Variable Low-Frequency Absorber for Multi Purpose Concert Halls

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ABSTRACT

Multi-purpose concert halls face a dilemma. They can host classical music concerts, rock concerts and spoken word performances in a matter of a short period. These different performance types require significantly different acoustic conditions in order to provide the best sound quality to both the performers and the audience. A recommended reverberation time for classical music may be in the range of 1.5-2 s, where rock music sounds best with a reverberation time around 0.8-1.5 s for empty halls. Modern rhythmic music often contains high levels of sound energy in the low frequency bands but still requires a high definition for good sound quality.

Ideally, the absorption of the hall should be adjustable in all frequency bands in order to provide good sound quality for all types of performances. The mid and high frequency absorption is easily regulated, but adjusting the low-frequency absorption has typically been too expensive or requires too much space to be practical for multi-purpose halls.

Measurements were made on a variable low-frequency absorber to develop a practical solution to the dilemma. The paper will present the results of the measurements as well as a possible design.

INTRODUCTION

Background

The acoustics of a venue can make or break the enjoyment of a musical performance. Both performers and audience members may choose not to return to a venue because of unsatisfactory acoustical conditions that adversely affected the perceived quality of the performance or even the performance itself.
Halls for classical music have the benefit of years (centuries?) of acoustical research and experience. This evidenced by the quantity of books and papers describing the acoustics of these halls and providing theory for designing new halls. The amount of literature available on the acoustics for halls intended for popular music is much smaller and it seems fair to bring more attention to these halls. By popular music, rhythmic genres, such as rock, pop, and jazz, are meant. Very few concert halls are built specifically for rock concerts, but rather serve multiple purposes, including for classical music concerts and even speech performances.

The first author of this paper is also a professional musician, educated at the Berklee College of Music, and has performed in well over 1000 concerts in the kind of halls described in this paper. This experience provided the motivation and background for an investigation to cover this area more in depth. Very few concert halls are built specifically for rock concerts. Often rock concerts are held in multi-purpose halls.

Popular music performances are almost always amplified by powerful PA systems. The SPL at rock concerts is often well above 100 dB in the center of the hall several meters from the stage. On stage, the sound sources (i.e. speakers, monitors, instruments) are also radiating sound levels of this magnitude in a frequency range from 40 Hz to 10 kHz towards the performers. A bass guitar typically has a low E string tuned to E1 or about 41 Hz. So the acoustic design and measurement range could in fact extend down to include the 40 Hz frequency band.

The musicians need a feeling of being connected to the hall and the audience in a natural and relaxed way. This feeling can come from early reflections from the walls, floor and ceiling of the stage area. Reflections from the back wall, often arriving late enough to be perceived as echoes, are of little use for the performers. A sound field dominated by late energy can make it difficult for the musicians to "navigate". The audience suffers from this as well. A low-frequency rumble, caused by high energy levels from the PA system in front of the stage combined with a long reverberation time in the low frequencies, can mask the direct sound. The sound absorption provided by a tightly packed standing audience (~3 people per m^2) is quite small in the low frequencies, relative to the high frequency absorption (see Figure 1). The absorption coefficients shown are based on the projected area of the audience on the floor, not on the actual surface area of the audience, therefore the absorption coefficients can be greater than 1.

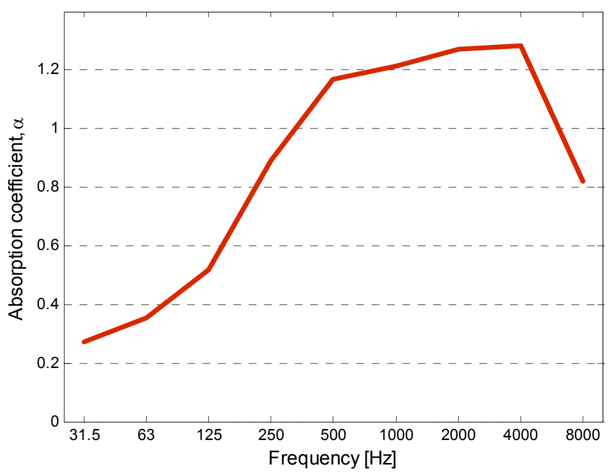


Figure 1: Absorption coefficients for standing audience. Full hall (650 people) measured at 3800 m^3 "Pumpehuset", Copenhagen, dec. 2004.

Membrane Absorbers

Membrane absorbers are often used as efficient low-frequency absorbers and therefore were selected as a starting concept. An air mattress was chosen for initial tests because they consist of an inflatable cavity with a thin membrane and are inexpensive and easily available. By inflating and deflating the mattresses, the sound absorption by the air mattress could be switched on and off. Therefore, the goal of this project was to investigate the sound absorption properties of air mattresses and soft layer membrane absorbers and develop a knowledge base for designing a variable sound absorber with a significant peak absorption coefficient (≥0.7), a resonance frequency in the range of 63 to 125 Hz and a reasonable half-power bandwidth (≥ one octave).

THEORY OF THE MEMBRANE ABSORBER

A membrane absorber consists of a light plate in front of a closed cavity, which is often filled with a porous material that provides damping for the system. When deriving the theoretical characteristic equations for a membrane absorber, the walls and back of the cavity are assumed to be rigid and the bending stiffness in the plate is assumed to be negligible compared to the stiffness of the air column in the cavity. The system is characterized by the mass per unit area of the plate, m, the depth of the cavity, d, and the internal losses of the system, r_i, consisting of the losses due to the flow resistance of the porous material, internal losses in the plate and losses in the joints along the edges of the plate [Rindel, 2000].

The acoustic impedance of the system can be shown to be [Rindel, 2000]:

$$Z = r_i + j\left(\omega m - \frac{\rho c^2}{\omega d}\right)$$

The resonance frequency of the system is found when Im{Z}=0:

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{\rho}{md}} \approx 60\,\frac{\sqrt{\mathrm{kg \cdot m}}}{s}\,\frac{1}{\sqrt{md}}$$

where c is the speed of sound in air (approx. 343 m/s) and ρ is the density of air (approx. 1.2 kg/m3).

This shows that the resonance frequency, where the absorption should be highest, is inversely proportional to the square root of both the mass of the membrane and the depth of the cavity. According to this theory, in order to have a maximum absorption at around 63 Hz, with a cavity depth of 0.2 m, the membrane must have a mass of about 5 kg/m2.

The impedance of the absorber can be tuned in order to maximize the absorption at the resonance frequency and the usable bandwidth of the absorber (half-power bandwidth, Br). If the impedance is too high, relative to the radiation resistance of the membrane, r_s, then the incident sound field will reflect off of the membrane and not be absorbed. If the impedance is too low, then the internal losses will be too small and not enough sound energy will be absorbed. The impedance ratio of the internal losses and the external radiation resistance can be expressed as: [Rindel, 2000]

$$\mu = \frac{r_i}{r_s}$$

The maximum absorption coefficient and absorption bandwidth can then be written as: [Rindel, 2000]

$$\alpha_{\max} = \frac{4\mu}{(1+\mu)^2}$$

$$\frac{B_r}{f_0} = (1+\mu)\sqrt{\frac{\rho d}{m}}$$

With these theoretical equations in mind, some parameters of the test samples were varied to achieve the project goals. It is noted, that an air mattress does not fulfill the requirements of a membrane absorber as described above in that the walls are not rigid.

MEASUREMENTS

The guidelines of ISO 354:1985 were followed with some deviations. The DIRAC software was used to measure the impulse responses of the reverberation room with and without test samples. A linear sweep of either 11 or 21 sec. duration was used for the signal and the results from six measurement positions were averaged. A dodecahedral speaker array with an additional subwoofer was used as the sound source and the room response was recorded by a microphone connected to the computer running the DIRAC software.

Air mattresses

Measurements were performed on four sets of air mattresses with different dimensions in order to determine the effect of the dimensions on the resonance frequency and absorption characteristics of the mattresses. The four mattress types will be referred to as FirstEver, Single, Double and DoubleThick. The relevant properties of the mattresses are shown in Table 1. The Single and Double mattresses were manufactured by the same company and were constructed of the same material, so only differed in mattress size. The other two mattresses had different manufacturers and slightly different materials, although all mattresses were made of PVC based membranes. The main body of each mattress did not have a uniform thickness, but had a regular pattern of indentations; either long columns or discrete points, from the internal webbing that helps the mattress maintain a generally flat shape when inflated.

Mattress Type	Thickness d (cm)	Mass m (kg/m2)	Area SS (m2)
FirstEver	20	0.5	9.9
Single	12	0.5	12.1
Double	12	0.5	11
DoubleThick	40	0.5	13.7

Table 1

The 4 types of air mattresses

Since the air mattresses had many parameters which were impossible to control and difficult to model, particularly the internal webbing, it was decided to construct test boxes over which greater parameter control could be exercised.

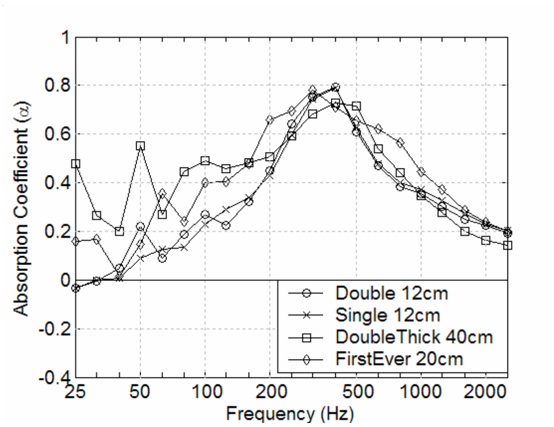
Test boxes

Four wooden test boxes were constructed with a plywood bottom and 22 mm thick walls that were 10 cm tall and gave the box a total outer dimension of 240 cm and a width of 100 cm. The wood was sealed on the inside with a layer of liquid sealant and on top with a window seal lining. A sheet of 2 mm soft PVC was stretched across the top of the box and clamped around the edges with a 22 × 22 mm wooden bar, screwed down around the top of the frame. A hole was drilled in a side of the box, to which an air pump could be fitted, and was blocked with a cork during measurements.

The membrane used for these tests was a 2 mm Rianyl N extruded soft PVC. This material was chosen because it had an appropriate mass (3 kg/m2) and was locally available. The soft material was chosen so that various depths could be tested through inflation and deflation without having to modify the test box and it should have a high internal damping so that there would not be as much need for extra damping material inside the box. It was expected that the high elasticity module of the membrane would provide a high degree of internal damping. For the tests, 2 Rockwool Flexi A-batts (30 × 605 × 1000 mm, air flow resistance 8.3 kPa·s/m^2) were used inside each test box.

The absorption of the test boxes was measured with the membrane approximately level with the top of the frame (i.e. 10 cm depth, referred to as “inflated”). In addition, measurements were made with two Rockwool batts in the box with the membrane inflated to a depth of about 25 cm (“hyper inflated”) and “vacuum deflated” so that as much air as possible was removed from the box. Since the Rockwool batts were in the box, the deflated depth was still around 2.5 cm

RESULTS



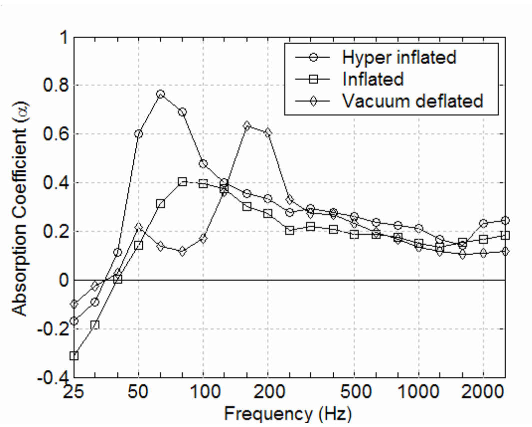


Figure 2 Absorption coefficients of 4 air mattresses **Figure 3 Absorption coefficients of 2mm PVC on testbox**

The first measurements were made on the FirstEver mattresses as a proof-of-concept measurement, to verify that an air mattress could in fact be used as a sound absorber. The results of this measurement were very promising (fig. 2). The absorption curves showed a significant peak around 315-400 Hz with a maximum value of about 0.8 and a half-power bandwidth of about three octaves. This showed that an air mattress could in fact be used as an effective mid-range sound absorber. The challenge remained to shift the frequency of maximum absorption towards lower frequencies without significantly reducing the maximum absorption coefficient (α) or the bandwidth.
The resonance frequency does not follow the model suggested in the Theory section and the curves are surprisingly similar in all 4 cases. With a membrane mass per unit area of about 0.5 kg/m^2 and a depth of about 0.2 m, the resonance frequency should be about 190 Hz. This is presumably due to the internal structure inside the mattress. This structure provides additional moving mass and additional stiffness and subdivides the membrane into small panels. Increasing the stiffness would increase the resonance frequency of the mattress. By subdividing the membrane into small panels, the small areas may not be large enough to vibrate freely at the low frequencies. Assuming that the mattress behaves as suggested by the theoretical expression, only with a different proportionality constant would mean that the product of the mass and depth must increase by a factor of sixteen in order to reduce the resonance frequency by a factor of four to be within the target range.

The absorption of the test boxes with the membrane at its extreme positions and with two Rockwool batts in each test box were compared to that measured at a slightly inflated position (fig.3). In the hyper-inflated position, with the membrane stretched to a maximum height of about 25 cm, a maximum α of almost 0.8 was measured at 63 Hz as predicted by the theoretical calculations, exactly at the lowest target frequency. The bandwidth of the absorption curve was over 4/3-octaves, so all of the absorption criteria were fulfilled. However, when the test box was switched off, in the vacuum deflated state, there was still a significant peak in the absorption curve at around 200 Hz. With two Rockwool batts in the test box, the membrane still had a depth of about 2.5 cm in the vacuum deflated state. Without Rockwool and with the membrane completely flush with the bottom of the box, this peak should disappear.

Furthermore tests were performed to measure the influence of pressure on the absorption. No unambiguous results could be deducted from these tests. Also it was noted that attempts to completely shut off the mattresses and test boxes by vacuum them proved difficult. Absorption coefficients of 0,4 to 0,6 were found of course at much higher frequencies.

DISCUSSION AND POSSIBLE DESIGN

The concept of an air mattress - type membrane absorbers being used as a flexible low-frequency absorber has potential. It was shown that the low-frequency absorption can be switched on by creating a cavity and that a plastic membrane absorber can be designed to work at 63 Hz with a maximum absorption coefficient of 0.8 and a bandwidth of over 4/3-octave.
PVC is often not legal for use in public buildings because of fire safety issues. Therefore, a material needs to be found that has similar mass and stiffness properties to the PVC used.
Patents are pending on the basic concept and several possible designs.

ACKNOWLEDGEMENTS

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