The examination of the influence of standing waves on reverberation time measurements in small reverberant rooms

Marko Horvat, Kristian Jambrosic and Hrvoje Domitrovic

Faculty of EE and Computing, Unska 3, Department of Electroacoustics, HR-10000 Zagreb, Croatia
marko.horvat@fer.hr

The measurements of reverberation time are performed in a small and rather reverberant shoe-box type room in order to determine the spatial distribution of reverberation time with respect to the formation of standing waves in the room itself. The measurements are made in a two-dimensional raster with equidistant distribution of measurement points. The goal is to investigate the conclusions made in an earlier work by Graber et al. that the distribution of reverberation time values along the fore mentioned raster reaches maximum values at the points of minimum sound pressure level and vice versa. The room in which the measurements are made is deliberately chosen to be relatively small in order to examine the lowest modes of standing waves that form in the room.

1 Introduction

Following the earlier work of Graber et al.[1], the goal of this paper is to investigate the correlation between spatial distribution of energy and spatial distribution of reverberation time measured in a shoe-box type room. This particular room shape has been chosen with regards to an uneven spatial distribution of energy in the room expected in the lowest octave or ⅓-octave bands that are of interest in reverberation time measurements. The unevenness of energy distribution occurs due to appearance of room modes at frequencies that fall into the fore mentioned frequency bands. Graber et al. addressed this phenomenon empirically by making reverberation time measurements in a shoe-box type reverberation chamber, as well as exploring the laboratory one-dimensional case by making measurements in an impedance tube. Finally, a theoretical explanation was proposed.

The research described in this paper directly follows the work described above with the intention to examine the findings in a realistic shoe-box type room that does not have extreme properties like the reverberation chamber investigated by Graber et al., but can still be considered as fairly reverberant. The room is deliberately chosen to be small in order to examine the influence of room modes that are as low as possible.

2 The genesis of room modes

Every shoe-box type room, enclosed with three pairs of parallel surfaces, inherently has a non-uniform distribution of acoustic energy at low frequencies. This phenomenon is directly related to the appearance of standing waves in the room itself. The forming of standing waves in a shoe-box type room is possible due to the existence of parallel surfaces enclosing the room, as stated above. Furthermore, the existence of standing waves between parallel surfaces enables the formation of room modes at certain frequencies. The frequency of a given room mode can be calculated from:

$$f_{(p,q,r)} = \frac{c}{2}\sqrt{\frac{p^2}{L^2}+\frac{q^2}{W^2}+\frac{r^2}{H^2}} \text{ [Hz]} \qquad (1)$$

where c is the speed of sound, L, W and H denote room length, width and height, while p, q and r are non-negative integers denoting a particular room mode. Eq.(1) reveals that the frequencies at which the room modes occur depend solely on room dimensions. Furthermore, three types of room modes can form in a shoe-box type room. The simplest type of room mode is called axial as only one pair of opposing surfaces contributes to its forming. Two pairs of opposing surfaces are responsible for forming the so-called tangential modes, while all three pairs of opposing surfaces will form oblique modes. In relation to Eq.(1), the frequencies of axial modes are calculated when only one of the three non-negative integers p, q and r is non-equal to zero. The frequencies of tangential modes can be obtained when two of the three integers are non-equal to zero, while the frequencies of oblique modes are conditioned with all three integers being non-equal to zero. Room mode types and their notation are shown in Table 1. This particular type of notation assumes p, q, $r > 0$.

Mode type	Notation
Axial	(p,0,0) or (0,q,0) or (0,0,r)
Tangential	(p,q,0) or (p,0,r) or (0,q,r)
Oblique	(p,q,r)

Table 1 Room mode types and their notation

3 Problems already encountered in reverberation time measurements

In the extensive ongoing research on reverberation time measurements and related problems, sets of measurements have been made in several spaces of different sizes, shapes and acoustic treatment using different measurement methods and different types of sound sources [2, 3]. Having analyzed the results obtained from these measurements, an interesting phenomenon has been noticed. In order to present the observed phenomenon, measurement results are given for two shoe-box shaped rooms of very different sizes and acoustic treatment. The layouts of both rooms are shown in Figs.1 and 2.

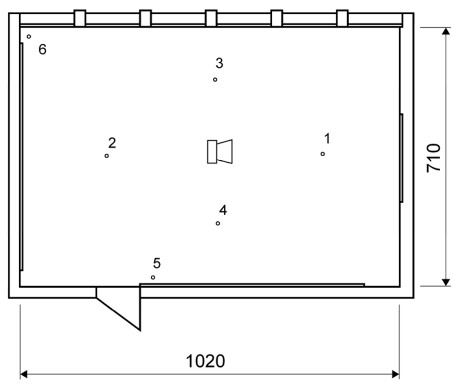

Fig.1. The layout of room 1.

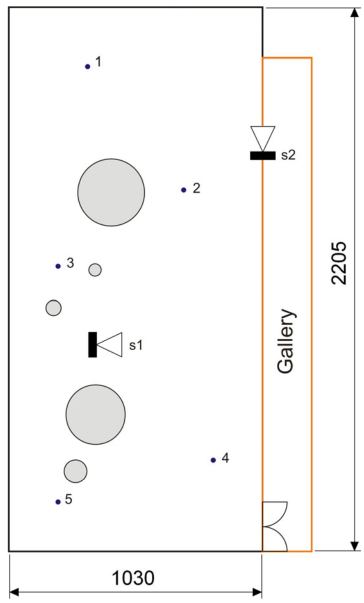

Fig.2. The layout of room 2.

Room 1 is an acoustically treated listening room of the following dimensions: length L = 10.20 m, width W = 7.10 m and height H = 3.21 m, giving the total room volume V = 230 m^3. On the other hand, room 2 has no acoustic treatment whatsoever due to its intended purpose of being a high voltage laboratory facility. Furthermore, it is much larger than room 1, having the following dimensions: length L = 22.05 m, width W = 10.30 m and height H = 8.60 m, giving the total room volume V ≈ 2000 m^3. The results of reverberation time measurements conducted in both rooms are shown in Figs.3 and 4.

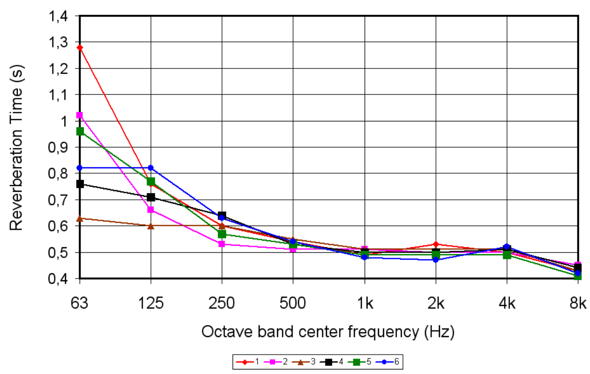

Fig.3. Reverberation time measured in room 1.

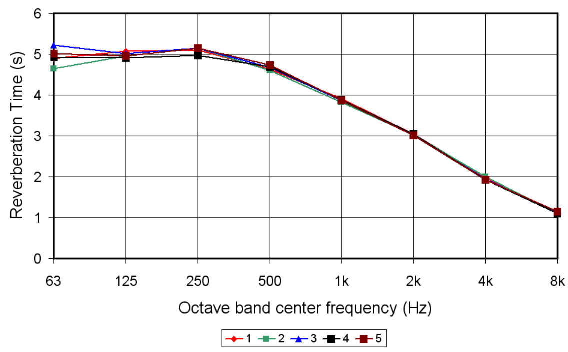

Fig.4. Reverberation time measured in room 2.

The measurements in both rooms were conducted using exactly the same measurement setup, namely, the same type of sound source and the same measurement method, in order to minimize measurement uncertainty and to enable direct comparison of the results.

Reverberation times were measured at several different measurement positions in each room, as shown on room layouts in Figs.1 and 2. As expected, reverberation times in these two rooms differ significantly due to the great difference in size and acoustic treatment of the rooms.

The results of reverberation time measurements conducted in room 1 show significant dispersion in octave bands with center frequencies of 250, 125 and 63 Hz. On the other hand, the results obtained in room 2 show the first signs of dispersion in the lowest octave band centered around 63 Hz. Furthermore, the dispersion of results obtained in room 1 tends to grow larger with the decrease of frequency. Unfortunately, the behavior of dispersion in room 2 could not be examined due to inability to measure the reverberation time in octave bands with center frequencies of 31.5 and 16 Hz. However, it is clear that the first appearance of significant dispersion of reverberation time has been shifted to lower octave bands with the increase of room dimensions.

The findings stated above have led to the assumption that the cause of the fore mentioned dispersion of reverberation time has to be connected with the relationship between the wavelength (and frequency) of sound and room dimensions. Since both rooms are shoe-box shaped, the logical conclusion was that the problem lies in the formation of standing waves and room modes at certain frequencies, as expressed by Eq.(1). Graber et al.[1] have offered a theoretical explanation to this problem by examining a one-dimensional case, i.e. standing waves formed in an impedance tube. Their examination revealed that the reverberation time measured along the tube length reaches its minimum values at points where the sound pressure level reaches its maximum values and vice versa. In other words, the uneven distribution of energy along the tube length leads to uneven distribution of reverberation time.

Encouraged by these findings, we have formed the principal hypothesis that the conclusions made for one-dimensional laboratory case can be extended to real shoe-box shaped rooms in which the standing waves form in all three dimensions. As a consequence, room modes are directly responsible for the uneven spatial distribution of energy inside a shoe-box shaped room at low frequencies, which then leads to an uneven spatial distribution of reverberation time.

As stated before, the results of reverberation time measurements performed in room 1 at different measurement positions clearly show the dispersion of reverberation time at low octave bands, which tends to decrease with the increase of frequency. Assuming the hypothesis made above is true, the following explanation has been offered: reverberation time is usually measured in frequency bands having a constant relative bandwidth, i.e. octave or ⅓-octave bands centered at predefined frequencies. It is reasonable to assume that the number of modes that fall within a given octave (or ⅓-octave) band will grow larger with the increase of center frequency. There are two reasons for this: first, as the frequency increases, the room mode density increases, and second, the absolute bandwidth of an octave band increases with center frequency. A small number of room modes falling within a given octave band will produce an uneven spatial distribution of energy in that band. As the number of modes falling within each consecutive octave band grows larger, the total spatial distribution of energy in that band will tend to assume the ideal uniform shape, thereby minimizing the dispersion of reverberation time.

The conclusions made above have been expanded to explain the results obtained in room 2. Since room 2 is of much larger size than room 1, room modes start to form at lower frequencies. Due to that fact, the number of modes falling within a specific octave band will be larger in a larger room, in this case in room 2. For example, 170 room modes formed in room 2 fall within the octave band centered at 63 Hz, compared to only 28 room modes formed in room 1. Following the conclusion made above, the total spatial distribution of energy in room 1 in this particular octave band will be much more uneven than the spatial distribution of energy in room 2 in that same octave band, resulting in a much larger dispersion of reverberation time in room 1 measured in given octave band.

4 Measured space and measurement setup

In order to examine the problem described above and to verify our initial hypothesis, a shoe-box shaped room with realistic properties has been chosen, namely, a small classroom having the following dimensions: room length L = 7.20 m, room width W = 6.66 m and room height H = 3.21 m. Prior to commencing the measurements, all moveable furniture had been removed from the room, leaving only several cupboards too heavy to be moved. The final layout of the room is shown in Fig.5. The photograph showing the appearance of the room and the placement of the measuring equipment is shown in Fig.6.

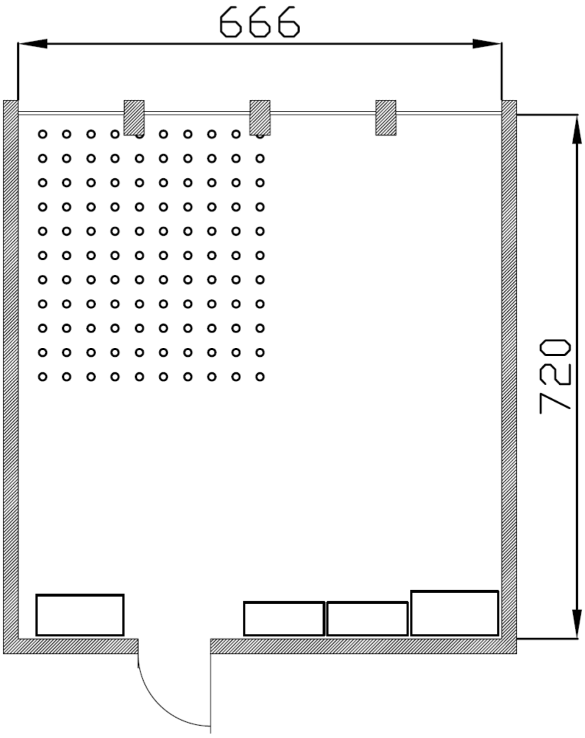

Fig.5. The layout of measured room.

Fig.6. The room prepared for conducting the measurements.

The layout in Fig.5 shows the positions of the cupboards mentioned above, occupying the wall with the door built in it. Unfortunately, these pieces of furniture, as well as the door itself, undoubtedly introduce a certain amount of low-frequency absorption, thereby reducing the reverberation time in octave bands of interest, namely, the ones with center frequencies of 63 and 125 Hz. Furthermore, the opposing wall contains eight large double-glass windows, partly showing in the photograph in Fig.6, which cover approximately two thirds of the total surface of the wall. These windows also contribute to low frequency absorption, reducing the reverberation time at low frequencies even further. At first, this somewhat unfortunate layout of the room has been viewed as a potential problem due to the fact that the reverberation time at low frequencies was shorter than expected. The question has been raised whether or not the room should be considered reverberant, as initially announced. Later, however, this disadvantage was welcomed, accepting the fact that this room with all its imperfections is, in fact, a very good representative of typical rooms that can be found everywhere. Therefore, if the initial hypothesis could be verified in a very common room that is far from ideal for this particular research, e.g. a shoe-box shaped reverberant chamber, it would be a rewarding success, in the opinion of the authors.

In order to examine the spatial distributions of energy and of reverberation time in the room, a grid of 110 measurement points has been defined, as shown in Fig.5. The distance between the neighboring points in both axes has been set to 33 cm in order to obtain an adequate spatial resolution of 9 measurement points per square meter. The point of origin for these measurements has been positioned to the center of the room. The decision has been made to make the measurements in one quadrant of the room floor plan and to extrapolate the results to the whole surface area of the room. Although this approach gives results that may not be valid for the whole room due to its imperfections, the assumption was made that the spatial distribution of energy, greatly influenced by room modes, has symmetric behavior.

After the measurement grid had been defined, the impulse response of the room was measured in each of the 110 measurement positions. In order to make these measurements, a laptop computer containing ARTA software [4] has been used as both the signal source and analyzer. Sine sweep has been used as the excitation signal, as earlier work [2, 5] revealed its properties to be superior to MLS and pink noise. An omni-directional sound source of our own design [6] has been used as the sound source. In order to enhance the performance at frequencies below 80 Hz, a subwoofer has been added. Fig.6 shows the measurement setup. The sound source has deliberately been placed to the very corner of the room in order to provide maximum possible amount of excitation with regards to forming of room modes. The impulse response measurements were taken in a single horizontal plane at half the room height. The impulse responses obtained as described above served as a basis for obtaining both the spatial distribution of energy and of reverberation time.

5 The results

The starting point of the measurements described in this paper was to examine the agreement between the theoretical values of room mode frequencies calculated for this particular room and the values obtained from actual measurements. For this purpose, several lowest room mode frequencies were calculated using Eq.(1). The results are shown in Table 2.

Frequency (Hz)	p	q	r	Mode
23.9	1	0	0	Axial
25.9	0	1	0	Axial
35.2	1	1	0	Tangential
47.8	2	0	0	Axial
51.7	0	2	0	Axial
53.6	0	0	1	Axial
54.4	2	1	0	Tangential
57.0	1	2	0	Tangential
58.7	1	0	1	Tangential

Table 2 Several room mode frequencies calculated for measured room.

Figs.7 and 8 show axial modes (1,0,0) and (0,1,0), as well as tangential mode (1,1,0). The magnitude values shown in the graphs are normalized to the maximum value and presented in decibels, as indicated by the color bars.

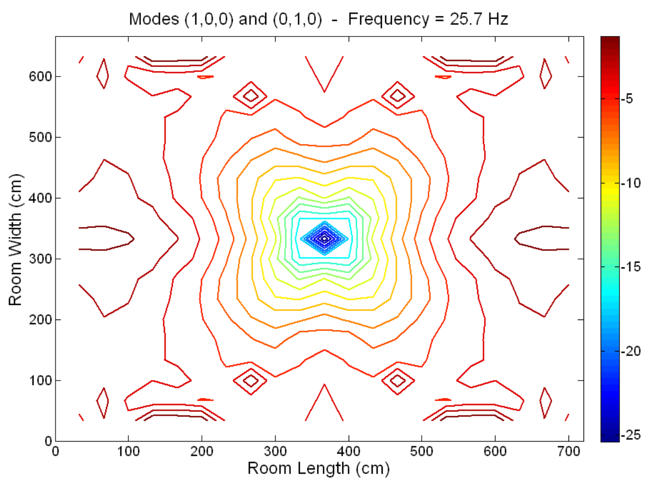

Fig.7. Axial modes (1,0,0) and (0,1,0) at 25.7 Hz.

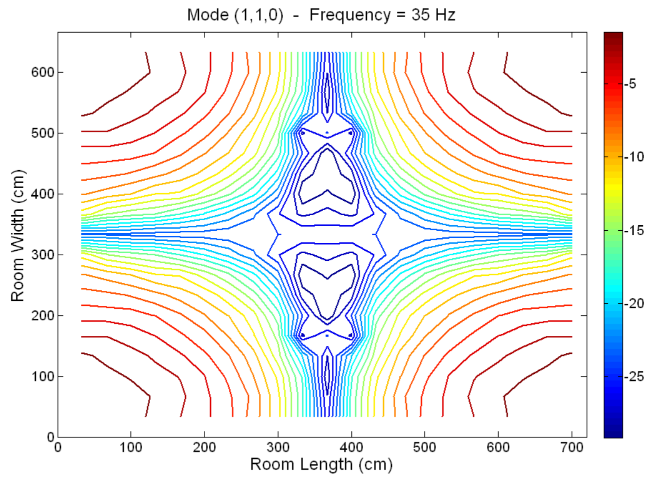

Fig.8. Tangential mode (1,1,0) at 35 Hz.

The measurements did not reveal the existence of axial mode (1,0,0) along the room length at the expected frequency, but have shown simultaneous appearance of axial modes (1,0,0) and (0,1,0) at the same frequency of 25.7 Hz, as shown in Fig.7. Table 2 reveals that this frequency is consistent with the lowest axial mode forming along the room width. On the other hand, the layout of the room shown in Fig.5 reveals that the pieces of furniture, namely, the cupboards positioned against one of the walls inevitably change the geometry of the room. This may be the cause of the disagreement between theoretically calculated and measured frequency of the lowest axial mode along the length of the room. The tangential mode (1,1,0) measured at 35 Hz, on the other hand, is in perfect agreement with the theoretical value.

As stated before, the reverberation time is usually measured in octave or ⅓-octave bands rather than on single frequencies. Since our measurements were performed with the emphasis on octave bands with center frequencies of 63 and 125 Hz, the calculations reveal that 19 and 113 room modes forming in this particular room will fall within these octave bands, respectively. Following the conclusions made in chapter 3, it is expected that the spatial distribution of energy and of reverberation time will be much more uneven in the octave band at 63 Hz than in the one at 125 Hz. The direct comparison of results obtained from measurements is shown in Figs.9 and 10 for octave band at 63 Hz and Figs. 11 and 12 for octave band at 125 Hz.

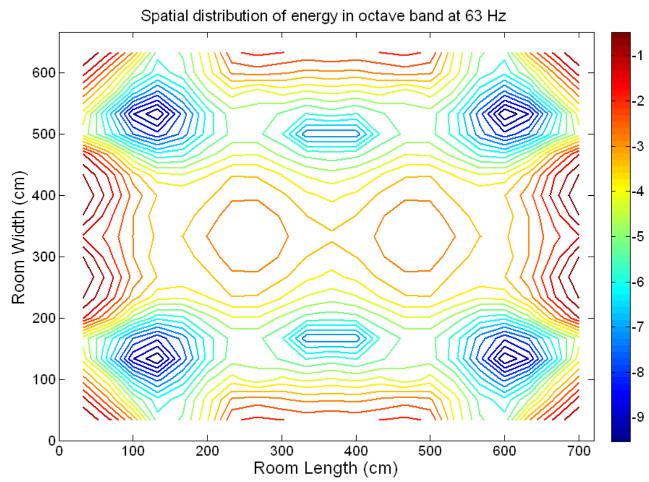

Fig.9. Spatial distribution of energy measured in octave band at 63 Hz.

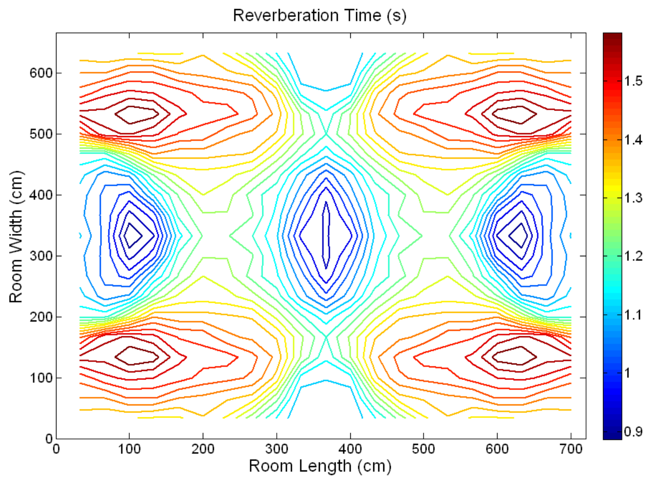

Fig.10. Spatial distribution of reverberation time measured in octave band at 63 Hz.

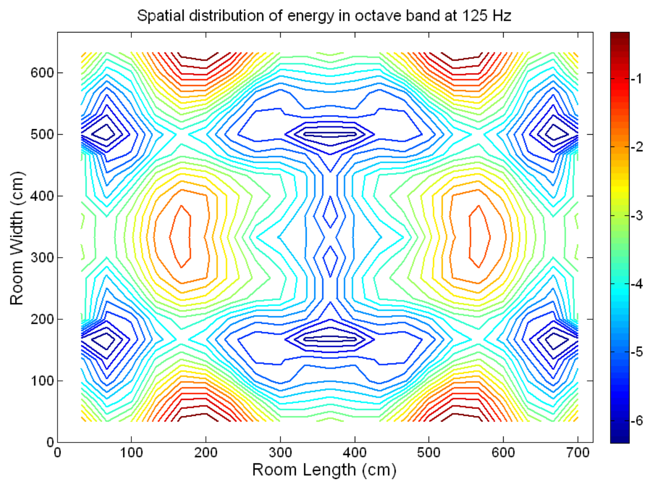

Fig.11. Spatial distribution of energy measured in octave band at 125 Hz.

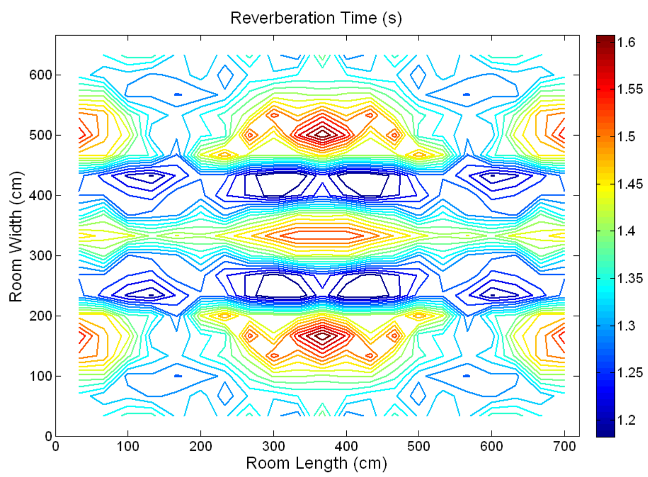

Fig.12. Spatial distribution of reverberation time measured in octave band at 125 Hz.

The color bars in Figs.9 and 11 indicate magnitude in decibels, with 0 as the maximum value, while color bars in Figs. 10 and 12 show the range of reverberation time measured in the room in the respective octave band.

The results shown above verify the initial hypothesis that the uneven spatial distribution of energy within a given octave band results in an uneven spatial distribution of reverberation time measured in that octave band. Furthermore, the maximum values of reverberation time were obtained at minimums of spatial distribution of energy and vice versa. This phenomenon is particularly emphasized in the octave band at 63 Hz, due to the fact that room modes falling within that band have a dominant influence on formation of sound field in a room of this size. The measurements made in octave band at 125 Hz show similar results, although it is reasonable to assume that the influence of room modes falling within this octave band on formation of sound field is somewhat diminished.

5 Conclusion

In this paper an attempt was made to question the hypothesis that standing waves have a significant influence on reverberation time at low frequencies, being the dominant factor in formation of sound field at those frequencies in shoe-box shaped rooms. The results obtained from earlier work, as well as the ones presented in this paper verify this hypothesis, proving that an uneven spatial distribution of energy in a room, caused by formation of room modes, will result in an uneven spatial distribution of reverberation time. Therefore, the hypothesis originally made on a one-dimensional model may now be extended to real three-dimensional spaces.

However, the results presented in this paper point to the unfortunate fact that the choice of measurement positions in a particular room, as random as it gets, may have a significant influence on the final results of reverberation time measurements conducted in shoe-box shaped rooms at low frequencies.

In the near future, further effort shall be made to investigate this phenomenon further by repeating the measurements in a different room of similar size, perhaps using a finer raster and extending the grid of measurements points to all three dimensions.

References

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