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Sound Absorption of Gypsum Board Cavity Walls*

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Although gypsum board is probably the most common interior surface treatment in use in the United States and Canada today, the sound-absorbing properties of many common wall constructions are not well known. The results of sound absorption tests performed on several gypsum board cavity walls are reported. A calculation model was developed that accurately fits the measured data. The increased low-frequency absorption is related to the mass–air–mass resonance of the wall construction. The model also includes a residual high-frequency sound absorption component related to the properties of the exposed surface of the wall. This model can now be used to conveniently predict the sound absorption of other similar gypsum board wall constructions and to design walls with some specified minimal amount of low-frequency absorption.

0 INTRODUCTION

Gypsum board is the ubiquitous interior surface treatment in modern North American buildings. While it is a very commonly used material, its sound-absoring properties are not precisely known. Sometimes its properties are dismissed as "so small it can be ignored," while on other occasions many layers of gypsum board are recommended to minimize low-frequency sound absorption. In many rooms gypsum board provides the built-in low-frequency absorption that prevents them from having an unpleasant "boomy" sound. However, it is not clear how one should design a gypsum board cavity wall to minimize or provide a known amount of low-frequency sound absorption.

This paper presents the results of sound absorption measurements of several gypsum board walls and a calculation model for estimating the properties of other similar walls. Sound absorption tests were performed in a large reverberation chamber on four basic wall constructions. Further sound absorption tests were performed on gypsum board walls with different surface treatments. The calculation model was fitted to the measurement data assuming the properties of a simple single-degree-of-freedom system to model the resonant low-frequency absorption characteristics. Further sound absorption data obtained from the reverberation time measurements associated with sound transmission loss tests were used to extend the validation of the model. The validated model can be used to predict the absorption versus frequency characteristics of a range of gypsum board cavity walls.

1 CALCULATION MODEL

The sound-absorbing characteristics of gypsum board walls vary considerably with frequency. Typically sound absorption coefficients are much larger at low frequencies than at medium and higher frequencies. These properties are generally assumed to be due to the resonant low-frequency sound absorption of the wall construction. The mass of the gypsum board surface layers and the stiffness of the contained air produce a simple mass–air–mass (MAM) resonance frequency. The MAM resonance frequency can be calculated as follows [1], [2]:

$$f_{\mathrm{MAM}} = 1900 \sqrt{\frac{m_1 + m_2}{d \cdot m_1 \cdot m_2}} \quad [\mathrm{Hz}] \tag{1}$$

where m_1 and m_2 are the surface densities of the two gypsum board layers in kilograms per square meter, d is the depth of space between the two layers in millimeters.

When the wall cavity is filled with porous sound-absorbing material, such as glass fiber batts, the constant changes from 1900 to 1362 because the behavior of the air in the cavity changes from adiabatic to isothermal [2].

The calculation model assumes that the sound absorption of the wall construction peaks at the MAM resonance frequency f_{MAM} and decreases above this fre-

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quency inversely proportional to the frequency squared. (Of course, the absorption would also be expected to decrease below the MAM resonance frequency. However, it is usually not possible to make accurate absorption measurements at these very low frequencies.) The model further assumes that the high-frequency sound absorption has some limiting small value due to the properties of the exposed surface of the gypsum board. This would be modified by paint or other surface treatments. With these assumptions the form of the model of sound absorption versus frequency is

$$\alpha(f) = \alpha_{\mathrm{MAM}} \left(\frac{f_{\mathrm{MAM}}}{f}\right)^2 + \alpha_s \tag{2}$$

where α_{MAM} is the maximum absorption at the MAM resonance frequency, α_s is the residual high-frequency surface absorption, and f is frequency. The values of α_{MAM} and α_s were determined by fitting Eq. (2) to the measured data as will be discussed. The MAM resonance frequency f_{MAM} is calculated using Eq. (1).

2 TEST PROCEDURES

Sound absorption measurements were made in a 250-m^3 reverberation chamber according to the ASTM C423 standard [3]. The chamber includes several fixed diffusing panels as well as a large rotating vane to ensure diffuse conditions. The measurement frequency range was extended down to 80 Hz to better describe the low-frequency properties of the walls. However, the measurement uncertainty of the lowest frequency results is quite large. The tests were conducted using four independent pink noise sources and measuring ten repeats of sound decays at nine different microphone positions. The tests are completely computer controlled and use a Norwegian Electronics type 830 one-third-octave real-time analyzer for data acquisition.

The large reverberation chamber is part of a wall transmission loss suite, and the test walls were built in the wall opening between the two reverberation chambers. The dimensions of the opening and the test walls are 2.44 by 3.05 m. The test wall was positioned so that its surface facing into the large reverberation chamber was as close as possible to being flush with the reverberation chamber interior surface. A massive lead-loaded door could be closed across the test wall for measurement of the "no-sample" conditions in the chamber.

Some further sound absorption data were obtained from previous sound transmission loss tests of several walls according to the ASTM E90 procedure. Transmission loss tests include reverberation time measurements in the receiving room, which was the same large reverberation chamber used in the absorption tests. These reverberation time data were used to estimate the sound absorption of the walls. Using the Sabine reverberation time equation, the total sound absorption in the large reverberation chamber was calculated from the measured reverberation times. The sound absorption of the no-sample case was then subtracted and the result corrected for differences in air absorption. Reverberation times with a painted concrete block wall in place were used as the no-sample case.

It was not always possible to determine the absorbing characteristics of the gypsum board walls accurately. Frequently the high-frequency absorption was much greater than occurs normally for gypsum board. Errors occurred because many wall constructions included the addition of other materials that changed the total absorption in the reverberation chamber by an unknown amount. (For example, flanking strips that include porous absorbing material are added to reduce sound transmission via the frame in which the test walls are mounted.) Also, in the sound transmission loss tests the walls were usually positioned midway between the two reverberation chambers and not flush with the interior surface of the large chamber. There were further possible sources of error related to attempts to correct for differences in air absorption. In spite of these problems, some sound absorption data were obtained from transmission loss tests. While they provide less accurate measurements of absorption coefficients, they allow validation of the calculation model for a wider range of wall constructions.

3 GYPSUM BOARD ON STEEL STUDS WITH EMPTY CAVITY

Sound absorption tests were performed on wall constructions using 90- and 150-mm lightweight steel studs. Fig. 1 shows the measured sound absorption coefficients and 95% confidence limits for gypsum board cavity walls on 90-mm steel studs. While the confidence limits are very small at higher frequencies (± 0.01), they increase to as much as ± 0.2 at low frequencies.

Fig. 1(a) gives results for one layer of 13-mm type-X gypsum board on each side of 90-mm lightweight steel studs and with an empty cavity. The calculated MAM resonance frequency for this case is 90 Hz. The solid line shows the calculated values using $\alpha_{\mathrm{MAM}} = 0.44$ and $\alpha_s = 0.045$ in Eq. (2). The calculated results are seen to be a good fit to the measurements above the MAM resonance frequency. The second set of measured absorption coefficients shown on this plot was obtained from a transmission loss measurement and agrees quite well with the calculated values and the absorption test results above the MAM resonance frequency.

Fig. 1(b) shows results for two layers of 13-mm type-X gypsum board on each side of 90-mm lightweight steel studs. The calculated MAM resonance frequency for this case is 63 Hz, and the calculated values were obtained using $\alpha_{\mathrm{MAM}} = 0.44$ and $\alpha_s = 0.06$. These results again show good agreement between measured and calculated values and describe well the rise in absorption at low frequencies. The results in Fig. 1 suggest that the residual high-frequency absorption is slightly greater for a double layer than for a single layer, that is, $\alpha_s = 0.006$ for a double layer and $\alpha_s = 0.045$ for a single layer. This additional absorption for the double layer may be due to friction between double layers of gypsum board.

Fig. 2 shows results similar to those of Fig. 1, but for constructions using 150-mm lightweight steel studs and again with empty cavities. The results in Fig. 2(a) are for a construction with one layer of 13-mm type-X gypsum board on each side of 150-mm steel studs. The calculated MAM resonance frequency is 69 Hz. The calculated results (solid lines) were obtained using $\alpha_{MAM} = 0.44$ and $\alpha_s = 0.045$. Fig. 2(b) shows the sound absorption coefficients of a wall consisting of two layers of 13-mm type-X gypsum board on each side of 150-mm steel studs. For this case the calculated MAM resonance frequency is 49 Hz. The calculated reslts were obtained using $\alpha_{MAM} = 0.44$ and $\alpha_s = 0.06$. Thus for the four sets of data in Figs. 1 and 2 all calculated results used $\alpha_{MAM} = 0.44$. For both stud sizes calculations were successfully performed using $\alpha_s = 0.045$ for single layers of gypsum board and $\alpha_s = 0.06$ for double layers.

Although it was not possible to perform further sound absorption tests of other gypsum board cavity walls, additional data were obtained from wall transmission loss tests for walls using 65-mm lightweight steel studs. Fig. 3 plots the sound absorption coefficients from these measurements and the corresponding calculated values. This wall construction consisted of one layer of 13-mm gypsum board on each side of 65-mm steel studs. The calculated MAM resonance frequency is 105 Hz. The calculated results (solid line) were obtained using $\alpha_{MAM} = 0.44$ and $\alpha_s = 0.045$. The dotted line shows a possible further correction to the calculated results to account for the nonporous surface of this wall. (The gypsum board was vinyl coated in this case). This is discussed further in relation to surface treatments in Section 5.

The measurements from gypsum board cavity walls using 65-, 90-, and 150-mm steel studs and with empty cavities show how the low-frequency absorption varies with the tuning of the MAM resonance, and all agree well with the calculations using Eq. (2).

4 GYPSUM BOARD ON STEEL STUDS WITH ABSORBING MATERIAL IN CAVITY

Eq. (1) predicts lower MAM resonance frequencies when the wall cavities are filled with porous sound-absorbing material. This is because the behavior of air in the cavity changes from adiabatic to isothermal when the cavity is filled with absorbing material. Lowering the resonance frequency would tend to reduce the sound absorption of the gypsum board wall at low frequencies above the MAM resonance frequency. It was unfortunately not possible to perform sound absorption tests on gypsum board walls where the cavities are filled with sound-absorbing material, but some data were obtained

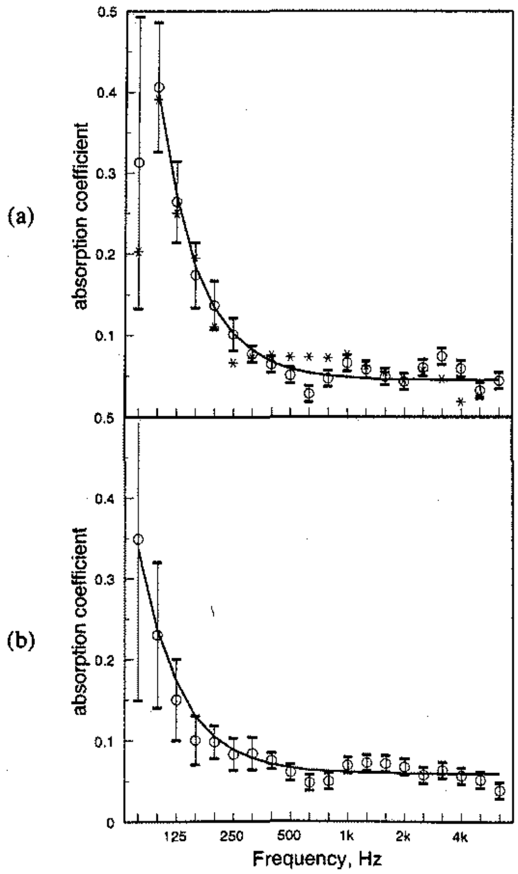

Fig. 1. Sound absorption coefficients versus one-third-octave band frequency, 13-mm gypsum board on each side of 90-mm steel studs. Open circles—measured; vertical bars—95% confidence limits; solid line—calculated. (a) One layer. (b) Two layers.

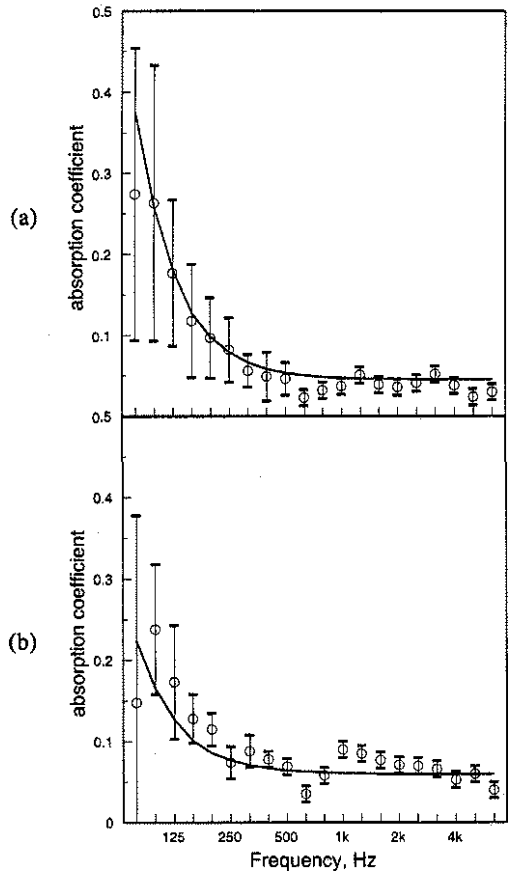

Fig. 2. Sound absorption coefficient versus one-third-octave band frequency, 13-mm gypsum board on each side of 150-mm steel studs. Open circles—measured; vertical bars—95% confidence limits; solid line—calculated. (a) One layer. (b) Two layers.

from previous transmission loss test results.

Fig. 4 shows absorption coefficients for a wall consisting of one layer of 13-mm gypsum board on each side of 90-mm lightweight steel studs and with glass fiber material in the cavity. The MAM resonance frequency was calculated to be 64 Hz for this construction. Again the solid line in Fig. 4 gives the calculated absorption coefficients using Eq. (2). These calculated results were obtained with $\alpha_{MAM} = 0.44$ and $\alpha_s = 0.06$.

One other example of an absorbant-filled cavity wall was obtained for a construction based on 65-mm lightweight steel studs. Fig. 5 illustrates the absorption coefficients for a construction of one layer of gypsum board on each side of 65-mm steel studs and with glass fiber in the cavity. The MAM resonance frequency was calculated to be 76 Hz for this construction. As for the previous results, the calculated absorption coefficients were obtained with $\alpha_{MAM} = 0.44$ and $\alpha_s = 0.06$.

These data for absorbant-filled cavities obtained from transmission loss tests show inferior agreement with the calculated values than the data from absorption tests. There is more uncertainty as to the high-frequency residual absorption α_s, and apparently some error in the MAM resonance frequency for the 65-mm wall results in Fig. 5. However, the results are probably satisfactory to validate the calculation procedure for absorbant-filled cavity walls.

5 SURFACE TREATMENTS

In actual buildings gypsum board walls almost always have some surface treatment. This may be paint, vinyl covering, or even added layers of materials such as ceramic tiles. These surface treatments are expected to reduce the high-frequency residual absorption of the gypsum board surface slightly, that is, untreated gypsum board is a little porous and will tend to absorb sound at higher frequencies. Painting or some similar surface treatment will largely eliminate this porosity and hence reduce the measured high-frequency absorption associated with the surface.

Three different gypsum board walls were tested for the effects of painting the exposed surface. In all cases two layers of oil-based paint were added to the gypsum board surface. One wall consisted of one layer of 13-mm gypsum board on each side of 90-mm lightweight steel studs. The second wall consisted of two layers of 13-mm gypsum board on each side of 150-mm lightweight steel studs. The third wall construction was a single layer of 13-mm gypsum board on only one side of 90-mm lightweight steel studs. Sound absorption tests were performed for the painted and the corresponding unpainted walls. The changes in absorption coefficients when paint was added were then calculated and are plotted in Fig. 6. While the results in the lowest frequency bands are not as reliable because of larger experimental errors, the medium and higher frequency results show a systematic trend with increasing frequency. The straight-line fit to these changes in absorption coefficients de-

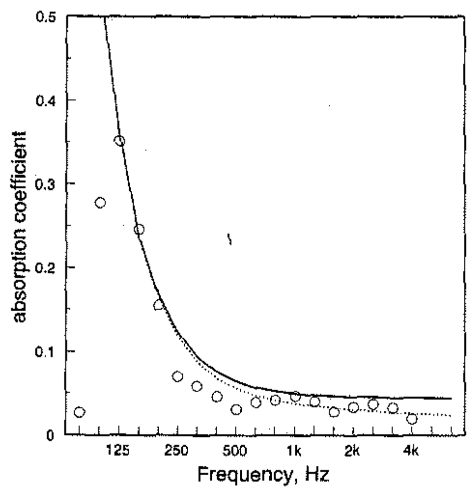

Fig. 3. Sound absorption coefficient versus one-third-octave band frequency, one layer of 13-mm gypsum board on each side of 65-mm steel studs. Open circles—measured; solid line—calculated; dotted line—calculated with correction for nonporous surface.

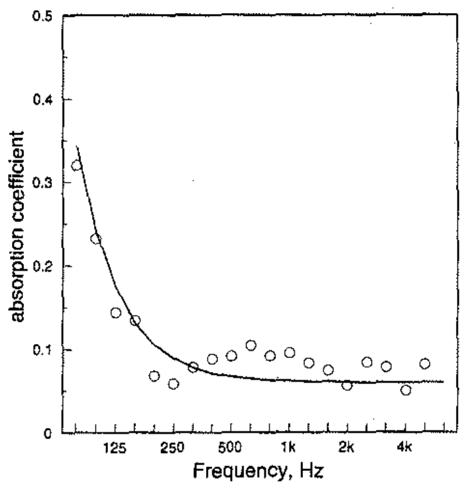

Fig. 4. Sound absorption coefficient versus one-third-octave band frequency, one layer of 13-mm gypsum board on each side of 90-mm steel studs with glass fiber insulation in cavity. Open circles—measured; solid line—calculated.

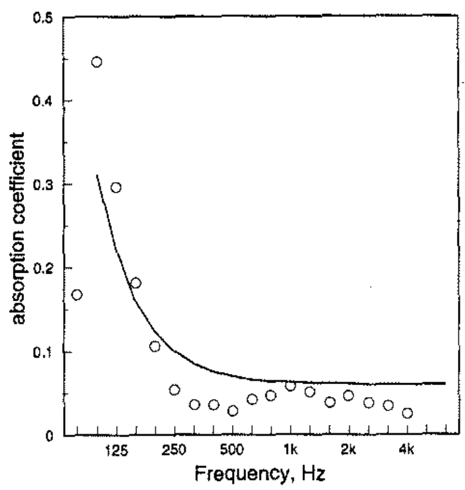

Fig. 5. Sound absorption coefficient versus one-third-octave band frequency, one layer of 13-mm gypsum board on each side of 65-mm steel studs with glass fiber insulation in cavity. Open circles—measured; solid line—calculated.

creases at 0.0036 per octave above 100 Hz. Although there is significant scatter about this line, the overall effects are small, and this relationship seems practically adequate to predict the effect of painting a gypsum board surface.

It is assumed that this same correction will be satisfactory to explain the effect of other surface treatments that eliminate the porous gypsum board surface. For example, vinyl-surfaced gypsum board is expected to have similar properties to painted gypsum board. Accordingly Fig. 3 includes a second calculated result (dotted line) that adds the expected effect of a nonporous surface treatment to the calculation of Eq. (2). That is, the absorption coefficients calculated from Eq. (2) are reduced a further 0.0036 per octave above 100 Hz. The correction is quite small and is only larger than the measurement confidence limits at higher frequencies. It does seem to improve the prediction of the absorbing properties of gypsum board walls with nonporous surface treatments.

As a further example of a surface treatment, heavy quarry tiles were added to a wall to demonstrate the possible improvements in terms of decreased sound absorption coefficients. It was expected that the added weight of the tiles would lower the MAM resonance frequency and hence reduce low-frequency absorption above this frequency and that the nonporous surface of the tiles would also reduce the high-frequency absorption of the wall. The wall construction consisted of two layers of 13-mm gypsum board on each side of 150-mm steel studs with an empty cavity. The quarry tiles were approximately 13 mm thick and had a surface density of 28 kg/m^2. The MAM resonance frequency for this construction was calculated to be 41 Hz. Calculated absorption coefficients were obtained using $\alpha_{MAM} = 0.44$ and $\alpha_s = 0.06$, as for other cases with double layers of gypsum board. The calculations were further modified by adding the -0.0036 per octave correction from Fig. 6 for nonporous surfaces. Fig. 7 compares measured absorption coefficients with calculated values for this construction. Measured and calculated absorption coefficients agree well, and these results validate both the calculations based on Eq. (2) and the nonporous surface correction.

6 SINGLE LAYER OF GYPSUM BOARD

In some cases a single layer of gypsum board may exist without a second layer on the other side of the supporting studs. For example, many gypsum board ceilings would approximate this case. Two sets of measurements of single gypsum board layers were made, and the results are shown in Fig. 8. The absorption coefficients were obtained from sound absorption tests of single layers of 13-mm type-X gypsum board on one side of 90-mm and 150-mm lightweight steel studs. The two wall constructions led to almost identical results, and one must conclude that the different stud sizes have no effect.

Some further tests were performed to determine the cause of the slightly increased absorption at lower fre-

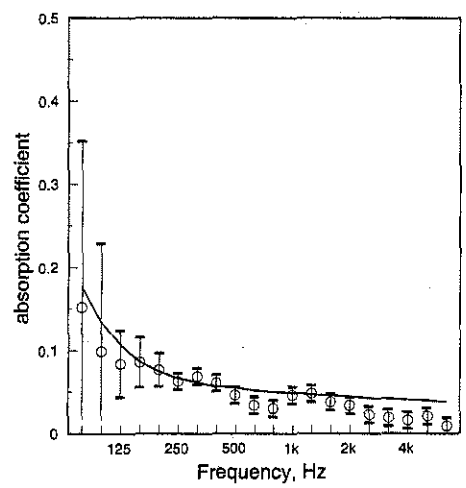

Fig. 7. Sound absorption coefficients versus one-third-octave band frequency, two layers of 13-mm gypsum board on each side of 150-mm steel studs with quarry tiles on exposed surface. Open circles—measured; solid line—calculated.

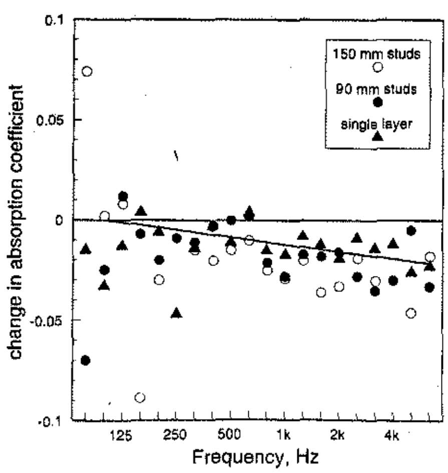

Fig. 6. Change in sound absorption coefficients versus one-third-octave band frequency because of paint added to exposed gypsum board surface.

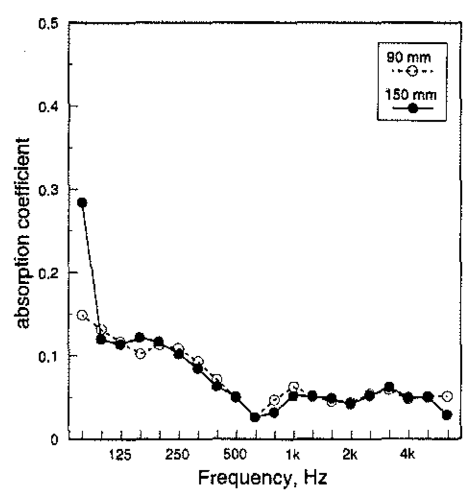

Fig. 8. Measured sound absorption coefficients versus one-third-octave band frequency for one layer of 13-mm gypsum board on one side of 90- and 150-mm steel studs.

quencies for the two results in Fig. 8. In one test a large amount of sound-absorbing material was added to the reverberation chamber behind the test wall. Because the transmission loss of a single layer of gypsum board is quite small at lower frequencies, it was thought that the reverberation of the backing chamber might influence the results. The addition of the absorption material to the backing chamber reduced the sound absorption in the 100- and 125-Hz one-third-octave bands by a small amount. A second test was performed after removing the supporting steel studs from the construction. The gypsum board panels were held together with aluminum tape and supported only at the periphery. Removing the supporting studs reduced the sound absorption coefficients in the one-third-octave bands between 200 and 400 Hz by a small amount. Thus much of the measured low-frequency absorption for a wall consisting of a single layer of gypsum board on steel studs is due to the vibrational properties of the construction and was only slightly influenced by the measurement technique.

7 DESIGNING FOR MINIMAL LOW-FREQUENCY ABSORPTION

The procedures used to calculate the sound absorption of gypsum board walls have been shown to agree well with a variety of measured results for walls built on lightweight steel studs. It therefore seems reasonable to base a design procedure for predicting the sound absorption of these types of walls on this same calculation method. Where low-frequency absorption is needed at a particular frequency, one could use a wall construction with an appropriately tuned MAM resonance frequency. Where it is desired to design for some particular reduced low-frequency absorption, one could use the complete calculation procedure to predict the absorption coefficients as a function of frequency for the desired construction.

To estimate the complete absorption characteristics of a gypsum board wall, one must first calculate the MAM resonance frequency using Eq. (1). As examples of this calculation, the calculated MAM resonance frequencies have been given in this paper for each of the measured test constructions. The absorption coefficients versus frequency characteristics can then be calculated using Eq. (2). Values of the parameters α_{MAM} and α_s have been determined from the measurements reported in this paper. The value of $\alpha_{MAM} = 0.44$ was found to be acceptable for all constructions. Two values of α_s were used. For single layers without a surface treatment a value of $\alpha_s = 0.045$ was found to be suitable. For double layers of untreated gypsum board and for constructions with absorbing material in the cavity a value of $\alpha_s = 0.06$ was used. Where the exposed surface of the gypsum board is treated with some nonporous material, a further correction of -0.0036 per octave above 100 Hz should also be added.

Fig. 9 illustrates example calculations for walls built on 90-mm lightweight steel studs. The gradual reduction in low-frequency absorption is seen as more layers of gypsum board are added and the MAM resonance frequency is lowered. Thus while a single layer of gypsum board on each side of the 90-mm studs would lead to almost 40% absorption at 100 Hz, four layers would reduce this to about 13%. However, this figure also illustrates that the same reduced absorption could be achieved using only two layers of gypsum board on each side of the studs with an absorbant-filled cavity. Thus, adding sound-absorbing material in the cavity can reduce the low-frequency absorption of a gypsum board wall significantly.

As a final design aid it is useful to relate the low-frequency sound absorption to the MAM resonance frequency. One can calculate the expected 125-Hz absorption coefficient from the following equation:

$$\alpha(125) = 0.44(f_{MAM}/125)^2 + \alpha_s . \quad (3)$$

For example, an MAM resonance frequency of 100 Hz would lead to 34% absorption at 125 Hz, but a 40-Hz MAM resonance frequency would reduce the 125-Hz absorption to about 10%. After deciding on a required MAM resonance frequency, one must determine the wall construction required to produce this MAM resonance frequency. Then one can calculate the absorption characteristics using Eq. (2) and the procedures outlined in this paper, knowing that the required minimum low-frequency absorption will be achieved.

8 CONCLUSIONS

The measured sound absorption coefficients presented in this paper give accurate descriptions of the sound-absorbing properties of several gypsum board wall constructions. A simple calculation model was presented that accurately fits the measured data and is a convenient means of estimating the sound-absorbing properties of other similar gypsum board walls at frequencies above the MAM resonance frequency. The model takes into account the MAM resonance that normally determines

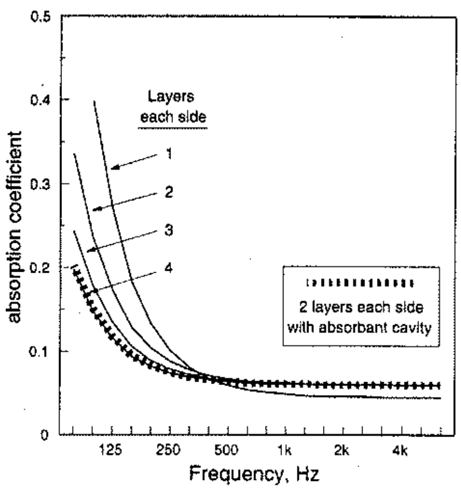

Fig. 9. Calculated absorption coefficients for various numbers of layers of 13-mm gypsum board on both sides of 90-mm steel studs. Solid lines—empty cavity; dashed line—glass fiber insulation in cavity.

the low-frequency sound absorption of gypsum board cavity walls. The model also estimates the residual high-frequency sound absorption of several types of surface treatments. The model has been validated for a range of constructions consisting of gypsum board on lightweight steel studs both with and without sound absorbing material in the cavity.

There are several possible sources of error in the measured sound absorption results. Precise measurements at low frequencies in a reverberation chamber are difficult to obtain. The increased confidence limits at lower frequencies associated with the measured values in Figs. 1 and 2 indicate the possible magnitude of this source of errors. Further small errors are possible at medium and higher frequencies due to the procedure used to obtain a no-sample case. When the heavy sliding door was opened, it hung approximately 10 mm from the reverberation chamber wall. Tests suggested that this small gap could add a small amount of absorption at medium and higher frequencies equivalent to a wall absorption coefficient of 0.01–0.03. This would tend to increase the measured medium- and high-frequency wall absorption values incorrectly. However, similar effects are possible when the heavy door was closed to cover the sample wall, which would tend to decrease the measured sound absorption coefficients. It is not possible to be sure of the net magnitude of these types of errors in the measured absorption coefficients, but they are unlikely to be greater than 0.01–0.03.

There are a number of other types of wall constructions that were not tested. Further work is suggested to determine the validity of the calculation model for these other constructions. They would include gypsum board walls built on wood studs and concrete block walls with gypsum board surfaces separated from the block by relatively small air spaces. Some construction details might also influence the sound absorption of the gypsum board walls and should be investigated. These would include the stud spacing and the type of bonding between multiple layers of gypsum board.

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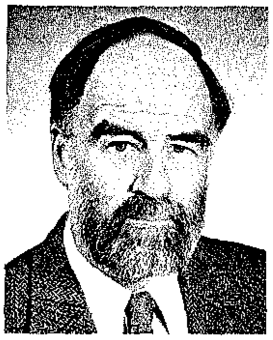
THE AUTHOR



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After teaching acoustics and noise control for several years in the Faculty of Engineering at the University of Western Ontario, he joined the National Research Council. His work has concentrated on both room acoustics and subjective studies. He has completed studies on the annoyance of various types of noises as well as measurement studies in various rooms. Most recently he has been concerned with the accuracy of various room acoustics measurements as well as the subjective importance of these quantities.