Acoustical measurements of an artificial reverberation system with wooden

Berndtsson, G.

journal: STL-QPSR
volume: 33
number: 4
year: 1992
pages: 087-096

http://www.speech.kth.se/qpsr
ACOUSTICAL MEASUREMENTS OF AN ARTIFICIAL REVERBERATION SYSTEM WITH WOODEN LOUDSPEAKERS

Gunilla Berndtsson

Abstract

Georg Bolin, a recognized Swedish guitar maker, has developed two types of sound enhancement systems, "tone tables," which are used for reinforcing the sound from certain musical instruments, and "acoustic walls," which are used for increasing the reverberation time so as to improve room acoustics for music performance. The goal of the present investigation was to study some of the acoustical properties of the acoustic walls.

INTRODUCTION

Commercial systems for artificial reverberation generally use traditional loudspeaker elements (Krokstad, 1988). In a different approach taken by Georg Bolin, a recognized Swedish guitar maker, wooden loudspeakers are used. According to some musicians, the resulting room acoustics is better with this system, compared to other enhancement systems. The aim of the present investigation was to document some characteristic features of the Bolin system.

Tone table design

The development of the Bolin room acoustic enhancement system started from experiments with a "natural" reinforcement of the sound of guitars. For that purpose, Bolin designed a "tone table," a loudspeaker with the membrane replaced by a wooden plate of approximately the size of a guitar top plate. The tone table can be considered as an external resonant body of the guitar. A piezo electric crystal is attached to the guitar top plate, and the signal is amplified and transferred to a conventional electrodynamical driving system in the tone table, consisting of a strong, fixed magnet, and a moving coil attached to the wooden plate. The tone table has been received favorably by guitar players, and also for the use with harpsichords and clavichords in ensembles. It is widely considered as a unique tool for "natural" reinforcement of these instruments.

Room acoustic enhancement system design

Later, Bolin developed a type of "wooden" loudspeakers called "acoustic walls," or "acoustic ceilings," if placed in the ceiling, intended for use in a system for improvement of poor room acoustics. The system itself is of conventional design, but the components used, as microphones and loudspeakers, are of novel construction.

The signal to the acoustic walls is picked up in the vicinity of the played instrument by means of a special microphone, called "macrophone," also an invention by Bolin. The macrophone uses a plate of expanded polystyrene as membrane, to which a piezo electric crystal is attached. In many cases, conventional microphones can also be used. If more than one macrophone is used, the signals from the macrophones are mixed before further processing (see Fig. 1). Compression is applied in cases of very high sound levels. An equaliser, dividing the frequency range into 1/3
octave bands, is used to modify the frequency curve. The equaliser output is fed to an artificial reverberation unit, which is connected to power amplifiers, one for each pair of acoustic walls.

![Diagram of the Bolin reverberation system]

**Acoustic wall design**

The acoustic walls consist of pairs of rectangular boxes, one smaller square shaped (0.6 m x 0.6 m), and one larger rectangular (0.6 m x 1.2 m). In the following, such a pair of acoustic wall elements will be referred to as an acoustic wall set. The depth of the acoustic wall is 0.13 m. Normally the larger box is standing upright, with the smaller box on top. The soundboards of the acoustic walls are made of specially sawn, three-layered, close grained spruce (*picea excelsa*). The thickness of the soundboards are 9 mm for the large box, and 8 mm for the small. Strengthening bars, resembling the bars of the guitar top plate ("struts"), are attached to the soundboard. A large loudspeaker magnet, with a mass of several kilogram, is screwed to an aluminium beam, which is fixed to the frame of the box, and the loudspeaker coil is attached to the soundboard. The driving coil is placed on the central vertical line of the soundboard, slightly below the middle.

**MEASUREMENTS**

The performance of the tone table and the acoustic walls has previously not been evaluated by measurements. During the development, Bolin has been guided mainly by intuition, combined with careful listening. The goal of the measurements presented in this report has been to determine some of the characteristic features of the tone tables and acoustic walls, primarily their resonances and sound radiation properties. The study is by no means exhaustive, but provides some basic information needed when discussing the use of tone tables and acoustic walls, and when making comparisons with conventional loudspeakers. The study includes measurements of (1) impulse response, (2) frequency response, (3) sound intensity, and (4) modal properties.

**Impulse response**

A first acquaintance with the properties of the tone table was made by recording the impulse response in an anechoic room. The impulse responses from a loudspeaker and a tone table can be compared in Fig. 2. The response is much shorter for the loudspeaker than for the tone table (and the acoustic wall). The duration of the impulse response reflects how the magnitude of the energy storage elements (masses and springs) relates to that of the loss elements, often recognized as a Q-value.
The wooden plate in the tone table is rather heavy (approximately 0.5 kg). In contrast, the loudspeaker membrane is lighter by a factor of about 50.

It can be seen that the tone table rings for a considerable time, with a time constant of about 30 ms, while the impulse response of the loudspeaker is some 5 times shorter. Thus, the damping of the tone table is 5 times less efficient, even though its losses are high. The table acts as a reverberator, more compact than a room, with a similar reverberation time.

The ringing is traced to several frequencies of the wooden box, among them a clearly visible resonance at 200 Hz. The reverberator is thus not very neutral or ideal; it imposes a special colouring to the spectrum. In comparison, a 200-Hz fundamental resonance in a room would correspond to a room dimension of the order of 1 meter, not too impressive for a room size.

**Frequency response**

A first study of the sound radiation properties was made by recording the frequency response in an anechoic room, using the conventional technique with a swept sinusoid. These measurements were made in several different directions relative to the plane of the soundboard, at a distance of 1 m from the geometrical midpoint of the acoustic wall set. A frequency response curve measured perpendicular to the soundboard (0°) is shown in Fig. 3.

As seen in the figure, the acoustic walls radiate mainly in a frequency range between 100 and 5000 Hz. Unlike conventional loudspeakers, the frequency response of the acoustic walls show clear resonance peaks. The pronounced resonance at 200 Hz was also observed in the impulse response.

A frequency response curve for 90° relative to the normal of the soundboard plane (perpendicular to a side of the acoustic wall) is shown in Fig. 4. As for a conventional
loudspeaker, the radiation is poorer perpendicular to the normal of the radiating surface, in particular at higher frequencies. It is true that also the sides of the acoustic walls radiate, as the vibrations not are limited to the soundboard alone, but it is not possible to estimate the contributions from these surfaces from a frequency response measurement.

**Sound intensity**

The initial frequency response measurements were supplemented by measurements of sound intensity (Fahy, 1989). These measurements were also used to calculate radiated sound power.

The intensity measurements were made using white noise. The intensity probe, with a spacing of 23 mm between the microphones, was slowly swept over one surface of the acoustic wall set at a time at a distance of approximately 50 mm. The result was presented in 1/3 octave bands. Guided by the frequency response measurements, which showed that little energy was radiated below 100 Hz and above 5000 Hz, it was decided to limit the intensity measurements to this frequency band. The total radiated sound power was calculated by integrating the sound intensity measured perpendicular to the front, the back, the left, and right sides, and the top of the acoustic wall set (see Fig. 5).

The sound intensity measurements do not allow an identification of the contributions in radiated
sound from individual peaks but, on the other hand, they give a reasonable estimation of the averaged sound radiation in the different directions. In particular, for a large vibrating structure, like an acoustic wall which breaks up into many small areas at higher frequencies, the intensity measurements could be expected to give a more informative picture of the sound radiation properties than the frequency response.

It can be seen that sound power level varied within ±20 dB in the frequency range analyzed. The lowest levels occurred at 100 Hz and 5000 Hz. At 200 Hz the sound power level reached its maximum. This is probably due to the fact that the small and large boxes both have strong resonances in this frequency region. As the boxes differ in size, one might expect the resonances to appear at different frequencies, but, as it turned out, the large box has its third resonance near 200 Hz, while the small one has its second resonance in the same frequency region.

Fig. 6. Relative sound intensity levels, in 1/3 octave bands, overlayed on the corresponding frequency response curves, a) 0°, b) 90°.

Fig. 6a shows the relative sound intensity level in front of the acoustic wall set, perpendicular to the plane of the soundboard (0°). The sound intensity is overlayed on the corresponding frequency curve (cf. Fig. 3). Fig. 6b shows the average over the left and right sides of the acoustic wall set, measured perpendicular to the surface of these sides (90°), drawn together with the frequency curve from Fig. 4.

It can be seen, that the level of the frontally radiated sound is higher than that of the laterally radiated sound, and much higher than the sound radiated backwards. The sound radiation behind the acoustic wall set showed a steeper slope toward higher frequencies, as expected.

Modal analysis
In order to understand the behaviour of the acoustic walls, it is important to analyse the vibration patterns occurring at the resonances. Theoretically, a plate with fixed edges possesses a specific set of modes. With increasing excitation frequency, they appear in a certain order, from the simplest, where the whole surface vibrates in phase, to more complicated modes, where the vibrating surface is divided into sev-
eral vibrating "islands" (Jansson, 1992). The first four modes for a plate with fixed edges are schematically illustrated in Fig. 7.

Fig. 7. Modes of a plate with fixed edges according to the theory. The straight lines are nodal lines, where the plate does not vibrate. Each ellipse indicates the shape of iso-amplitude-lines. The signs represent the phase relationship between the modes, such that regions with opposite signs vibrate in antiphase.

Modal analysis was used to investigate the vibrational mode patterns for the acoustic wall sets (Ewins, 1986). An accelerometer recorded the soundboard vibrations when hit with a small force hammer. The excitation points were defined by a grid with 10 cm squares. The modes are shown at their extreme displacements, as dotted lines, see Figs. 8 and 9.

The modes of an acoustic wall did not fully agree with those predicted by theory for a plate with fixed edges. For example, there were two modes resembling the theoretical mode #1, with only one single vibrating region. This splitting of the mode, which was observed for both the smaller and the larger box, is due to the fact that there is an interaction between the soundboard and the other parts of the boxes, which leads to coupled oscillations (Fletcher & Rossing, 1991). The two modal patterns resembling mode #1 for the small box are shown in Fig. 8a and b.

Fig. 8. The two lowest modes for the smaller quadratic box, a) at 130 Hz b) at 212 Hz

Another factor influencing the modes are the bars that are glued on the plate. These bars stiffen the lower part more than the upper part of the soundboard. The asymmetry results in a division of the soundboard into two vibrating systems, with a certain coupling, which leads to a duplication of higher modes. For example, for the large box, theoretical mode #3 is divided into two modes; the upper part of the soundboard vibrates at 245 Hz, while the lower part vibrates at 317 Hz (see Fig. 9). The stiffness difference implies that the main vibrations occur at lower frequencies in the upper part of the soundboard than in the lower part, in line with the observations.
Which modes are excited?

The influence of the position of the driving point (the coil) was studied briefly, in order to determine to what degree the various modes actually could be excited under normal conditions.

The accelerometer was placed close the striking point, and the plate was struck with the force hammer at the point of the driving element. The result shows the mobility of the plate at the point of excitation, giving an indication of which resonances are efficiently excited by the driving system (see Fig. 10).

Clear resonance peaks could be observed up to about 1000 Hz. In particular, resonances in the lower frequency range are strongly excited. For example, the strongest resonance in Fig. 9a is found at approximately 200 Hz, corresponding to mode #2 in the small box. It is notable that the curve for the large box showed a positive slope towards higher frequencies. An explanation for this has not yet been found.

DISCUSSION

As shown by the measurements, there are large differences between the acoustic walls and a conventional loudspeaker. What is the significance of these differences if the wooden loudspeakers are used in a sound enhancement system? Could some of these differences be advantageous?

There are several properties of a loudspeaker which are relevant to the design of an artificial reverberation system. The following will be discussed: (1) the importance of a flat frequency response, (2) the required resonance density for a colourless reverberation, and (3) how the directivity affects the possibilities to create an incoherent sound field.

A distinctive difference between the acoustic walls and a conventional loudspeaker is found in the frequency response. Good loudspeakers generally have rather flat frequency responses, while the acoustic walls, on the other hand, show a response curve with numerous pronounced resonance peaks. The perceptual implications of such a difference has not been studied formally. Usually, loudspeaker de-
signers strive for a frequency curve as flat as possible, but the universal relevance of such a criterion seems somewhat unclear (Gabrielson, Lindström, & Till, 1986).

To achieve a colourless reverberation with a resonant system, a large number of resonances was required, well distributed in frequency and approximately equal in amplitude. Kuhl has performed subjective tests to find the necessary density for colourless reverberation (Kuhl, 1968). The critical signal in the tests was filtered noise. The results indicate that more than 3 resonances/Hz are needed at 1200 Hz, while 0.1/Hz is sufficient at 300 Hz and at 10,000 Hz. A computation indicates that the mode density of the acoustic walls presently is 0.05/Hz for the large box and 0.03/Hz for the small box. The estimations are based on a formula for bending resonances in plates (Cremer, Heckl, & Ungar, 1973). In this respect, it seems desirable to improve the design of the acoustic wall.

Fig. 10. Mobility at the driving point for a) the small box b) the large box.

A fundamental factor affecting the resonance frequencies and their density is the size of the boxes; larger boxes have their lowest resonances at a lower frequency than smaller boxes, and the density of the resonances is higher. By supplementing the present acoustic wall set by one or several new units of different size, a higher overall resonance density can be achieved. Another possibility is to decrease the thickness of the soundboard in the present design, which will result in an increased resonance density. If desirable, the damping of the resonances can be reduced by using a material with lower internal losses for the back of the boxes; presently masonite is used.

Also the driving system would seem interesting for further experimentation and development. For instance, Bolin has tried to optimize the location of the driving loudspeaker element empirically, but it may be possible to find alternative locations that may work even better. More asymmetric locations relative to the vertical midline should increase the amplitudes of the higher modes, at the expense of the two lowest modes. Also, it may be worthwhile to try replacing the electrodynamic driving system, originally devised for light membranes with relatively large amplitude of motion, by some other type of excitation mechanism, such as an electromagnetic system or magnetostrictive system.

Loudspeakers and acoustic walls differ considerably also with regard to the directivity of sound radiation. In an acoustic wall, the whole wooden box radiates
sound, and as the vibration pattern is quite complex, radiation varies drastically both with frequency and direction. This should produce an incoherent sound field with characteristics resembling the sound in an ordinary room with natural reverberation. The origin of the sound is very difficult to localize in such a sound field. Precisely this aspect, that the acoustic walls would be hard to localize, is interesting. In a conventional loudspeaker, the radiating element has relatively small dimensions. This makes the loudspeaker act like a point source with essentially omnidirectional radiation at lower frequencies. At higher frequencies, however, the radiation becomes increasingly more directed, and the sound source will be relatively easy to localize (Kutruff, 1979). This is one of the major problems with artificial enhancement systems. To solve this problem, a large number of loudspeakers is often used, which makes the system expensive. The acoustic walls, on the other hand, will probably be more difficult to localize if used in a reverberation enhancement system, and this may be a quite important advantage. In fact, this would seem to be one of the most interesting features of the acoustic walls. Some quantitative perceptual effects of the use of acoustic walls in a room will be described in a future article.

Apart from the aspects considered above, it may be mentioned that the acoustic walls also act as efficient passive reflectors because of their large dimensions. If appropriately placed, they may provide valuable early reflections.

Finally, it may also be pointed out that the acoustic walls may turn out to be quite useful in contexts other than enhancement of room reverberation. If used as a complement to or replacement for the loudspeakers of a synthesizer, the acoustic walls may add certain valuable properties, producing a resonant sound quality, and providing some of the sound radiation characteristics which are typical of traditional music instruments.

ACKNOWLEDGEMENTS

This work has been supported by the Swedish Council for Building Research, as a part of a larger project aiming at a documentation of Bolin’s tone tables and acoustic wall systems. I have profited from the valuable help from Johan Sundberg, Professor of Musical Acoustics, KTH, and the head of the project, and Asbjørn Krokstad, Professor of Acoustics at the Norwegian Institute of Technology, Trondheim. Valuable support was given by Erik Jansson, Anders Askenfelt, and Johan Liljencrants at our department, and by Rodney Day, guest researcher from CSIRO, Lindsfield, NSW, Australia. The equipment for sound intensity measurements was kindly put to my disposal by the Department of Technical Acoustics, KTH.

REFERENCES


