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Low Frequency Sound Field Control in Rectangular Listening Rooms using CABS (Controlled Acoustic Bass System) will also reduce sound transmission to neighbour rooms.

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Summary
Sound reproduction is often taking place in small and medium sized rectangular rooms. As rectangular rooms have 3 pairs of parallel walls the reflections at especially low frequencies will cause up to 30 dB spatial variations of the sound pressure level in the room. This will take place not only at resonance frequencies, but more or less at all frequencies. A time based room correction system named CABS (Controlled Acoustic Bass System) has been developed and is able to create a homogeneous sound field in the whole room at low frequencies by proper placement of multiple loudspeakers. A normal setup using CABS is based on 2 loudspeakers like a stereo setup placed close to a wall so a plane wave is created from the front wall at low frequencies. At the opposite wall another 2 loudspeakers are placed playing the same low frequency part of the signal, but processed in order to cancel the reflection from the rear wall, and thereby leaving only the plane wave in the room. With a room size of (7.8 x 4.1 x 2.8) m. it is possible to prevent modal frequencies up to 100 Hz. An investigation has shown that the sound transmitted to a neighbour room also will be reduced if CABS is used. The principle and the understanding of why and how it works will also be discussed. CABS is controlled by a developed DSP (Digital Signal Processing) system.
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1. Introduction

Reproduction of sound is mostly taking place by using loudspeakers in small and medium sized rectangular rooms, such as ordinary living rooms, small concert halls, control rooms etc. The rectangular room shape is probably being used because of practical construction and interior reasons, but seen from an acoustical point of view the shape has some build in problems especially at low frequencies. Sound transmission in air is an almost lossless process mainly decreased by scattering and absorption by interior and hitting walls, the sound will therefore be reflected in the room many times. At low frequencies absorption is low and the wavelengths can be at the same proportion as the room or longer being 10 m at 34 Hz and 3,4 m at 100Hz.

Resonance or modal frequencies will occur in the rectangular room given by Equation 1 [1]

$$f_{n+} = \frac{c}{2}\sqrt{\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2} \qquad (1)$$

In Eq.(1) fn+ are the modal frequencies given by the dimensions of the room Lx, Ly, Lz and n_x, n_y, n_z are integers starting from 0, 1, 2 .. and c is the speed of sound in the air.
An IEC 268-13 standard listening room at Aalborg University in simulations named “Room A” with dimensions: (W x L x H) = (4,12 x 7,80 x 2,78) m has the first resonances in the length of the room at 22, 44 and 66 Hz and anti resonance frequencies at 11, 33, 55 Hz calculated from equation 1 using the dimensions of the room.

These resonance frequencies f+ exist when a sound from a source will be reflected from 2 or more walls and return to the source in phase with the source and will then be added to the source, and as an anti resonance frequency f- returning to the source in opposite phase. This will create a standing wave pattern in the room, with normally more than 20 dB spatial variations in the sound pressure level (SPL). These phenomena have been described by many such as [2] [3] [4].

These big spatial variations in SPL are especially noticeable at low frequencies because they are few and the distance between them in a room is relatively big leaving large areas in the room with a very high SPL to areas with almost no sound at all. A lot of research has been done in order to improve and optimize reproduced sound from loudspeakers in rooms, only a few are listed here [5],[6],[7]. They are basically aiming at using digital signal processing such as equalizing the signal delivered to the loudspeakers, but the problem is an acoustical problem taking place in time in the room and by the room. A PhD. project [8] took the approach first to develop a time based room simulation program using Finite Difference Time Domain (FDTD) method [9], to give the possibility to observe how the sound propagates in any point at any time in a room. From the idea that as sound propagates in time it is best to investigate and understand the problem in the time domain opposite to the frequency domain.

2. Controlled Acoustic Bass System

Having the FDTD simulation program as a tool to simulate multiple loudspeakers in a room and with different time signals, an intuitively idea occurred first being simulated and later build and understood. The system is named Controlled Acoustic Bass System (CABS) to make it easy to refer to. The idea is that by proper placement of loudspeakers close to a wall it is possible at low frequencies to create and maintain a plane wave propagating from front to rear. When the plane wave hits the rear wall another set of loudspeakers close to the wall will create a delayed version of the frontal signal but in opposite phase and with a proper gain so the reflection at the rear wall will be cancelled. A principle block diagram can be seen in figure 1. The loudspeakers must be placed close to a reflecting wall (front wall), at the height equal to half the height from floor to ceiling and at ¼ and ¾ of the width of the room from the sidewalls. The loudspeakers and their mirror sources will then create a symmetric wall of loudspeakers, producing a plane wave at low frequencies. Simulation and later building of the system has shown that by removing the reflection from the rear wall a homogeneous sound field will exist in the whole room. That is what CABS is doing. CABS has been developed from scratch on a DSP (Digital Signal Processing). [10], [11]

2.1 CABS notation

A notation is formed describing the number of loudspeakers used:

CABS Fr. F. B

Fr = number of front–wall full–range loudspeakers
F = number of front–wall low freq. loudspeakers
B = number of back–wall low freq. loudspeakers

CABS 2.0.0 is a normal stereo setup, CABS 0.2.2 will have 2 subwoofers at the front wall and 2 subwoofers at the rear wall.

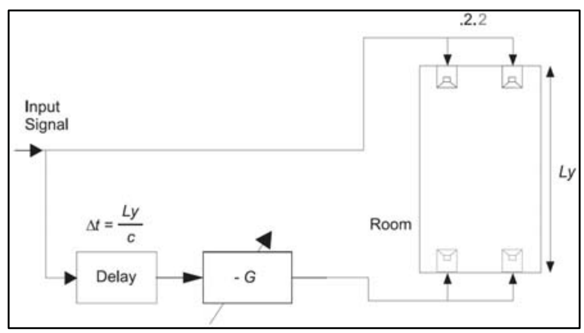

Figure 1. Block diagram of the implementation of CABS 0.2.2 or 2.0.2 to cancel the reflection from the rear wall

As CABS works in the time domain, it will work at all frequencies where the plane wave is maintained, which for room A using CABS 2.0.2 is up to 100 Hz, so CABS is restricted to only work at low frequencies. How low depends on the size of the room and the number of loudspeakers used. All modal modes in the length of the room are then removed below 100Hz. Figure 2 shows a simulation of room A with and without CABS at 44Hz which is the second resonance frequency in the length of the room n_L (+2,0,0). Figure 3 show measurements in Room A at 25 positions equally spaced within (1,92 x 1,92) m at height 1,38 m without, and with CABS turned on.

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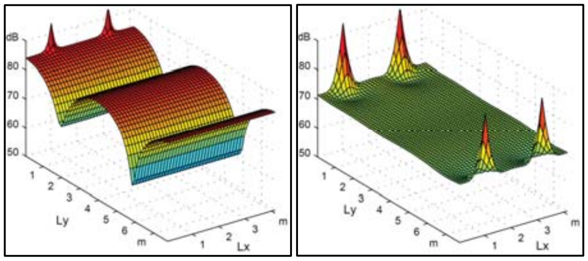

Figure 2. Simulation of 44Hz in room A .
Left: CABS off (0.2.0)   Right: CABS on (0.2.2)

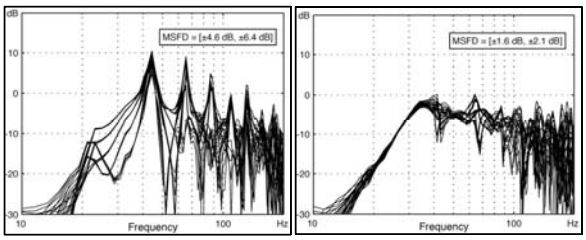

Figure 3. Measurements in Room A at 25 positions
Left: CABS off (0.2.0)   Right: CABS on (0.2.2)

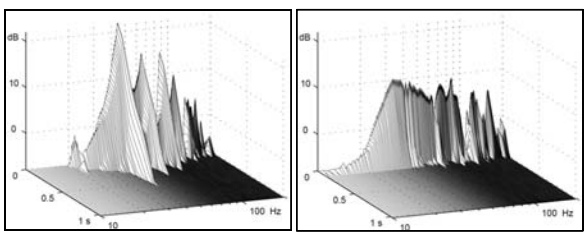

Figure 4. Measured cumulative spectral decay in room A in one point.
Left: CABS off (0.2.0)   Right: CABS on (0.2.2)

The cumulative spectral decay in figure 4 shows a long ringing decay at resonance frequencies, without CABS and a very short impulse response using CABS.

2.2 Understanding CABS

The presentation of CABS has raised these questions and comments:

1) Adding extra sound energy (using extra loudspeakers) will increase the sound pressure level in the room!

2) Wouldn't the sound pressure in neighbour rooms increase with CABS on?

3) Your measurements are in rooms with brick walls, what happens in the room and in the neighbour rooms if gypsum walls are used?

Adding more loudspeakers to a room will normally give a higher sound pressure in the room as the total acoustical power from non correlated sources will be the sum of energy from each of the sound sources. The combination P_{tot} of two pure tones with the sound pressure P_1 and P_2 in Pascal at the same frequency but with different phase is known to be as (Eq. 2).

$$P_{tot} = \sqrt{P_1^2 + P_2^2 + 2 \cdot P_1 \cdot P_2 \cdot \cos(\Theta_1 - \Theta_2)} \quad (2)$$

So for $P_1 = P_2$ and $(\Theta_1 - \Theta_2) = 0°$ P_{tot} will double (+6dB) and if $(\Theta_1 - \Theta_2) = 180°$ P_{tot} will be zero, but this will normally only happen at single points where two waves are crossing each other travelling in different directions. For two waves to cancel each other totally they need to travel in the same direction with the same radiation pattern and with precisely the same amplitude but in opposite phase. This is very seldom the case and why active noise cancelling is only possible in a small volume or at very controlled situations. That is what CABS does at the rear wall: produce a new plane wave identical to the reflecting plane wave, with the same direction but in opposite phase, and the reflection is cancelled. It is worth noticing:

If the first rear wall reflection is cancelled then there are NO reflections at all but only a plane wave travelling from the front wall loudspeaker(s) and being totally absorbed at the rear wall. A transmission through the wall will though still take place as the sound pressures at the walls are not zero.

3. Transmission to neighbour rooms

The transmission of sound from one room using CABS to neighbour rooms has not until now had the attention by the authors, as the main focus has been to improve the sound in the room with the loudspeakers named the **source room.** It is however obvious that CABS will have impact on the sound transmitted to neighbour rooms called **receiver rooms.** The hypothesis to be investigated is:

*Removing the modal frequencies in the source room and thereby the build-up effect at the walls will also reduce the energy transmitted to neighbour rooms***.**

Then it is likely to assume that the sound transmitted through a wall will also be reduced no matter which material the wall might be made of e.g. brick or gypsum, but this has to be verified.

3.1 Measurement setup

A test has been performed in real rooms using a kitchen/meeting room at the university as the source room and a neighbour office and a hall as the receiver rooms (see figure 5). The walls to the receiver rooms are light gypsum walls made of double layer of 13 mm gypsum at light metal frames, and 100 mm rock wool isolation. There is no knowledge or measurements being made showing how the flange transmission and transmission through the ventilation system and through cable boxes add to the wall transmission (it might be significant).

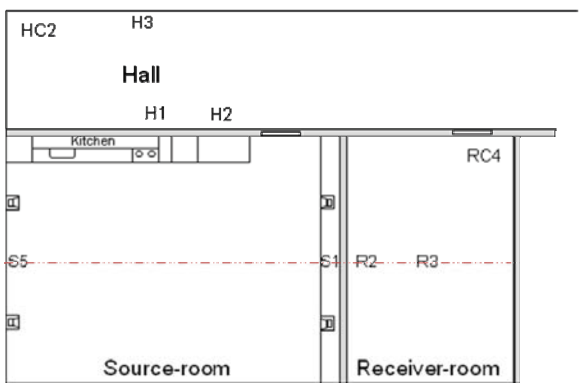

Figure 5. The 3 rooms used for measurements.

Table 2 Room dimensions and Modal frequencies

Modal Freq.	Source room	Receiver room	Hall
44 Hz	L2+ ,0,0	L1+ ,0,0	
55Hz	L3- ,0,0		
60 Hz	0,W2+,0	0,W2+,0	
66Hz	L3+ ,0,0	L2- ,0,0	
Length	7,71m	3,85m	>30m
Width	5,70	5,70	2,71
Height	2,76	2,76	2,76

The Source room has a kitchen at one side wall, and windows at the other side wall, it also has a 0,33 m lowered absorbing ceiling. In the middle of the room a long table is placed and 24 chairs. The end wall at position S5 is an empty brick wall, beside 3 paintings. The other end wall at S1 is a gypsum wall with shelves at almost the entire wall and filled with books.

The Receiver room is an office with 4 working positions with tables and some shelves at the wall next to the source room. It has a concrete ceiling and one brick wall.

The **Hall** is empty with a brick wall opposite to the gypsum wall to the source room. All rooms have concrete floors with linoleum cover.

The rooms chosen are far from perfect, but they are real rooms, and no attempt has been made to improve them. CABS (2,0.2) has been set up and automatic calibrated. The 4 loudspeakers used are high quality full range loudspeakers Genelec 1031A. The dimensions of the receiver room and the source room do unfortunately have some identical modal frequencies, (see table 2) The signals chosen for the test has been 4 single sinusoidal frequencies with same amplitude at: 44, 55, 60 and 66Hz and a band limited noise signal (MLS signal from 20 to 100Hz) at a lower level. The single frequencies are 2 axial resonance frequencies (44 and 66Hz), and one axial anti resonance frequency (55Hz) for the source room.

All measurements have been made using a B&K 2238 sound level meter set to one octave band at 63 Hz and 5 sec. average. Measurements were made close to walls at 1,4 m height and in corners at the floor as these points will reflect the maximum levels in a room [12], especially at modal frequencies. The sound level meter was placed at each measurement point and going through all 5 signals one by one with CABS turned off (no signal to the rear loudspeakers) and then repeating it all with CABS turned on.

The transmission through the wall as such has not been the focus in itself, but more the change in the sound transmission. The difference in SPL in dB (CABS off – CABS on) is calculated and positive difference in dB indicates the decrease in level with CABS on, and a negative difference indicates an increase in level with CABS on. Measurements were made with CABS having the rear loud-speakers at the wall next to the receiver room (S1)

4. Measurement results

The measurements in the **receiver** room can be seen in table 3 and figure 6. Although the reflection at the rear wall has been cancelled in the source room at S1 using CABS, reflections will still take place on the transmitted sound in neighbour rooms. This can be seen at 44Hz which is the first resonance frequency for the receiver room with high SPL build up at the wall (R2).

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The difference in sound pressure level at the wall (R2) and in the middle of the room (R3) has been measured to 20dB. In the source room 55Hz is an anti resonance frequency which will normally give a lower level in the room but by using CABS the resonance and anti resonance frequencies will no longer exist, so the SPL will increase at anti resonances in the source room, and is thereby also expected to increase in the neighbour rooms, which can also be seen by the measurements with a negative change in decibel in table 3 and 4. The same is seen at 60 Hz which is not a modal frequency in the length of the source room. At the resonance frequencies 44 and 66Hz for the source room the level in both the source room and the receiver room has been reduced around 10 dB using CABS. Change in the front/rear direction of the loudspeaker in the source room gives a bit different response in the receiver room, but the tendency is the same.

Table 3: Measured SPL in dB in the Source and the Receiver rooms with CABS OFF and ON

Freq.	44Hz	55Hz	60Hz	66Hz	Noise
S1 OFF	89,5	85,5	88,0	94,5	73dB
S1 ON	78,5	82,0	83,0	80,5	67,5
S1 diff.	11	3,5	5,0	14,0	5,5
R2 OFF	86,5	72	69,5	69,5	61
R2 ON	75	73,5	71	60	55
R2 diff.	11,5	-1,5	-1,5	9,5	6
R3 OFF	66	68	70,5	70,0	52,5
R3 ON	55,5	69,5	74,5	63,0	49,5
R3 diff.	10,5	-1,5	-4,0	7,0	3,0
RC4OFF	86,0	68,0	69,5	74,0	64,0
RC4 ON	76,5	70,0	77,0	64,0	59,5
RC4diff	9,5	-2,0	-7,5	10,0	4,5

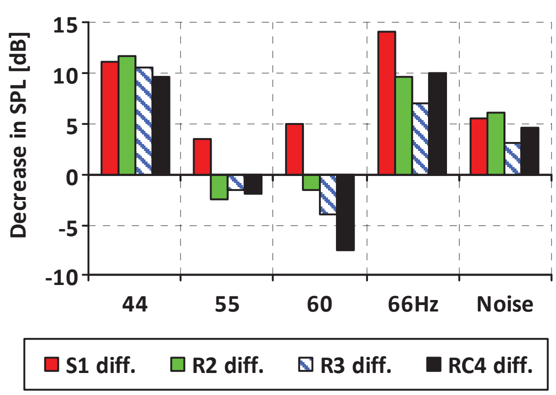

Figure 6: Change in SPL in Receiver Room with CABS ON

Measurements in the **hall** can be seen in table 4 and figure 7 with the same signal in the source room S1 as in table 3. The measurements are made in 4 different arbitrary positions: H1= 3,6 m H2 = 4,8 m and H3 = 3,3 m from the end wall all at height 1,4 m and HC4 which is 5 cm from a corner at the floor. H1 and H2 are at the wall next to the source room and H3 at the opposite wall. As the hall is quite long and narrow, strong standing waves are not expected in the length of the room. The measurements in the hall will follow the distribution in the length of the source room with large differences in maximum and minimum SPL with CABS off. With CABS on an even SPL in the source room will be achieved and will increase SPL at anti resonance frequencies which can explain the increment in 7 dB at H2 at 55 Hz.

Table 4: Measured SPL in dB in the Hall with CABS OFF and On

Freq.	44Hz	55Hz	60Hz	66Hz	Noise
H1 OFF	79,5	65,5	69,0	80,0	56,0
H1 ON	71,5	66,5	72,5	74,5	54,5
H1 diff.	8,0	-1,0	-3,5	5,5	1,5
H2 OFF	77,5	52,0	61,0	80,0	54,5
H2 ON	70,5	65,0	59,5	65,5	52,0
H2 diff.	7,0	-7,0	1,5	14,5	2,5
H3 OFF	78,5	63,0	70,0	82,0	57,0
H3 ON	71,0	70,5	77,0	77,0	55,5
H3 diff.	7,0	-7,5	-7,0	5,0	1,5
HC2OF	76,5	75,5	77,5	87,0	63,0
HC2ON	70,5	76,0	77,5	81,0	60,0
HC2diff	6,5	-0,5	0,0	6,0	3,0

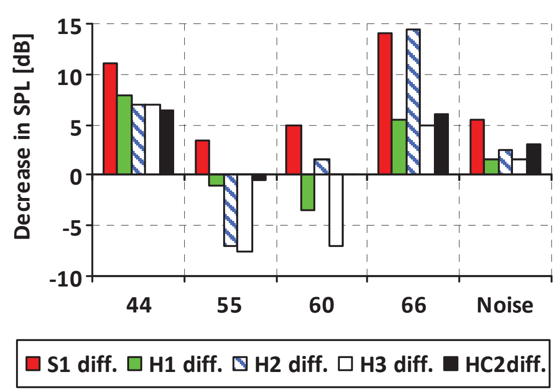

Figure 7: Change in SPL in Hall with CABS ON

5. Discussion

In general, multiple reflections will happen in both the receiver room and in the hall both with CABS on and off, but the variations at different frequencies is less with CABS on. It does not make sense to average all measurements to one number for each room, though it can be done by finding the total energy level for the 4 different frequencies as non correlated sources with CABS on and off. This number will always be close to the maximum level at a resonance frequency. If a single frequency is being played it is of interest how that frequency will be perceived in the source room as well as neighbour rooms.

At axial modal frequencies the sound pressure will increase significantly at the reflecting walls, and the built up gain G will follow equation 3 [13] with α being the energy absorption coefficient at both walls and N is then number of reflection divided by two and $r = (1-\alpha)$ and for $N \rightarrow \infty$

$$G = P_N / P_0 = (1 + r + r^2 + r^3 + \quad + r^N) \approx 1/\alpha \quad (3)$$

For the axial mode in the length of the room and with α = 0,1 at both reflecting walls the built up gain G will be 20 dB.

6. Conclusion

With proper placement of 2 subwoofers or 2 full range loudspeakers at a (front) wall a plane wave will be created up to 100 Hz for a room with a 5,7 m width. The reflection at the rear wall can be removed by a similar arrangement of loudspeakers at the rear wall playing the same low frequency signal (<100Hz) as at the front, but in opposite phase and proper amplitude and delayed the same as the original source $\Delta t \approx$ (Length of the room) / (the speed of sound). Having removed the reflection from the rear wall will remove the modal frequencies in the length of the room. This will give a homogeneous sound pressure in the whole room up to 100Hz and a very short impulse response (see Figure 4) – Therefore no booming bass.

Measurements at neighbour rooms with gypsum walls have shown around 10 dB SPL reduction at resonance frequencies but an increase of a few dB at anti resonance frequencies but at a lower level. When using broadband noise with CABS the level has been reduced (1,5 – 5 dB) in all measurements points in neighbour rooms.

Listening to music being played instead of a single frequency clearly shows that with CABS the booming bass is removed in the source room and clearly reduced in the neighbour rooms. Maybe not surprisingly CABS is not only improving the sound in the source room but will also reduce the sound transmitted to neighbour rooms.

References

[1] H. Kuttruff, “*Room Acoustics”*, 3th. Ed. E \& FN Spon. (1999)

[2] P. A. Nelson and A.R.D. Curtis S. J. Elliott and A.J. Bullmore, ”The Active Minimazation of Harmonic Enclosed Sound Fields Part I - III” *Journal of Sound and Vibration (1987) 117 (1)*

[3] J.A.S. Angus “The Behaviour of Rooms at Low Frequencies” presented at the *102nd Convention of the Audio Engineering Society*, preprint 4421. (March 1997)

[4] A. R. Groh, “High-Fidelity Sound System Equalization by Analysis of Standing Waves,” *J. Audio Eng. Soc.*, vol. 22, pp. 795-799 (December 1974)

[5] T. Welti and A. Devatier “Low-Frequency Optimization Using Multiple Subwoofers” *J. Audio Eng. Soc.* Vol. 54, No 5 pp. 347-364 (May 2006)

[6] J. A. Pedersen and K. Thomsen. “Fully Automatic Loudspeaker Room Adaptation – the Room Perfect system” The proceedings of the AES 32nd International Conference Hillerød Denmark pp 11–20 (September 2007) ISBN978-0-937803-60-8

[7] P. Antsalo and M. Karjalainen and A. Mäkivirta and V. Välimäki. “Comparison of Modal Equalizer Design Methods” presented at the *114th Convention of the Audio Engineering Society,* preprint 5844. (March 2003)

[8] A. Celestinos “Low Frequency Sound Field Enhancement System for Rectangular Rooms Using Multiple Loudspeakers” Ph.D Thesis *Aalborg University*, *Denmark*, (April 2007)

[9] A. Celestinos and S. B. Nielsen, “Low- Frequency Loudspeaker-Room Simulation Using Finite Difference in the Time Domain- Part 1: Analysis” *J. Audio Eng. Soc.* vol. 56, No. 11 pp. 772-786 (October 2008).

[10] A. Celestinos and S. B. Nielsen, “Controlled Acoustic Bass System (CABS) A Method to Achieve Uniform Sound Field at Low Frequencies in Rectangular Rooms” *J. Audio Eng. Soc.* vol. 56, No. 11 pp. 915-931 (November 2008)

[11] S.B. Nielsen: “Time Based Room Correction System for Low Frequencies Using Multiple Loudspeakers” The proceedings of the AES 32nd International Conference: DSP for Loudspeakers, Hillerød Denmark pp 30 – 39 (September 2007) ISBN978-0-937803-60-8

[12]. S. Pedersen, H. Møller and K Persson-Waye: “Indoor measurements of noise at low frequencies-problems and solutions”. Journal of Low Frequency Noise Vibration and Active Control. Vol. 26, Nr. 4, 2007, s. 249-270.

[13] S. B. Nielsen and A. Celestinos “Low Frequency Sound Field Control for Loudspeakers in Rectangular Rooms using CABS (Controlled Acoustical Bass System)” presented at the 14th International Meeting on Low Frequency Noise and Vibration and its Control, Aalborg, Denmark (June2010) ISBN978-87-92328-33-5

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