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Low Frequency Sound Reproduction In Irregular Rooms using CABS (Control Acoustic Bass System)

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Summary
Early investigations on low frequency sound reproduction in rectangular rooms using CABS (Controlled Acoustic Bass System) have shown good results on simulations and measurements in real rooms. CABS takes the advantage of having a rectangular room with parallel walls. By using two low frequency loudspeakers well positioned at the end of the room a virtual array is formed propagating plane waves along the length of the room in one direction. This will correct the sound field distribution in the room. When plane wave arrives to the end wall two more loudspeakers have to be placed connected with the same signal in counter phase and with a delay corresponding to approximately the length of the room. This is to cancel the reflection and maintain the plane wave propagating along the room. Real life rooms are not necessary rectangular and can be of different shapes. In this paper simulations of an irregular room model using the FDTD (Finite Difference Time Domain) method has been presented. CABS has been simulated in the irregular room model. Measurements of CABS in a real irregular room haven been performed. The performance of CABS was affected by the irregular shape of the room due to the corner diffracting the plane wave. Nevertheless CABS improved spatial and magnitude deviations.

PACS no. 43.55.Jz, 43.55.Ka

1. Introduction

Full range loudspeakers are typically used for high fidelity sound reproduction. These systems are typically placed in small or medium size listening spaces e.g. listening rooms, control rooms for studios, home theater rooms, cars etc. At the listener position the spectral response of the loudspeaker is extremely modified over the full frequency range. This is due to the combination of the direct sound and the multiple reflection, diffraction and scattering of sound at the walls and different objects in the sound path. Especially at low frequencies the sound level distribution over the room will experience differences of more than 20 dB. Mid and high frequencies can be controlled by acoustic treatment of the room, but when the loudspeaker radiates longer wavelengths e.g. from 10 m to 3 m (34 Hz – 114 Hz) the acoustic solutions become unpractical. To tackle these problems several approaches have been investigated by a number of authors. Some efforts have been conducted towards the analysis and optimization of the placement of the loudspeakers in the room [1, 2]. Other approaches have been directed to control the acoustic radiation power of the loudspeaker [3], by means of digital signal processing but most of the investigations have been conducted on the correction of the loudspeaker–room response by digital filters [4, 5]. Another approach also making use of digital filters presented in [6] has been implemented in a low frequency sound reproduction chamber at Aalborg University. This approach is based on the simulation of a plane wave in a small room by the use of 2 x 20 loudspeakers build into two opposite walls. Every loudspeaker is controlled by an independent amplification channel and a Finite Impulse Response (FIR) filter. Differently from the solution proposed in Santillan's work the system presented in this paper utilizes less loudspeakers and can be implemented in larger rooms with a much simpler setup. The idea of the Controlled Acoustic Bass System (CABS) is to built a plane wave traveling towards the opposite wall with the front loudspeakers by optimizing their placement. This will produce uniform

Table I. Absorption coefficient used in the simulation model.

Wall	A	B	C	D	E	F	G	Floor	Ceiling
α	0.09	0.09	0.12	0.18	0.09	0.18	0.09	0.06	0.16

sound field distribution only if the reflection is then cancelled out by similar loudspeakers at the rear wall with a delayed version of the signal but in anti–phase maintaining the plane wave along the room [7, 8, 9]. The main goal of this paper is to evaluate CABS in a real irregular room by simulations and measurements.

1.1. Room simulation model

By utilizing the Finite Differences in the Time Domain method (FDTD) the room simulation model is constructed in MATLAB [8, 10, 11]. This model solves the linear lossless wave equation applying the relation between the particle velocity (lossless wave equation) and the acoustic pressure (force equation). In this fashion these two equations are combined to compute the acoustic pressure produced by a number of sound sources in the entire enclosure. The boundary conditions are defined by calculating the wall impedance from estimated absorption coefficients α and the normal component of the particle velocity to the wall. The sound field produced by multiple loudspeakers in a rectangular room can be calculated. Moreover irregular room shapes can also be modeled [8]. In this method the calculations are performed directly in the time domain, and therefore the pressure amplitude and the particle velocity are always available for analysis and visualization purposes. In addition the impulse response of the transfer function from a number of sound sources to desired positions in the room can be obtained.

The virtual room model can be seen in Figure 1 indicating the different walls with letters from A to G. To discretize the room a 12 cm cell size and a sampling frequency $f_s = 8000$ Hz has been used in the simulation model. The loudspeakers are modeled as vented box type ocupying 3 x 3 x 3 cells for each loudspeaker. Two pressure points in front of the box corresponding to the driver and vent are defined by two impulse responses. These impluse responses are calculated from a measurement of the particle velocity of a vented box type loudspeaker with a laser vibrometer. The absorption coefficient for each wall is shown in Table I. The impulse response in 5 x 5 = 25 virtual microphone positions of a listening area of approx. 2 x 2 m in the room is recorded. Aditionally a pure tone can be produced by the loudspeaker and the sound pressure level disribution can be calculated in the horizontal plane at a desired height in the room.

1.2. Loudspeaker–room response simulations

The response of the loudspeaker is highly influenced by the multiple reflections of sound on the walls of the room. In some sections of the room there can be differences of more than 20 dB in amplitude. In Figures 2, 3 and 4 variation in sound pressure level distribution can be observed on three different loudspeaker positions in the room.

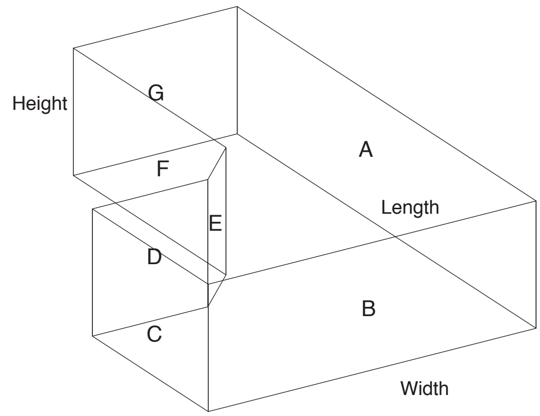

Figure 1. Irregular virtual room model. Length = 10.68 m. Width = 7.32 m. Height = 2.64 m.

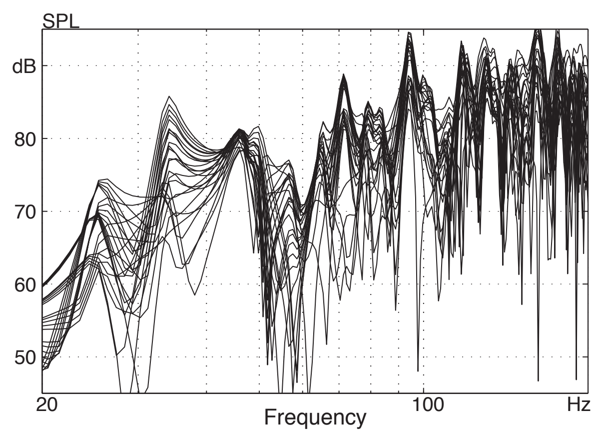

Figure 2. Frequency response of the transfer function at 25 virtual microphone positions throughout the listening area. Loudspeaker placement: 1.50 m from wall A and 1.02 m from wall B, 1.26 m height.

1.3. Room–width sound field correction

In a rectangular room the sound field distribution along the width of the room can be even up to 100 Hz by using two front loudspeakers placed at one end of the room each at 1/4 of the width from side walls, and at 1/2 height of the room [7]. In this way an infinite horizontal array is formed constructing plane waves traveling along the room in one direction. This effect

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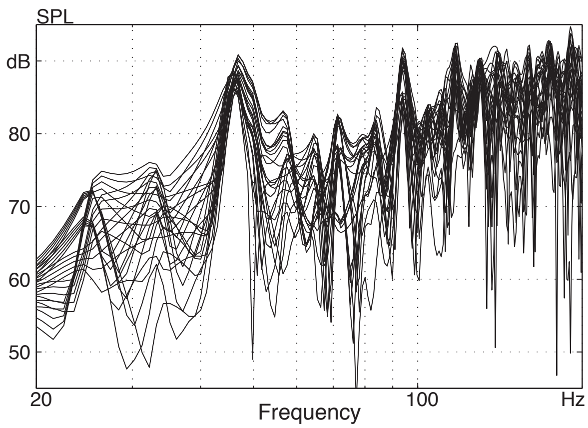

Figure 3. Frequency response of the transfer function at 25 virtual microphone positions throughout the listening area. Loudspeaker placement: 1.26 m from wall C and 3.18 m from wall B, 1.26 m height.

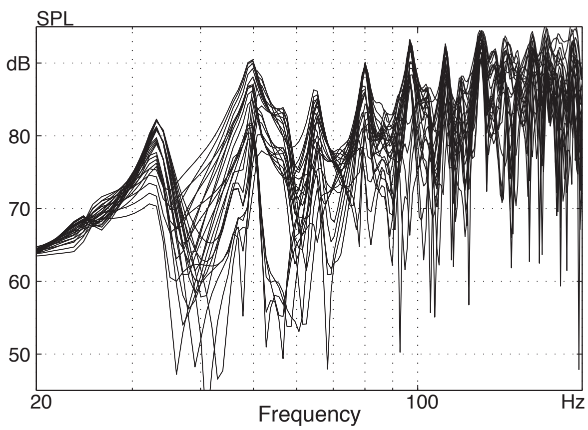

Figure 4. Frequency response of the transfer function at 25 virtual microphone positions throughout the listening area. Loudspeaker placement: 0.90 m from wall A and 1.50 m from wall G, 1.26 m height.

will cause even sound pressure distribution along the width of the room at a single frequency. But still great spectral (magnitude) variation will occur at single positions in the room.

1.4. Controlled Acoustic Bass System (CABS)

Once the plane wave is formed then the reflection of the back wall has to be acoustically cancelled. This is done by adding two extra loudspeakers with proper gain at the rear wall with the same signal as the front loudspeakers but in counter phase and with a delay related to approximately the length of the room, see Figure. 5. This can be achieved e.g. with two subwoofers at the front wall and two sub woofers at the rear wall. Alternatively two full range loudspeakers can be used at the front wall and two full range loudspeakers at the rear wall. In the later case a low pass filter has to be connected before CABS to filter out the mid and high frequency content.

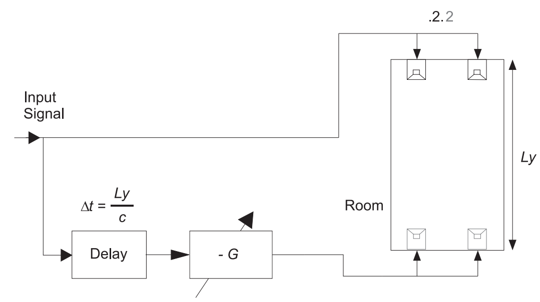

Figure 5. Block diagram of CABS .2.2 system to minimize the reflection of the rear wall, G its a factor according to the damping characteristics of the room and the attenuation of sound by the air.

1.4.1. CABS notation

A notation for CABS is introduced to easily indicate the number of loudspeakers used and their rough positions:

$$\textbf{CABS Fr.F.B} \tag{1}$$

where

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

To indicate e.g. a stereo setup of two full range loudspeakers the notation 2.0.0 is used. The notation 0.2.2 indicates a configuration with two low frequency loudspeakers at the front wall of the room and two low frequency loudspeakers on the back wall.

1.5. CABS in irregular rooms

It has been shown that CABS works fine in small and middle size rectangular rooms obtaining good results below 100 Hz depending on the size of the room. But in a irregular room the effect of CABS might be deteriorated by diffraction of sound at the corner of the room and addition of reflected sound to the sound field constructed by CABS. Another problem is that the reflection at the rear wall may not be completely removed. Since CABS 2.0.2 is only able to cancel out one reflection e.g. at the rear wall. Therefore diffracted sound would propagate and reflect along the width+length of the room destroying the sound field formed by CABS 2.0.2. The fundamental questions here are:

1. How much this room shape would deteriorate the effect of CABS?
2. What setup of CABS is optimal in an irregular room?

To answer these questions simulations of CABS 2.0.2 in an irregular room model have been calculated.

1.6. Simulations of CABS

Three scenarios have been simulated in the irregular virtual room model. In each setup CABS 2.0.0 and CABS 2.0.2 is simulated. In Setup I the front loudspeakers are located as close as possible to wall A facing wall C, one at 1.02 m from wall B and one at 3.18 m from wall B. The rear loudspeakers are at wall C facing wall A at the same distances from wall B. Since the baffle is also included in the simulation the acoustic centre of the loudspeakers are 54 cm from the wall. In Setup II the loudspeakers are at the same position as in Setup I but the front loudspeakers are then at wall C and the rear ones are now at wall A instead. In Setup III the front loudspeakers are at wall G each at 0.90 m from walls A and F respectively. The rear loudspeakers are at the same positions as front loudspeakers but at the opposite wall B. In all setups

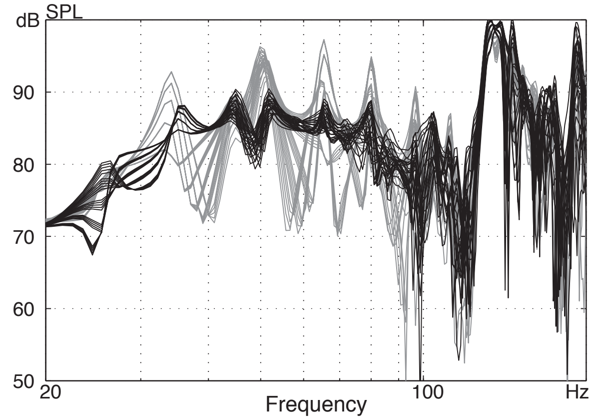

Figure 8. Simulation of CABS in irregular virtual room Setup III. Frequency responses of transfer function at 25 virtual microphone positions throughout listening area; Grey curves, CABS 2.0.0. Black curves, CABS 2.0.2.

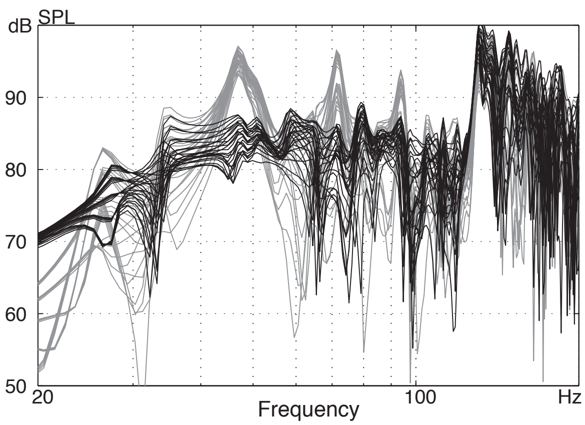

Figure 6. Simulation of CABS in irregular virtual room Setup I. Frequency responses of transfer function at 25 virtual microphone positions throughout listening area; Grey curves, CABS 2.0.0. Black curves, CABS 2.0.2.

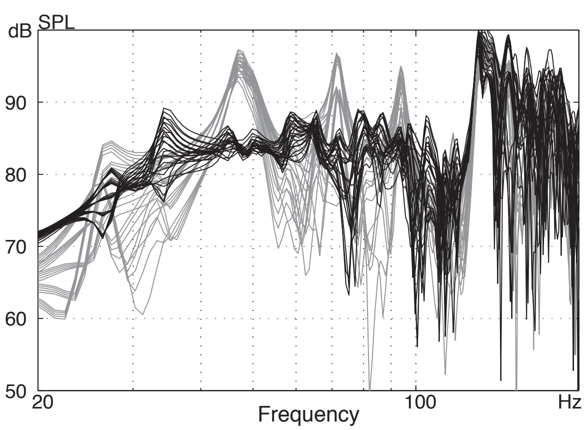

Figure 7. Simulation of CABS in irregular virtual room Setup II. Frequency responses of transfer function at 25 virtual microphone positions throughout listening area; Grey curves, CABS 2.0.0. Black curves, CABS 2.0.2.

the loudspeakers are at 1.26 m height. In Figures 6, 7 and 8 result of simulation of CABS 2.0.2 in the three setups are shown. In Figure 9 the sound pressure level distribution resulted from simulation of CABS 2.0.0 and CABS 2.0.2 in the three setups is shown.

1.7. Measurements of CABS

A laboratory room has been utilized to set up and evaluate CABS 2.0.2. The laboratory has a rectangular room chamber inside dedicated to electro–magnetic measurements. This chamber gives the irregular shape needed. The room dimensions are approx. the same as the simulation being: Length = 10.63 m. Width = 7.37 m. Height = 2.70 m. The damping of the chamber walls is lower than the rest of the other walls. The ceiling is a false ceiling and the floor is concrete much harder than the rest of the walls. Different equipment and furniture as lab tables, chairs etc was in the room when measurements were performed. The internal corner (wall E) is actually a metal door for the chamber. The placement of the loudspeakers was compromised by some of the furniture and equipment in the room. In Setup I and II the loudspeakers at wall C and A were not place as optimal as in the simulations having a misplacement of about 30-50 cm from the optimal position. The loudspeakers were placed facing the room and the acoustic centre of the loudspeakers was located approx. 50 cm from front–wall and rear–wall respectively. In Setup I and II the loudspeakers were set at a height of 1.26 m and in Setup III at a height of 1.38 m.

The loudspeakers utilized are compact full-range vented type with a 16.5 cm woofer and 16 liters cabinet volume. The frequency response of the loudspeaker is 46 Hz - 25 kHz, ± 3 dB. The sensitivity is 89 dB at 2.83 V/m. The delay and gain was implemented in a professional audio DSP unit for loudpeaker management. A 4th order low pass filter was

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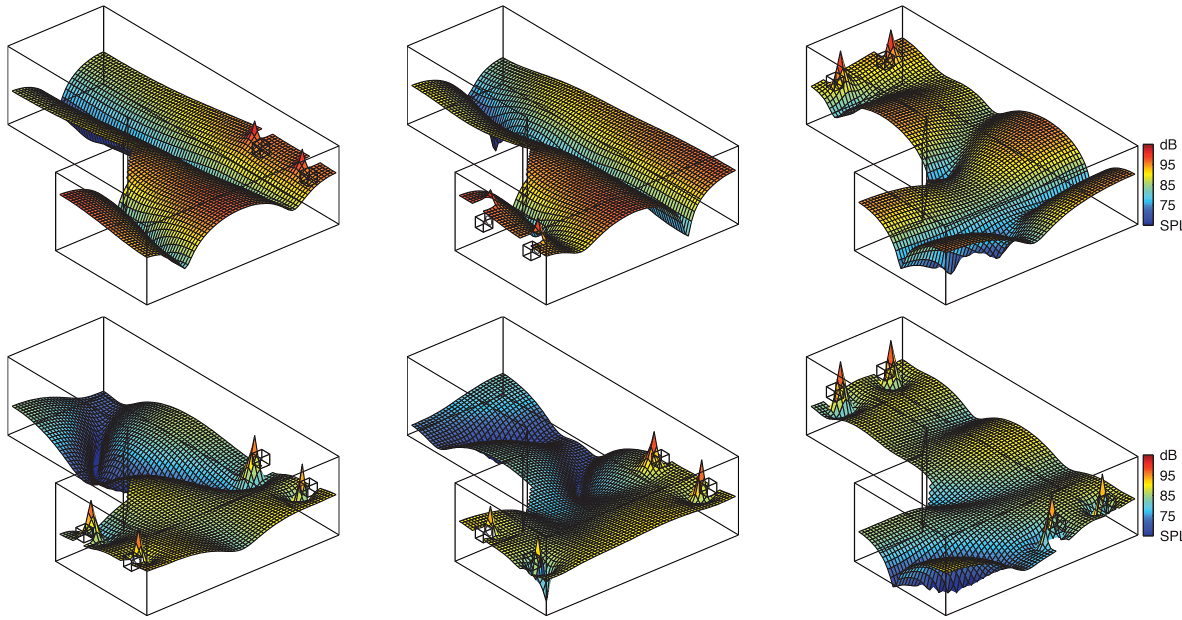

Figure 9. Sound pressure level distribution resulting from the simulation of the irregular virtual room calculated on a plane at a height of 1.26 m. Left column, Setup I 46 Hz (modal frequency). Middle column, Setup II 46 Hz (modal frequency). Right column, Setup III 48 Hz (modal frequency). Upper row using only the front loudspeakers CABS 2.0.0. Lower row using CABS 2.0.2.

used at 109 Hz (in Setup I and II) and at 200 Hz (in Setup III) to filter out the mid and high frequencies. Due to the present furniture and lab equipment only 8 to 10 microphone positions scattered around the listening area about 1.5 to 4 meters from the front loudspeakers were measured in every setup. In Setup III ten microphone positions were set in pairs with a separation of 1.25 m from each other along the width of the room and 1 m separation from each pair along the length of the room starting at 2.6 m from front loudspeakers.

The parameters of the system (delay and gain of the rear loudspeakers) were fine-tuned empirically to achieve the best performance. A selective frequency sweep with a resolution of 0.49 Hz was utilized to measure the frequency response of the loudspeakers and the room with CABS. In Figures 10, 11 and 12. the frequency response measurements at the microphone positions with CABS 2.0.0 compared to CABS 2.0.2 are shown for each Setup.

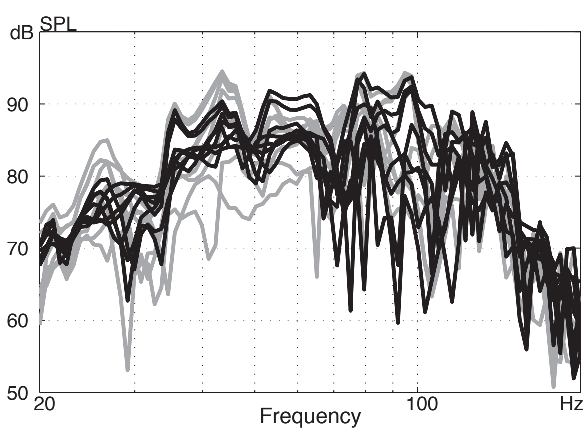

Figure 10. Measurements in irregular room Setup I. Frequency responses of transfer function at 8 microphone positions throughout listening area; Grey curves, CABS 2.0.0. Black curves, CABS 2.0.2.

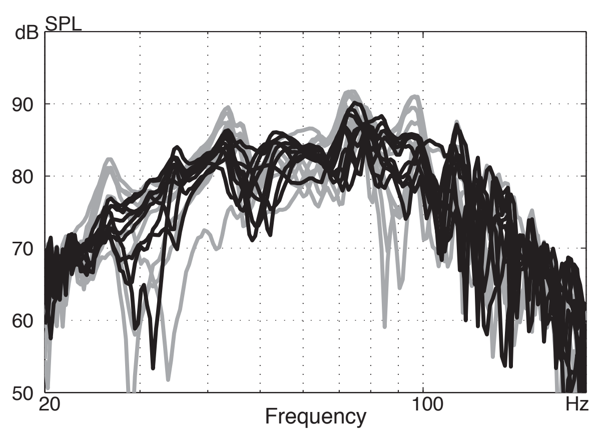

Figure 11. Measurements in irregular room Setup II. Frequency responses of transfer function at 8 microphone positions throughout listening area; Grey curves, CABS 2.0.0. Black curves, CABS 2.0.2.

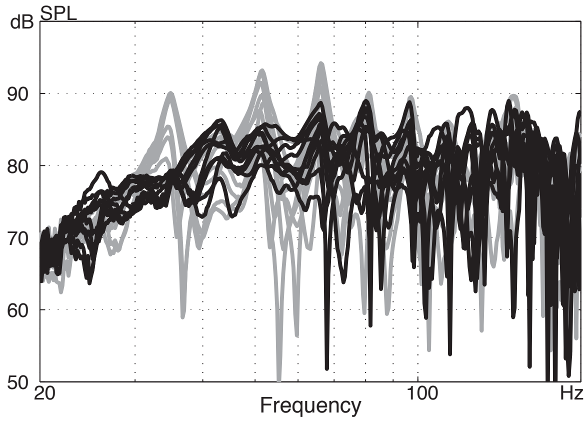

Figure 12. Measurements in irregular room Setup III. Frequency responses of transfer function at 10 microphone positions throughout listening area; Grey curves, CABS 2.0.0. Black curves, CABS 2.0.2.

2. DISCUSSION

From the three configurations in the irregular room CABS 2.0.2 in Setup III presents the best results. Setup II presented satisfactory results. In Setup I CABS 2.0.2 presented poor results though the simulation result is not as bad as the result in the real room. Although it is evident that the reflection at the rear wall C was reduced the spatial distribution could not be evened. This is because wall G is too far from the front loudspeakers and the horizontal array is not constructed properly. For Setup I the reflection of the metal door (wall E) is quite strong and destroys the sound field produced by CABS 2.0.2. It was observed that the sound pressure level at some frequencies is higher close to wall B. In Setup I and II the cancelation of the rear–wall reflection is achived but then the influence of the room resonances corresponding to the length and lenght+width of the room are still evident. In Setup III the plane waves are well formed and traveling in one direction until they arrive to the corner inside the room then waves start to diffract towards not only rear wall B but also wall C. These reflections will return an disturb the sound field. In Setup III apparently the rear wall reflection can be reduced but only good results can be seen below 70 Hz.

3. CONCLUSIONS

Three setups in the irregular room have been simulated and measured. CABS 2.0.2 presented best results in Setup III and satisfactory results in Setup II. In Setup I CABS 2.0.2 presented poor results. Simulations and measurements suggest that extra loudspeakers may be utilized e.g. in case of Setup II at wall G in counter phase with front loudspeakers with a delay correspondent to the traveling distance from wall C to G or width + length and proper gain. The same might be done for Setup III with an extra loudspeaker at wall C and/or extra loudspeakers along wall B. When CABS 2.0.2 is set up in a irregular room in configurations with front loudspeakers at 1/4 of the width and at one end of the room the sound field at low frequencies can be improved. These configurations would form plane waves with the side walls having variations of about ± 6 dB. This is a significant improvement compared to the resulting sound field from a single loudspeaker in a irregular room that would give about ± 20 dB deviations or the typical stereo setup that would give deviations of ± 15 dB.

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