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Using Wave Based Geometrical Acoustics (WBGA) to investigate room resonances

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Room modes can easily be calculated for simple room shapes using analytical equations. When room shapes are irregular, room wave phenomena can be calculated using numerical methods such as Finite Element Method or similar which are computationally heavy. Conventional geometrical acoustics, using plane wave propagation and sound absorption coefficients, fail to calculate room resonances. In contrast, Wave Based Geometrical Acoustic, WBGA, based on the image source method, spherical wave propagation, impedance discontinuities and sound pressure summation, can accurately simulate room resonances both in the frequency and spatial domain. This paper presents room resonances simulations using the WBGA and compares them to measured data.

1 Introduction

When a source emits sound in a room, normal modes of vibration are excited, each responding according to the source-receiver position, room shape and surfaces materials. Above a certain frequency [1] these modes seize to have a phase relationship due to sound scattering thus the field is said to become diffused, meaning isotropic and homogeneous. In contrast, below the Schroeder frequency, the excited sound field has precise phase relationships among the modes of vibration thus forming standing waves. Until the advent of computers, the study of standing waves or resonances could only be performed using analytical solutions applicable only to symmetrical rooms. Currently, numerical methods (BEM, FEM and others) heavy in computational time, can be used to analyse room resonances in asymmetrical rooms with finite surface impedances. Another method used in room acoustics and popular in the acoustical community is Geometrical Acoustics (GA). This is based on the concept derived from Optics that wave fronts travel in straight lines [2]. The use of GA in room acoustics has been proven to be a very useful tool. However, the lack of phase information in sound rays due to sound propagation discontinuities, limits the range of applications which GA can be used. In contrast, Wave Based Geometrical Acoustics (WBGA) [3] extends GA to account for impedance surfaces, complex pressure summation, spherical wave propagation, and with the use of the image source method, can account for the phenomena of reflection, diffraction, refraction, transmission and others. It has been shown [3] that in rectangular rooms the WBGA is as accurate as the BEM. This paper presents calculations of room resonances in a rectangular room using Olive Tree Lab-Suite [4], a sound propagation software application which employs WBGA in a 3D simulation environment, and compares them to sound measurements. The sound measurements were taken in the TV room of the first author. Results are presented both in the spatial and frequency domain. As far as the authors are concerned, they are not aware of many such studies other the ones found in these references [5,6]. The difference between this study and the others is that the room under investigation includes furniture, such as a sound absorbing sofa, both for measuring and simulations purposes. This paper is divided into the following parts. Section 2 provides a comparison between published data and OTL-Suite (a WBGA software) results for validation purposes. It is followed by a description of the procedure followed for sound measurements and 3D simulation. Section 4 provides the measured results while Section 5 a comparison between measured and simulated results in the frequency and spatial domain. This is followed by a section with discussion and conclusions.

2 Validating Olive Tree Lab-Suite

Recently, the second author has prepared a trilogy of papers dealing with WBGA. One of the papers [7] validates Olive Tree Lab-Suite in terms of sound reflection in calculating room resonances, based on the work of R.H.Bolt [5]. The second [8] validates Olive Tree Lab-Suite (OTL-Suite) in terms of sound diffraction in calculating the seat dip effect based on the work of Ando [9]. A short description of the findings are presented here.

2.1 Room Resonances - Calculation vs experimental results

For validation purposes, Figures 17 and 18 of Bolt's paper [5] were used. In that paper, Bolt experimented with a small scale room, essentially two-dimensional, with non-parallel walls. The height of the model was small compared to the sound wavelength used therefore no normal modes with vertical components could develop. The figures below show in colour the results calculated using Wave Based Geometrical Acoustics (WBGA) by means of OTL-Suite. The 3D model used in the calculations was a full scale (multiplied by a factor of 10). Superimposed are the experimental results, courtesy of the Journal of The Acoustical Society of America.

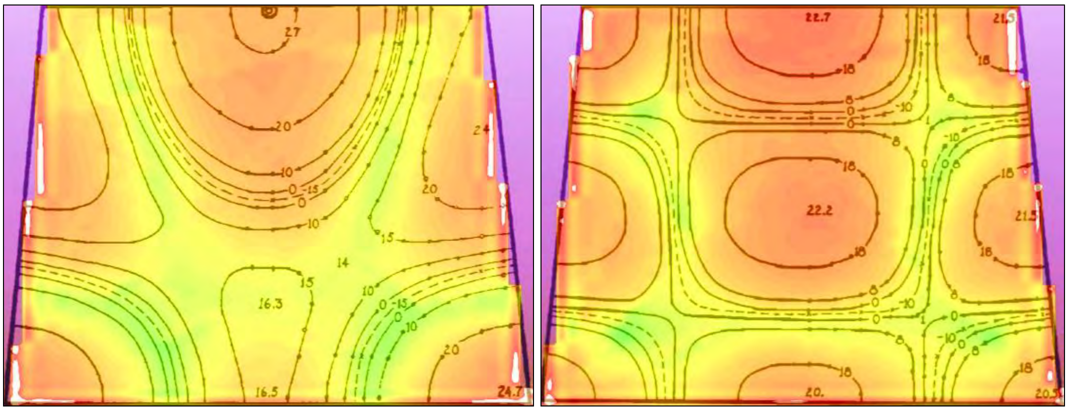


Figure 1: Mapping on the left is at 1721 Hz (experimental data, courtesy of the JASA) while the coloured mapping in the 1/3rd octave band of 200 Hz. The mapping on the right is at 2302 Hz (experimental data) while the coloured mapping in the 1/3rd octave band of 250 Hz. In red high sound levels and in green low [5].

From the figure above, one may conclude that there is adequate correspondence between measurements and calculations especially if one takes into consideration the following:

- During the experiments only a single frequency was used while for the simulation, 4 frequencies within the 1/3rd octave band (mapping in 1/12th octave).
- The 1/3rd octave bands centre frequencies values do not correspond to the frequency values reported by Bolt.
- As reported by Bolt in the same paper, microphone positioning was very sensitive to sound level changes. This means that frequency deviations (wavelength) cause equally abrupt changes in level.

2.2 Validation of the WBGA in simulating Seat Dip Effect

The Seat Dip Effect is a well-studied phenomenon of low frequency sound attenuation at grazing incidence over surfaces characterized by roughness, either of periodic or non-periodic in structure [10]. This phenomenon is called the seat dip effect because it is mainly observed in theatres and halls. In effect, the total sound pressure is made up of the direct sound wave, scattered and reflected waves off seat rows and floor. For validation purposes, we present below the results from the 1982 paper by Ando [9].

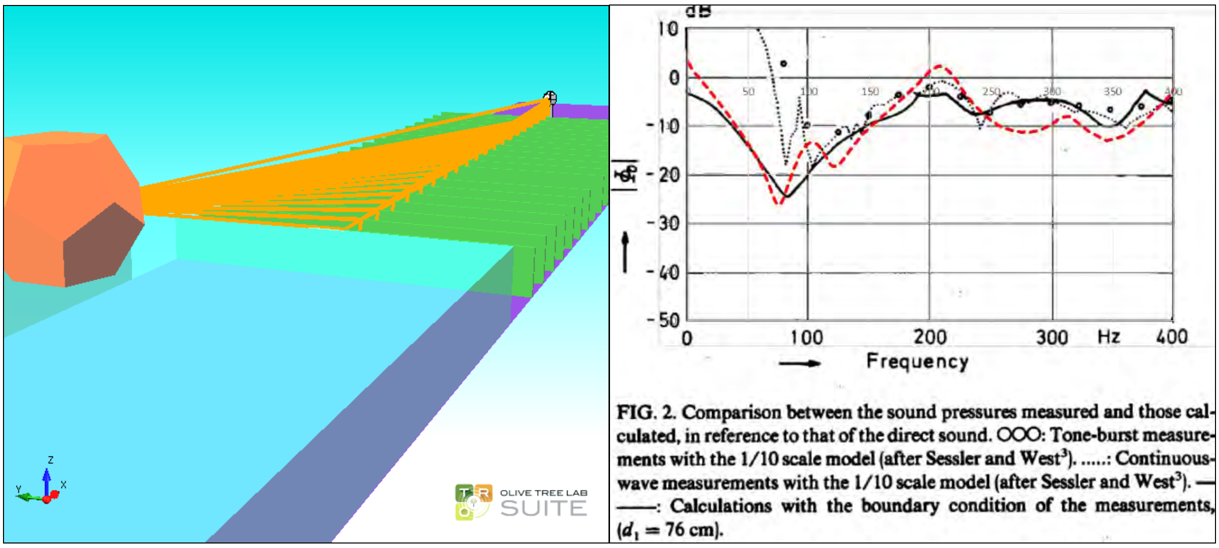


FIG. 2. Comparison between the sound pressures measured and those calculated, in reference to that of the direct sound. OOO: Tone-burst measurements with the 1/10 scale model (after Sessler and West[3]). ......: Continuous-wave measurements with the 1/10 scale model (after Sessler and West[3]). ——: Calculations with the boundary condition of the measurements, ($d_1 = 76$ cm).

Figure 2: On the left, the 3D full scale model used for calculations. On the right Ando's results compared to experimental data. Calculations are superimposed as a red curve over the original graph by Ando (courtesy of the Journal of the Acoustical Society of America).

3 Room under investigation

The objective of the exercise is to compare measurements with simulated results in terms of spatial sound distribution and frequency response. The figure below shows the 3D model of the room which has 23 surfaces. It also shows a grid of 6 x 6 at a height of 1.2 m from the floor where simulations and sound measurements were performed. On the right, a picture of the room with the sofa.

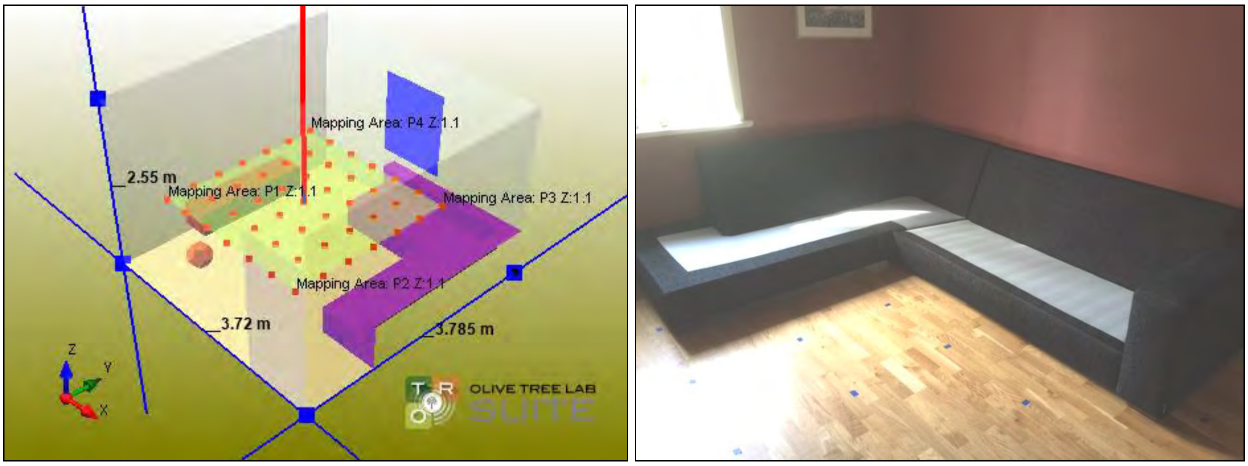


Figure 3: On the left, the 3D model of the room and on the right, a picture of the room with the sofa.

Since the measurements and sound mapping grid was set at 0.5m, the maximum frequency which can be mapped without aliasing is of the order of 343 Hz.

3.1 Measurements – Instrumentation

The measurements were performed using a measurement system for 3D impulse responses, IRIS [11], from Marshall Day Acoustics. It utilizes a compact tetrahedral microphone array, the Core Sound TetraMic, which is placed in the desired receiver position. The room is excited by a single sweep sine stimulus. The IRIS software provides the stimulus, records the room's response and processes and visualizes the result immediately. The IRIS system allows you to trace individual impulses back to the surface where they came from by looking at intensity vectors. You can select individual impulses and the corresponding vector is highlighted.

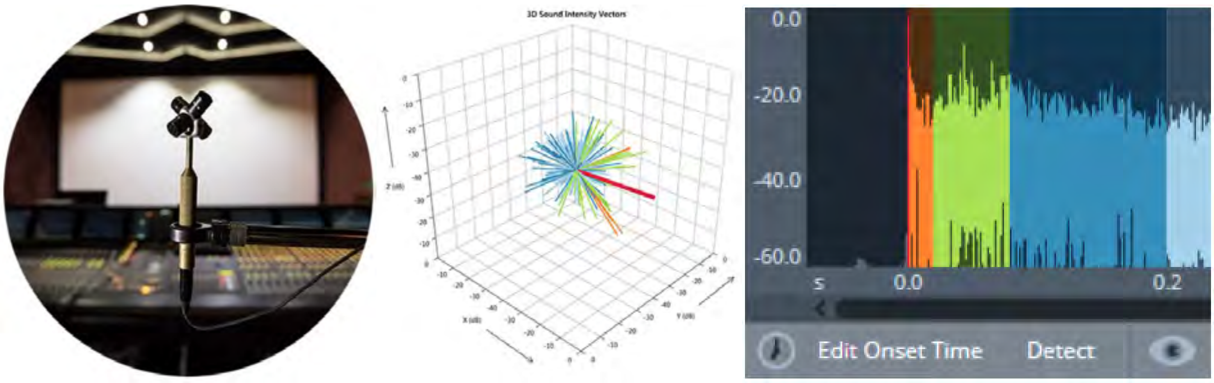


Figure 4: On the left, Tetrahedral microphone array. In the middle, the IRIS sound intensity vector plot. On the right, the IRIS impulse response

A custom made LF speaker was used for the excitation. The speaker has an 8-inch driver which is omnidirectional at frequencies up to about 500 Hz. The speaker's frequency response was measured and simulated, see figure below.

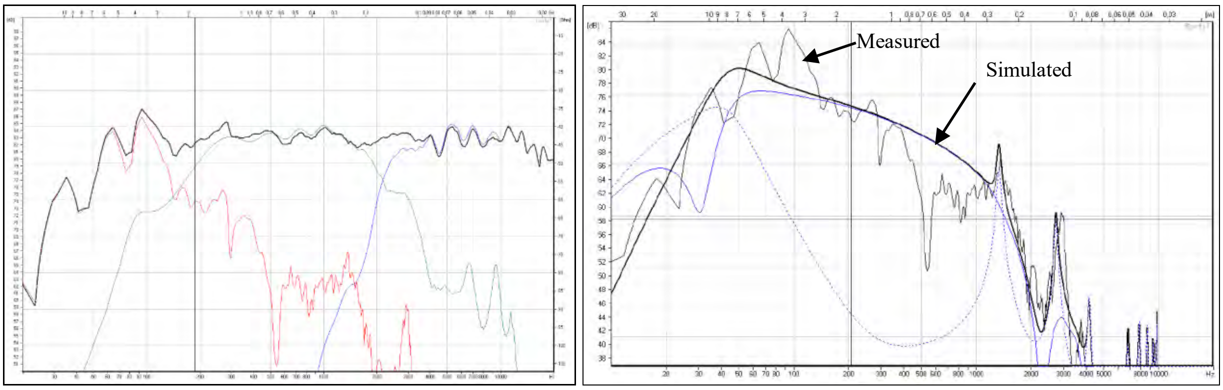


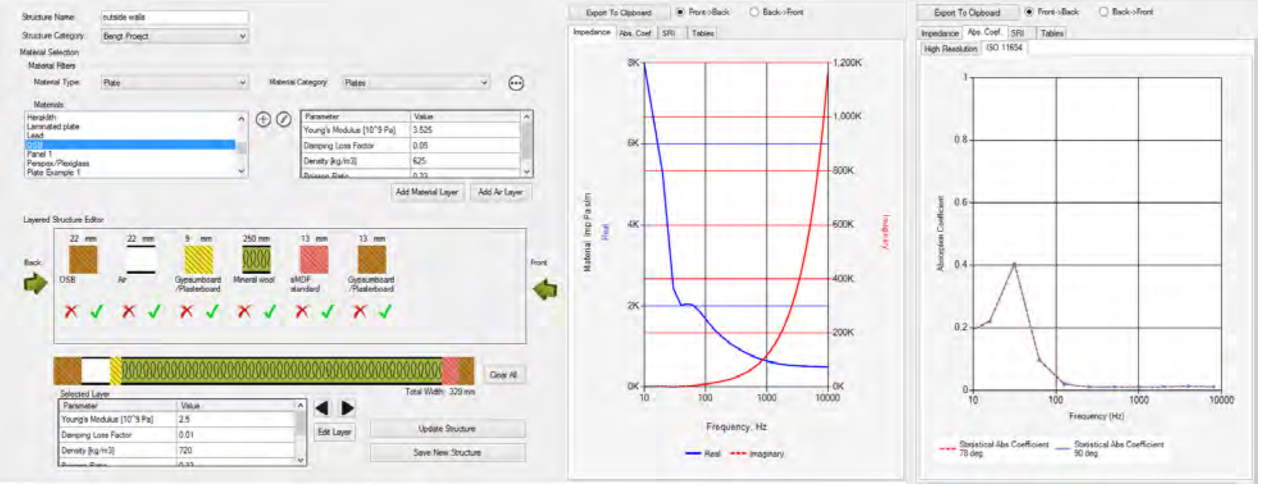
Figure 5: On the left, the measured frequency response of the complete custom made speaker including the red curve for the LF unit. On the right the measured and simulated frequency response of the LF unit alone. The measurement was made in the Tyréns semi-anechoic chamber. Despite 1 m deep sound absorbing wedges on all walls and ceiling. room resonances are affecting the measurement result at low frequencies. For the OTL-Suite model, the simulated frequency response was used.

3.2 Measurements – Procedure

Measurements were made at 36 positions in the room at a height of 1.2 m. The same positions were also used in the simulation in OTL Suite. In each position the 3D impulse response was recorded and, in this case, exported in mono from IRIS to WinMLS [12] for post processing.

3.3 3D model – Room sound field simulation

One of the most crucial parameter in simulating sound propagation in a 3D environment is to model the space under study with its most essential features, such as its geometry and materials. The geometry should include enough detail according to the frequency range of the experiment. In this particular case, since the range investigated is in the low frequencies, 40 Hz (determined by the loudspeaker) to 343 Hz (or 315 Hz 1/3rd octave band, determined by the microphone positions grid), the room geometry is not very demanding in detail. However, there is an open question about the presence of the loudspeaker column and its scattering effect as well for the equipment rack-cupboard which acts as resonator (Figure 7 below). The model simulates the speaker box as a point source, which is a very theoretical assumption while the equipment furniture as a closed box. For the materials in the 3D modelled room, we have used as a parameter surface impedance calculated with the Multilayered Structure Builder (MLSB) of OTL-Suite which is based on the Transfer Matrix Method (TMM) [13].


Structure Name: outside walls
Structure Category: Bengt Proejct
Material Type: Plate
Material Category: Plates
Materials: Heraklith, Laminated plate, Lead, OSB, Panel 1, Perspex/Plexiglass, Plate Example 1

Parameter	Value
Young's Modulus [10^9 Pa]	3.525
Damping Loss Factor	0.05
Density [kg/m3]	625
Poisson Ratio	0.33

Layered Structure Editor: 22 mm OSB; 22 mm Air; 9 mm Gypsumboard /Plasterboard; 250 mm Mineral wool; 13 mm sMDF standard; 13 mm Gypsumboard /Plasterboard

Total Width: 329 mm

Selected Layer

Parameter	Value
Young's Modulus [10^9 Pa]	2.5
Damping Loss Factor	0.01
Density [kg/m3]	720
Poisson Ratio	0.33

● Front->Back ○ Back->Front

Figure 6: The Multilayered Structure Builder of OTL-Suite used to calculate properties of one of the walls of the room. The graphs give the spectra of the surface impedance and the equivalent sound absorption coefficient.

The figure above, shows as an example the material layers used for one of room walls. The graphs give the spectra of the surface impedance and the equivalent sound absorption coefficient. The surface impedance values are taken directly into the 3D model for calculation purposes. The source spectrum used in modeling was taken from a narrow band simulated analysis which was transformed into 1/3rd octave bands in OTL-Suite. The spectrum and levels used are shown in the left figure below, while on the right, shows a picture of the loudspeaker used for the measurements.

Figure 7: On the left, the 1/3rd oct. band spectrum of the source derived from simulated narrow band values, while on the right shows the LF speaker used for the sound measurements.

4 Measurements results

The figure below shows the raw data as they are seen in WinMLS, used for post processing purposes. In order to be able to compare measurements with calculated results in the spatial domain, raw sound measurements data were exported from WinMLS in 1/3rd octave bands. These were then introduced into OTL-Suite which can provide visualization of such data as a 3D mapping for each of the relevant octave bands, i.e., 40 – 315 Hz. As far as the frequency domain is concerned, a comparison between the measured and calculated results is made for two of the receivers in the room in high resolution. The measured data resolution was 0.624991 Hz while the calculated spectra resolution was set at 1 Hz. To be able to compare measurements with calculated results, the high resolution measured data were shifted to the calculated level.

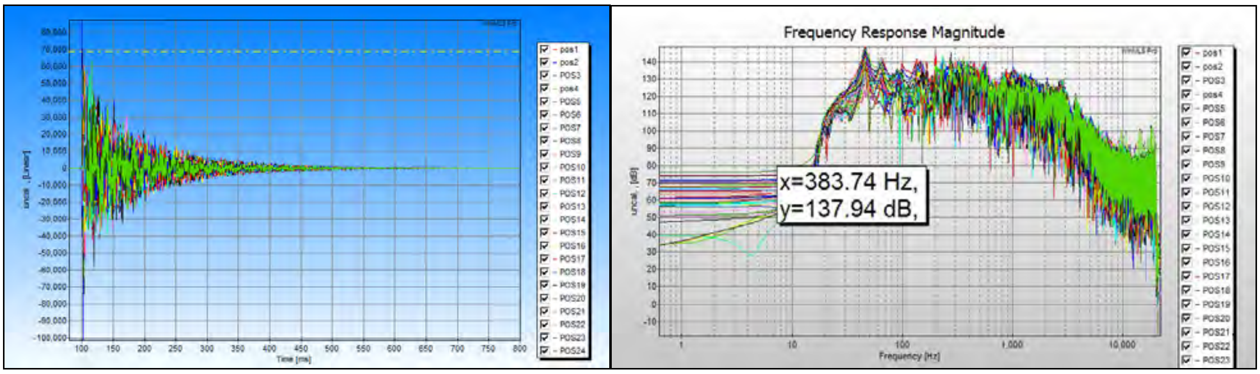


Figure 8: Raw data of the frequency responses and impulse response at the 36 points as they are read from IRIS into WinMLS.

5 Measured vs Simulation results

5.1 Spatial Domain

The 3D model has 21 surfaces. For mapping, the calculation time for a grid 6 x 6 (36 calculation positions) at a height of 1.2m, took about 5 minutes with a typical laptop when taking into account 5 orders of reflection, 1 order of diffraction. For 9 orders of reflection and 1 order of diffraction, it took about 36 hours. The latter were the settings of the calculation results presented in the figures shown below, which portray the spatial sound field distribution (mapping) for both measurements and calculations. The grid is 0.5m for both cases. Measured data are shown as the top map, while calculated results as the bottom map.

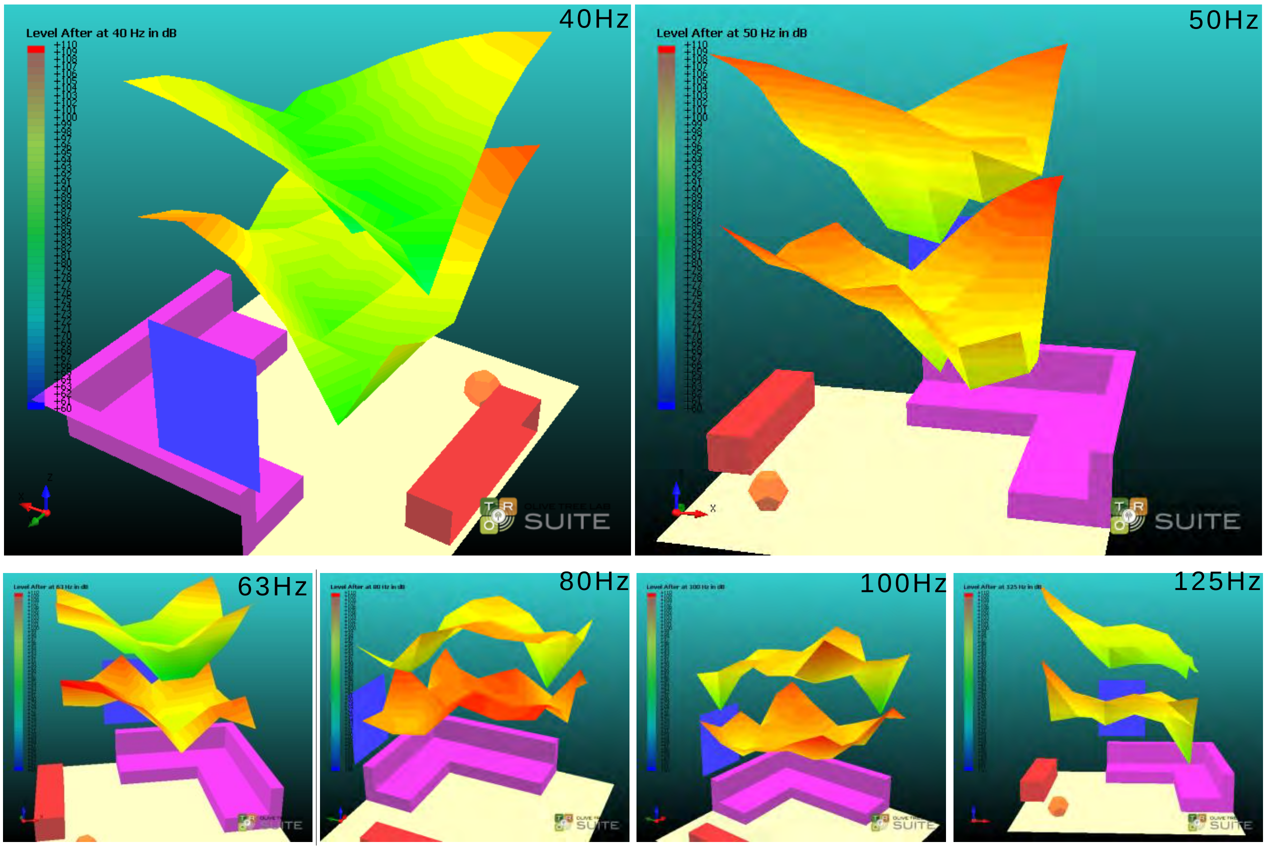


Figure 9: Room sound field mapping on a grid 6 x 6 at 0.5m and a height of 1.2m, top map - measured versus calculated results – bottom map. Some of the objects of the room are left in the picture for orientation purposes. Each picture label indicates the 1/3rd octave band results are presented.

5.2 Frequency Domain

For the frequency response two calculations were ran. One for Rec. 4 and another for Rec. 15. The locations of the receivers are shown in Figure 10 (left) which also shows the sound source as a point source without the presence of the loudspeaker cabinet. Figure 10 (right), shows the driver being located on one side of the speaker cabinet which prevents direct sound from the source to a number of receivers. This is demonstrated in Figure 10 (middle) which shows the IR of the 2 receivers. Rec.4 had direct sound from the loudspeaker driver while Rec. 15 had no direct sound but diffracted sound around the speaker cabinet. The calculation time for Rec. 4, with 7 orders of reflection and 1 order of diffraction, took about 5 minutes. The calculation time for Rec. 15, with 9 orders of reflection, 1 order of diffraction and 1 reflection in between diffraction edges, took about 4 hours.

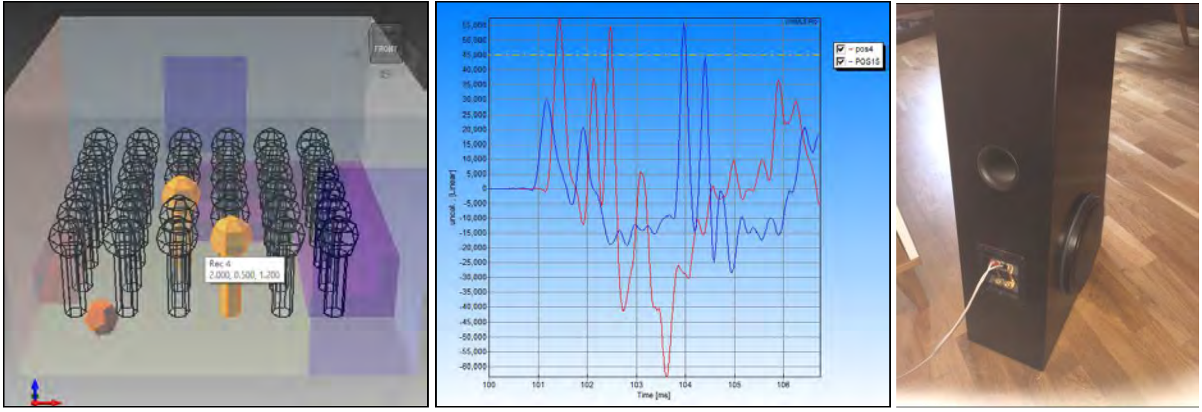


Figure 10: On the left, two of the 36 receivers for which a frequency analysis was simulated and shown below, Rec. 4 (distinguished by a white label) and Rec 15, both shown in orange. Middle: The IR of the two receivers which shows that Rec.4 had direct sound from the loudspeaker driver on one side of the cabinet (shown on the right) while Rec. 15 had no direct sound but diffracted sound around the speaker cabinet. Right: Speaker cabinet showing the driver location.

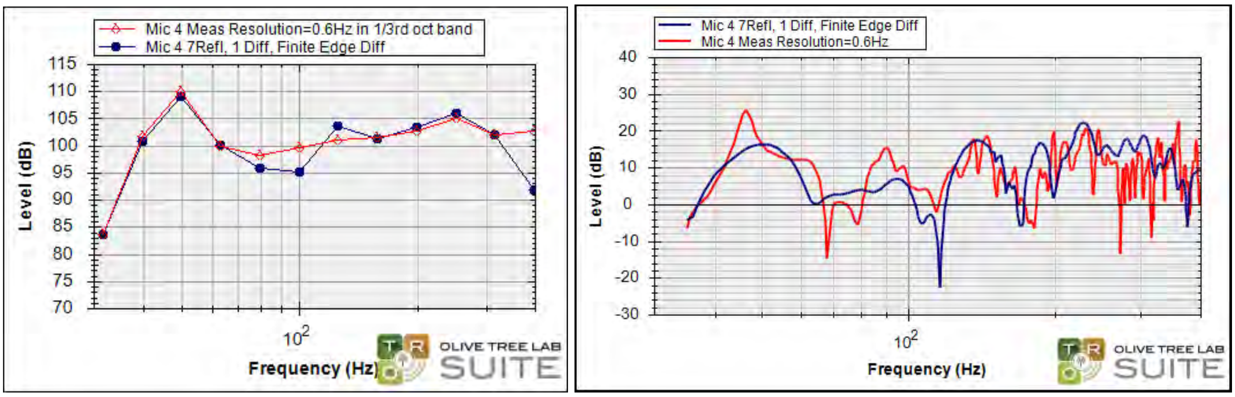


Figure 11: Rec. 4, with 7 orders of Reflection, 1 order of Diffraction, ***Finite*** Edge Diffraction

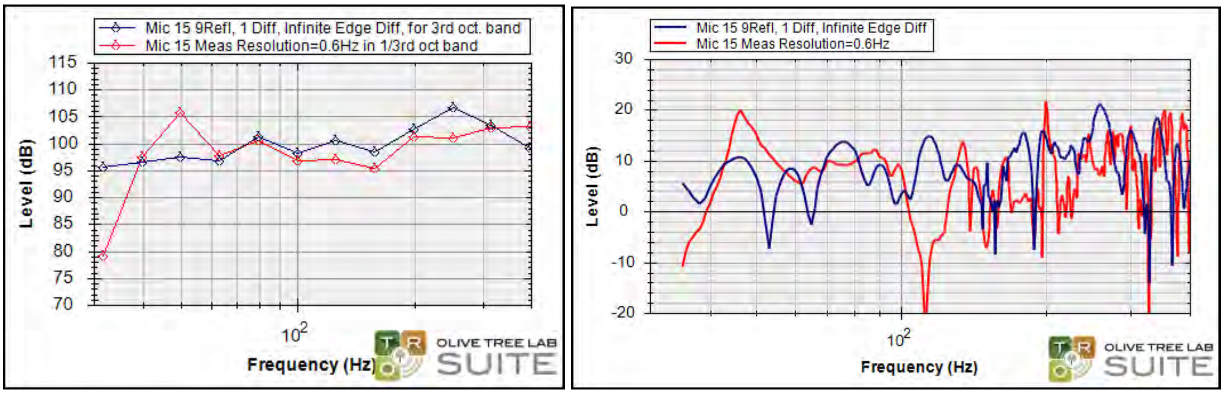


Figure 12: Rec. 15, with 9 orders of Reflection, 1 order of Diffraction, ***Infinite*** Edge Diffraction

6 Discussion and conclusions

As always, the results of an experiment depend very much on the accurate representation of the conditions one studies. Measured and simulated results show that they have definitely the same tendency, but some results have more differences than others. The following discusses the possible reasons for the deviations observed. Firstly, the orders of sound reflection and diffraction used in the calculations, the higher the orders of reflection and diffraction the better the results. The orders used for this particular study could be considered as low, taking into account the room content. It is anticipated that with higher orders of reflection and diffraction, results would be closer to the measured data. Another very crucial parameter was the calculation of the acoustical properties of the room structure. We have included what is thought to be an accurate representation of how room surfaces or objects were built. Yet, structures behaviour could deviate considerably if some of the assumptions are not correct, for example walls and floor would resonate at a different frequencies if the cavities are different to the assumptions made. Other examples are the TV, the audio and video equipment furniture (rack), the loudspeaker column and other objects in the room which were not included in the model and could contribute due to sympathetic response to the sound field excitation. Therefore, not only do the properties of the materials in the room affect the outcome, but also the geometry of the room content. Of course, all these are directly linked to the accuracy with which sound measurements were taken in terms of microphone and loudspeaker positioning as well as the signal chain used. If one allows for all the above unknowns and parameters and that interference phenomena are sensitive to measurements and modelling details, it is remarkable that there is such a good agreement between measurements and calculated results. This study has shown once more [3, 7, 8] that WBGA provide accurate and fast calculation results and a good alternative to numerical methods (BEM, FEM and others). Now, GA has the advantage of being complemented with the accuracy of the wave nature of Wave Based Geometrical Acoustics which provide sound propagation simulation, visualisation and auralisation.

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