23rd International Congress on Sound & Vibration
Athens, Greece 10-14 July 2016
ICSV23

ROOM RESONANCES USING WAVE BASED GEOMETRICAL ACOUSTICS (WBGA)

Panos Economou, Panagiotis Charalampous

P.E. Mediterranean Acoustics Research & Development Ltd, Cyprus
email: panos@pemard.com

Geometrical acoustics, using plane wave propagation and sound absorption coefficients, fail to calculate room resonances. Usually such wave phenomena are being calculated with numerical methods such as Finite Element Method or similar which are computationally heavy. The WBGA, which is 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. In this paper we present calculation results of room resonances using the WBGA compared to published data.

1. Introduction

In one of his 1939 JASA paper [1], Richard H. Bolt a pioneer in room modal acoustics, has conducted an experiment to map the presence of normal modes of vibration in nonrectangular rooms. This has been the inspiration of this paper, one of a trilogy of papers presented in this conference with the aim to demonstrate that Wave Based Geometrical Acoustics can be applied with success in calculating sound wave phenomena.

Room sound modal analysis is very difficult, especially in nonrectangular rooms, since a room may be considered as an assemblage of an infinite number of resonators [2, 3], with an infinite number of solutions. For non-symmetrical rooms there are no analytical solutions, therefore such wave phenomena are usually being calculated with numerical methods such as Finite Element Method or similar which are computationally heavy. So far any attempts to simulate room modal behaviour with Geometrical Acoustics (GA) have failed, since the typical approach in GA is the use of sound energy rather than complex sound pressure [4]. Room resonances are sound wave phenomena which can only be calculated using Wave Based Geometrical Acoustics (WBGA) to be introduced below.

This paper is divided into five parts which follow. The first part introduces the concept of Wave Based Geometrical Acoustics. The second part validates Olive Tree Lab-Suite [5], the software application used to simulate room resonances and applies WBGA. The third part conducts further investigation of the model used for validation purposes, while the fourth part extends the use of WBGA in engineering applications. Finally conclusions are presented at the end.

2. Wave Based Geometrical Acoustics (WBGA)

Geometrical Acoustics (GA) is based on the concept derived from Optics that wave fronts travel in straight lines until they encounter a discontinuity, an impedance change [6]. 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 has applicability. In contrast, WBGA [4] extends GA to accommodate 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 [4] that in rectangular rooms the WBGA is as accurate as the BEM. This paper presents calculations of room resonances in nonrectangular rooms using Olive Tree Lab-Suite, a sound propagation software application which employs WBGA in a 3D simulation environment.

3. Validating Olive Tree Lab-Suite using Bolts setup [1]

To validate OTL-Suite, the authors needed to find a researcher who has mapped sound distribution within a nonrectangular room. To the authors' knowledge, the only paper which reports on sound distribution measurements taken within a nonrectangular room is the 1939 paper by R.H. Bolt [1]. This paper was also chosen because of its 2-dimensional nature where a clearer picture can emerge on the workings behind the building up of standing waves (as compared to a 3-dimensional space where oblique modes are also involved).

3.1 The 1939 model

Bolt, in his effort to be able to measure sound distribution within a nonrectangular room, had devised an apparatus which enabled him to vary the angles of the walls of a scaled room model made out of brass plates, highly sound reflective materials. The height of the model was small compared to the sound wavelength used therefore no normal modes with vertical components could develop. Essentially the model was a 2-dimensional model where axial and tangential modes of vibration were investigated. The source was flush mounted on the hard "ceiling", and the microphone located on the floor (we assume at zero height). Rather than moving the microphone around the model, he devised an apparatus which enabled a microphone to be fixed at a table top while the model would move about the microphone, with the table top acting as the room's hard "floor". At the same time a drawing board in conjunction with a microphone positioning recording system was used to record the trajectory of the microphone, which according to the same paper, a 0.1" (2.54mm) change in space would have a sound level variation as much as 10 dB. The size of the original model, a trapezoid, had dimensions given in the figure below, but was smaller by a factor of 10. The frequency range investigated in the experiments varied between 886 Hz and 2302 Hz, the range the source could provide adequate and linear sound.

3.2 The digital model

The 3D model setup in OTL-Suite is shown in the figure below. It is bigger by a factor of 10 than the original scale model, therefore, the results in the digital model are examined at frequencies divided by a factor of 10. OTL-Suite for the time being maps at the standard 1/3rd octave band frequencies, therefore, since during the 1939 experiments the frequencies used were chosen arbitrarily, there is no exact correspondence between OTL-Suite mapping and Bolt's mapping. Also, digital mapping can only be done in rectangles, therefore it was mostly confined to the centre of the trapezoid. A 30x30 matrix of receivers was used in mapping for validation purposes. All walls were hard and had an impedance calculated according to Delany-Bazley (D&B) model [7] which corresponds to a flow resistivity of 20MPas/m^2. In the calculations, 8 orders of reflections were used even though the signature of the modal pattern was clearly evident with 1 order of reflection. No diffraction calculations were involved.

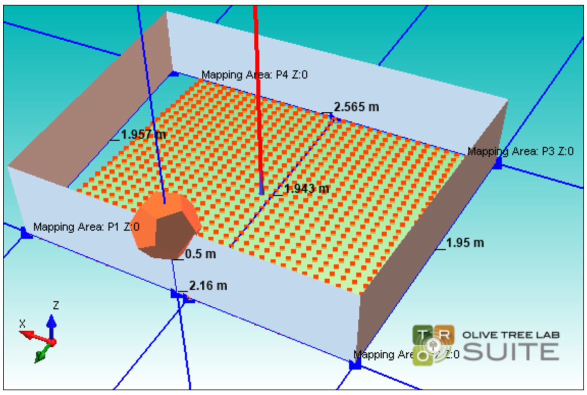

Figure 1: The OTL-Suite model and its dimensions (multiplied by a factor of 10 compared to Bolt's model). Mapping was done on z=0 with a matrix of 30x30 receivers.

3.3 Calculation vs experimental results

For validation purposes, Figures 17 and 18 of Bolt's paper were used corresponding to frequencies of 1721 and 2302 Hz respectively. These frequencies are equivalent to 172.1 and 230.2 Hz in the digital model's scale. The figures below show in colour the results calculated based on Wave Based Geometrical Acoustics using OTL-Suite. Superimposed are the experimental results, courtesy of the Journal of The Acoustical Society of America.

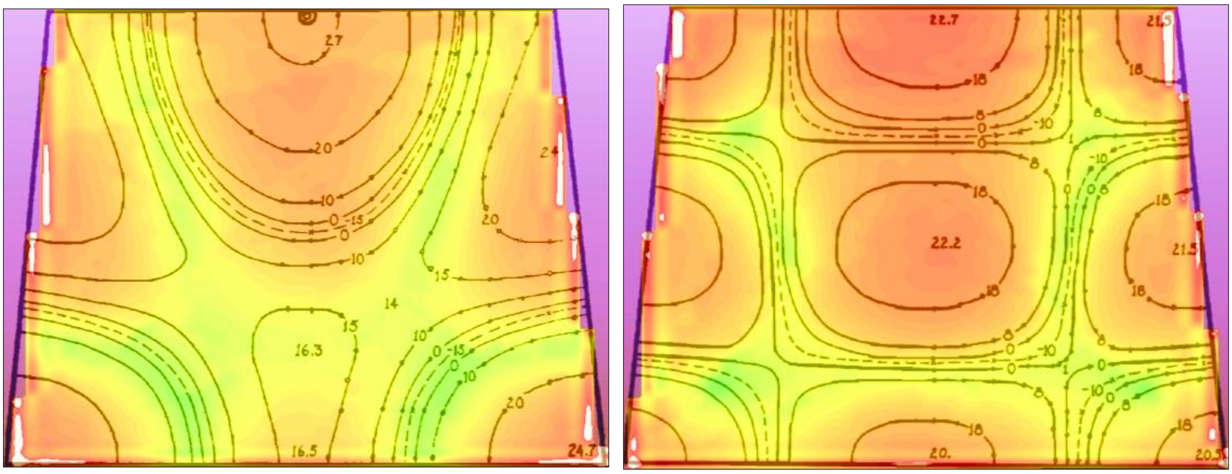

Figure 2: Mapping on the left is at 1721 Hz (experimental data, courtesy of the JASA) while the coloured mapping in the 1/3rd octave band of 200 Hz. The mapping on the right is at 2302 Hz (experimental data) while the coloured mapping in the 1/3rd octave band of 250 Hz**.** In red high sound levels and in green low.

From the above figure, 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.

The figures below show in a 3D representation the mapping results above. One is able to visualise resonances in sound distribution within a 2D trapezoidal room, determine the nodes and anti-nodes, their levels and their spread.

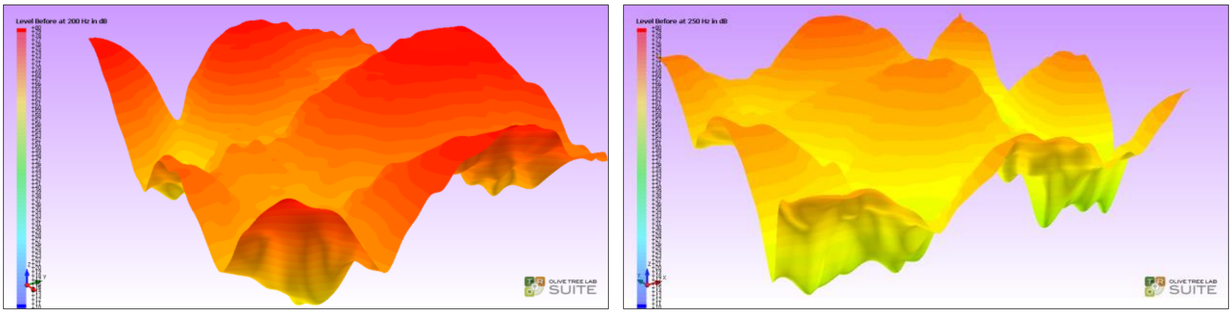

Figure 3: The 3D mapping on the left is in the 1/3rd octave band of 200 Hz. The mapping on the right is in the 1/3rd octave band of 250 Hz. The figures correspond to the images of Figure 2 above.

On page 138 of Reviews of Modern Physics [8], Bolt also presents measurements of cross-sectional sound distribution. The figure below shows OTL-Suite results on planes based on an estimated guess of where the measurements were taken. The figure on the right shows mapping results as a red curve, superimposed on the data according to Figure 29 of [8], courtesy of the Reviews of Modern Physics. From the comparison it can be seen that there are deviations but the general trend of the results are the same.

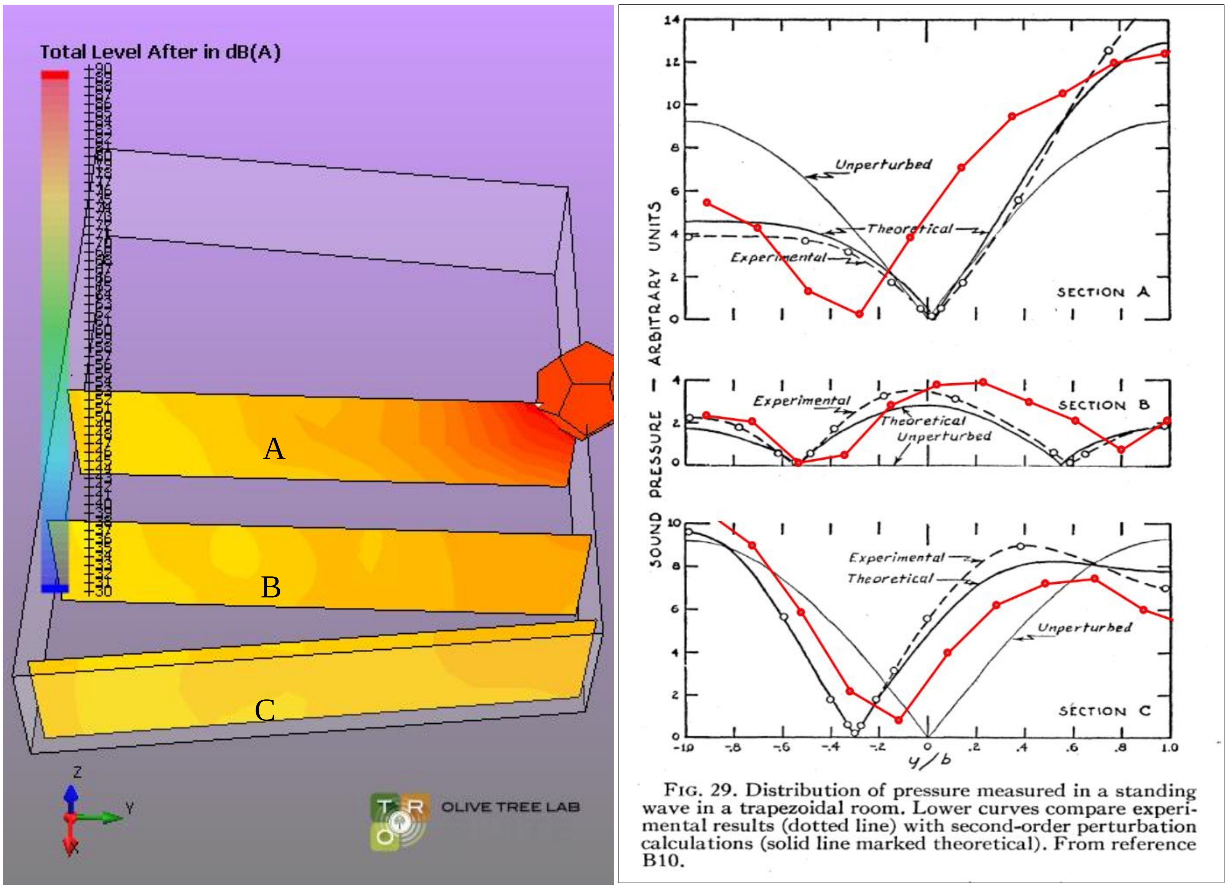

Figure 4: On the left, the planes (sections A,B,C) where sound mapping was carried out. These correspond approximately to the sections Bolt is referring to in his experiment. On the right, mapping results in red, superimposed on the data according to Figure 29 [8], courtesy of the Reviews of Modern Physics.

4. Further investigation of a trapezoidal room

To demonstrate the power of WBGA, Bolt's setup was used again to show that in calculating sound wave phenomena it is imperative to account for surface impedance, spherical wave propagation and complex pressure summation.

Next, the following comparisons are made:

1. Calculations with spherical wave using complex pressure summation and low surface impedance corresponding to flow resistivity of 200kPas/m^2 for all surfaces (WBGA).
2. Calculations with plane wave using complex pressure summation and low surface impedance, as above.
3. Calculations with plane wave using complex pressure summation and sound absorption coefficient calculated with the Delany and Bazley method corresponding to flow resistivity of 200kPas/m2.
4. Calculations with plane wave using energy summation (pressure squared) and a sound absorption coefficient as above.

In order to make the differences more clear, before presenting mapping results with the above mentioned approaches, we present below a source and receiver over a surface of finite impedance (corresponding to flow resistivity of 200kPas/m^2). We show the effect of summing the direct and reflected path applying the above mentioned methods. The figure on the left shows the configuration while the figure on the right Excess Attenuation in dB (the ratio of total over direct sound field).

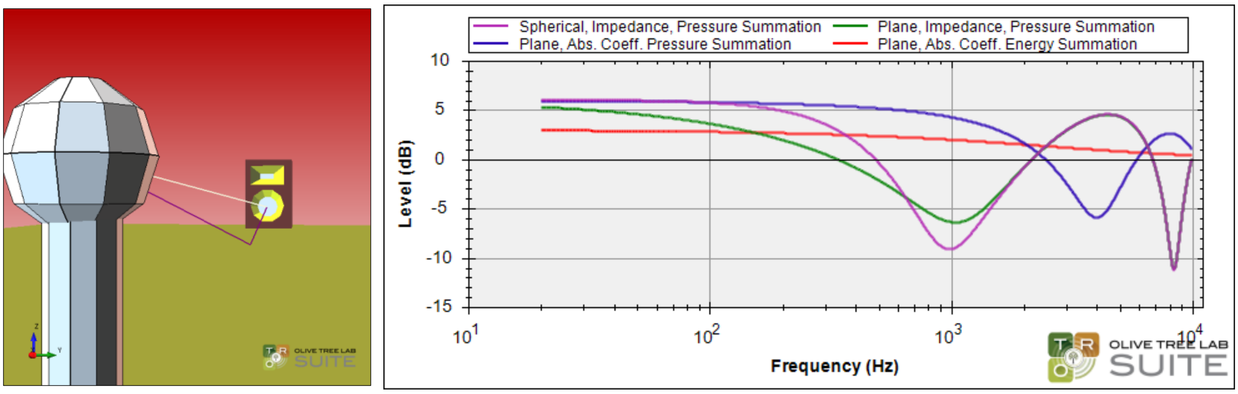

Figure 5: A source and receiver over a surface of finite impedance (corresponding to flow resistivity of 200kPas/m2). On the right, the effect of summing the direct and reflected path applying the different methods, shown as Excess Attenuation in dB (the ratio of total over direct sound field). Note that by using the energy method the +3 dB wrongly applied rule for source 'directivity' over a surface [9] becomes evident, in contrast to the correct increase in sound pressure level by 6 dB at low frequencies.

From the above, one can see clearly the differences in calculation results which can derive from the aforementioned methods. Bearing this in mind we can examine next the results of sound distribution in a trapezoidal 2D room using the same setup, but with low surface impedance. The figure below shows sound distribution at 250 Hz in the 1/3rd octave band, within a trapezoidal 2D room. Resonances are evident when sound pressure summation is applied but not necessarily at the correct level or location. Energy summation does not provide interference effects.

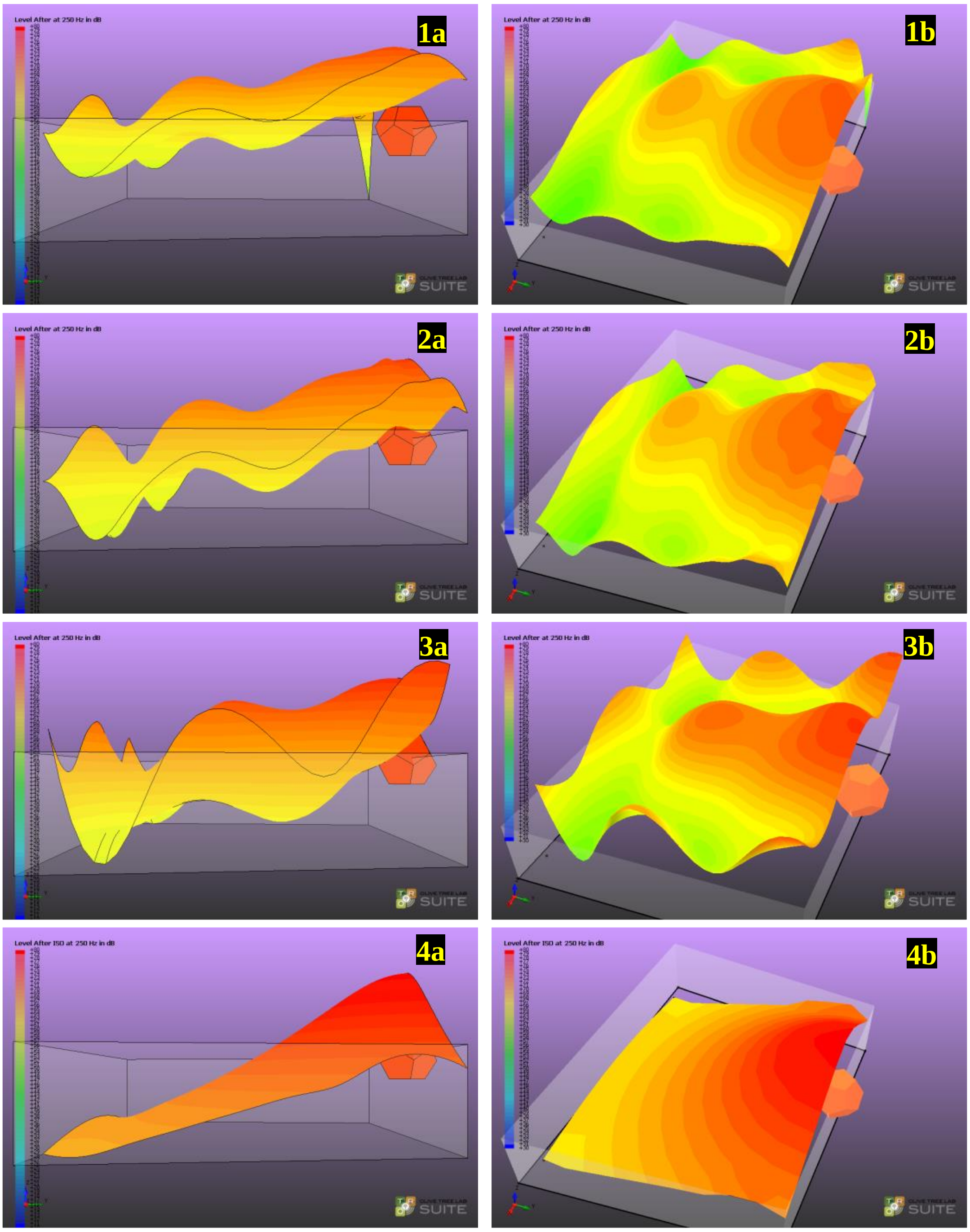

Figure 6: Legend - 1: Spherical wave, Impedance, pressure summation, 2: Plane wave, Impedance, pressure summation, 3: Plane wave, absorption coefficient, pressure summation, 4: Plane wave, absorption coefficient, energy summation. On the left, side view and on the right isometric view.

5. Engineering applications – Audio Control Room

All the above analysis has direct impact on how we design small rooms, such as recording studios. The figure below shows the simulated distribution of sound and room resonances in a control room of a recording studio. The calculation time with a typical laptop took about 30 minutes when taking into account 5 orders of reflection, 1 order of diffraction and 1 reflection in between diffractions, a tiny time span compared to the much longer calculation times of numerical methods (FEM, BEM, etc). The 3D model has 77 surfaces. In another paper by the same authors written for this conference, WBGA investigates sound diffraction and reflections off mixing consoles in control rooms.

OTL-Suite imposes no limit on reflection or diffraction orders, however, calculation time increases with order level. Depending on the complexity of the project, beyond a certain number of orders of reflection, usually 2 orders of diffraction and 1 in between reflection, the calculations reach a steady state quickly.

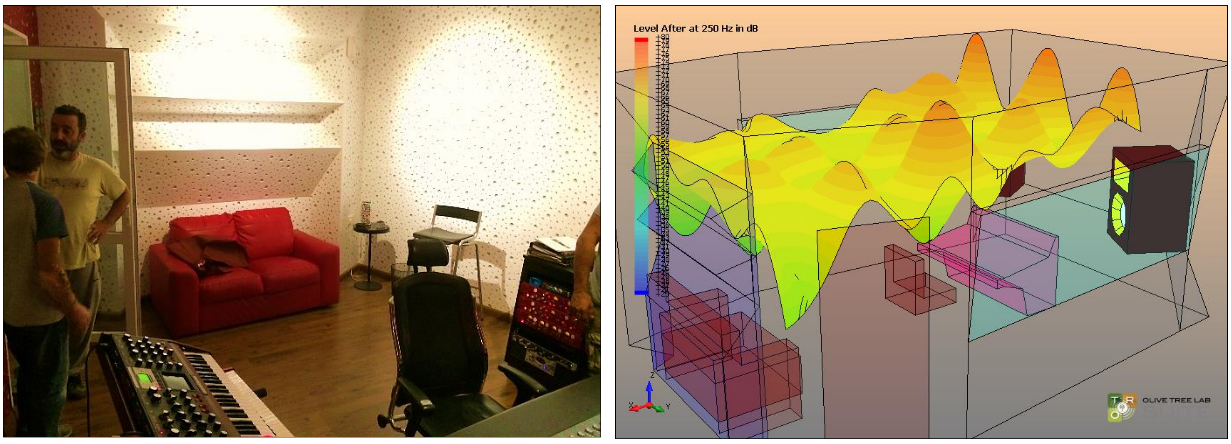

Figure 7: Picture of an audio control room and the simulated sound distribution in the 1/3rd octave band of 250 Hz. The room resonances are clearly evident.

6. Conclusions

The above results demonstrate that Wave Based Geometrical Acoustics provide accurate representation of sound wave phenomena in rooms. Any discrepancies reported above between calculated and measured results are expected since sound interference phenomena depend on the geometries of the experiments as well as the details in sound measurements procedures.

We have also demonstrated that Geometrical Acoustics using plane wave propagation cannot calculate accurately sound wave phenomena such as room modal analysis. In contrast WBGA with spherical wave propagation can accurately reproduce such effects.

The advantages of WBGA are numerous, including accuracy, user friendliness, calculation speed, visualisation and auralisation of acoustical phenomena, practicality and efficiency. WBGA compared to other wave based numerical methods, offer an alternative to engineers and provide the necessary tools to be able to perform insightful calculations. Sound rays in WBGA simulate sound propagation in a three dimensional environment with a possibility of eventually including all phenomena deemed important in acoustics. They carry information on how to lose intensity with distance, how to reflect, diffract and transmit when they encounter objects and how to interact with the atmosphere.

Finally, a word of gratitude to those pioneers of acoustics, in this case R.H.Bolt, who have offered us so much in understanding the workings of normal modes of vibration.

REFERENCES

1 Bolt, R.H., Normal Modes of Vibration in Room Acoustics: Experimental Investigations in Nonrectangular Enclosures, *Journal of the Acoustical Society of America*, **11,** 184-197, (1939).

2 Morse, P.M., *Vibration and Sound*, The Acoustical Society of America, (1948).

3 Skudrzyk, E., *The Foundations of Acoustics: Basic Mathematics and Basic Acoustics*, Springer - Verlag, (1971).

4 Lam, Y.W., Issues for computer modelling of room acoustics in non-concert hall settings, *Acoustical Science and Technology Journal*, **26** (2), 145-155, (2005).

5 Olive Tree Lab Suite software. [Online.] available: http://www.olivetreelab.com

6 Pierce, A.D., *Acoustics, An Introduction to Its Physical Principles and Applications*, The Acoustical Society of America, (1989).

7 Delany, E. and Bazley, E.N., Acoustical properties of fibrous absorbent materials, Applied Acous*tics*, **3**, 105-116, (1970).

8 Morse, P.M. and Bolt, R.H., Reviews of Modern Physics: Sound Waves in Rooms, *Massachusetts Institute of Technology*, **16** (2), 69-150, (1944).

9 ASHRAE HANDBOOK, *Sound and Vibration Control*, Chapter 48, (2015).