Diffuseness and sound field distribution at room boundaries

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In the present work, a classical modal analysis is used up to medium frequencies to study the sound field distribution, and its diffusivity, particularly at boundaries. Due to intensification zones at boundaries, the diffuse field distribution at room boundaries can not be assimilated to the distribution inside the room. Moreover, diffusivity at room boundaries, that is of interest for sound insulation measurement , is usually only related to an incidence angle while inside the room volume several descriptors such as a correlation function and the spatial uniformity are necessary to characterize a diffuse field. In this paper, we present a new descriptor adapted to characterize the sound field diffusivity at boundaries. This descriptor is called Boundary Diffuse Field Index. Its averaged value over a specific surface can be related to a limit incidence angle, and its standard deviation can be related to the spatial distribution over the surface. Finally, thanks to this descriptor, Sabine's assumptions of diffuse sound field are also evaluated in this study.

1 Introduction

Sound transmission measurements in laboratory are usually made with the two reverberant rooms conventional method. However, several studies [5, 3, 9], have shown the variability of these measurements between different laboratories, at low frequencies but also surprisingly at high frequencies with differences higher than those authorized by the norm [1]. Indeed, at high frequencies, one could expect to have a diffuse field independent of excitation conditions, and therefore a good reproducibility of measurements. The same problem is encountered for sound absorption coefficient measurements at high frequencies in [2, 14]. Indeed, sound absorption coefficients can vary according to excitation conditions such as room absorption, room shape and the number of diffusers in the room.

According to Sabine's theory, above the cut-off frequency [13], modal separation is small compared to modal overlapping, and the sound field can be considered as diffuse. This means that propagation of sound in any direction is equally probable, and that sound waves are not correlated. In this case, Sabine's theory gives a relation between the mean-square pressure in the room, room absorption and room dimensions. However, room geometry, damping distribution and variation of absorption coefficient with incidence angle are not taken into account.

In the work presented here, a classical modal analysis is used at medium frequencies to study the sound field distribution in a rectangular room, and its diffusivity, particularly at boundaries. Sabine's assumptions of diffuse sound field are also evaluated in this study. As noticed in [7], the modal analysis method works well to model reverberant sound field as long as modal coupling is taken into account. For small damping coefficients, modal decoupling can however be assumed. In the following, modal uncoupling is used as simplification. In the same way, the eigenmode and the free-wave models are found consistent to describe diffuse sound fields in [16]. Indeed, the same space correlation function and the same interference pattern anomalies are found with the two models.

In fact, classical modal analysis has already been employed by the past to study sound diffusion in reverberation chambers [12, 10]. Angular distribution of sound energy flux, averaged over the measuring wall, has hence been determined. Other studies have also been performed to characterize a diffuse sound field distribution. Damping effects on spatial distribution have been studied in [7]. Cross-sectionally averaged mean-square pressure distribution is presented in [6]. Finally, directional and spatial variations of sound fields have been examined experimentally. However, sound field distribution over the measuring wall has not been studied in details. Finally, a spatial correlation function in sin(kx)/kx has been established for a perfect diffuse field [8]. However, a sound field having such spatial correlation function is not necessarily mean diffuse. It is therefore necessary to study the spatial distribution of the sound field to evaluate its diffusivity. Some statistical properties of reverberant sound fields are for example given in [15]. However, in these studies, a perfect diffuse field is assumed with random phased plane waves.

More recently in [11], the characterization of a diffuse field in reverberant rooms has been studied with two descriptors evaluated with the classical modal method: the correlation function, and the spatial uniformity. A minimum of 20-30 modes in the measurement band is recommended in conclusion of this study to get a good diffuse field. However, the spatial uniformity is evaluated with 20 measurement points located far from the walls. Therefore, diffusivity at room boundaries is not included in this study.

In conclusion, diffusivity at room boundaries is usually restricted to a limit incidence angle while inside the room volume several descriptors are necessary to characterize a diffuse field. Due to intensification zones at boundaries [17], the diffuse field distribution at room boundaries can not be assimilated to the distribution inside the volume. In this paper, we present a new descriptor adapted to characterize the sound field diffusivity at boundaries. This descriptor is called Boundary Diffuse Field Index (BDFI). Its averaged value over a measurement surface can be related to a limit incidence angle, and its standard deviation can be related to the spatial distribution over the surface. This descriptor is first evaluated with the classical modal method. Then measurements of the Boundary Diffuse Field Index in a reverberant chamber are presented. Finally, influences of excitation conditions on the the boundary diffuse field index and on transmission loss are compared in order to relate the acoustic field difuseness with variations of the transmission loss. .

2 Acoustic Field Model

Several kinds of model can be used to describe the acoustic field inside a room. For small rooms, a modal expansion of the pressure can be employed, while for large rooms with high reverberation, wave's models are preferred. In this section, two models are presented and used to characterize a reverberant room.

2.1 Classical Modal Analysis

Reverberant and boundary pressures are calculated with the following modal expansion of the room pressure:

$$P(x,y,z) = \sum_{p,q,r} A_{pqr}\psi_{pqr}(x,y,z) \quad . \tag{1}$$

Time dependence is omitted for sake of simplicity. In this expansion, a mode pqr is defined by an amplitude A_{pqr}, a norm N_{pqr}, a wave number k_{pqr}, and a shape ψ_{pqr} :

$$A_{pqr} = \frac{\int_{V_r} \psi_{pqr}(x,y,z)S(x,y,z)dV}{\left(k^{*2} - k_{pqr}^2\right).N_{pqr}} \quad , \tag{2}$$

$$N_{pqr} = \int_{V_r} \psi_{pqr}^2(x,y,z)dV \quad , \tag{3}$$

with Vr the room volume, S(x,y,z) the source distribution, and k the complex acoustic wave number that takes into account acoustic damping η_r such as $k = \frac{\omega}{c\sqrt{(1+j\eta_r)}}$.
Acoustic damping can also be related to the room reverberation time thanks to $\eta_r = \frac{2.2}{f.Tr}$.
In the following, a rectangular room is considered with rigid boundary conditions and excited by a point omnidirectional source located at x_0, y_0, z_0 :

$$\psi_{pqr}(x,y,z) = cos(\frac{p\pi}{lx}x)cos(\frac{q\pi}{ly}y)cos(\frac{r\pi}{lz}z) \quad , \tag{4}$$

$$S(x,y,z) = S_0.\delta(x-x_0).\delta(y-y_0).\delta(z-z_0) \quad . \tag{5}$$

Quadratic room pressure P_r is then obtained by averaging the room pressure squared inside the room volume:

$$P_r^2 = \frac{1}{2}\frac{\sum_{pqr}\int_{V_r}(|A_{pqr}^2|\left(\psi_{pqr}(x,y,z)\right)^2)dV}{V_r} \quad . \tag{6}$$

Finally, the local boundary pressure, also called blocked pressure P_b, is obtained by averaging the room pressure on a small boundary surface Si:

$$< P_b >_i = \int_{Si}\left(\sum_{p,q,r} A_{pqr}\psi_{pqr}(x,y_0,z)\right)dxdz \quad . \tag{7}$$

2.2 Free Wave model

A perfect diffuse field is assumed according to Sabine's theory with an isotropic sound field made of incident uncorrelated plane waves coming from all directions. The reverberant pressure Pr is therefore related to incident plane waves' amplitude Pi as follows :

$$P_r^2 = \int_\Omega P_i^2 d\Omega = \int_0^{2\pi}\int_0^{\pi} P_i^2 sin(\theta)d\theta d\varphi = 4\pi P_i^2. \tag{8}$$

Local boundary pressure is obtained by limiting the solid angle to a half space, and by taking into account reflected waves:

$$P_b^2 = \int_{\Omega/2}(2P_i)^2 d\Omega = \int_0^{\pi}\int_0^{\pi} 4P_i^2 sin(\theta)d\theta d\varphi 4\pi$$
$$= 8\pi P_i^2 = 2P_r^2. \tag{9}$$

This equation shows the well known increase of +3dB in a diffuse field at boundaries. It is also possible to use a limit incidence angle to suppress grazing waves. In acoustic transparency, this limit angle is commonly used with a value around 78°. In this case, a ratio of 1.6 is obtained between the blocked pressure and the room pressure
From the wave model, the sound field distribution in the room volume and at room boundaries is clearly uniform. On the other hand, the classical modal analysis enables to study the sound field distribution. It is thus interesting to see if the sound field uniformity is verified with this other approach.

3 Boundary Diffuse Field Index

This section presents a boundary diffuse field index employed to characterize an acoustic boundary field.

A perfect diffuse field according to Sabine's assumptions gives a ratio of 2 between the boundary pressure and the room pressure (equation (9)). From the classical modal analysis, it is possible to evaluate this ratio locally by using the averaged boundary pressure over a patch surface (7) and the room pressure (6). This ratio can be seen as an index of diffusivity at boundaries, and is therefore called the Boundary Diffuse Field Index:

$$BDFI = \frac{\langle P_b \rangle_i^2}{\mathrm{P}_r^2} \quad . \tag{10}$$

However, the local value of the Boundary Diffuse Field Index is not pertinent statistically. It is indeed important to see its mean value and its standard deviation over a large surface to evaluate the diffusivity of the sound field at boundaries:

$$\overline{BDFI} = \frac{\sum_{i=1}^{N}\langle P_b \rangle_i^2}{N.\mathrm{P}_r^2} \quad , \tag{11}$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{\langle P_b \rangle_i^2}{\mathrm{P}_r^2} - \overline{BDFI}\right)^2} \quad . \tag{12}$$

Here the room pressure is assumed uniform in the room. In practice, special devices such as a moving microphone enables to get a good evaluation of the mean room pressure.
An example of Boundary Diffuse Field Index averaged over a large surface with 247 patches is presented in Fig(1). Mean values and standard deviations are represented on each third octave band.
In third octaves, averaged values tends to 1.6 with a standard variation of 0.5. Globally the perfect diffusivity assumed with the plane wave summation is not

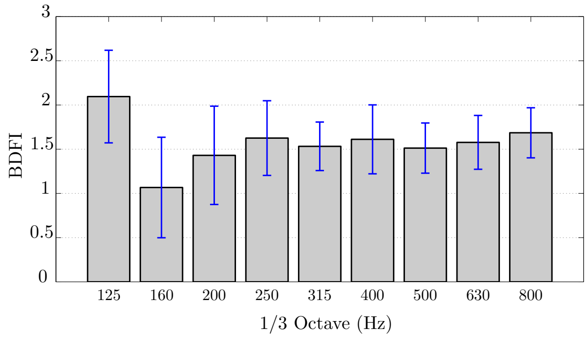

Figure 1: Calculated mean BDFI value and standard deviations - Room dimensions: lx=11.5m, ly=8.69m, lz=4.03m - 247 patches over a surface of 0.96m x 1.5m centered on x=6m y=0m z=1.75m - Patch dimensions : $\Delta X = 0.08$m, $\Delta Z = 0.074$m - Source position x=2m, y=4m, z=1m - Cut-off frequency: 187Hz

reached. A correlation between incident plane waves can lead to a BDFI greater than two. On the contrary a lack of incidence angles can lead to a BDFI lower than two. In fact the two phenomenons can interact in opposite ways and cannot be distinguished. Comparison with the theoretical value of a perfect diffuse field gives then only the main phenomenon. In practice, at low frequency the BDFI can exhibit very high or very low values, but is not pertinent due to the room modal behaviour. On the contrary, above the Shroeder cut off frequency, i.e. 187Hz for the tested room, a diffuse field is expected.
In this later case, values lower than 2 can be related to a limit incidence angle. Indeed, by introducing a limit incidence angle between 78° and 90°, the theoretical BDFI varies from 1.6 to 2. The BDFI high frequency limit obtained for the tested surface leads therefore to consider a limit angle of 78°.
The standard deviation presented in Fig(1) is also a good tool to verify the diffusivity of the sound field at boundaries. It is indeed possible, at low frequency for example, to get a mean BDFI of 2 without having a good uniformity of the local BDFI on patches. At high frequency where a good uniformity is obtained, the standard deviation is very low. At medium frequency, uniformity on some third octaves is not always reached. It is however important to distinguish the sound field uniformity, and its diffusivity that is related to properties of isotropy. For instance, an adding of absorption will improve the sound field uniformity but not necessary its diffusivity.
Experimental BDFI distribution over a large surface on two third octaves 80Hz and 2000Hz are presented in figures (2) and (3). At low frequency, modal behavior is observed, while at high frequency source directivity appears clearly. The source direct contribution, without appearing as clearly as in the presented case, can however lead to heterogeneities in the acoustic boundary field that can be then observed with BDFI standard deviations. Hence, thanks to the BDFI mean values and standard deviations, different kinds of phenomenon can be detected such as a modal behaviour, an important direct source contribution, or the effect of an intensification zone.

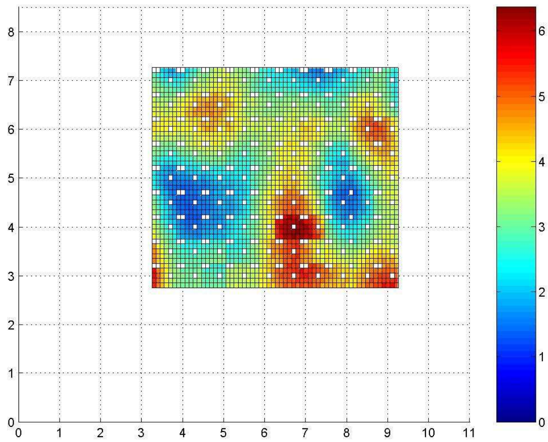

Figure 2: xy spatial BDFI distribution at 80Hz - Room dimension : Lx=11.5m Ly=8.69m Lz=4.03m - Cutoff frequency: 187 Hz - Source Location : x=2m y=2m z=0.5m

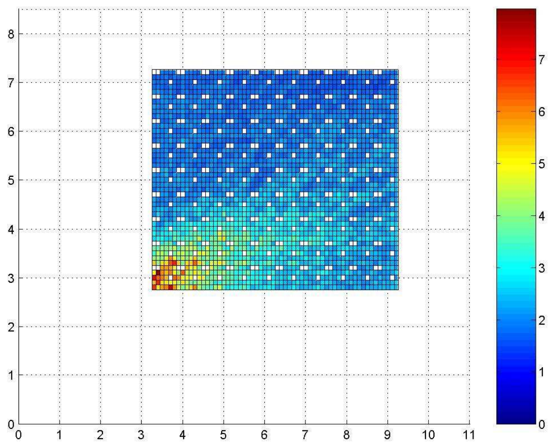

Figure 3: xy spatial BDFI distribution at 2000Hz - Room dimension : Lx=11.5m Ly=8.69m Lz=4.03m - Cutoff frequency: 187 Hz - Source Location : x=2m y=2m z=0.5m

4 Effects of sound field diffusivity on sound transmission

4.1 Theoretical study

In order to study the influence of source location on the sound pressure diffusivity over a boundary surface, three source locations have been tested. The studied case is presented in Table (1).

Mean BDFI obtained with these three source conditions are presented in Fig(4) and show that the boundary pressure field diffusivity is very sensitive to the source location below 500Hz. Above 500Hz, the mean BDFI tends to the same value of 1.6 and confirms the lack of grazing waves that is already known and taken into account with the limit incidence angle.
Spatial standard deviations obtained with the same three

Room dimensions	lx=11.5, ly=8.69, lz=4.03
Cut-off frequency	187 Hz
Surface dimension	lx=0.96, lz=1.5
Surface center	x=6, y=0, z=1.75
Patch dimensions	Δx = 0.08, Δz = 0.074
HP 1 position	x=2, y=4, z=1
HP 2 position	x=4, y=2, z=1.5
HP 3 position	x=0.25, y=0.25, z=0.25

Table 1: Theoretical study parameters (lengths in m)

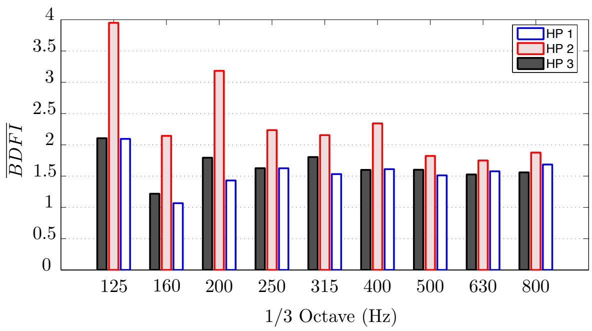

Figure 4: Mean BDFI for three source positions

source conditions are presented in Fig(5). The global trend shows a reduction of the standard deviation at high frequency. Therefore, as expected, the boundary pressure field is more uniform at high frequency. However, the standard deviation does not necessary decreases above the cut-off frequency, and is also very dependant on the source location. One can also notice that the position HP2 gives standard deviations higher than other positions. This is due to a small distance between the studied boundary surface and the source.

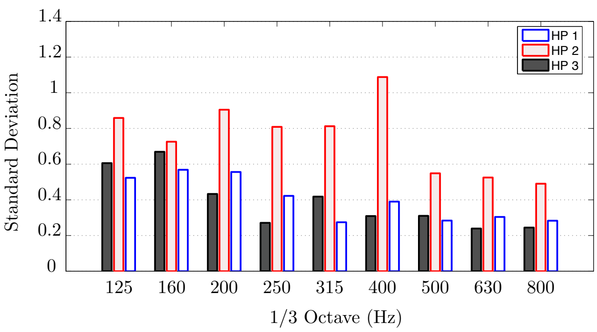

Figure 5: Standard deviations for 3 source positions

The main question that remains now is to explain differences obtained in transmission loss according to excitation conditions. It is well known that grazing waves are detrimental to acoustic isolation. Moreover, if blocked pressures applied to the panel tested are more important for a same room pressure, this will inevitably lead to a decrease of acoustic isolation. Hence, an increase in the mean BDFI leads to a decrease of transmission loss. However, when differences between two BDFI are low compared to standard deviations, no conclusions can be given. A high standard deviation is indeed related to a boundary field that is not uniform, and with a particular distribution that can be more or less coupled with the panel. Hence, for high standard deviations, the expected global tendency between the mean BDFI and the transmission loss is not necessary verified.

Influence of source location over sound transmission of a double panel is presented in Fig(6). Calculations are made using the patch-mobility method presented in [4]. Great differences are observed with the tree source locations, even above the cut off frequency of 187Hz. This confirms that the diffusivity is not perfect. Moreover, the link between the BDFI and the transmission loss that was expected is verified with these results. The only exception is at 800Hz for the source position HP2, but the higher standard deviation for this location due to the direct field explains this singularity.

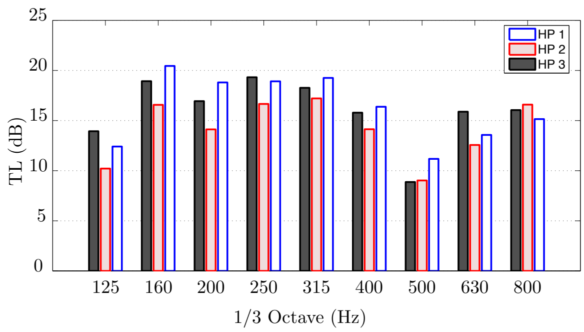

Figure 6: TL of a double aluminum panel (2mm and 1.5mm thickness, separated by 3cm of air) for three source positions

4.2 Experimental study

Sound transmission measurements with two source positions in an room with a volume of $80m^3$ and having a cutoff frequency around 300Hz are presented in Fig(8). Corresponding measured BDFI are also presented in Fig(7). Except at low frequencies, transmission losses are well related to the BDFI. Indeed, a higher mean BDFI leads to a lower transmission loss. As discussed previously, the BDFI increase can be explained by an increase of grazing waves and correlated plane waves, and these two physical phenomenons are known to reduce the transmission loss.

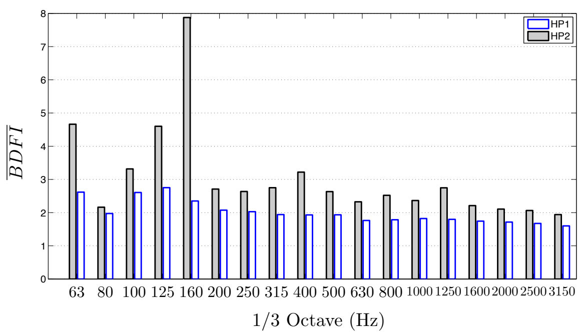

Figure 7: Measured BDFI with two source positions

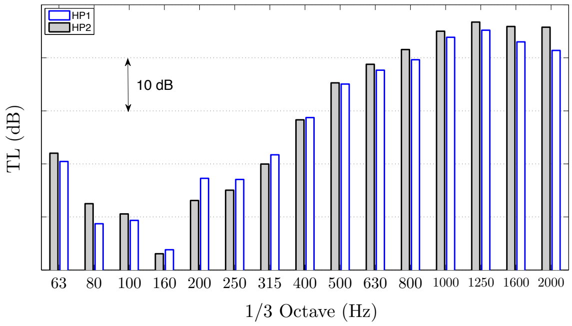

Figure 8: Measured Transmission Loss of a plasterboard panel with two source positions

5 Conclusion

Several parameters can change the diffusivity of a boundary sound field. The position of the surface on the wall can be of some importance due to intensification zones at the edges and in the corners. Loudspeaker location in the room can also be an influent parameter if the direct source contribution is important. Absorption material distribution in the room, and diffuser position have also an influence on the boundary surface diffusivity. In general a slight absorption is required in reverberant rooms to deacrease the cutoff frequency. However, an adding of absorption also decreases the number of wave reflexions in the room, leading hence in a decrease of the diffusivity.

The Boundary Diffuse Field Index presented in this article enables to study, either theoretically or experimentally, the global diffusivity due to all these phenomenons of a boundary sound field. Two particular aspects can hence be analysed: the isotropy of the field characterized by a limit incidence angle, and the correlation of incident waves.

The Boundary Diffuse Field Index can thus be employed as a tool to characterize facilities used in transmission loss measurements. A perfect emitting room must have very low BDFI standard deviations for homogeneity reasons of the boundary pressure field, and a mean BDFI close to 2 to have a perfect isotropy of the boundary pressure field. Finally, the study of sound transmission realised in this article yielded to the following global trend: higher the BDFI, lower the transmission loss. This global trend is however not always verified in the case of large BDFI standard deviations.

References

[1] AFNOR. Acoustique - mesurage de l'isolement acoustique des immeubles et des éléments de construction - partie 1 : Spécifications relatives aux laboratoires sans transmissions latérales. *ISO 140-1*, 1997.

[2] C.G. Balachandran. Random sound field in reverberation chambers. *Journal of Acoustical Society of America*, 31(10):1319–1321, 1959.

[3] T. Bravo and S.J. Elliott. Variability of low frequency sound transmission measurements. *Journal of Acoustical Society of America*, 115(6):2986–2997, 2004.

[4] J.D. Chazot and J.L. Guyader. Prediction of transmission loss of double panels with a patch-mobility method. *Journal of Acoustical Society of America*, 121(1):267–278, 2007.

[5] P. Fausti, R. Pompoli, and R.S. Smith. An intercomparison of laboratory measurements of airborne sound insulation of lightweight plasterboard walls. *Building Acoustics*, 6:127–140, 1999.

[6] L.P. Franzoni. A power conservation approach to predict the spatial variation of the cross-sectionally averaged mean-square pressure in reverberant enclosures. *Journal of Acoustical Society of America*, 110(6):3055–3063, 2001.

[7] L.P. Franzoni and D.S. Labrozzi. A study of damping effects on spatial distribution and level of reverberant sound in a rectangular acoustic cavity. *Journal of Acoustical Society of America*, 106(2):802–815, 1999.

[8] F. Jacobsen and T. Roisin. The coherence of reverberant sound fields. *Journal of Acoustical Society of America*, 108(1):204–210, 2000.

[9] R.E. Jones. Intercomparisons of laboratory determinations of airborne sound transmission loss. *Journal of Acoustical Society of America*, 66(1):148–164, 1979.

[10] Y. Kubota and E.H. Dowell. Asymptotic modal analysis for sound fields of a reverberant chamber. *Journal of Acoustical Society of America*, 92(2):1106– 1112, 1992.

[11] H. Nélisse and J. Nicolas. Characterization of a diffuse field in a reverberant room. *Journal of Acoustical Society of America*, 101(6):3517–3524, 1997.

[12] M.R. Schroeder. Measurement of sound diffusion in reverberation chambers. *Journal of Acoustical Society of America*, 31(11):1407–1414, 1959.

[13] M.R. Schroeder. The schroeder frequency revisited. *Journal of Acoustical Society of America*, 99(5):3240–3241, 1996.

[14] A. Toyoda, S. Sakamoto, and H. Tachibana. Effects of room shape and diffusing treatment on the measurement of sound absorption coefficient in a reverberation room. *Acoust. Sci. and Tech.*, 25(4), 2004.

[15] R. Waterhouse. Statistical properties of reverberant sound fields. *Journal of Acoustical Society of America*, 43(6), 1968.

[16] R.V. Waterhouse and Cook R.K. Diffuse sound fields: Eigenmode and free-wave models. *Journal of Acoustical Society of America*, 59(3):576–581, 1976.

[17] R.V. Waterhouse, J.G. Ryan, and M.R. Stinson. Interference patterns in reverberant sound fields. *Journal of Acoustical Society of America*, 27(2), 1955.