above 300 Hz. The increase in the absolute values of the resistance and the reactance resulted in a general decrease in the absorption coefficient. As can be seen in Fig. 5, the rolloff in the absorption coefficient curve at higher densities started at higher frequencies.

Layered Variable Density Configurations

It was desired to improve on the measured absorption coefficient curves of Fig. 5. The high absorption at 250 Hz for the lowest density was followed at increasing frequencies by a dip in the curve. The attempt to damp out the resonance that caused this dip with higher density treatment resulted in a loss of low frequency absorption. The higher densities were more resistant to the sound entering the material. As discussed in Ref. (11), if the first layers of material have a low resistance to the sound entering due to a low density, then that sound can be further attenuated by material with higher densities inside the treatment.

Two Layer Configurations

In the two layer configuration, a way to change the density gradient was to vary the second layer density while holding the first layer density constant. Figure 6 shows the measured specific acoustic impedances for Configurations A, B, and C. (See Table I for density descriptions and note the bar charts on the figures for qualitative comparisons.) The first layer was held constant at 7.4 kg/m^3 (0.46 lb/ft^3) and the second layer had densities of 11.1 kg/m^3 (0.69 lb/ft^3), 14.7 kg/m^3 (0.92 lb/ft^3), and 19.7 kg/m^3 (1.23 lb/ft^3) for A, B, and C, respectively. The resistance and the reactance both showed little change in value at the low frequencies. At frequencies above 250 Hz, the level of the resonances in both the resistance and the reactance curves began to dampen out as the density of the second layer was increased from Configuration A to B to C. The impedance was little affected at the highest frequencies measured. The resistance was already close to 1.0 and the reactance was near 0.0. These were the desired values for the material's resistance and reactance since they were equivalent to those of air, the medium in which the incident sound propagates. Thus, the reflections from the material were minimized. Increasing the second layer density brought the resistance closer to 1.0 over most of the frequency range. The reactance was closer to 0.0 in the 400 to 700 Hz range, but further from 0.0 in the 200 to 400 Hz range.

The effect on material absorption is shown in the normal absorption coefficient plots of Fig. 7. Configuration A had a large dip in its curve as expected from the impedance characteristics. More damping was seen in the curves for Configurations B and C as the second layer density was increased. The increase in second layer density resulted in a smoothing of the absorption coefficient curve. Higher absorption coefficients were achieved in the 300 to 600 Hz frequency range at the expense of a small loss in absorption coefficient in the 230 to 300 Hz range. An absorptive lining with a smooth, high absorption coefficient curve was the desirable characteristic for the lining. The liner would absorb the sound almost uniformly with frequency down to the lowest frequency possible for that thickness of lining.

Varying the first layer density with the second layer density fixed resulted in the specific acoustic impedance curves shown in Fig. 8. Configurations A and D were compared first. The first layer density was increased from 7.4 kg/m^3 (0.46 lb/ft^3) to 9.8 kg/m^3 (0.61 lb/ft^3) and the second layer density was fixed at 11.1 kg/m^3 (0.69 lb/ft^3). The comparison showed a general increase in resistance across the measured frequency range. The largest increase was seen at the lowest frequencies. For the reactance, the increased first layer density resulted in a general movement of the reactance curve to larger negative values, especially below 800 Hz. As can be seen in both the resistance and the reactance curves, there was little effect on the resonances from an increase in first layer density. The second comparison was between Configurations B and E where the second layer density was fixed at 14.7 kg/m^3 (0.92 lb/ft^3). With the same first layer variation, this comparison gave the same general trends as the comparison between A and D.

The normal absorption coefficient curves for these first layer density variations are shown in Fig. 9. In going from the lower density to the higher density, the absorption coefficient decreased in the 200 to 700 Hz range without much effect on the resonance levels. Thus, the increase in the first layer density did not have the effect of damping out the resonances in the absorption coefficient curve. It kept more of the sound from entering the absorptive material in the 200 to 700 Hz range where more absorption was desired.

Four Layer Configurations

The measured results for the four layer configurations followed the same general trends as the two layer configurations. Figure 10 shows the specific acoustic impedance and Fig. 11 shows the normal absorption coefficient.

A change in density gradient was shown in comparing Configurations F and G. Both configurations had a density of 7.4 kg/m^3 (0.46 lb/ft^3) in the first layer. In subsequent layers, Configuration F had density increases of 2.4 kg/m^3 (0.15 lb/ft^3) per layer and Configuration G had double the increase at 4.9 kg/m^3 (0.30 lb/ft^3) per layer. The impedance and the absorption coefficient both showed that an increase in density gradient reduced the resonances in the data with some decrease in the low frequency absorption.

An increase in the first layer density, gave results similar to that previously described. Configuration H compared to Configuration G showed an increase in resistance especially at the low frequencies. The reactance had also, in general, moved to larger negative values after the first layer density was increased. This resulted in a decrease in absorption as seen in Fig. 11.

Configuration I had the same density gradient as Configuration G but the first layer of Configuration I started at a higher density. There was a loss in absorption for Configuration I compared to G. This was due both to a larger resistance and a more negative reactance.

In a comparison between Configuration I and Configuration H, the length of the first layer was effectively decreased. Configuration H had the same density of 12.3 kg/m^3 (0.77 lb/ft^3) in the first two layers followed by increases of 4.9 kg/m^3 (0.30 lb/ft^3) per layer. Configuration I only had one layer at 12.3 kg/m^3 (0.77 lb/ft^3) with the same subsequent step increases per layer. The data showed that the absorption was approximately the same above 400 Hz. However, the lower frequencies were affected in the change from Configuration H to Configuration I. The absorption was reduced and it was primarily due to the more negative reactance at low frequency.

Two and Four Layer Comparison

The comparison between two and four layer configurations was made using an assumed linear density gradient. Configurations B and F had the same effective linear density gradient with the same density in the first layer. Their absorption coefficient curves, shown in Figs. 7 and 11, were similar in shape. The resonance at 280 Hz for the two layer Configuration B had shifted to 320 Hz for the four layer Configuration F. The width of the resonance and the levels of the absorption coefficient at the peak and at the dip at higher frequencies were approximately the same for both configurations. The four layer configuration had less low frequency absorption than the two layer configuration. This was due to the higher resonant frequency in the four layer configuration causing the low frequency absorption to rolloff sooner than in the two layer configuration.

Increasing the density gradient dampened resonances as shown in Fig. 7 for Configurations B to C and as shown in Fig. 11 for Configurations F to G. The four layer configurations were showing greater losses in absorption coefficients at lower frequencies than the two layer configurations over a similar range of linear density gradients. The four layer configuration was a better approximation to a continuous linear density gradient than the two layer configuration. The two layer configuration would be better modeled in a functional form where the density remained relatively constant to let low frequency sound into the treatment and then increased rapidly to dampen resonances and attenuate the higher frequency sound. Therefore, it appeared less desirable to have a linear density gradient. From the results shown in Fig. 7, the two layer configuration provided a way to implement a nonlinear type of density gradient that effectively attenuated the sound down to 250 Hz for the 30.5-cm (12-in) treatment depth.

CONCLUDING REMARKS

Experiments were conducted to improve the test section absorptive lining of the NASA Lewis 9- by 15-Foot Wind Tunnel and to obtain data for the development of bulk absorber lining models. A low density bulk absorber was used to pack various configurations of uniform density, two layer variable density, and four layer variable density absorbers. Comparison between the measured results from the uniform density bulk absorber and the predictions from the model of Hersh and Walker showed good agreement in trends and general impedance values even though the model was based on data from higher density materials than those used in this study. Some modifications of the model are probably necessary to get closer agreement in the values for the specific acoustic resistance and reactance. The layered variable density data showed that improvements in the absorption coefficient were possible above those obtained for the uniform absorber. With the lowest possible density in the first layer, the density gradient was increased in order to dampen the resonances in the impedance and the absorption coefficient curves. Thus, the absorptive characteristics of a liner can be smooth and near a coefficient of 1.0 at the frequencies above the low frequency rolloff associated with the depth of the absorptive lining. For the 9- by 15-Foot Wind Tunnel, an absorptive lining was chosen for installation consisting of two layers each 17.2-cm (6.75-in) thick with the first layer having a nominal density of 6.4 kg/m^3 (0.4 lb/ft^3) and the second layer having a nominal density of 17.7 kg/m^3 (1.1 lb/ft^3). This lining was similar to Configuration C and it was designed to meet the above criterium for frequencies above 250 Hz.

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TABLE I. - TABLE OF MULTILAYERED CONFIGURATIONS[a]

(a) Two layer configurations

	Layer 1	Layer 2
A	7.4 (0.46)	11.1 (0.69)
B	7.4 (.46)	14.7 (.92)
C	7.4 (.46)	19.7 (1.23)
D	9.8 (.61)	11.1 (.69)
E	9.8 (.61)	14.7 (.92)

(b) Four layer configurations

	Layer 1	Layer 2	Layer 3	Layer 4
F	7.4 (0.46)	9.8 (0.61)	12.3 (0.77)	14.7 (0.92)
G	7.4 (.46)	12.3 (.77)	17.2 (1.07)	22.1 (1.38)
H	12.3 (.77)	12.3 (.77)	17.2 (1.07)	22.1 (1.38)
I	12.3 (.77)	17.2 (1.07)	22.1 (1.38)	27.0 (1.69)

[a]All units are in kg/m^3 (lb/ft^3).

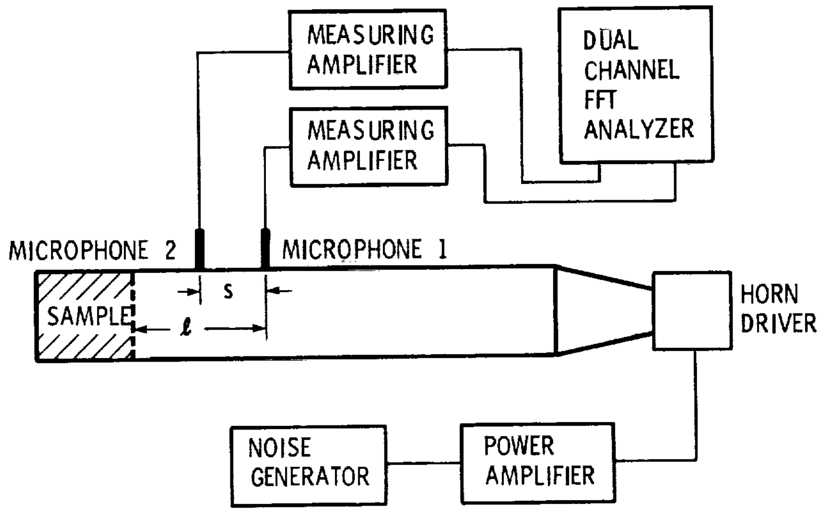
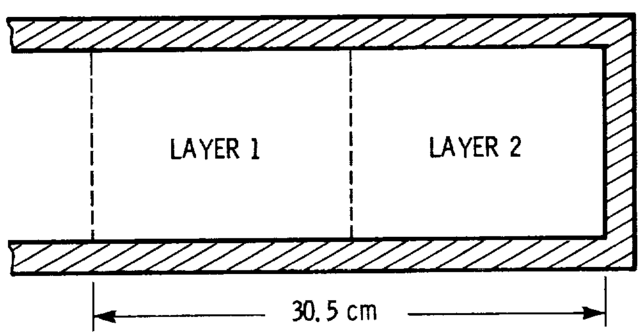
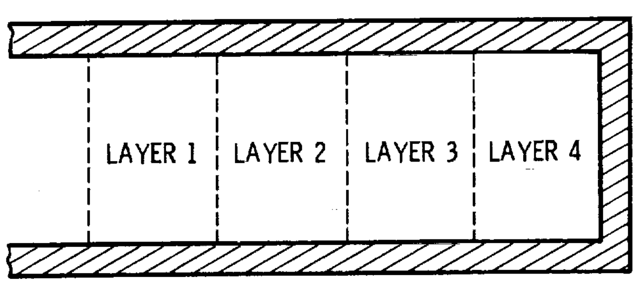


Figure 1. - Acoustic impedance tube schematic and equipment block diagram.



(a) 2 Layer configuration.



(b) 4 Layer configuration.

Figure 2. - Diagrams of multilayered test configurations.

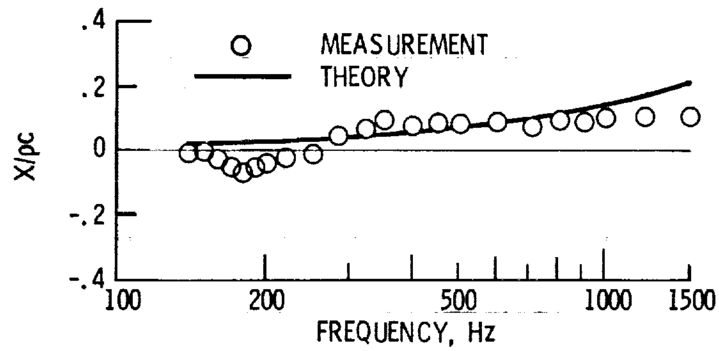


Figure 3. - Specific acoustic reactance of a 40% open perforated plate.

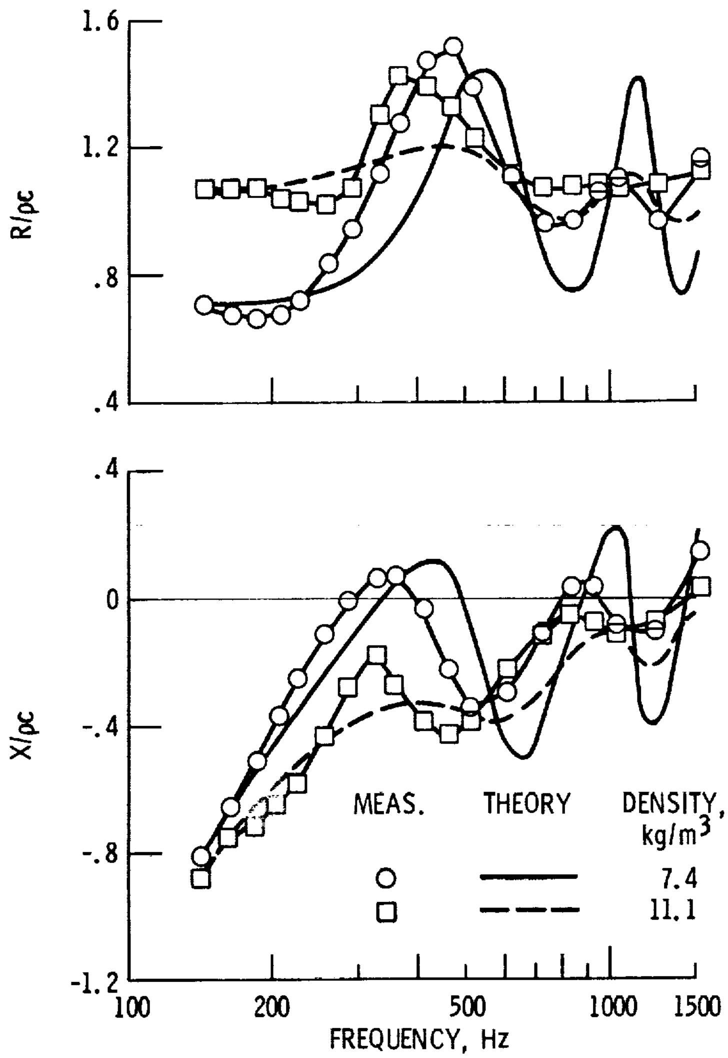


Figure 4. - Specific acoustic impedance of uniform density bulk absorbers with depth of 30.5 cm (12 in).

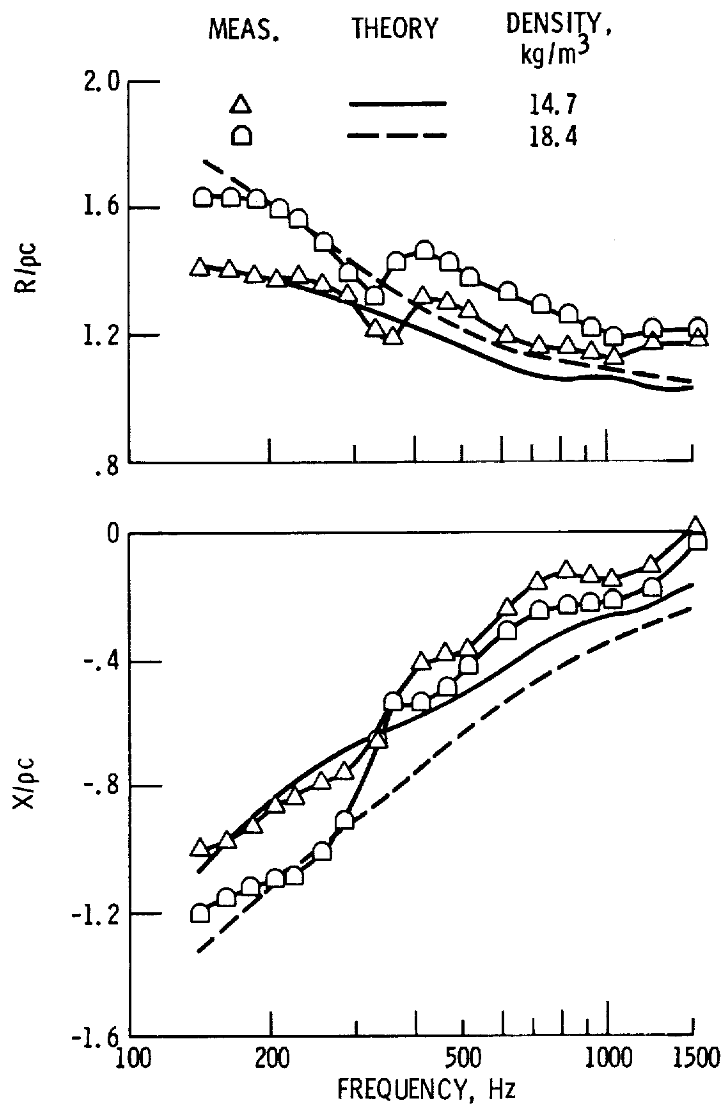


Figure 4. - Concluded.

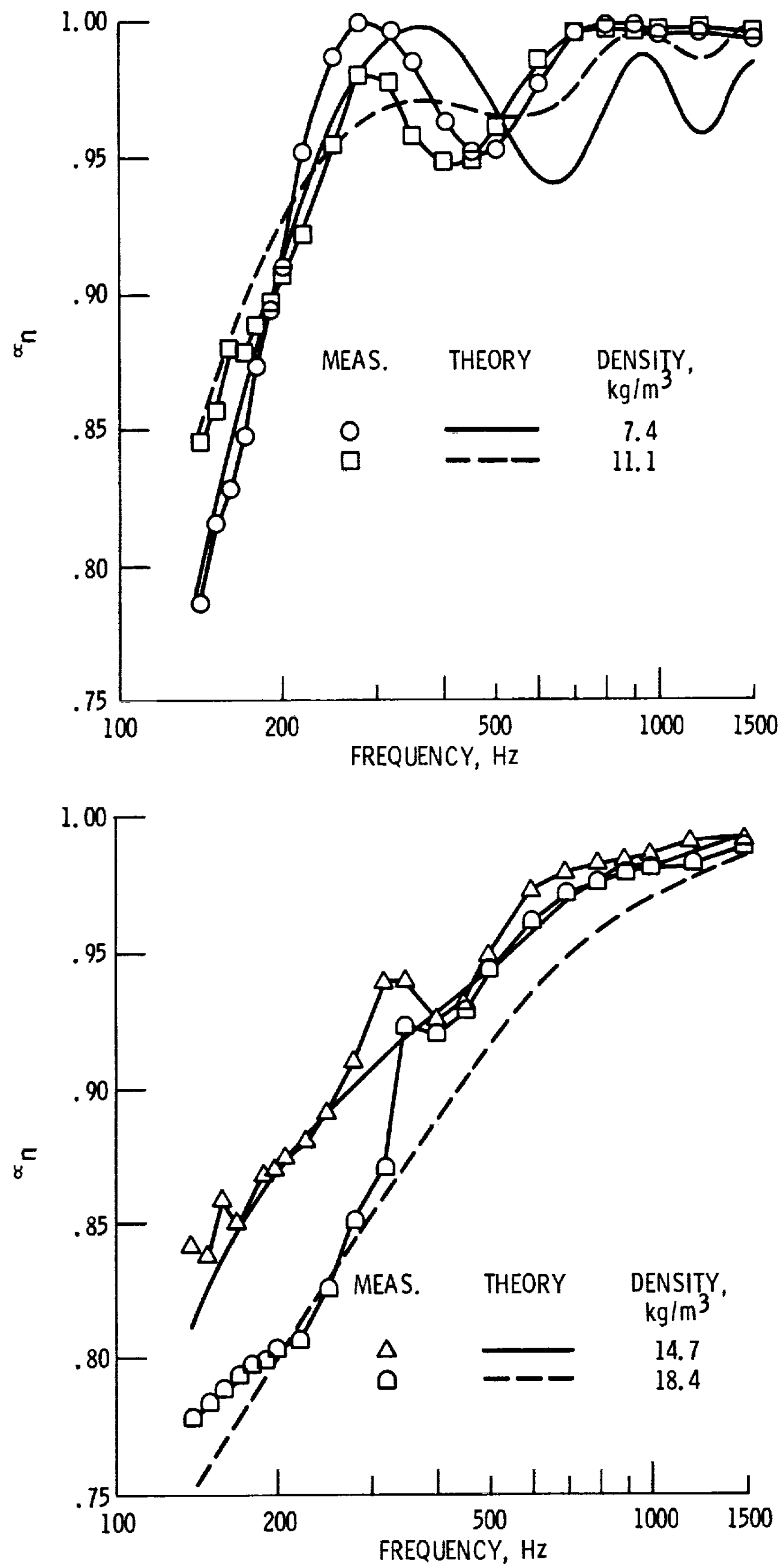


Figure 5. - Normal absorption coefficient of uniform density bulk absorbers with depth of 30.5 cm (12 in).

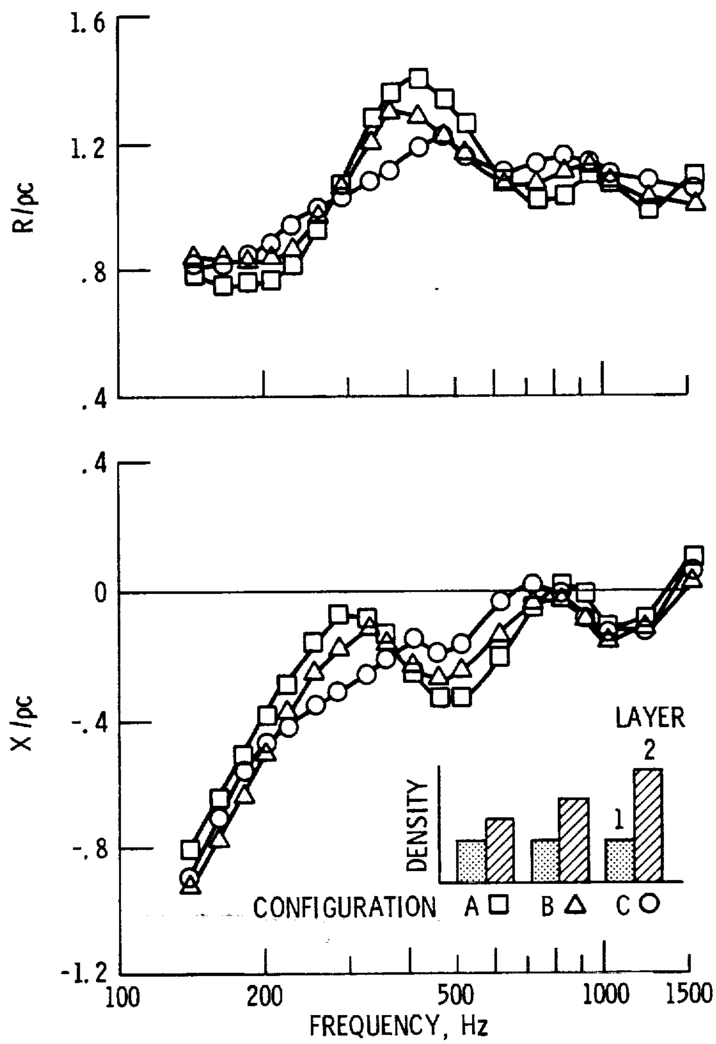


Figure 6. - Measured specific acoustic impedence of 2 layer configurations with variations in the second layer density.

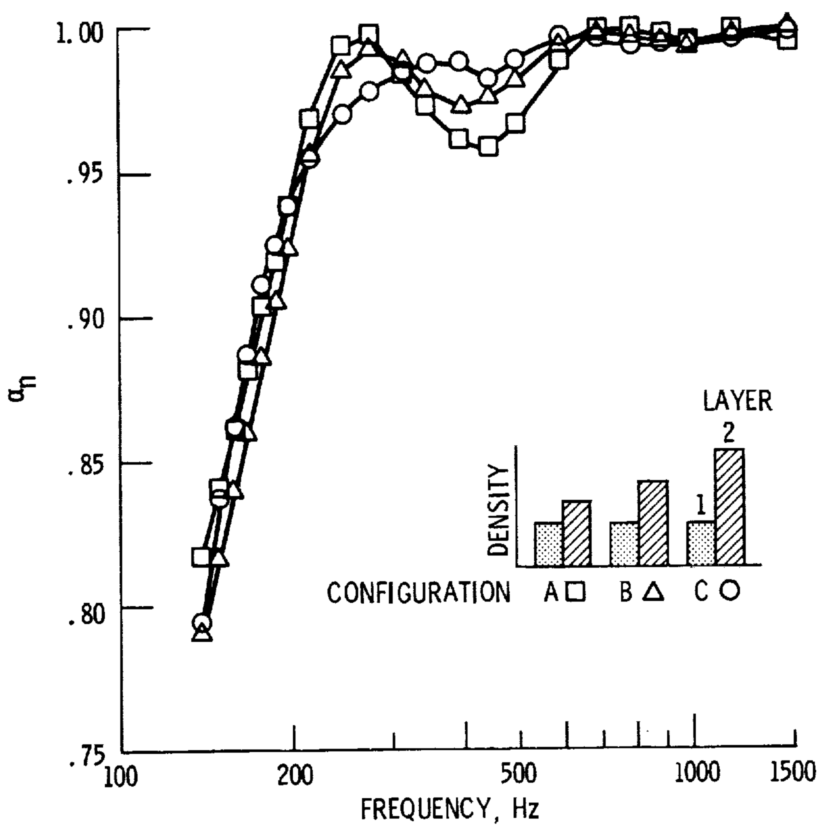


Figure 7. - Measured normal absorption coefficients of 2 layer configurations with variations in the second layer density.

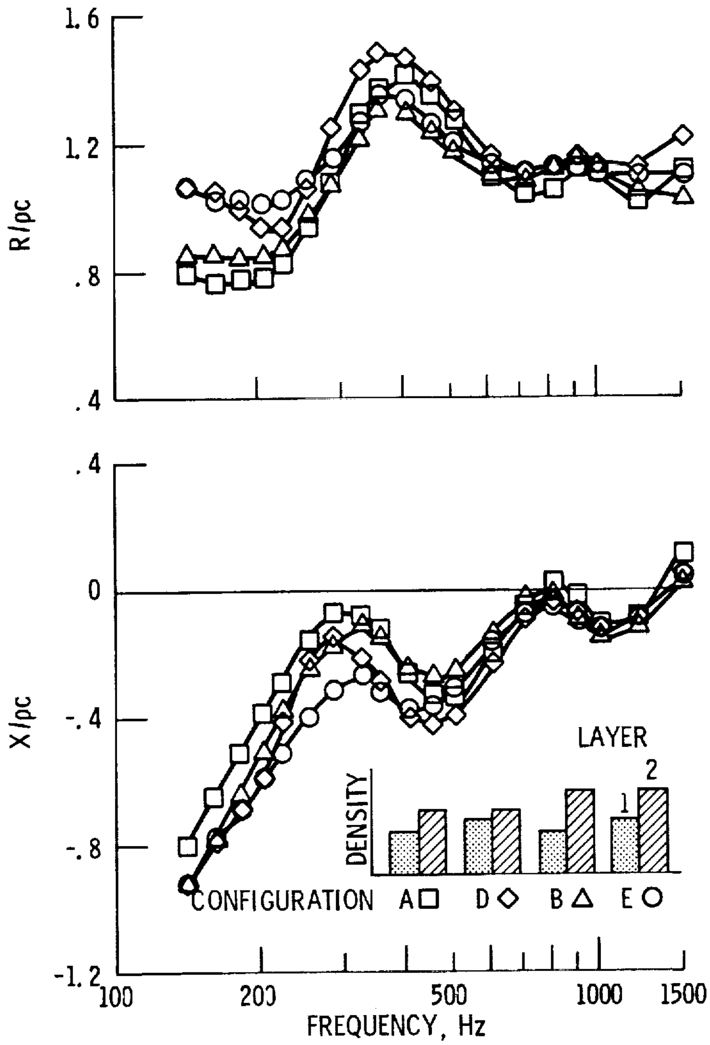


Figure 8. - Measured specific acoustic impedance of 2 layer configurations with variations in the first layer density.

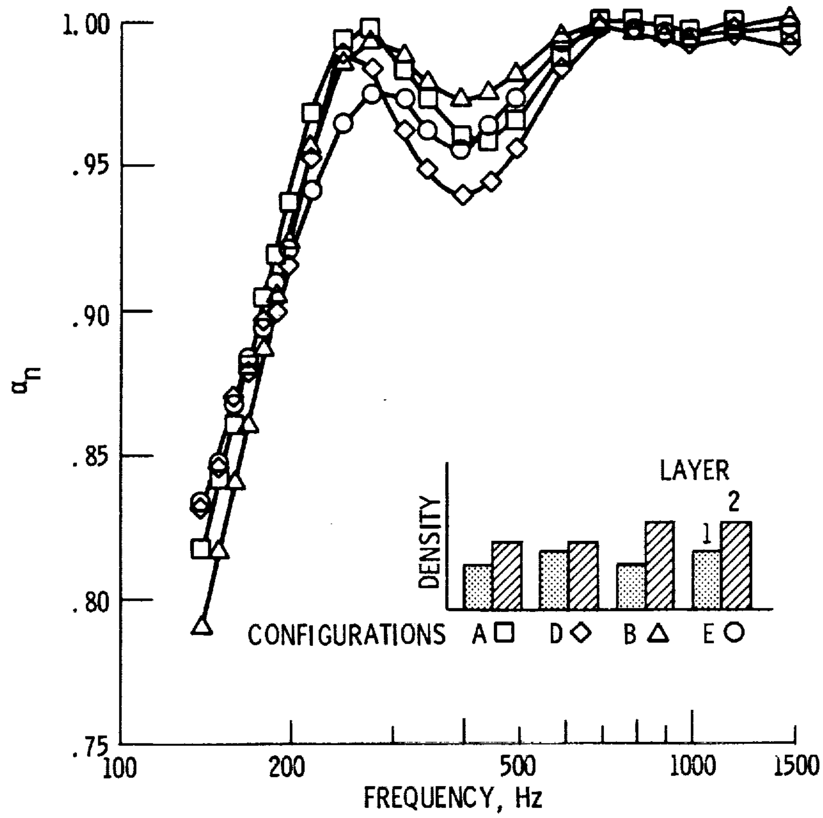


Figure 9. - Measured normal absorption coefficients of 2 layer configurations with variations in the first layer density.

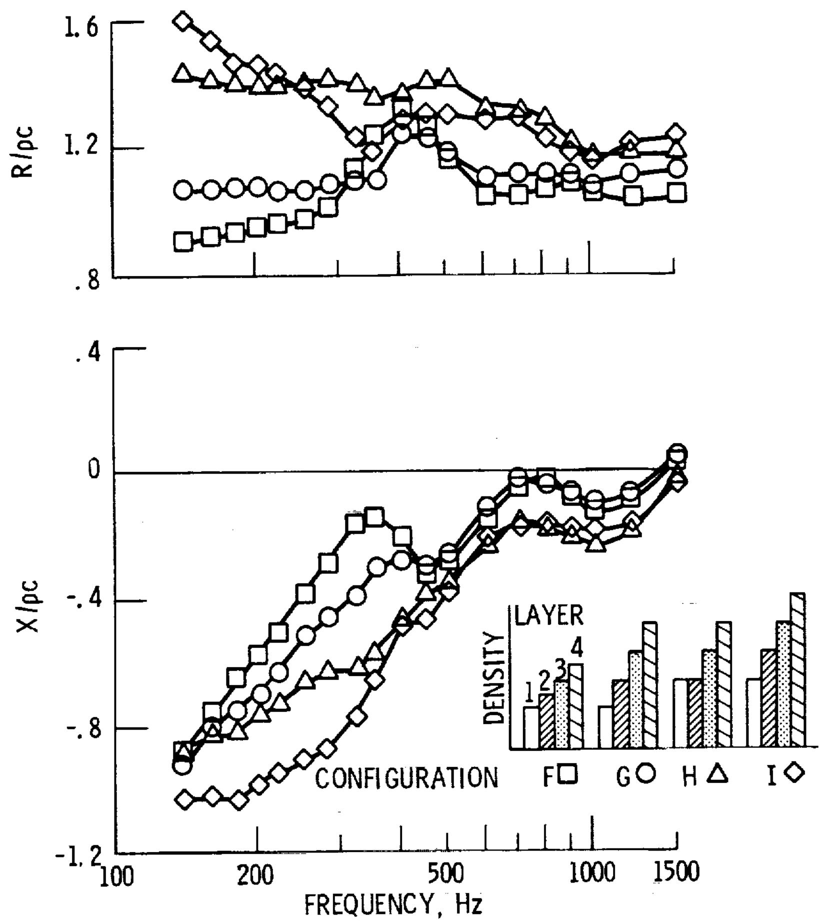


Figure 10. - Measured specific acoustics impedance of 4 layer configurations.

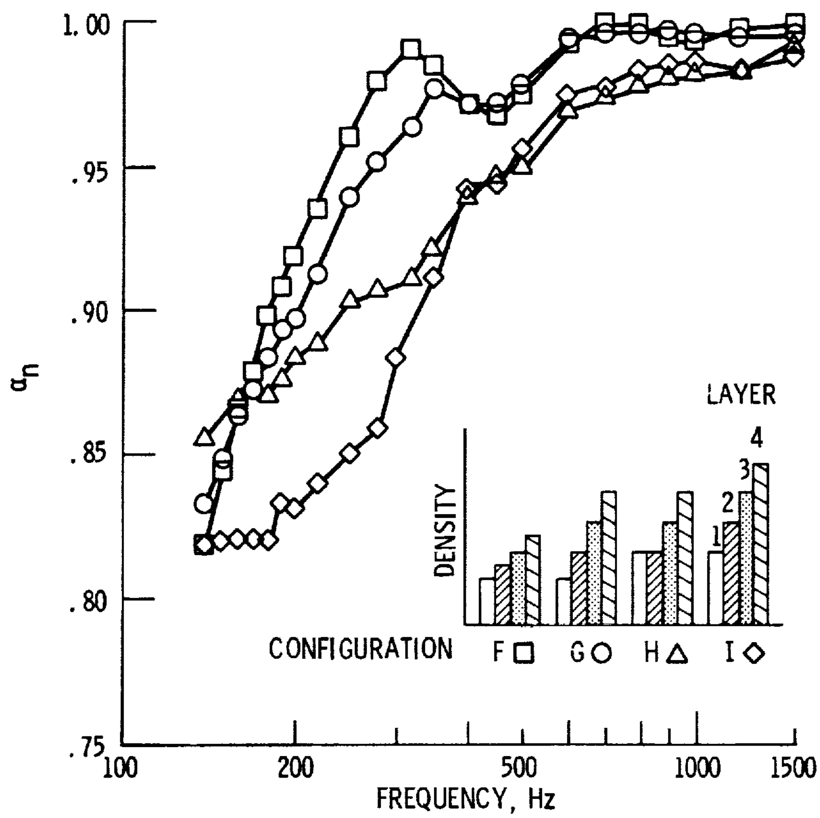


Figure 11. - Measured normal absorption coefficients of 4 layer configurations.

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15. Supplementary Notes

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16. Abstract

Experimental data were taken to determine the acoustic absorbing properties of uniform low density and layered variable density samples using a bulk absorber with a perforated plate facing to hold the material in place. In the layered variable density case, the bulk absorber was packed such that the lowest density layer began at the surface of the sample and progressed to higher density layers deeper inside. The samples were placed in a rectangular duct and measurements were taken using the two microphone method. The data were used to calculate specific acoustic impedances and normal incidence absorption coefficients. Results showed that for uniform density samples the absorption coefficient at low frequencies decreased with increasing density and resonances occurred in the absorption coefficient curve at lower densities. These results were confirmed by a model for uniform density bulk absorbers. Results from layered variable density samples showed that low frequency absorption was the highest when the lowest density possible was packed in the first layer near the exposed surface. The layers of increasing density within the sample had the effect of damping the resonances.

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