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THE SEAT DIP EFFECT USING WAVE BASED GEOMETRICAL ACOUSTICS (WBGA)

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The seat dip effect is considered to be one of the intractable acoustical phenomena in room acoustical simulations. This phenomenon is mainly due to edge sound diffraction and scattering. Wave Based Geometrical Acoustics (WBGA), which originates from the image source method, spherical wave propagation, impedance discontinuities and sound pressure summation, accounts for wave phenomena such as reflection from planes, diffraction from edges, refraction due to stratification of mediums to mention a few. By applying WBGA, we demonstrate that the seat dip effect can be accurately calculated and predicted. This paper compares results of the seat dip effect calculated using WBGA with published and measured data.

1. Introduction

A well-studied phenomenon is the attenuation of low frequency sound at grazing incidence over surfaces characterised by roughness, either of periodic or non-periodic structure [1, 2, 3, 4]. The seat dip effect, the same phenomenon, is also 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. According to Attenborough [4], periodically space roughness, provides multiple attenuation maxima while randomly spaced roughness provides one broadband attenuation maximum. This is due to the fact that periodically placed objects over a surface, like in the case of theatre seating over a floor, scatter sound in a coherent fashion, thus providing dip-interference effects in the frequency domain. Theatre seating in essence is made of periodically spaced objects. The seat dip effect was first observed at the beginning of the 1960's [5, 6]. An overview of the theatre seat dip effect is given by Bradley [7] while an updated reference list is given by Lokki [8]. Seat dip attenuation varies between 80 and 300 Hz depending on seat height and row spacing [8]. This phenomenon is more pronounced within the first 20ms and in seating areas where sound arrives free from reflections.

The study of seat dip phenomenon by the use of models is mainly done with numerical methods [9] or analytical models [10, 11]. As far as the authors of this paper are concerned, the method of Wave Based Geometrical Acoustics (WBGA) has never been used in the analysis of this phenomenon. This paper attempts to validate the use of WBGA in the study of the seat dip effect (SDE).

This paper is divided into four parts which follow. The first part introduces the concept of WBGA. The second part analyses the SDE and its components to understand its mechanism. The third part, validates Olive Tree Lab-Suite, the software application which applies WBGA and was used to calculate the SDE using published and measured data, the latter from a theatre. 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 [12]. 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 [13] 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 [13] that in rectangular rooms the WBGA is as accurate as the BEM. This paper presents calculations of the SDE using Olive Tree Lab-Suite [14], a sound propagation software application which employs WBGA in a 3D simulation environment.

3. Analysing the Seat Dip Effect (SDE) and its components

Ishida [15] presented a very insightful study of the SDE. He used two barriers between source and receiver to analyse the sound paths which make up the SDE. In general, when a barrier shields the sound path between source and receiver, the diffracted path has no phase change, while in the opposite case when there is direct sound between a source, a receiver and a barrier, the diffracted path has a phase reversal and becomes negative. The following figure shows on the left, a barrier blocking direct sound while on the right there is direct sound between source and receiver over a barrier. The inset graphs on the left of each picture show the frequency response, while the graphs on the right of each picture show the time response with the impulses and directions for the two cases.

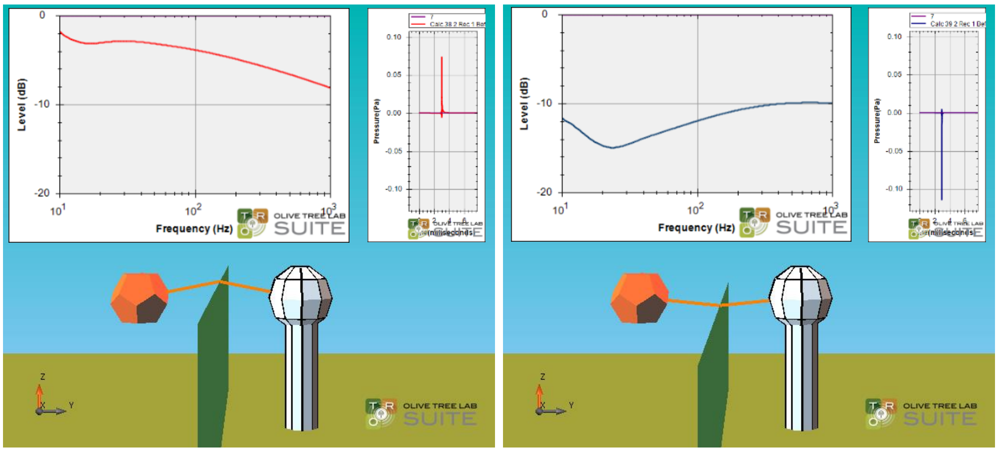
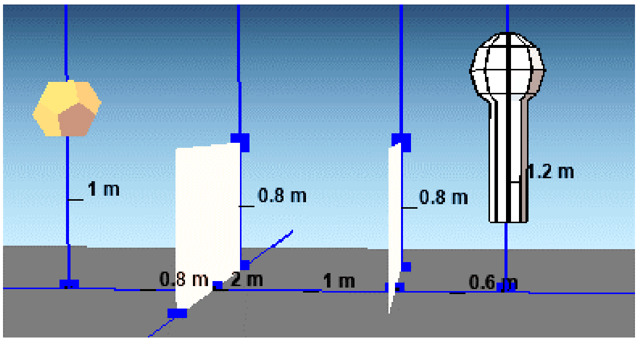


Figure 1: When a barrier shields the sound path between source and receiver, the impulse of the diffracted path is positive, while when there is direct sound between source and receiver, the diffracted path is negative. The inset graphs on the left of each picture show the frequency response, while the graphs on the right of each picture the time response with the impulses and directions for the two cases.

Figure 2 below shows Ishida's experimental setup. The model was 1/4th of full scale with seat (barrier) spacing of 1.0m and seat height of 0.8m. Figure 3 shows the individual contribution of the first 7 sound paths including combinations of diffracted - reflected paths off the floor. The direct sound path is not shown.



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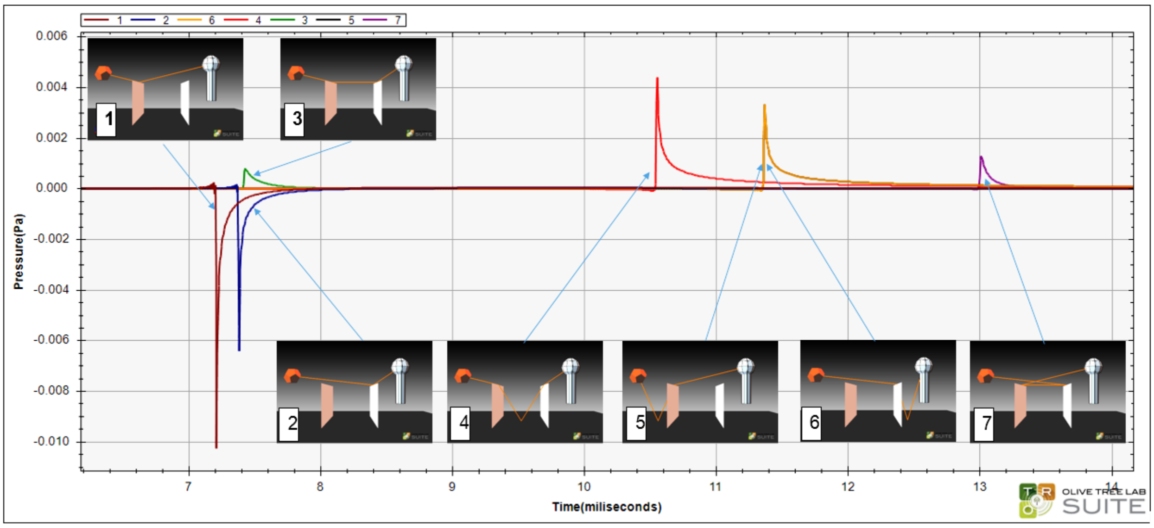

Figure 3: The individual contribution of the first 7 sound paths including combinations of diffracted /reflected paths off the floor and barriers.

Figure 4 shows the same but in the frequency domain. The calculations include in each case the contribution of the direct sound.

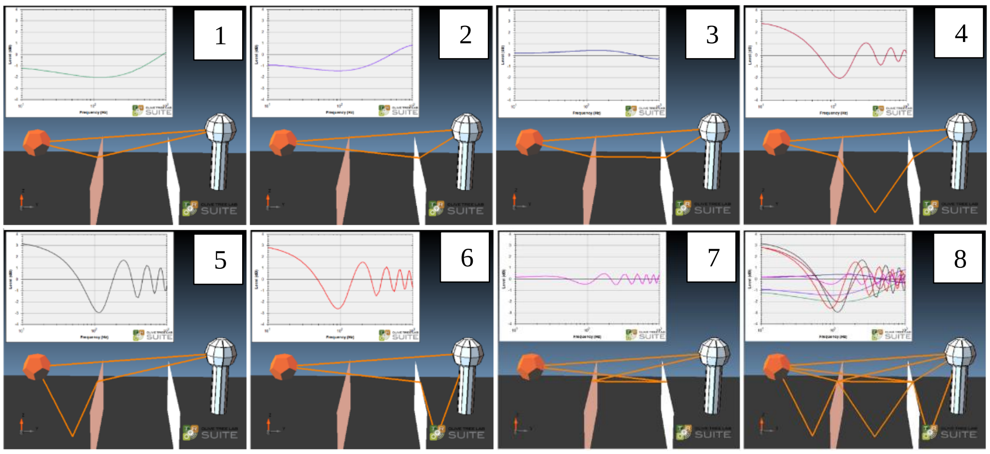

Figure 4: The individual contribution of the first 7 sound paths combined with direct sound. The last picture, number 8, shows all of the paths together for comparison purposes.

Figure 5 below on the left, shows that for a particular calculation with 3 orders of diffraction and 3 reflections in between diffractions, the calculated number of paths is 156. The inset figure shows the combined effect of all 156 paths with a dip around 95 Hz. The figure in the middle shows the first 8 sound paths between source and receiver with the dip located around 100 Hz. The figure on the right shows the barriers with the effect of a 20cm underpass and the dip calculated around 145 Hz. Ishida's measurements without underpass show a dip around 135 Hz (compared to our calculations at 110 Hz, middle picture below). Ishida's measurements with an underpass, showed the dip to be close to 200 Hz (compared to our calculations at 135 Hz, right picture below).

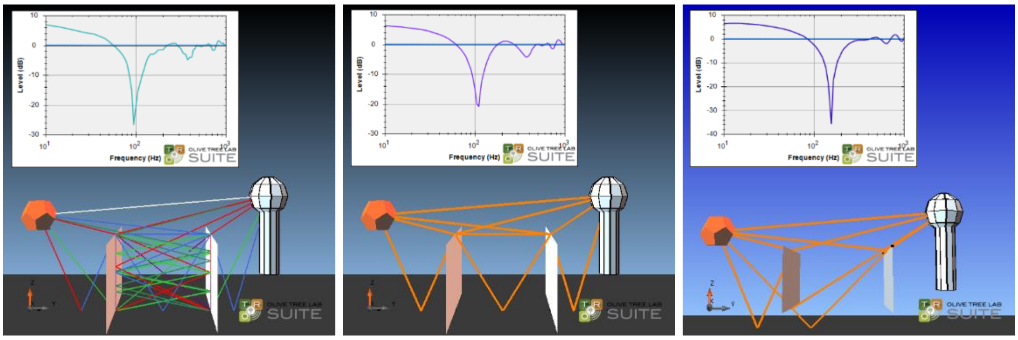

Figure 5: The figure on the left shows calculation results with 3rd order diffraction and 3 reflections in between diffractions, producing 156 paths. The figure in the middle shows the first 8 sound paths between the source and receiver. The figure on the right shows the barriers with the effect of a 20cm underpass. All inset figures show the combined effect of these paths.

Finally, based on the same setup, the effect of making the floor sound absorptive was also examined. For the hard floor calculations, all surfaces had a flow resistivity of 20 MPas/m^2 corresponding to a sound absorption coefficient, α_{stat}=0.010 at 100Hz, according to the Delany and Bazley method [16]. For the sound absorbing floor calculations the floor surface had a flow resistivity of 200kPas/m^2 (α_{stat}=0.087 at 100 Hz). It can be seen that the dip with a sound absorbing floor is not as deep as the one calculated with a sound reflecting floor. This configuration was not investigated by Ishida in his paper to provide a comparison.

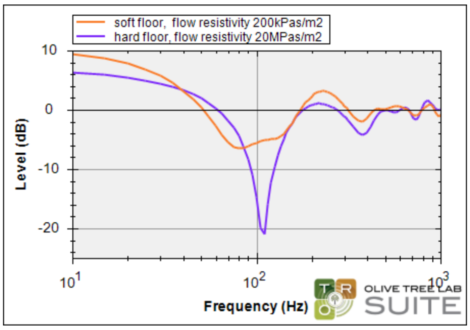

Figure 6: Calculations show that the Seat Dip Effect diminishes when the floor is sound absorbing.

4. Validation of the WBGA in simulating the Seat Dip Effect

For validation purposes, we present below the results from the 1982 paper by Ando [11]. On the left, the 3D full scale model used which corresponds to the experimental 1/10 scale model by Sessler and West [6], some of the first researchers to conduct experiments on the SDE when it was first observed during the period 1960 - 64. Ando used their results to compare his calculation methodology with measured data. Our calculations are superimposed as a red curve over the original graph by Ando (courtesy of the Journal of the Acoustical Society of America).

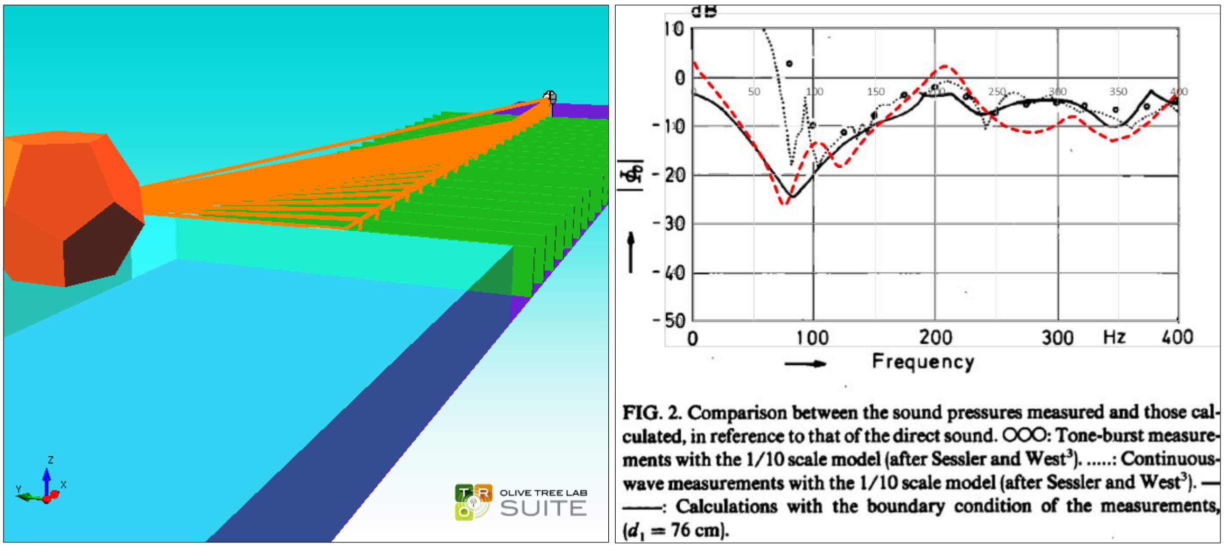

Figure 7: On the left, the 3D full scale model used for our calculations showing the source and 20 rows of seats with a spacing of 82 cm. Microphone height 110 cm. On the right Ando's results compared to experimental data. Our calculations are superimposed as a red curve over the original graph by Ando (courtesy of the Journal of the Acoustical Society of America).

4.1 Validating OTL-Suite using a built theatre

The model of the theatre used for additional validation purposes, is the Pattichion Theatre completed in Limassol, Cyprus in 2015. Figure 8 shows on the left a 3D model of the theatre, while on the right a photograph of it.

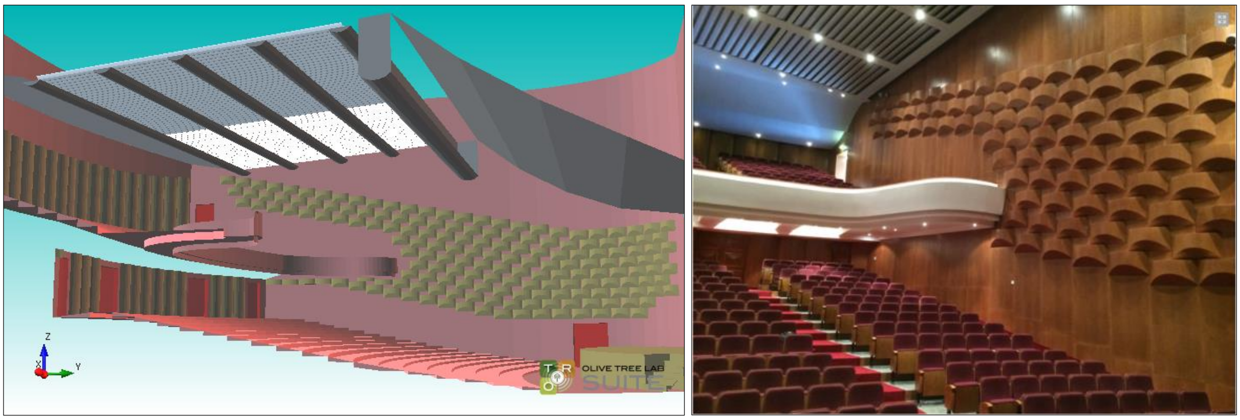

Figure 8: On the left a 3D model of the Pattichion theatre and its photograph on the right.

Figure 9 below shows the measured seat dip effect close to the middle of the 10th row after applying approximately a 10ms rectangular window to the measurement results. Since the seat dip effect is more pronounced in the first 20ms, the only participating surfaces in the 3D model, are the seats, the steps and the stage of the Pattichion theatre. The source height was 2.00m from the bottom of the stage, while the receiver at 3.40m. There are 19 seat rows in the theatre having a distance of 86cm between each row, while each row has 28 seats. The floor has two seats slopes which are, 10cm/step for the first 8 rows and 16cm/step for the rest.

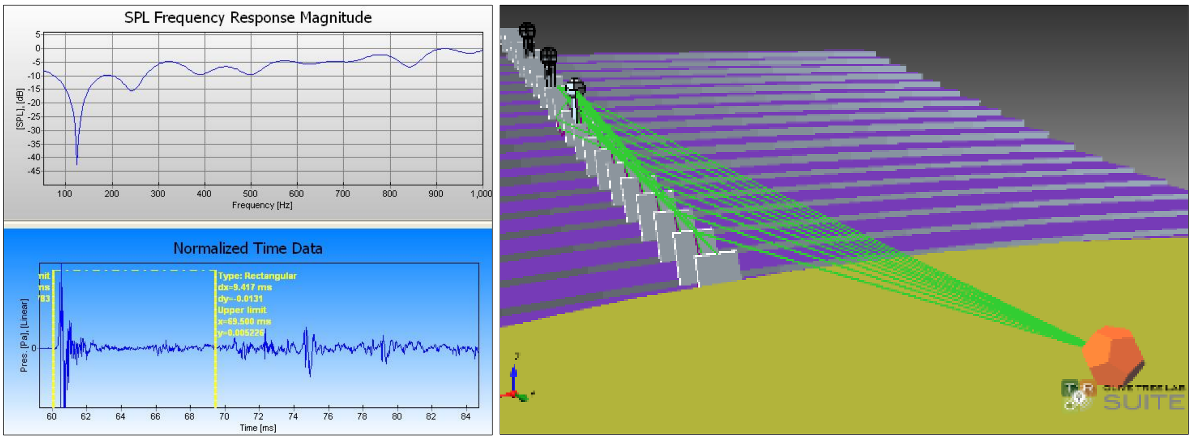

Figure 9: On the left, the measured SDE and the windowed impulse response. On the right the model showing the sound rays to the microphone of the 10th row of seats, the steps and the stage.

The figure below shows a comparison between the measured and calculated results. From the graph it may be seen that the measured seat dip effect is located at around 120Hz while the calculated SDE is found around 105 Hz.

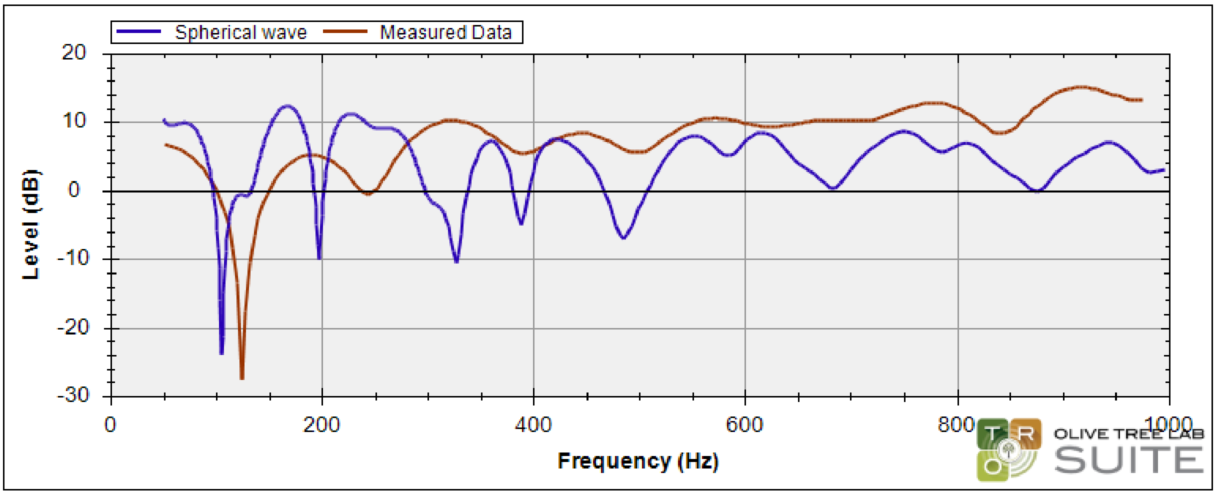

Figure 10: The SDE effect calculated using spherical wave propagation and how it compares to the measured results.

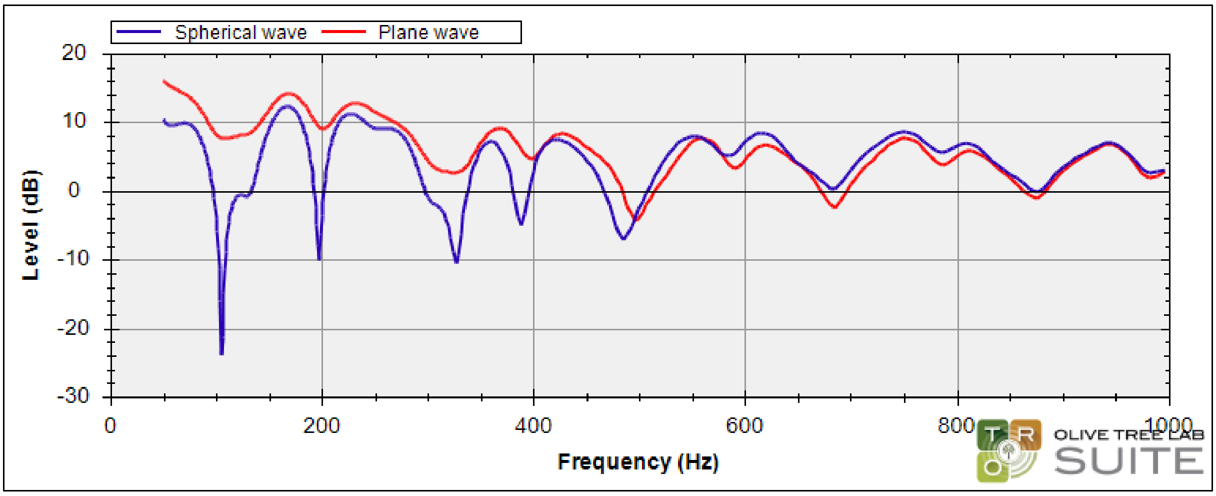

Figure 11: The SDE effect calculated using spherical and plane wave propagation.

The figure above shows a comparison between the calculated SDE using spherical wave propagation and plane wave propagation, employed in Geometrical Acoustics. It may be seen that plane wave propagation fails to capture the seat dip effect.

5. Conclusions

The above results demonstrate that WBGA provide an accurate and fast alternative solution in studying wave phenomena in theatres such as the Seat Dip Effect. 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 demonstrated that the WBGA approach has certain advantages over other wave based methods. These are:

1. WBGA can very easily isolate each sound path or a group of paths and show their contribution both in the frequency and time domain. Over and above, auralise isolated paths.
2. WBGA is faster than other numerical methods
3. WBGA is equally accurate as numerical methods
4. WBGA visually assists the understanding of physical processes.

We have also demonstrated that Geometrical Acoustics using plane wave propagation cannot calculate accurately sound wave phenomena such as the Seat Dip Effect. In contrast Wave Based Geometrical Acoustics with spherical wave propagation can accurately reproduce this effect.

Finally, 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.

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