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THE INFLUENCE OF STANDING WAVES ON THE REVERBERATION TIME IN LARGE HALLS

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Abstract: *The acoustic situation of the St. Stephan's Cathedral in Vienna was investigated with the aim to find suggestions for the improvement of the acoustic condition for the musicians as well as for the audience. The results were reported at different conferences. Within this project extensive acoustic measurements were made with the aim to get information about the fine structure of the sound field. The analysis of the reverberation time showed that there could be a connection between standing waves and reverberation time. First discussions however came to a result that this could not be possible because the reverberation time is independent from sound pressure level: regardless whether the sound pressure level is high or low, as it could be observed at standing waves, the reverberation time should be the same, because it only depends on the absorption properties of the walls. Further investigations and measurements were done to solve this question. This paper will present the results of the measurements and give a theoretical interpretation.*

Key words: room acoustics, reverberation time, standing waves

1. INTRODUCTION

It was the aim of a acoustic research project to investigate the acoustic situation of the St. Stephan's Cathedral in Vienna. The results were published and presented at different conferences [1], [2], [3], [4]. Within this project it was decided, to get information about the fine structure of the sound field in this unique acoustic environment and therefore to take a much higher number of the measurement points then suggested by the different standards for reverberation time measurements (RT-M). The main reason for this decision was a quite diffuse idea, something like finding some nice acoustic phenomena not having a clue what it really could be.
As therefore lots of data were to handle, another decision followed quite logically: for a detailed evaluation a statistical handling of the data was not enough. For getting a in-depth overview of the data and curious about seeing some unexpected phenomena a tool was developed for the spatial 3-dimensional depiction of the data. On the one side this tool can display all the measurement data on the plain of the cathedral, and on the other side the data coming from room acoustic simulations can be displayed and compared with the measurements in a 3-dimensional plot. As an example **Fig. 1** shows the reverberation time (RT) at 125 Hz all over the cathedral (213 measurement points) with the excitation source positioned in the front of the right side aisle at the blue break-in.

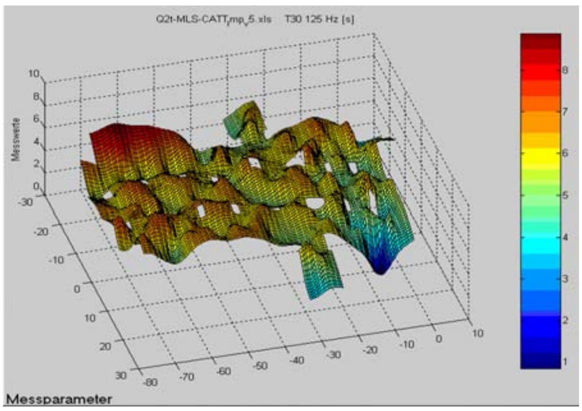


Fig. 1: spatial distribution of RT of 213 measurement points at 125 Hz

Fig. 1 was also shown at the first presentation of the results of this project at a meeting of the AES-Austrian-Section in Vienna [5]. A controversial discussion on the wavy distribution oft the RT in **Fig. 1** came to two contradicting points of view. One statement was that the wavy RT is caused by standing waves. The controversial position said, that standing waves could not be the reason for the wavy RT, because the existence of standing waves means only locally different SPL and reverberation time is independent from SPL as known since the first experiments made by Sabine. Everything looked like the second statement was the right one an the first statement had to be wrong. But the lecturer at this presentation had in the back of his mind the spatial distribution of the RT in a reverberation room as shown in **Fig. 2** as the result of an earlier project [6]. Easily can be recognized that the spatial distribution of the RT seems to have a relation to the SPL of standing waves, as the distance of the peaks of the RT is something about half the wavelength (at 63 Hz $\lambda / 2 = 2{,}7$ m).

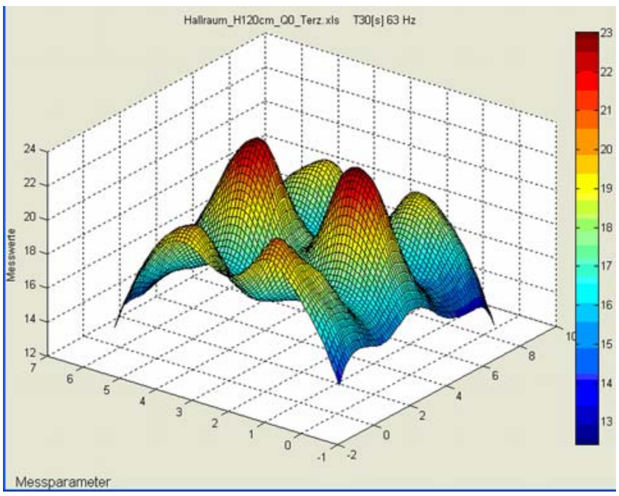


Fig. 2: spatial distribution of the RT in a reverberation room at 63 Hz, room size: 8,3 x 6 x 4,9 m

As it was not possible at this discussion to come to a final reliable result further investigations and experiments were necessary to get a clear idea what really is happening [8].

2. EMPIRICAL VERIFICATION

2.1. Evaluation of the spatial distribution of the reverberation time in a reverberation room

The first step was to take a closer look at the measurement data of the above mentioned reverberation room at Graz University of Technology with a size of 8,3 x 6 x 4,9 m (L x B x H) and to check, if the waviness of the spatial distribution of the RT resembles the shape of the SPL of standing waves. As the reverberation room is equipped with wave breaking plains, standing waves can only be observed at low frequencies. **Fig. 3** shows a 3D-view of the spatial distribution of the RT at 40, 50 and 63 Hz.

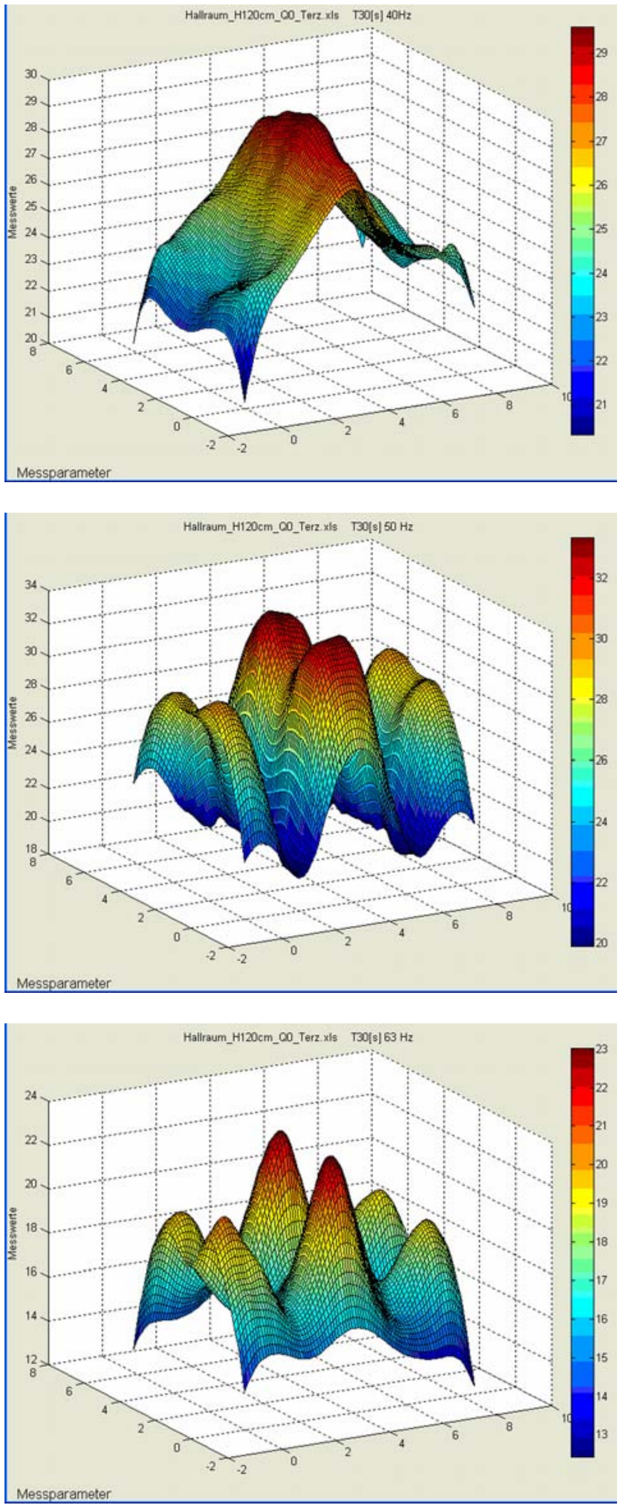


Fig. 3: spatial distribution of the RT in a reverberation room at 40, 50 and 63 Hz

It is quite obvious that the wavy shape of the RT is similar to a SPL of a sound field with standing waves. For measuring the distance of the minima of the RT the profile of the spatial distribution of the RT is shown in **Fig. 4**.

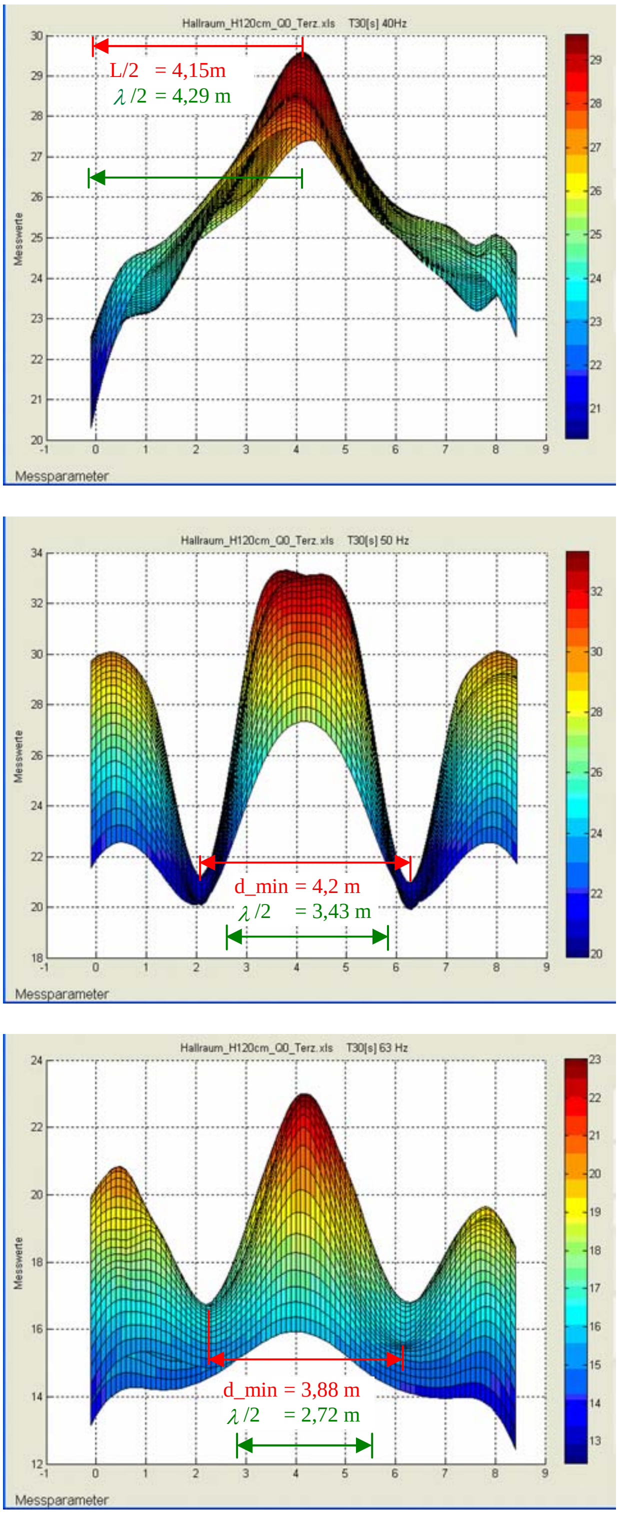


Fig. 4: profile of the spatial distribution of the RT at 40, 50 and 63 Hz

Table 1 gives the wave length respectively half the wave length at the interesting frequencies. At 40 Hz the wave length is 8,57 m which corresponds quite good to the length of the reverberation room (L = 8,3m). Therefore the shape of the RT can be interpreted as "one wave length" from RT_min at the left side over RT_max in the middle to RT_min at the right side. As can easily be seen at 50 and 63 Hz the distance of the minima d_min of the RT is about the size of half the wave length but there are deviations between d_min and $\lambda/2$ of more then 25%. This is because the RT was measured with a microphone height of 1,2 m. Thus the minima in the RT shows the minima in the measurement plain which must not be the true minimum of the RT in the reverberation room. It is easy to imagine that the true minima of the RT are outside the measurement plain, because it is the matter of a 3-dimensional sound field.

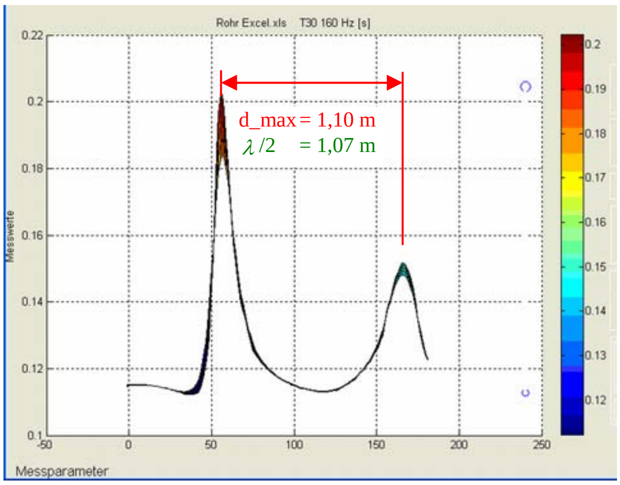
f [Hz]	λ [m]	$\lambda/2$ [m]
40	8,57	4,29
50	6,86	3,43
63	5,44	2,72

Table 1. wave length at 40, 50, and 63 Hz

As can be seen in **Fig. 4** there seems to be a relation between the spatial distribution of the RT and the sound field of standing waves. For further verification it was decided to change to the much simpler one dimensional sound field of a impedance tube where the local mapping of SPL minima and maxima respective the RT_min and RT_max is well defined.

2.2. Evaluation of the spatial distribution of the reverberation time in an impedance tube

The used impedance tube has a length of 2,4 m and a diameter of 0,08 m so plain wave propagation is possible between 70 and 2100 Hz. The spatial distribution of the RT was measured from the end of the impedance tube to the side where the loudspeaker is mounted. The distance of the measurement points is 1 cm. As at least one wave length should be seen in the impedance tube the lowest measurement frequency was set to 160 Hz. **Fig. 5** depicts the RT in the impedance tube at 160, 315 and 500 Hz.



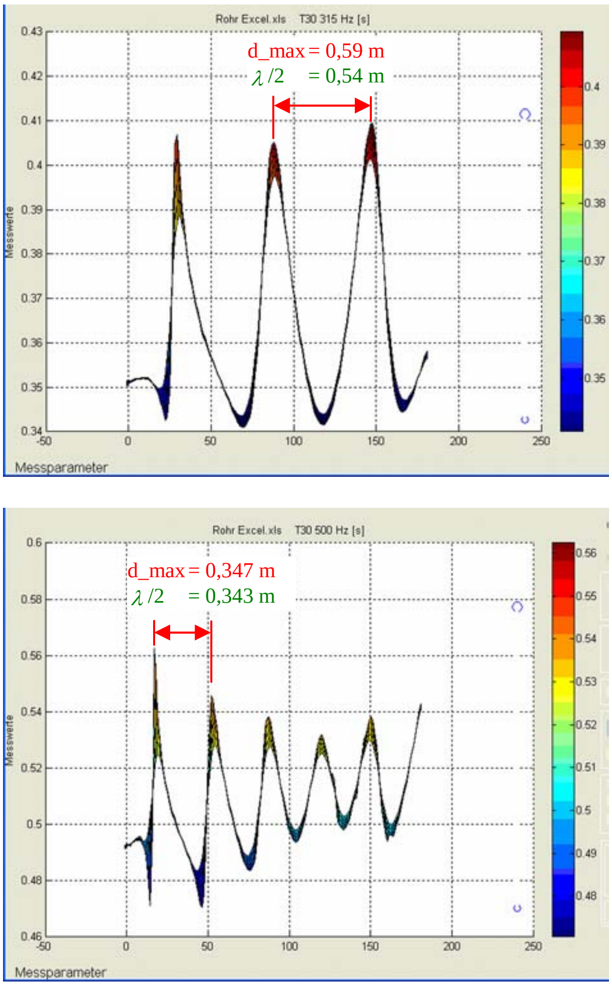


Fig. 5: spatial distribution of the RT in the impedance tube at 160, 315 and 500 Hz

It is quite obvious that the wavy distribution of the RT exists and that the distance of the RT_max matches very good with $\lambda/2$. As in an earlier project the standing waves in the impedance tube were measured and simulated [7] it was quite easy to find the relation between the waviness of the RT and the SPL of the standing waves. As an example **Fig.** 6 illustrates the SPL of the standing wave at 160 Hz.

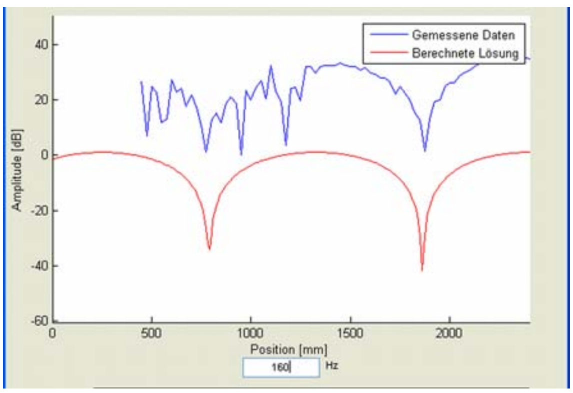


Fig. 6: SPL of the standing wave at 160 Hz in the impedance tube: measurement (blue) and simulation (red)

The next step was to superpose the SPL of the standing wave with the RT measurement which is shown in **Fig. 7.**

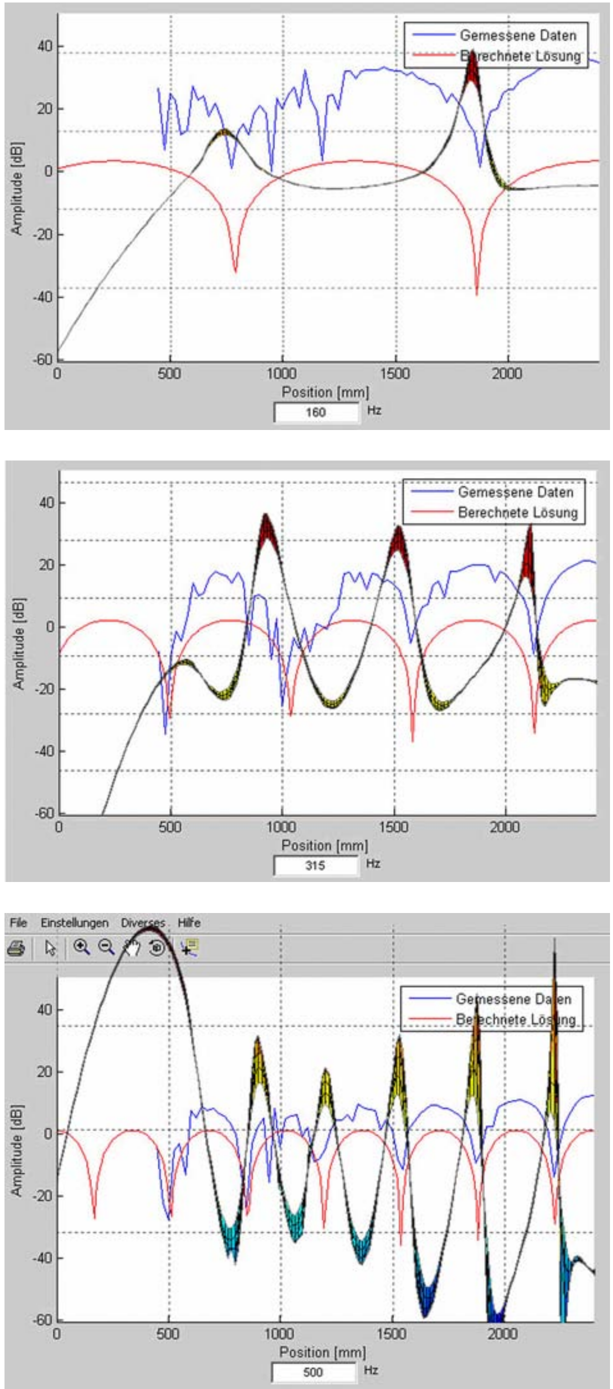


Fig. 7: SPL of the standing wave superposed with the RT at 160, 315 and 500 Hz in the impedance tube: SPL measurement (blue), SPL simulation (red), RT measurement (colored)

The superposition of the SPL data and the RT data gives a very interesting result: the maximum of the RT is located at the SPL minimum of the standing wave. This result provided the key to set up a hypothesis for the solution of the problem.

3. HYPOTHESIS ON THE RELATION OF THE SPL OF STANDING WAVES AND REVERBERATION TIME

First some basics in room acoustics had to be remembered.

- The statistical room acoustic assumes that the energy density is the same all over the room. If this is the case, also the RT should be the same at any position of the room.
- The appearance of the SPL minima and maxima of standing waves results in the phase relation of the incident and the reflected waves. If one assumes a total reflection on a wall, the incident wave and the reflected wave are in phase at the reflecting wall and in distances of $n \cdot \lambda / 2$ in front of the wall and they are out of phase at distances of $(2n-1) \cdot \lambda / 4$. At the maxima of the envelope of the standing wave the incident and reflected wave are in phase and at the minima they are out of phase as shown in **Fig. 8**.

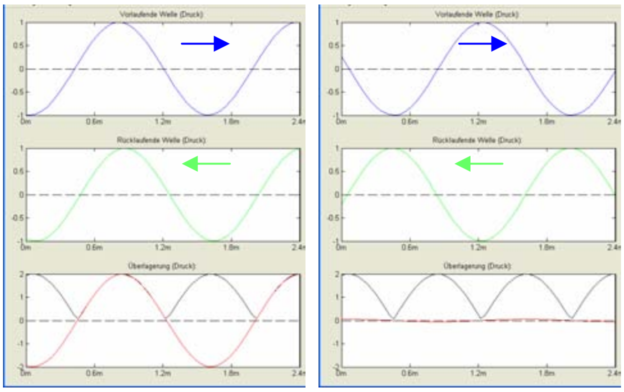


Fig. 8: incident wave (blue), reflected wave (green), standing wave (red), envelope of the standing wave (black); reflective wall at the right hand side; left: in phase situation – SPL maximum (red), right: out of phase situation – SPL minimum (red).

Taking into account this conditions it is clear that the high SPL maximum of the standing wave is a result of two or more waves which are in phase (**Fig. 8**: left red curve). As the sound source remains on the standing wave will be stable. But when the sound source is turned off the standing wave will collapse as there is no incident wave. The SPL will be reduced immediately about 6 dB. Afterwards the normal decay due to the room acoustic environment takes place. The sudden SPL reduction caused by the collapsing standing wave leads to a shorter RT at this location.

Contrary the SPL minimum of the standing wave is the result of two or more waves which superpose out of phase and thus resulting in a very small SPL (**Fig. 8**: right red curve). Switching off the incident wave from the sound source leads to a sudden increase of the SPL and afterwards the decay according the room acoustic situation takes place. As the evaluation of the RT starts at the SPL minimum and there is a significant increase of the SPL after switching off the incident wave the measured RT will be larger in this location.

Taking into account the superposition of a normal decay as described by the statistical room acoustic and a standing wave we can put the following hypothesis:

When the collapsing of the SPL minimum respectively SPL maximum of the standing wave superposes with the normal decay, a wavy RT will result at all standing wave frequencies with RT_max at the SPL minima of the standing wave and RT_min at the SPL maxima of the standing wave. All the frequency range outside the standing wave frequencies is free from the spatial waviness of the RT and has more or less the same RT at all positions in the room.

4. VERIFICATION OF THE HYPOTHESIS

The verification of the hypothesis was again done by a measurement in the impedance tube. The impedance tube was excited with a sinusoidal wave and the signal was recorded in a SPL minimum respective SPL maximum of the standing wave. Switching off the excitation signal should show the effect described in the hypothesis.

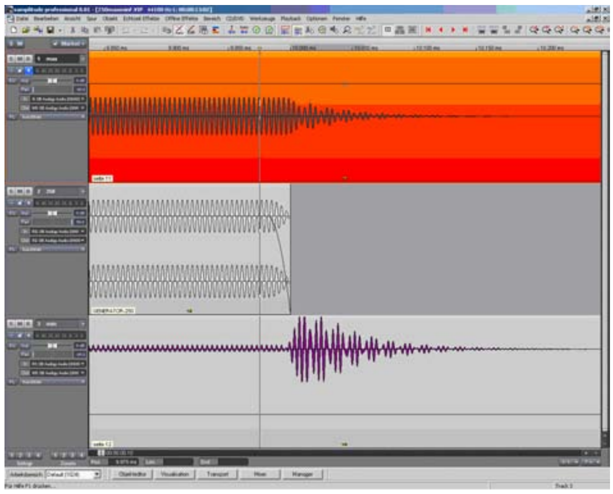


Fig. 9: Verification of the hypothesis:
2nd line: excitation signal (250 Hz)
1st line: decay at a SPL maximum
3rd line: decay at the SPL minimum

Fig. 9 depicts quite clear the expected effect: The 2nd line shows the excitation signal, which was faded out to avoid switch off clicking. In the 1st line the SPL maximum is recorded, in the 3rd line the SPL minimum. Clearly can be seen the sudden increase of the SPL minimum after switching off the source signal in the 3rd line, which leads to a significant longer decay than in the 1st line. Considering the evaluation of the RT takes the stationary SPL before switching off the source signal as 0 dB and calculates from this level the -60 dB decay, it is quit obvious that this decay is reached much earlier in the 1st line then in the 3rd line. This means that the RT at a SPL maximum is smaller then at the SPL minimum.

5. CONCLUSION

The starting point of this paper were the contradictory statements on the spatial waviness of the RT in the St. Stephan's Cathedral in Vienna as shown in **Fig. 1**. One statement posted that the spatial waviness in RT is caused by standing waves the other said that this isn't possible. It was empirically shown, that in reverberation rooms at low frequencies a significant spatial waviness can be observed. With some further experiments in the impedance tube it could be demonstrated, that there is a relation between the SPL maximum of a standing wave and the RT_min respective the SPL minimum of a standing wave and RT_max. Finally an explanation for this effect was given. It was proved that standing waves cause a wavy distribution of RT.

REFERENCES

[1] M. Fellner, F. Graf, et al.: **Untersuchungen und wissenschaftliche Forschungen zur Akustik und musikalischen Aufführungspraxis des Domes zu St. Stephan in Wien mit dem Ziel der Ausarbeitung von Verbesserungsmöglichkeiten**, Österreichische Nationalbank, Wien, 2005

[2] M. Fellner, F. Graf, et al.: **Zur Akustik im Dom zu St. Stephan in Wien**, DAGA2006, Braunschweig, 2006

[3] G. Graber, P. Gutmann, et. al.: **Die Nachhallakustik großer langgestreckter Räume**, DAGA2006, Braunschweig, 2006

[4] M. Fellner, F. Graf, et al.: **The Acoustic Situation in the St. Stephan's Cathedral in Vienna**, Forum Acusticum 2005, Budapest, 2005

[5] G. Graber, M. Fellner, et al.: **Die Akustik im Dom zu St. Stephan - Ist eine akustische Verbesserung der Musiziersituation möglich?,** Vortrag am 25. 5. 2005 im Rahmen des Meetings der AES-Austrian-Section, Wien 2005

[6] M. Geigl: **Messungen an mikroperforierten Folien im Hallraum,** Diplomarbeit an der TU-Graz, Graz 2004

[7] H. Hiebel: **Das Kundtsche Rohr - Matlab-Simulation unter Berücksichtigung von Mehrfachreflexionen,** Projektarbeit an der TU-Graz, Graz 2005

[8] P. Gutmann: **Nachhallakustik langgestreckter Räume,** Projektarbeit an der TU-Graz, Graz 2007