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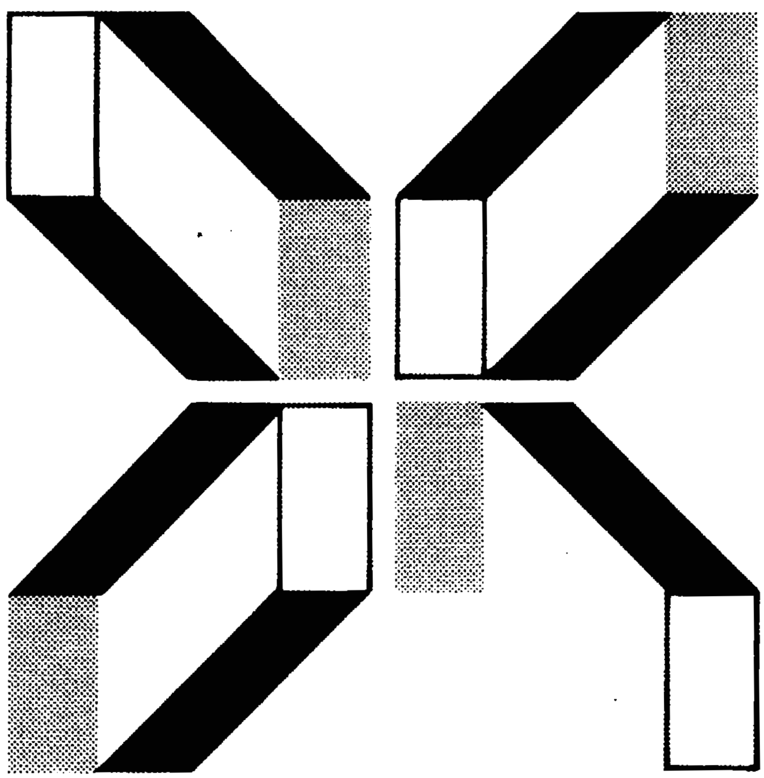
by J.S. Bradley



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INSERTION LOSS OF SUSPENDED DECORATIVE CYLINDERS

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ABSTRACT

The acoustical insertion loss of linear arrays of equally spaced suspended cylinders was measured. Insertion loss values were obtained for a varied number of cylinders, angle of incidence, and tube spacing for both solid, and expanded metal cylinders. The expanded metal cylinders were found to produce the same visual effects without the large insertion losses that the solid tubes produced.

RÉSUMÉ

Des mesures de la perte du son par insertion de rangées de tubes suspendus à égale distance ont été effectuées. Des valeurs de la perte par insertion ont été obtenues pour un nombre varié de cylindres en métal solide et déployé, d'angles d'incidence et d'espacements entre les tubes. On a observé que les cylindres en métal déployé produisaient le mêmes effets visuels que les tubes en métal solide sans toutefois entraîner d'importantes pertes par insertion.

INTRODUCTION

Various materials are sometimes suspended from ceilings in large halls and auditoria, as an architectural feature. In such cases the material is there only for visual reasons and is not intended to affect the acoustical conditions in the hall. One of the simplest of such decorative materials is a regular linear array of equally spaced cylinders. This report summarizes measurements of the insertion loss of linear arrays of suspended cylinders that were part of a larger practical study. Both solid, and open-mesh expanded metal cylinders were tested using varied numbers of cylinders, varied spacing, and varied angle of incidence. Although measurements were limited to arrays of cylinders, they give some idea as to the magnitude and frequency of effects to be expected from other suspended objects.

MEASUREMENT PROCEDURES

Two different measurement techniques were used in this study. Initial measurements were made using a 0.38 calibre blank pistol, and recording pulse responses both with and without the test array in place between the gun and the microphone. Fourier analysis of the gated pulse responses was then used to obtain insertion loss spectra for the test cylinders. Because of the low insertion loss of the expanded metal cylinders and the lack of precise repeatability of this method, these cylinders were also tested in an anechoic room using 200 steady state pure tones logarithmically spaced between 20 and 20,000 Hz, and produced by a loudspeaker.

In both cases the source was two metres in front of the centre of the array, and the receiver was one metre behind the array; the source, receiver, and the centre of the array were on the same staight line for all angles of incidence. Both tests were insertion loss measurements; the response was measured at the receiver both with and without the array of cylinders and the insertion loss spectra were determined from the differences between the two sets of sound levels. In the anechoic room tests, the spectra were obtained directly using varied frequency steady state pure tones, and thus only narrow band spectra were obtained. For the tests using the gun pulses, the gated pulses were Fourier analyzed, and both narrow band and 1/3 octave spectra were calculated.

The pistol shot responses were processed by computer. Each response was digitized and gated to remove unwanted reflections from the walls of the laboratory after displaying the full response on a computer graphics terminal. A total of 2048 points were digitized for each pulse at a sampling rate of 22,627 samples per second. This provided the required minimum of two points per cycle up to the upper corner frequency of the 8000 Hz octave band. Fourier analysis of these pulses gave narrow band spectra with a spacing between the spectral lines of 11.05 Hz. These narrow band values were converted to 1/3 octave band spectra by simply adding, on an energy basis, the spectral lines that fell within each 1/3 octave band. Although this ignores the effects of realistic 1/3 octave filter shapes, it is certainly adequate for relative comparisons between the various configurations tested. The process was more limited by the lack of precise repeatability. It was expected that by averaging the results of three repeated pulses, variations between shots could be reduced to satisfactory levels. For both the 1/3 octave and narrow band spectra, levels differed from the mean of three shots by no more than ±1.5 dB up to 4000 Hz. However when one set of three shots was completely repeated, including repositioning the source and receiver, the mean levels from each set of three shots differed from the overall mean of several such sets by up to ±2.5 dB over this same frequency range.

The cylinders tested were all 12.5 cm diameter and 2.44 m in length. Those referred to as solid were cloth-covered thick-walled cardboard tubes. The others were made of two types of expanded metal mesh. The larger mesh expanded metal had staggered holes approximately 0.9 by 0.3 cm, while the smaller mesh expanded metal had staggered holes approximately 0.3 by 0.2 cm. Viewed from one end, the cylinders showed a large proportion of open area; viewed from a perpendicular direction or from the other end, very little open area showed.

RESULTS

Solid Tubes Using Gun Source

The first tests on the solid tubes were carried out using gated pistol shot responses in a normal room. Figure 1 shows measured 1/3 octave insertion loss values with two, four, and six of the solid tubes hung with a 12.5 cm spacing between the outer surfaces of the tubes. For these 90 degree incidence tests, the basic shape of the curve is determined by the centre two tubes. As other tubes were added on either side of the centre tubes, a peak developed at 1.0 kHz and the sharp dip at 2.0 kHz was reduced in magnitude. Thus even two solid tubes could cause up to a 15 dB reduction at a particular frequency and location behind the tubes.

Figure 2 shows the effects of angle of incidence for six of the solid tubes with a 12.5 cm spacing between the tubes. At the 90 and 45 degree angles of incidence one could see through the array of cylinders, but for the 10 and 20 degree angles this was no longer possible. Although the array forms a more complete visual barrier at these smaller angles, the magnitude of 1/3 octave insertion loss values was quite similar. There is evidence that for lower frequencies, up to 500 Hz, the diffracted energy leads to increased sound levels behind the array. At these frequencies the attenuation of the array is minimal, and the path lengths involved are too small for the various diffracted paths to interfere destructively. Thus an increase due to increased diffracted energy occurs, which tends to increase as the angle of incidence decreases. The strengthening of this increase with decreasing angle of incidence was probably due to the smaller cross section of the array as seen from the source. Thus for the smaller angles of incidence this lower frequency energy was diffracted through smaller angles and travelled over shorter additional path lengths relative to the direct path. The repeatability errors of this procedure would also add some uncertainty to the magnitude of this effect.

Figure 3 shows the results of varied tube spacing for six solid tubes at 90 degree angle of incidence. As the spacing of the tubes is increased the outer tubes should have less

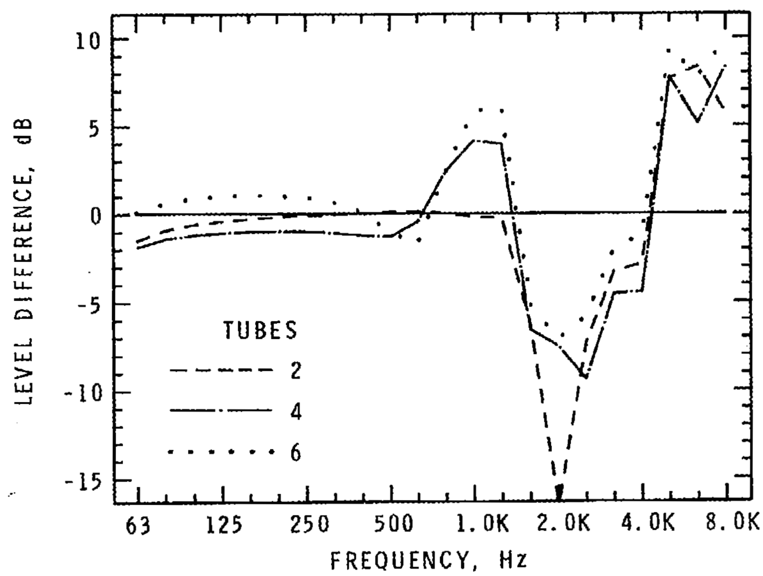

Figure 1. One-third octave band insertion loss, solid tubes, 90° incidence, 12.5 cm spacing

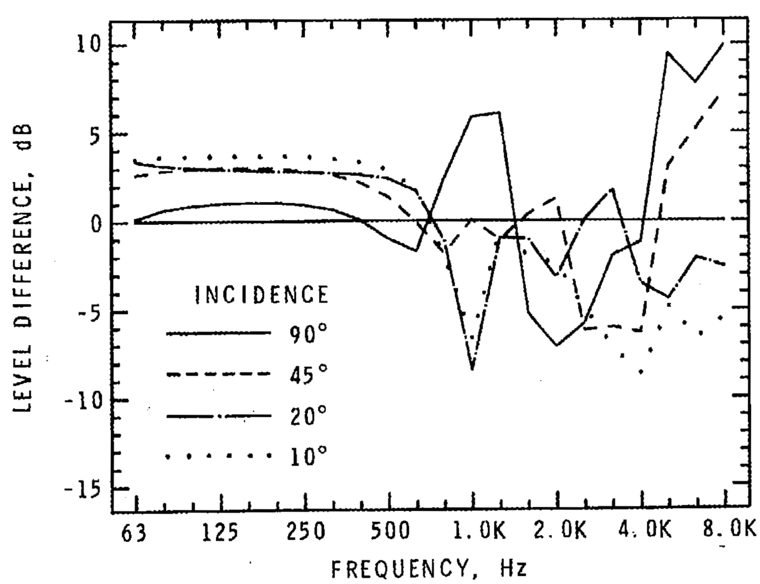

Figure 2. One-third octave band insertion loss, 6 solid tubes, 12.5 cm spacing

effect because of the larger distances and angles involved for sound diffracted from them to the receiver. This was confirmed by simulation studies discussed below. In Fig. 1, the peak at 1.0 kHz was only evident for more than two tubes. One might therefore expect this peak to be diminished or absent for cases of increased spacing. In addition, because the increased spacing would lead to longer paths from the tubes, one would expect some interference effects to move to lower frequencies. The results in Fig. 3 support this; the peak at 2.0 kHz is not evident at larger spacings and the major dip at 2.0 kHz moves to 1.0 kHz and 800 Hz as the spacing is increased to 25.0 and 37.5 cm.

Figure 4 shows the effect of tube spacing for a 20 degree angle of incidence. The lower frequency increase is least for widest spacing (37.5 cm) in agreement with the argument above, relating this to the cross section of the array as seen from the source. It is difficult to positively identify interference effects that systematically move to lower frequencies in this figure. Perhaps this is because at this angle the cross section of the array as seen from the source is quite small and the results are much more complicated due to the increased importance of the outer tubes.

Anechoic Room Tests

Figures 5 and 6 give the results of anechoic room tests on six solid tubes with 12.5 cm spacing between tubes for 90 and 20 degree angles of incidence. The sharp peak just below 200 Hz was an artifact introduced by the test equipment and should be ignored. Much more detail is evident in these results than in the previous 1/3 octave results because they are narrow band pure tone measurements. The corresponding 1/3 octave plot from Fig. 1 is included on Fig. 5 for comparison. There is reasonable agreement between the two methods, considering the difference in analysis bandwidths. The increased levels of the 1/3 octave curve at high frequencies are probably due to the increased energy that would be passed by the quite broad bandwidth higher frequency 1/3 octave filters. The 1/3 octave result from Fig. 1 (dashed line on Fig. 5), indicates the same major features of a peak at 1 kHz, with dips in the region of 2.0 kHz.

The expanded metal cylinders were first tested using the gated pulse technique, but the resulting insertion losses were much smaller than those obtained for the solid tubes, and close to the repeatability errors in that method. Further tests were carried out using pure tone insertion losses in the anechoic room. Figures 7 and 8 are the results for six large-mesh tubes with a 12.5 cm spacing for 90 and 20 degree angles of incidence. Compared to the results for the solid tubes (Figs. 5 and 6), the insertion losses are very much less for the expanded metal tubes. For the 90 degree incidence (Fig. 7), maximum insertion losses of up to about 3.0 dB occurred in the 5.0 kHz region. For 20 degrees (Fig. 8), maximum insertion losses were a little larger at very high frequencies above 10.0 kHz.

Figures 9 and 10 show the results for increased spacing of the large-mesh tubes at 20 degrees incidence to 25.0 and 37.5 cm. The changed spacing of the cylinders produced some small changes to the insertion loss values above 5.0 kHz. There were no obvious systematic shifts in peaks or dips with the spacing change. For 90 degrees incidence and

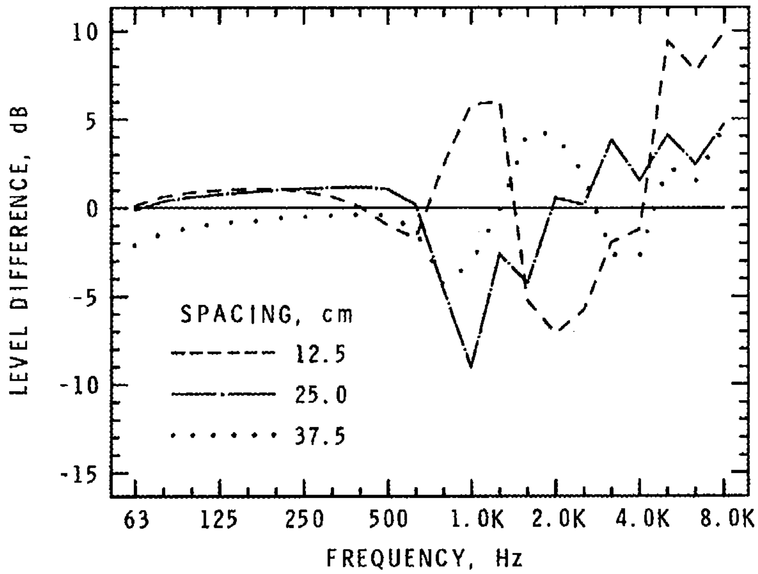

Figure 3. One-third octave band insertion loss, 6 solid tubes, 90° incidence

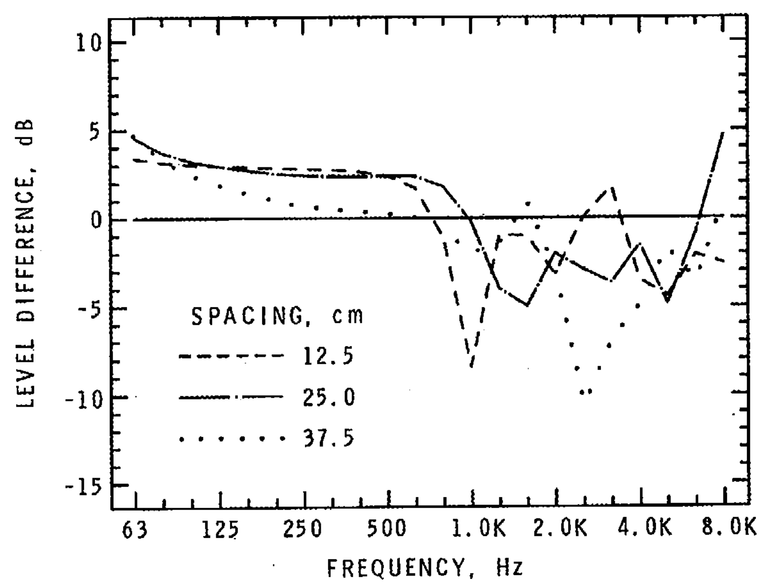

Figure 4. One-third octave band insertion loss, 6 solid tubes, 20° incidence

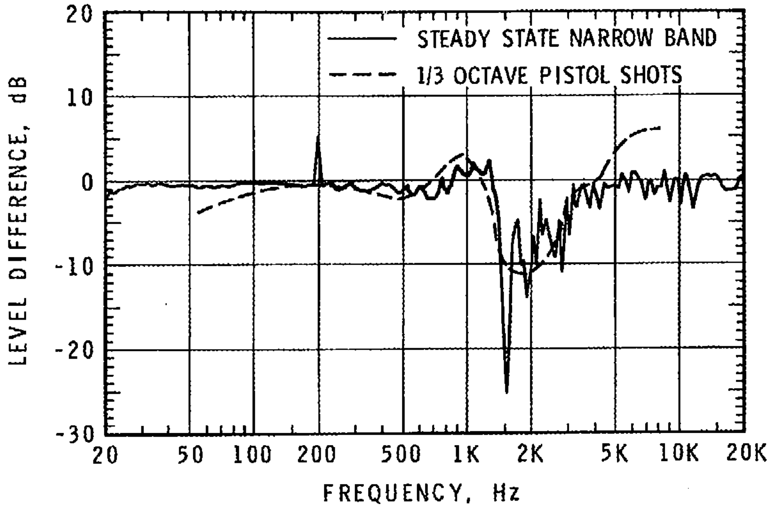

Figure 5. Comparison of steady (anechoic), and one-third octave pistol shot insertion loss, 6 solid tubes, 12.5 cm spacing, 90° incidence

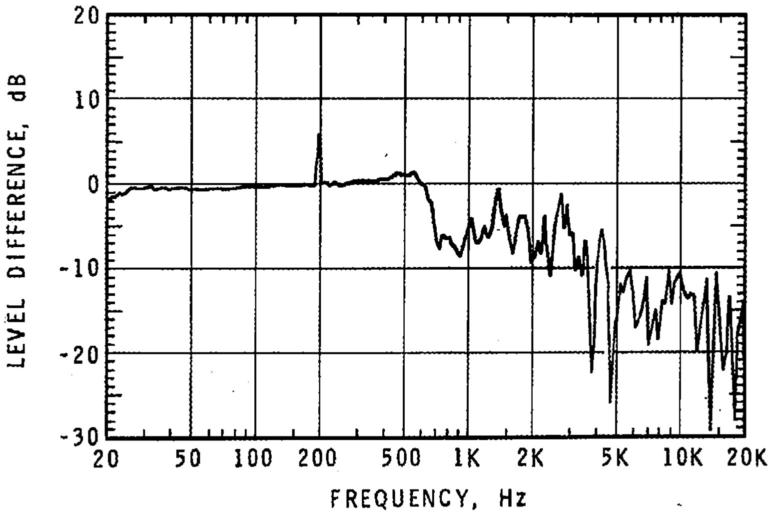

Figure 6. Narrow band insertion loss, 6 solid tubes, 20° incidence, 12.5 cm spacing

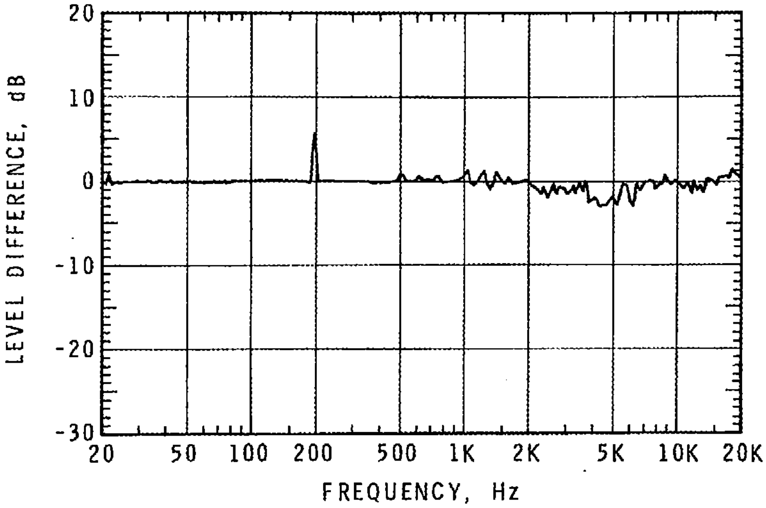

Figure 7. Narrow band insertion loss, 6 large-mesh tubes, 90° incidence, 12.5 cm spacing

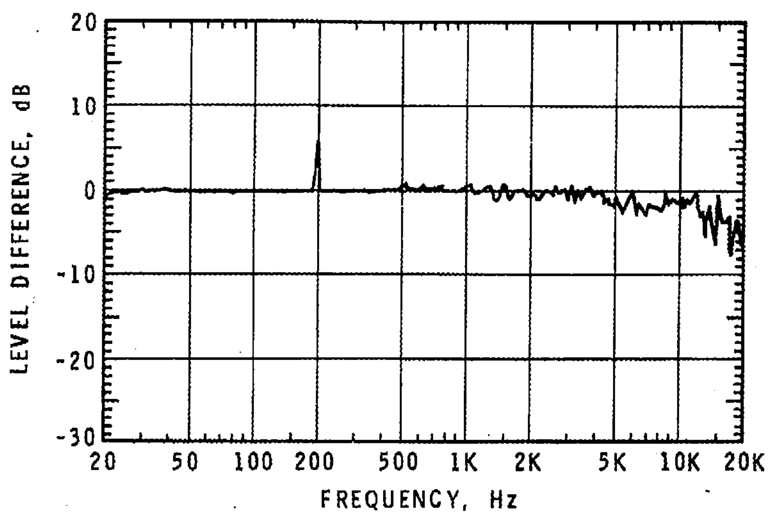

Figure 8. Narrow band insertion loss, 6 large-mesh tubes, 20° incidence, 12.5 cm spacing

the same large-mesh tubes, the increased spacing further diminished the effects compared to those observed in Fig. 7, so that at a 37.5 cm spacing the insertion loss was within ±1.0 dB from 20 to 20,000 Hz.

The small-mesh expanded metal tubes were not as extensively tested, but indicated effects similar to those observed for the larger mesh tubes. The results for six small-mesh tubes with a 12.5 cm spacing and 90 degree angle of incidence, were very similar to the results in Fig. 7, showing a shallow dip around 5.0 kHz. For the same tubes at a 20 degree angle of incidence, the results were similar to those of Fig. 8, with the greatest reductions at the highest frequencies. In the region above 5.0 kHz the small-mesh tube insertion losses were larger by several decibels.

To attempt to isolate the insertion loss of the expanded metal material from the insertion loss introduced by having a linear array of cylinders, a flat sheet of the large mesh material was also tested. At a 45 degree angle of incidence, the insertion loss was within ±0.5 dB up to at least 15.0 kHz. At a 90 degree angle of incidence, some slightly larger dips of up to about 1.0 dB were observed above 2.0 kHz. The insertion loss values for the flat sheet showed effects of about the same magnitude as the day-to-day repeatability of the no-tubes reference curves in these anechoic room tests. Thus one cannot be confident of the exact magnitude of its insertion loss from these measurements. The larger effects observed for both the large- and small-mesh cylinders appear to be due almost entirely to the presence of the array of cylinders, and not simply to the effects of the basic material.

Simulation of Solid Tubes

Although it was beyond the scope of this project to explain the present results in detail, a simple simulation experiment was carried out to confirm the effects of some parameters. Simulated insertion losses were calculated by treating each cylinder as a secondary source positioned at the centre of the cylinder. From the geometry of the arrangement of the tubes, source, and receiver in the horizontal plane through them, the arrival times of the direct sound and the pulses from the secondary sources (the diffracted sound) could be readily calculated. The secondary sources were given abitrary attenuations to simulate the losses associated with diffraction and their amplitudes were further reduced according to the distances that were travelled. In this way an ideal impulse response could be calculated starting with the direct pulse and followed by pulses representing the diffracted sound from each tube. By calculating responses both with and without the effect of the tubes, the same program that was used to process the pistol shots could be used to determine insertion loss spectra.

Figure 11 compares measured and synthesized results for two solid tubes separated by a distance of 1.0 m. Clearly phenomena occur at similar frequencies for both results. However, in many cases the direction of the effect is reversed. Up to a frequency of 2.0 kHz, (where the tubes are approximately one wavelength in diameter), peaks in the measured results correspond to dips in the synthesized values and vice versa. Above 2.0 kHz peaks and dips in the two curves correspond directly. As one would expect, the spacing of the

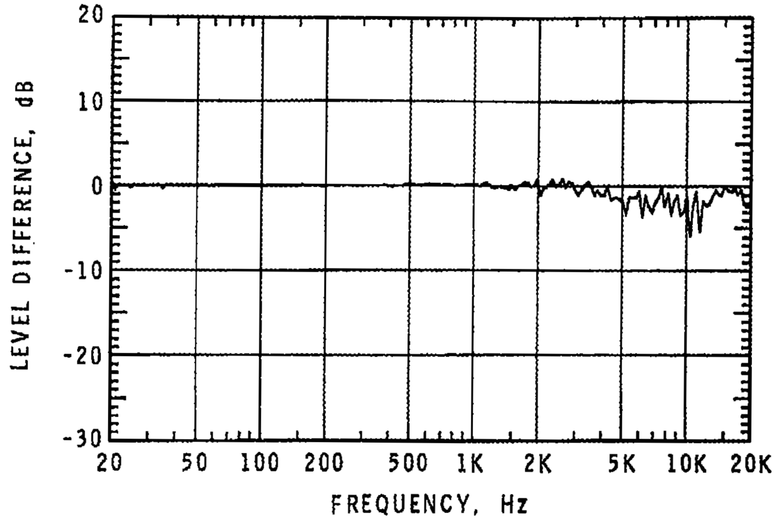

Figure 9. Narrow band insertion loss, 6 large-mesh tubes, 20° incidence, 25 cm spacing

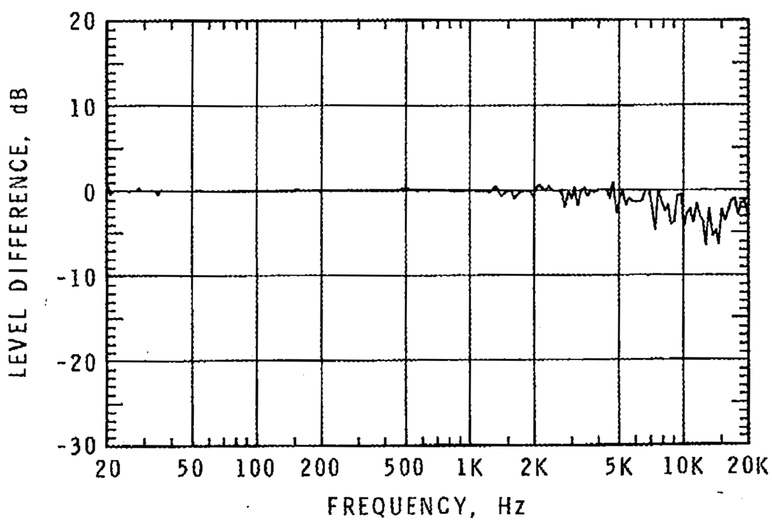

Figure 10. Narrow band insertion loss, 6 large-mesh tubes, 20° incidence, 37.5 cm spacing

tubes appears to determine the frequencies at which interference minima and maxima occur, and this simple model correctly predicts these frequencies. The amplitudes of the insertion loss maxima and minima also show reasonable agreement for this case, where the strength of the secondary sources was attenuated by a factor of 0.25 in addition to the effects of distance. It is not known why the peaks and dips are inverted between the two results below 2.0 kHz, but it could be caused by a frequency-dependent phase shift of the diffracted sound.

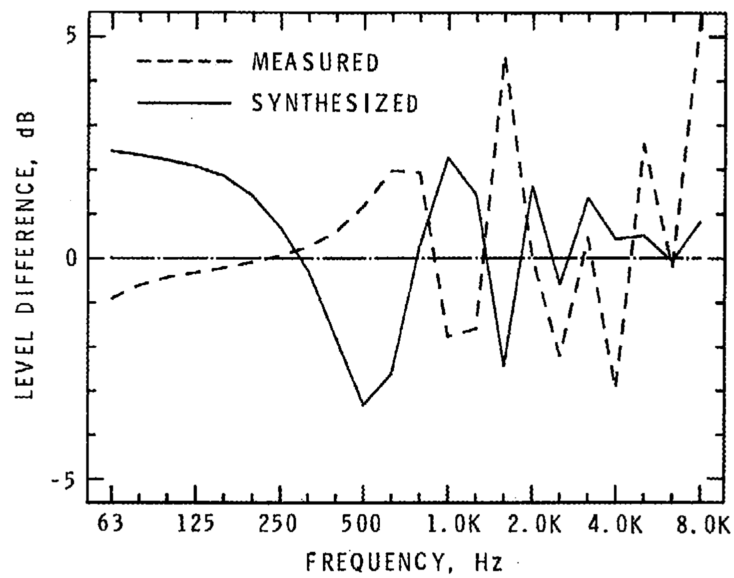

Figure 11. Comparison of measured and synthesized one-third octave spectra, 2 solid tubes, 1.0 m spacing, 90° incidence

Further experiments with synthesized results qualitatively confirmed the expected effects of the strength of the secondary sources, the tube spacing, and the number of tubes. When the strength of the secondary sources was less than the 0.25 used in the results of Fig. 11, the amplitude of the interference effects was diminished, i.e. both peaks and dips were smaller in magnitude, but occurred at the same frequencies. As the spacing of the two tubes was decreased, the position of the first minima moved systematically to higher frequencies because of the smaller differences between the direct and secondary paths. For smaller spacings similar to those used for the measurements of the real tubes, increasing the number of tubes produced further irregularities in the insertion loss spectra; these irregularities appeared at increasingly lower frequencies as more tubes were added. Also the addition of more tubes increased the low frequency energy buildup that was present for all synthesized results.

CONCLUSIONS

The hanging of slender solid tubes in a concert hall or auditorium might be assumed to have negligible effects on the sound field in the room. This is probably true if reverberation time is considered to be the sole criteria for optimum acoustics. From newer research, we now know that the direct sound, and particular early reflections, can have a critical influence on the clarity and definition of music and the intelligibility of speech. Thus arrays of solid cylinders similar to those tested here could dramatically interfere with particular sound reflections. Attenuations in excess of 10 dB are possible in certain medium to higher frequency bands; these attenuations would be expected to strongly affect perceived clarity and intelligibility.

No method of eliminating the insertion loss of the solid tubes was discovered. The insertion loss varied with the angle of incidence, the spacing of the tubes and the number of the tubes, but attenuations in excess of 5 dB occurred for all configurations at frequencies as low as 1.0 kHz. For very large spacings of several metres one would expect diminished insertion losses, but such cases were not tested.

The expanded metal tubes, having a quite large percentage of open area, produced much smaller attenuations. The combinations tested here produced significant insertion losses only at very high frequencies of 10 kHz or higher, which are probably subjectively unimportant. Thus one could suspend such tubes and obtain a desired visual effect without creating significant acoustical problems.