

PAPER

Variable reflection acoustic wall system by active sound radiation

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Abstract: In the acoustic design of special spaces, such as studios, it may be required to realize diffuse reflection from a specific surface of a wall. Moreover, this requirement often changes with time or situation. In this research study, a new acoustic wall system, which has the potential to cope with such strict requirements, is proposed. The proposed system can vary the reflection characteristics by radiating additional sound from a source located behind the absorbing material. Therefore, if sound is not emitted from the source, it is possible to use the system as a mere sound absorbing material. This system can be used as a rigid wall, provided sound of equal amplitude to the incident sound is emitted from the source. Furthermore, a trial was carried out to make the characteristics of radiated sound being diffuse by using appropriate devices. Several models are proposed and the fundamental characteristics such as directivity were examined. The results show the possibilities for realizing uniform reflection directivity and variable absorption characteristics.

Keywords: Absorbing material, Absorption coefficient, Reflection, Diffuse reflection

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1. INTRODUCTION

The acoustic design of special spaces, such as recording studios, may require the realization of diffuse reflection from a specific surface of a wall. Moreover, this requirement often changes with time or situation [1], i.e., a flexible reflection structure might be useful. In this research study, a new acoustic wall system, which has the potential to cope with such requirements by actively radiating sound, is proposed.

The system ("unit," hereafter) consists of a sound-absorbing material and a secondary source (loudspeaker) mounted behind the material. Since the sound-shielding efficiency of the absorbing material, such as fibrous material is usually low, the emitted sound from the secondary source can be radiated effectively to generate simulated reflection sound. Moreover, the device in front of the speaker can modify the characteristics of the radiated sound, e.g., diffuse radiation.

The idea of using a loudspeaker with a passive

absorbing material is not new. For example, Furstoss *et al.* [2] showed a hybrid system which uses a resistive material and a loudspeaker to control surface impedance. Other examples are also summarized in [2]. They are, however, mostly intended to realize active absorption systems which change incident sound energy into thermal energy inside the loudspeaker by the adjustment of the amplitude and phase of the emitted sound. The principal concepts of active absorption are shown, for example, in reference [3].

The proposed unit in this study is not intended to increase the absorption performance by the loudspeaker. Instead, the emitted sound from the speaker works to increase the reflection coefficient, and consequently, reduce the absorption performance. Therefore, the proposed unit cannot have a better absorption performance than its native characteristics that can be achieved without a loudspeaker.

Special structures which use secondary loudspeakers to reproduce reflected sound have already been designed, and a concept of using speakers to produce an effect equivalent to that of a quadratic residue diffuser (QRD) [4] was introduced by Cox and D'Antonio [5]. However, they considered neither the adjustment of the reflection coefficient nor absorption with a passive material.

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Since our unit uses secondary sources emitting additional sounds, it might be possible to categorize it as a kind of active control system. However, our unit neither cancels any sound nor uses any complicated adaptive algorithm for adjusting the emitted sound. It only emits the incident sound to simulate sound reflections.

In this study, we introduce the concept of such a simple system as mentioned above and show the results of some preliminary experiments. Particularly, a series of experiments are conducted to measure diffusivity and the sound absorption performance of the proposed unit.

2. BASIC CONCEPT

The acoustic wall system which we propose has possibilities for modifying the reflection characteristics freely. For example, we can change the reflection coefficient by modifying the amplitude of the simulated sound reflections emitted by the secondary source mounted inside the material. The basic concept of the proposed unit is shown in Fig. 1. The unit consists of a sound-absorbing material, a microphone, a controller and a loudspeaker.

In the unit, the energy of incident sound is partially absorbed in the absorbing material. The degree of absorption depends on the absorption performance of the material itself and the structure, such as airspace behind it. At the same time, the incident waveform is detected by the microphone. After passing through the controller, which adjusts the amplitude and other parameters of the sound, the modified sound will be emitted as simulated sound reflections from the loudspeaker. For example, if we add reverberation to the incident sound, this unit can behave like a reverberation enhancer used in an active field control system [6].

If we turn up the volume of the reflected sound, it is equivalent to increasing the reflection coefficient, i.e., making the boundary surface hard. At the same time, if we turn off the reflected sound, the unit works as a normal absorbing surface. This idea is based on the fact that the sound-absorbing material, mostly a fibrous material,

has low sound-shielding efficiency. Needless to say, the characteristics of the radiated sound might be varied during passage through the material. This deformation, such as changes in the frequency characteristics, can be compensated by, for example, the equalizer in the controller.

The radiation directivity is also an important subject for sound modification. A contrivance is therefore introduced to the construction of the absorbing structure. The characteristic of diffuse radiation is the aim of this study. Strictly speaking, diffuse reflection (diffuse radiation in this paper) can be defined as a uniform distribution of reflected sound in the 2π space in front of the wall. Our current design goal for diffuse radiation is slightly different from that and ‘vague’ but can be described as follows:

- not concentrated in a certain direction,
- not having special (regular) patterns.

The results of the experimental verification of the proposed unit are shown below.

The proposed wall system thus has possibilities for realizing the following simultaneously:

- 1) an absorption material,
- 2) a variable reflection coefficient,
- 3) a diffuse reflection,
- 4) a reverberation enhancer.

Images of practical applications are shown in Fig. 2 in which the control room of a recording studio and a soundproof room are used as examples.

In the control room of a studio, this unit is assumed to be used for changing the reflection characteristics of walls (to be diffuse) to be suitable for recording and mixing, for example. On the other hand, if the unit is used in a soundproof room to practice playing musical instruments, it can be used to change the atmosphere of the room from a ‘dead’ enclosure to a ‘live’ space.

In the practical application of the proposed system, undesired feedback between the loudspeaker and the closely located pick-up microphone must be avoided. However, in this paper, no detailed discussion is given for realizing an effective howling canceller and the focus is on the ideas for improving radiation directivity.

3. EXPERIMENTAL UNIT

3.1. Model with Array of Pipes

As a first trial, the units shown in Fig. 3 were constructed. They had similar shapes to the QRD. A QRD-type surface creates diffuse reflection by the interference of waves reflected from the bottoms of ‘wells’ of various depths. The proposed structures are intended to simulate a similar effect, i.e., the interference of various waves which passed through pipes of various lengths. At the same time, these pipes were filled with fibrous materials to achieve absorption. The various depths were realized by employing various lengths of fibrous material filled in the

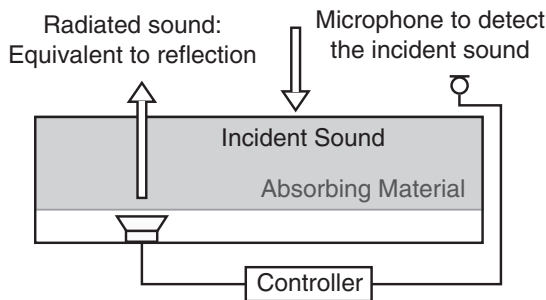
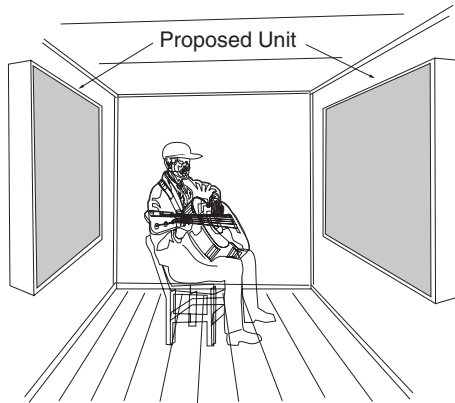


Fig. 1 Concept of proposed unit which consists of pick-up microphone, absorbing material and loudspeaker behind it.



(a) Example of application in studio



(b) Application in soundproof room

Fig. 2 Schematics of practical application of proposed unit. In studios, the unit functions as diffuse reflection walls with variable reflection coefficients. Also, the unit can be used as a tool by which to easily modify the atmosphere of a small enclosure, such as a soundproof room, from dead to live spaces.

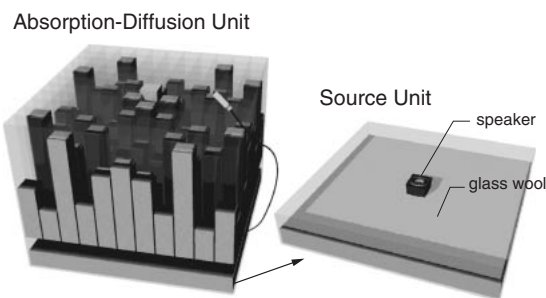


Fig. 3 Previously proposed unit which consists of absorption-diffusion unit with pipes filled with various depths of fibrous materials and source unit with secondary loudspeaker [7–9].

pipes. Note that there was no theoretical basis on which the proposed structure could realize a similar effect as a QRD.

A series of experiments was carried out to verify the directivity of radiated sound. The results shown in Refs. [7–9] can be summarized as follows.

- Radiation characteristics can be modified by a QRD-like pipe arrangement [7].

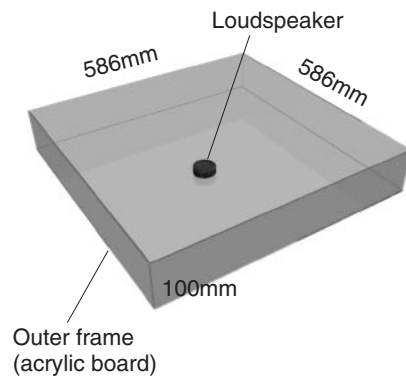


Fig. 4 Base unit which consists of small loudspeaker and outer frame.

- Arrays of pipes can create fairly uniform radiation characteristics.
- However, results which strongly support the effectiveness of the QRD-like arrangement of fibrous materials of various depths were not sufficient.

There may be some other possibilities for developing a useful unit with arrays of pipes, however, we ignored this type and attempted to construct other types of units which have smaller dimensions and lighter weight compared with the units shown in Fig. 3.

3.2. Model with QRD Walls and Scattering Balls

The next model was designed to realize lower height and lighter weight. The height was restricted to 100 mm. The ‘base’ structure assumed, in which a small loudspeaker was put inside a shallow frame, is shown in Fig. 4. A loudspeaker for a car audio system was used in this case.

The directivity of radiated sound from this unit was measured in an anechoic chamber. As shown in Fig. 5, the units are arranged on a turntable system. At every 5 degrees in rotation and elevation angles, the impulse responses from the source unit to the receivers are measured. A total of 1,368 responses are therefore obtained.

Relative sound pressure levels were calculated at 1/3-octave steps and the distributions of the levels are drawn as colored maps in circular shapes which are the shapes of hemispheres seen from the top. There are other methods of examining the diffuseness of reflected sound (radiated sound in this paper), such as the diffusion coefficient. Although such a single number is convenient for quantitative comparison, we adopted polar maps projected onto circular shapes because of their ease for grasping global radiation characteristics.

Results are shown in Fig. 6. In the results, the maximum levels are normalized to 15 dB and all the levels below 0 dB are rounded to 0 dB for convenience. In the results, regular patterns can be seen in the radiated sound. The modal characteristics of the frame might have a

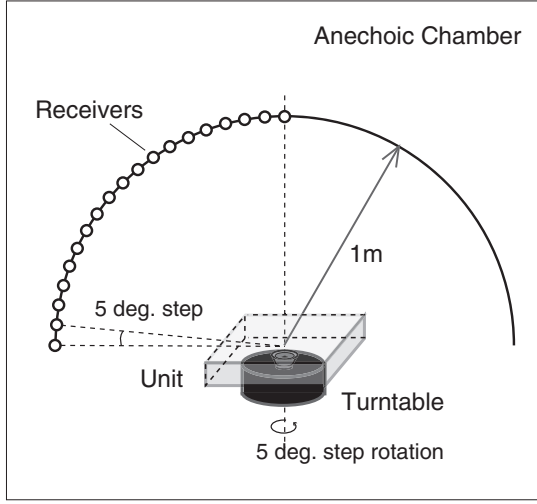


Fig. 5 Arrangement of unit and microphones for measurement of directivity.

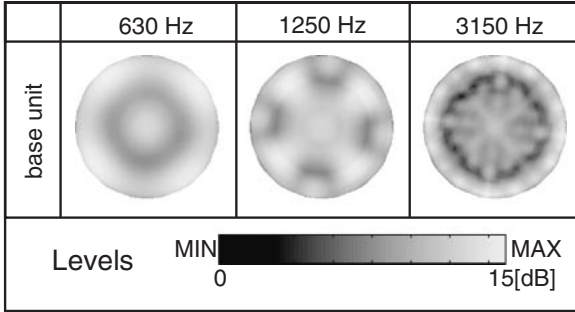


Fig. 6 Radiation characteristics of base unit.

stronger effect on the directivity pattern of the radiated sound.

Therefore, other devices were installed in the unit. These were QRD structures at the four walls intended to reduce the modal characteristics due to the square-shaped frame. The installation procedure is shown in Fig. 7. Firstly, the four walls of the ‘base’ unit were covered with a one-dimensional QRD structure, as shown in Fig. 7(a), whose depth of wells was designed using the following equation [4]:

$$L_n = \frac{\pi c}{N \omega_d} (n^2 \bmod N), \quad (1)$$

where c is the sound speed, N is a prime number, n is an integer which changes from 0 to $N - 1$, and ω_d is an arbitrary design frequency. $c = 340$ m/s, $N = 13$, and $\omega_d = 2\pi \times 1,635$ Hz are assumed here. The effective frequency in this case was from 1,770 to 5,667 Hz. The width of each well was 30 mm and the material was a polyurethane plate. These parameters, such as frequency and size, were chosen arbitrarily without any special meaning.

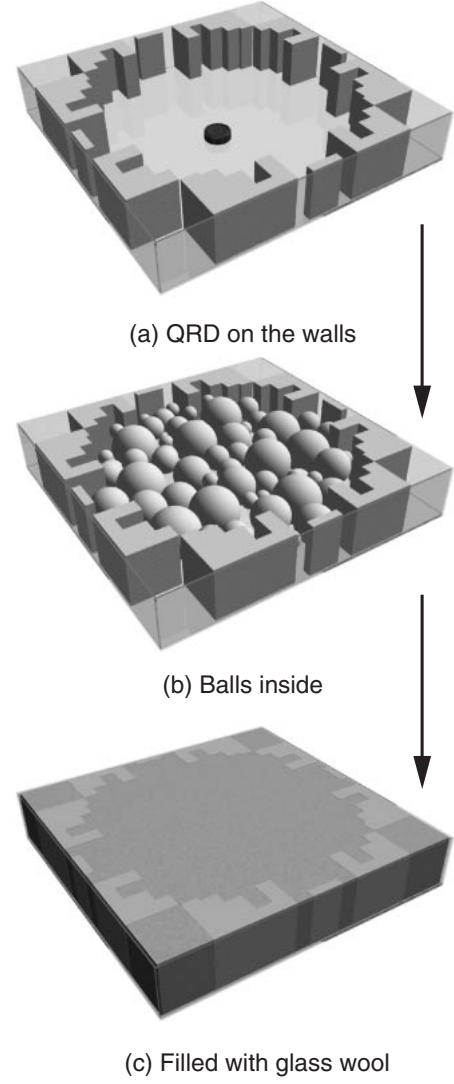


Fig. 7 Modification of unit using QRD on walls and balls. These devices were introduced to cancel modal characteristics of the outer frame and to scatter the sound emitted from the secondary source.

Additionally, the center space was filled with polyurethane balls (Fig. 7(b)). These balls were intended to scatter the radiated sound from the speaker located at the bottom of the unit. The chinks were filled with absorbing material, glass wool (Fig. 7(c)).

The measured directivities for units (a) and (c) in Fig. 7 are shown in Fig. 8 for the frequencies of 630, 1,250, and 3,150 Hz. The introduction of the QRD structure at the walls and the balls gradually reduced the regularity of radiation patterns, particularly in the case (c). Although some irregularity is observed in the case of high frequency, the structure shown in Fig. 7(c) showed other possibilities for realizing an absorption-diffusion unit.

Finally, the absorption characteristics of the proposed unit were measured. As mentioned above, the absorption coefficient of this unit can be varied by varying the amplitude of the sound radiated from the installed loud-

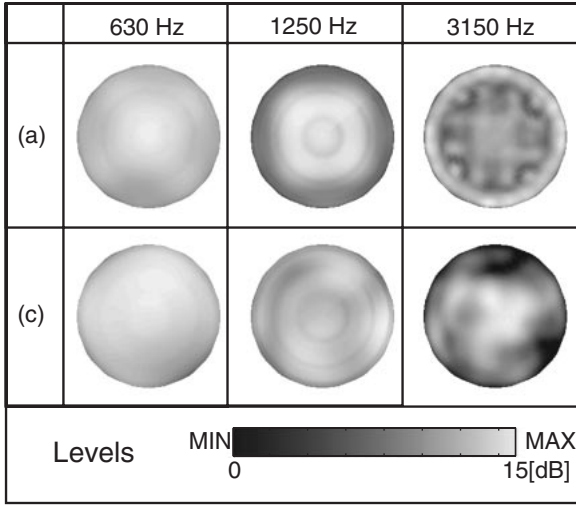


Fig. 8 Results of directivity measurement for proposed unit with QRD and balls.

speaker. Needless to say, the additional reverberation in the emitted sound can vary the ‘simulated’ absorption characteristics more effectively. As shown in Fig. 9, the unit was put into a 1/10-scale reverberation chamber and the reverberation times were measured under various conditions to evaluate the absorption coefficient α_r using the following equation:

$$\alpha_r = \frac{KV_0}{S_m} \left[\frac{1}{T_2} - \left(1 - \frac{S_m}{S_0} \right) \frac{1}{T_1} \right], \quad (2)$$

where K is the constant defined as $K = 24 \ln 10/c$, c is the sound speed, V_0 and S_0 are the volume and the surface area of the reverberation chamber, respectively, S_m is the surface area of the unit, and T_1 and T_2 are the reverberation times without and with the unit, respectively.

A block diagram of the measurement is also shown in Fig. 9. Needless to say, the practical performance of the proposed unit should be measured with the system shown in Fig. 1. However, since no feedback canceller is

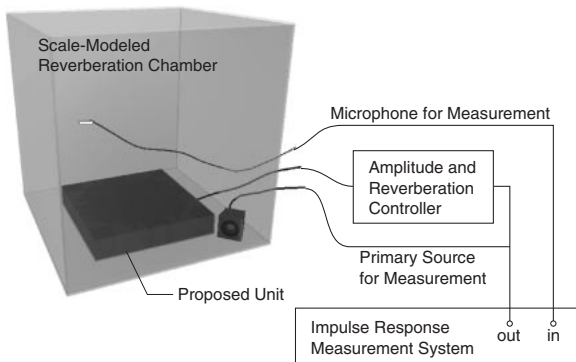


Fig. 9 Measurement of absorption coefficient in scale-modeled reverberation chamber.

considered at this time, the source signal (TSP signal) for the measurement of the impulse response was paralleled with the primary speaker in the reverberation chamber and the secondary source in the unit after passing through the controller. Note that this method was adopted to clarify the potential performance of the proposed unit by a simple method, and therefore, the obtained results should be interpreted as the ideal ones. The controller can vary the amplitude and add reverberation of various lengths, in the same way as the reverberation effector used for musical instruments.

Five steps of amplitude (from 0 to 4) and three steps of reverberation time (from 1 to 3) were carried out expediently. Zero amplitude meant no sound was emitted from the secondary source. Since changes in amplitude were realized by changing a discrete volume control clicks, the real changes in the levels were somewhat ‘nonlinear.’ If we assumed the maximum level of additional sound (step 4) to be 0 dB, the levels corresponding to steps 0, 1, 2, 3, and 4 were $-\infty$, -30 , -12 , -5 , and 0 dB, respectively (0 dB was determined arbitrarily by adjusting the volume through trial and error to yield the reasonable results). The three impulse responses 1, 2, and 3 which had reverberation times of 1.1, 1.6, and 3.7 seconds were introduced into the reverberation enhancement effector. (These reverberation times were the average of the three bands of 500 Hz, 1 kHz, and 2 kHz.)

For simplicity, the results of various amplitudes with reverberation step ‘2’ (1.6 s), and of various reverberations with amplitude step ‘4’ (0 dB) are shown in Figs. 10(a) and (b), respectively. The absorption coefficient was calculated at every 1/3-octave step. As shown in Fig. 10(a), the absorption without a secondary source is greater than approximately 0.5 for the range of 500 to 10,000 Hz. This result indicated that the proposed unit basically had absorbing characteristics. As the amplitudes of secondary signals were increased, the absorption coefficient decreased. Even negative values were observed at some frequencies. Also in Fig. 10(b), large variations of absorption coefficients were observed with various reverberations. As mentioned previously, the results shown here were obtained under idealized conditions. The practical performance, i.e., the extent of variation in absorption characteristics, should be examined carefully with the ‘practical’ system shown in Fig. 1.

Although it might be somewhat tricky to calculate the absorption coefficient with artificially modified reverberation characteristics, we believe that our results have indicated possibilities for realizing various absorption systems by the method proposed here.

4. CONCLUSIONS

A unit which makes sound reflection characteristics

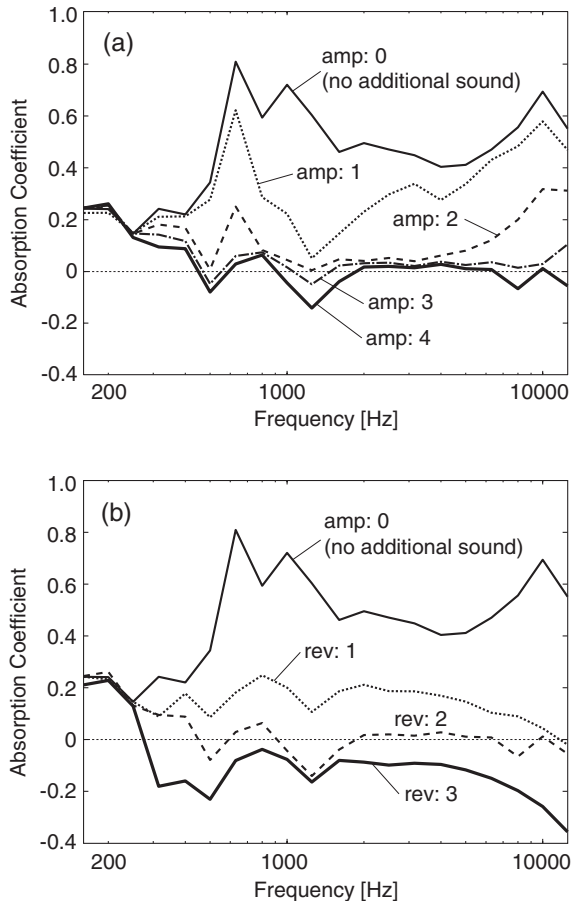


Fig. 10 Absorption coefficient measured in reverberation chamber with various amplitudes and reverberations of secondary sound.

variable using sound radiation was proposed. The radiation of simulated sound reflections resulted in changes in the absorption coefficient of the unit. In this study, we examined the basic characteristics of such units. Particularly the diffusivity of the radiated sound was considered, aiming at producing characteristics similar to those of diffuse reflection.

The proposed unit was designed to use a QRD structure on the walls and balls to scatter the sound radiating from the speaker. Reasonable radiation characteristics were obtained in the experimental verification. The absorption coefficient was also measured. The results indicated possibilities for realizing a variable absorption and reverberation unit by modifying the amplitude and reverberation components of the sound emitted from the secondary speaker.

The practical installation of the unit, and the design of the effective feedback canceller between a pick-up microphone and the secondary source are the current subjects of an ongoing research study.

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