Influence of room acoustics on music and music reproduction in small rooms

Ingolf Bork,
Physikalisch-Technische Bundesanstalt Braunschweig
Arbeitsgruppe Raumakustik, D-38116 Braunschweig, Bundesallee 100, Germany, **ingolf.bork@ptb.de**

For musicians, optimal room acoustical properties comparable to concert halls are not always given and for daily rehearsing, only small rooms with completely different acoustical behaviour are available. The restrictions due to standing waves (room resonances) and early reflections do not only influence the sound of the instrument played but also the complex feedback process via the musician's ears. For optimal reproduction of music via loudspeakers, room acoustical conditions are of similar importance. Typical problems will be demonstrated by means of auralisation gained by practical measurements and by computer simulation.

1 Introduction

The acoustical condition on the stage of a good concert hall is a major prerequisite for the performing musician in order to produce music of the highest possible quality level. The main factor is the acoustic response of the hall to the sounds radiated from his instrument, which serves as one of the most important parts of the feedback for the permanently active control-loop via his ears. Reverberation, sound colour, reflections, the sound transmission from other instruments are only a few of the parameters which the musician takes into account during his playing. But for preparing a concert, the room acoustical conditions are usually opposite: in small rehearsing rooms, a high degree if imagination is needed on the part of the musician to estimate the effect a certain concert hall has on the music played by him. Short reverberation times, resonances at low frequencies and early reflections from the walls characterise the acoustics of a typical room for rehearsing.

2 Room acoustical conditions in small rooms

2.1 Middle and high frequencies

The acoustical influence of a room on sound reproduction is commonly described by the impulse response of the transfer path between sound source and sound receiver. It can be measured by modern room acoustical measurement equipment and allows the estimation of distinct early reflection by visual inspection of the plotted or displayed impulse response. It is comparable with the acoustical effect of a short clap or a shot and contains all information about the sound propagation and also about the soundfield at the receiver position under the given conditions. For the evaluation of reverberation times, automatic filtering and regression procedures are implemented in the computer-controlled systems (e.g. [1]).

The spectral correspondent of the impulse response is the transfer function, which contains the spectral coloration properties of the transfer path. Modern room simulation programs today are able to calculate not only the impulse response and the transfer function but also the room acoustical parameters which characterise the quality of the simulated room with respect to speech and musical performances [2]. Furthermore it is possible to convolve arbitrary anechoically recorded music with the measured or calculated impulse response in order to get a binaural impression of the room properties for the selected music material.

The investigation of impulse responses in small rooms compared to those of concert halls reveals some significant differences:

- the reverberation time is shorter
- early reflections are very strong and follow the direct sound with a short delay of a few milliseconds
- these reflections can affect the sound colour if the direction of incidence is close to another reflection of similar amplitude with small delay (comb filter effect)
- the sound depends on the position of the musician (sound colour and reflections)

Figure 1 shows as an example two reflectograms, calculated by a room simulation program (CATT v8.0c) for a concert hall and a small room. They correspond to the transfer path from the instrument to the musician's ear. Here only reflections up to the order of four are displayed although in the case of the concert

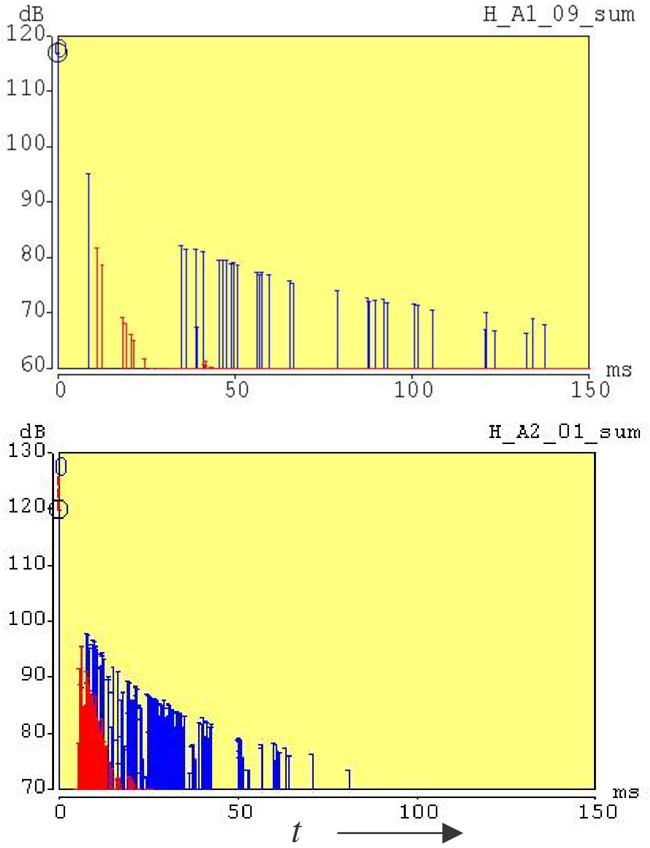

Figure 1: Calculated reflectograms at the musician's ear. Upper: in a concert hall (ELMIA hall, V = 11000 m³), lower: in a rehearsing room (V = 41 m³), the circle marks the direct sound

hall no further reflection is found within the first 150 ms if 5th order reflections are included. Diffuse reflections are printed in red. The comparison clearly shows the differences in reflection density and in time structure. For the concert hall (upper graph), after a direct reflection from the stage floor the first reflection from the stage wall arrives after 35 ms; all further sounds coming from the hall arrive later.

Although the musician hears his own instrument very loudly and the direct sound level is very strong, the sound of the room will always be perceived very clearly. High reverberation times are preferred, especially for soloists, because they enhance the impression of supplying a lot of sound energy into the hall and the musician prefers to feel enveloped by his own sound coming back from the hall. On the other hand, for rehearsing in small rooms short reverberation times enable a more critical and detailed judgement of melodic phrases and help the musician to improve his playing.

2.2 Low frequencies

While the concept of impulse responses concerns mainly the middle and high frequencies, in small rooms, as those which are mostly used for rehearsing, resonance effects come into play. The frequency which separates both regions is dependent on the room size and its reverberation time. As a simple rule of thumb the so-called Schroeder frequency f_s can be used for defining the upper limit of small-room behaviour:

$$f_s = 2000\sqrt{;T/V}$$

with the room volume V in m^3 and the reverberation time T in s. While at higher frequencies the rules of geometrical and statistical acoustics are applicable, below the Schroeder frequency wave effects like standing waves and diffraction have to be taken into account. That is why until now usual room simulation programs do not work correctly at low frequencies and auralisations are limited to higher frequencies.

2.3 Rectangular rooms

In ideal rectangular rooms, the soundfield can be calculated as the sum of the contributions of all its standing waves which in this special case show a sound pressure distribution in the three directions x,y,z following the equation

$$p = p_{max} * \Sigma \cos(n_x \pi * x) * \cos(n_y * \pi * y) * \cos(n_z * \pi z)$$

(n_x, n_y, n_z = 0,1,2,3..; x, y, z = 0...1)

The figures n_x, n_y, n_z indicate the number of pressure zeros along each direction. In a three-dimensional view these points form straight nodal lines. In Figure 2 positive pressure values are marked by red areas, negative ones are in blue. The straight nodal lines lie in middle of the green areas. Each resonance is characterised by the triple of its node numbers and called a mode, e.g. in Figure 2 the (2,3,1)-mode shows 2,3 and 1 nodal line in each of the three directions.

The corresponding modal frequencies are determined by the dimensions of the room. The lowest mode shows a standing wave which matches the space between the two walls with the largest mutual distance and with one nodal line in the middle.

For music performance in such a room, the sound transmission between the sound source and the receiver depends on the positions of both relative to the standing wave structure. In a pressure maximum (e.g. at $x = n_x * \pi$) the excitation as well as the received sound of the corresponding frequency reaches the maximum values with respect to the x-direction.

In contrast to this, a sounding modal frequency can neither be heard nor excited at the nodal lines of its corresponding standing wave.

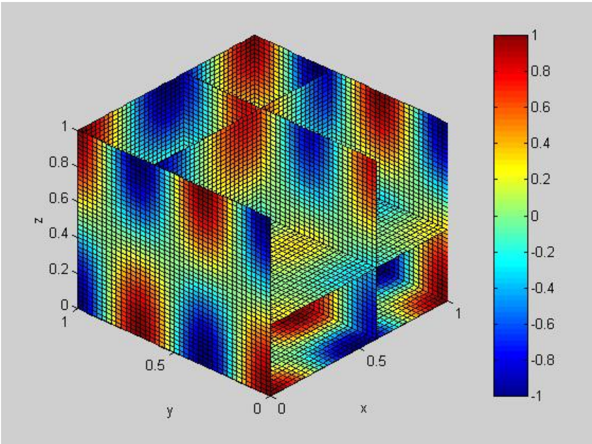

Figure 2: Sound pressure distribution of mode (2,3,1) in a rectangular room

2.4 Non-rectangular rooms

For more realistic room shapes, the exact calculation of mode shapes and frequencies is not so simple, but as FEM calculations have revealed, slight changes in the surfaces will not change the frequencies significantly whereas the nodal lines will move significantly (see Figure 3), making an exact prediction of sound transmission very complicated. The modal density, i.e. the number of modes per bandwidth, does not change with the room shape if the volume is kept constant.

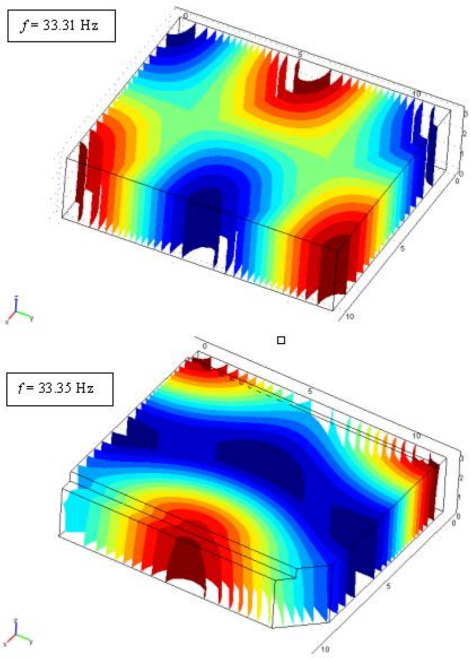

Figure 3: Different mode shapes in a rectangular room with slight geometrical changes, iso-pressure lines of mode (1,2,0)

3 Influence of the room on the sound

3.1 Musical instruments

The sound radiated by a musical instrument is generally influenced in many ways by the room. In *small* rooms the dependence on the position becomes a problem for the musician because not only the sound colour and the intensity of single partials will vary with movement but also the time dependence of the sound envelope may change. This becomes clear when a sudden tone attack is played with a note whose strongest partial matches exactly the resonance frequency of a room mode and the radiation takes place at a sound pressure maximum. The effect is the same as exciting an electric resonance circuit with a switched-on sine tuned to its resonance frequency: the amplitude will be reached after a finite attack time showing an exponential increase in its envelope. In musical practice: if a double bass string which is tuned to a room mode is plucked at a place of high sound pressure, a long attack process can be expected. In contrast, if such a note is suddenly damped, it may occur that the standing wave will decay slower than the bass string.

Such effects depend of course on the low-frequency absorption character of the room and can be avoided by applying modern low-frequency absorbers [3].

3.2 Sound reproduction via loudspeakers

For sound reproduction in small rooms via two or more loudspeakers, the same conditions are valid for the location-dependent sound effects. For standing wave effects, the position of the listener and of the loudspeakers is crucial, as well as the absorption properties of the room. In order to get optimal sound quality, high absorption at all frequencies is recommended and reflecting surfaces should be avoided or modified in such a way that early reflections from the loudspeaker sound will not reach the listener's ears. Sound diffusers are a useful possibility of distributing incident sound energy into a large radiation angle instead of producing a singular specular reflection.

If more than one low-frequency radiating loudspeaker (subwoofer) is used, the knowledge of the nodal lines can be used to avoid a transmission gap at certain room modes. If both subwoofers happen to be located on the same nodal line of mode (e.g. parallel to one wall at $\lambda/4$ distance), the corresponding frequency cannot be excited at all (cf. Figure 4). Moving one of them away from this line will improve the sound for all those modes which have nodal lines in the same direction. Then only one of the two speakers will stand in a node and the other will radiate always under different conditions.

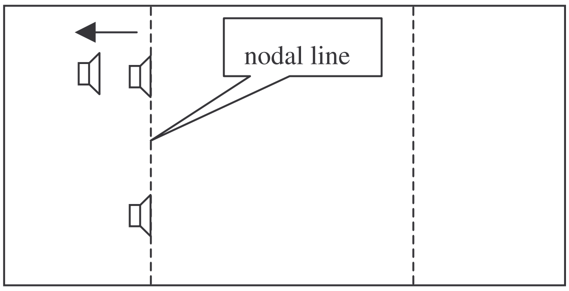

Figure 4: Improvement of low frequency sound reproduction in a rectangular room by removing one loudspeaker from a nodal line

Loudspeakers in a room corner will excite all room modes and will never be in a nodal line. This might be a good solution for many cases because sound radiation is generally improved in corners, and room resonances should be damped either if possible. For a proper arrangement of loudspeakers in a rectangular room, the room modes and the positions of their nodal lines should be known and avoided. Generally it can be recommended to choose an arrangement of loudspeakers and listener at an oblique angle with respect to the walls, in order to avoid a placement of both speakers in the same nodal line.

The influence of a standing wave on the sound of a special signal is documented in Figure 4. A tone burst with the frequency of 208 Hz (a), tuned to a resonance of a room, is radiated by a loudspeaker and recorded by a microphone. Depending on their position relative to the maxima and minima of the standing wave, the envelope of the sound signal is modified by the room in the displayed way: (b): loudspeaker in the pressure maximum, microphone in the minimum, (c) both in the pressure minimum, (d): both in the pressure maximum. In the worst case (d), the maximum of the envelope is delayed 200 ms, in a musical context, this means that at a playing tempo of 150 bpm this note will be delayed by one quaver.

4 Auralisation of wave effects in small rooms

Since room simulation programs are not able to auralise standing wave effects it has been tried to write a simple interactive demonstration program in MATLAB which enables the convolution of arbitrary sound signals with the transfer function of a rectangular room including the sum of all relevant modes depending on the position of source and receiver. If the damping of each individual mode is taken into account, the transfer function can be calculated for the low frequencies by summing up the contribution of each mode. The impulse response is calculated by applying the inverse FFT, and for convolution, the FFTFILT algorithm was used. To take into account also the standard room simulation frequency range, another convolution has to be applied to the resulting sound. First experiments with this program showed that not only a realistic small room impression could be produced but also transient effects as the one shown in Figure 4.

5 Summary

The acoustical properties of small rooms in contrast to concert halls are strongly influenced by low-frequency resonances appearing as standing waves. For the musician, the following low-frequency effects need attention during rehearsing:

- The sound at his ears is dependent on his and the instrument's position relative to the maxima and minima (nodes) of the standing waves.
- For each note played and each partial the conditions are different and fast changes of sound colour can occur
- The attack of single notes can be delayed significantly especially for plucked instruments and percussion
- The decay of damped single notes may be prolonged by a room resonance
- The smaller the room, the lower the modal density in the audible low-frequency range

Standing waves can be reduced by special low-frequency absorbers of low depth.

For higher frequencies, reflections at plane surfaces may change the sound of the instrument if direct sound and reflection come from a similar direction. To avoid specular reflections, diffusing elements should be applied. Broadband absorbers do not only reduce undesired reflections but also the total sound level.

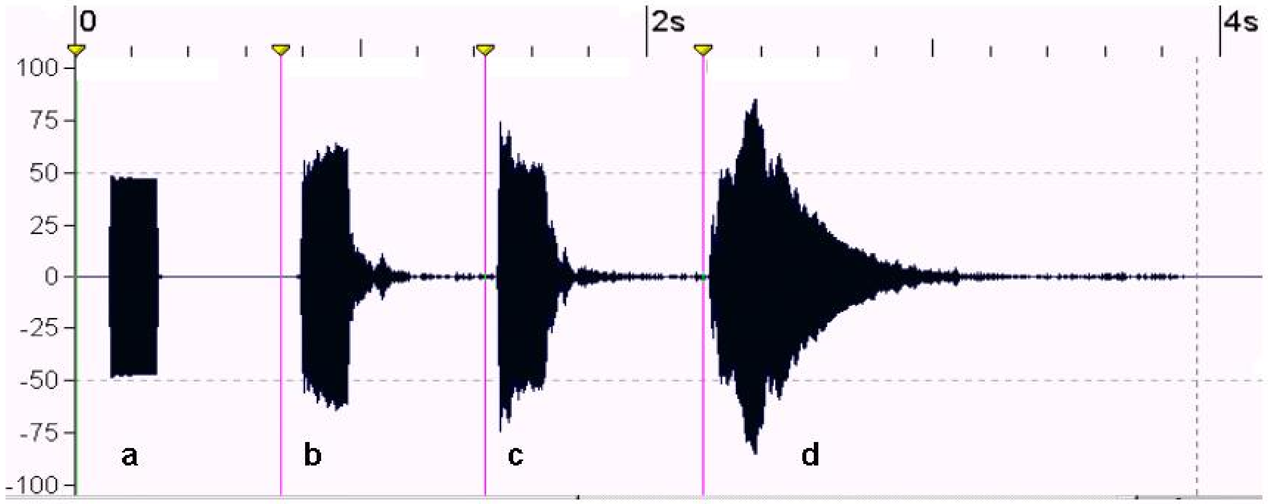

Figure 4: Tone burst 208 Hz and measured sound pressure envelopes:(a) source signal, (b): loudspeaker in the pressure maximum, microphone in the minimum, (c) both in the pressure minimum, (d): both in the pressure maximum

References

[1] www.winmls.com

[2] I. Bork: *Report on the 3rd Round Robin on Room Acoustical Computer Simulation - Part II: Calculations*, Acta Acustica united with Acustica vol. 91 (2005) in print

[3] H. Fuchs: *Lärmbekämpfung und Schalldämpfer: Einsatz faserfreier Absorber in der technischen Akustik*, Springer Verlag ISBN 3540626557