

# INVESTIGATIONS ON THE DEVELOPMENT OF THE FREQUENCY RESPONSE OVER TIME IN CONCERT HALLS

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## 1 INTRODUCTION

The subjective impression of the concert hall acoustics is usually formed around various descriptors, such as clarity and definition, and envelopment in the sound field. While room acoustics is evaluated from room impulse responses with several standardized objective parameters<sup>1</sup>, such as G, T60, C80, EDT, and LF, the frequency response of the hall is sometimes left for lesser importance. The overall frequency response commonly depends on the surface properties. Although the direct sound frequency response could be intuitively thought as flat, the "seat dip" phenomenon affects to the direct sound by attenuating low frequencies. The effect is noticed mainly around 100-300 Hz, but it can span up to 1000 Hz. The seat dip effect was first introduced with real and model measurements at different distances from the stage by Schultz and Watters, and Sessler and West in 1964<sup>2,3</sup>. The attenuation was noticed at approximately one-quarter wavelengths of the seat heights, when the sound is diffracted from the seat backs to the floor, and later integrates with the actual direct sound causing destructive interference. The effect was observed to increase with longer receiving distances up to 19 m. Subsequently, multiple papers have been published on the subject with measured and experimental data.

Bradley have presented measurements with scale models and 11 concert halls<sup>4</sup>. The seat dip effect was charted by correlating a 0-40 ms strength parameter G40 to the hall height and source-receiver distances. Incidence angles of 15 degrees or more were observed to improve G40. Finally, the importance of ceiling reflections with decreasing seat dip effect was suggested. Barron has suggested that the attenuation of the low frequencies due the seat dip effect should be compensated by increased amount of late energy at the affected frequencies<sup>5</sup>. This approach has later been criticized by Bradley<sup>6</sup>.

Davies and Lam have presented measurements in a large unoccupied hall<sup>7</sup>. The increase in the receiver height was noticed to decrease the frequency and magnitude of the attenuation, while lowering the source introduced a more prominent attenuation, also in broadband. In addition to a 50 ms fixed window after the direct sound, the development of the attenuation magnitude was studied with a varying-length time window. Later, Davies et al.<sup>8</sup> have studied the limits of the perceivable seat dip attenuation with hall simulations. Varying amounts of attenuation were applied to the direct sound and five lateral reflections by removing energy with one-octave band equalizers at the 200 Hz center frequency. Subjective listening tests with music yielded a threshold of around 4 dB within a 80 ms window. With 40 ms time window the threshold corresponded to around 6 dB attenuation, and -2 dB for the full impulse response. It was also suggested that the seat dip attenuation could be masked with unaffected early reflections instead of increasing the low-frequency reverberation.

Theoretical calculations on the seat dip effect have been presented by Ando et al.<sup>9</sup>. Takahashi has presented an analytical explanation for the phenomenon with the help of scale models of a small hall<sup>10</sup>. Structural suggestions for reducing the seat dip effect has been discussed in a number of publications<sup>7,9,10</sup>.

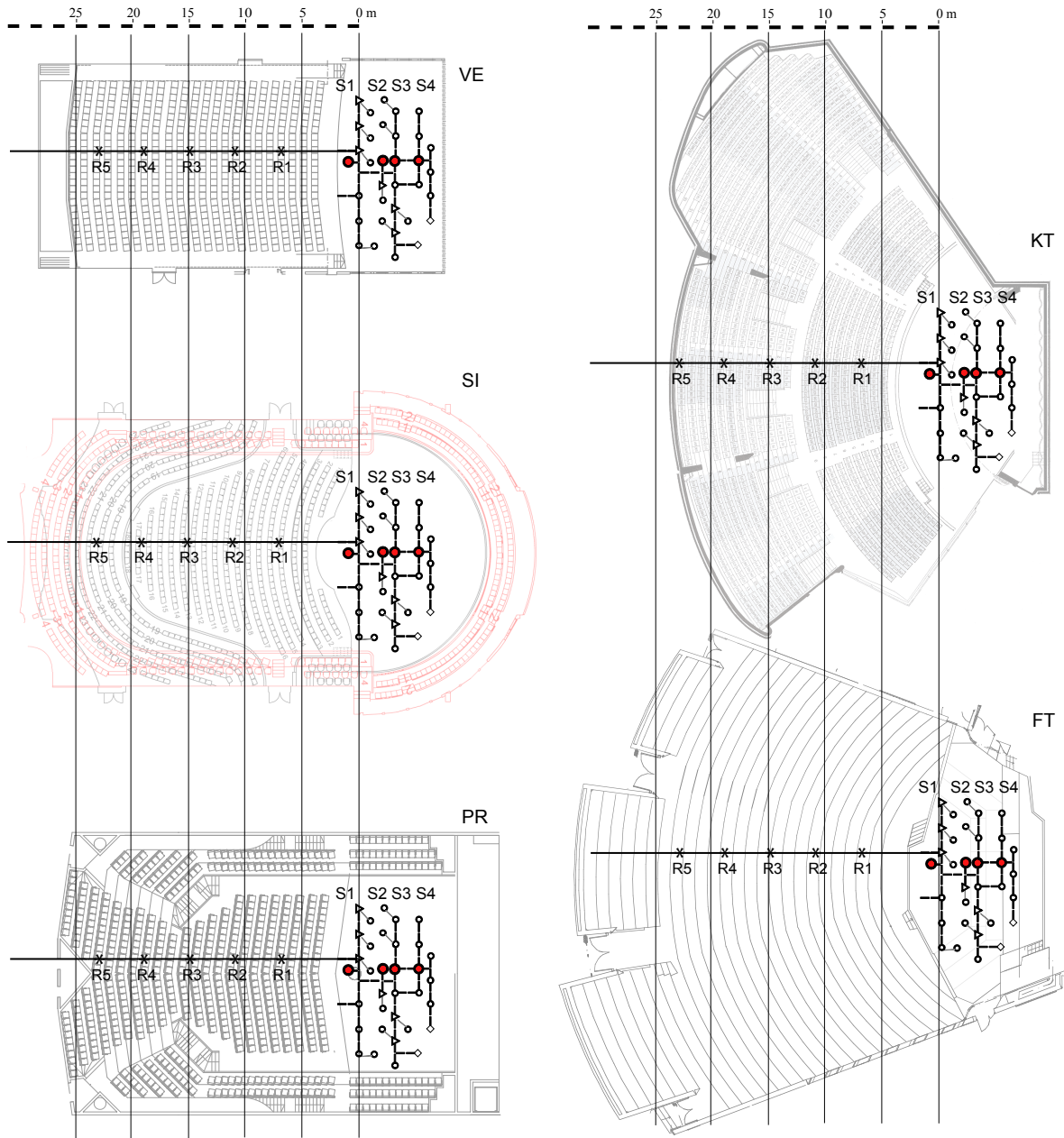


Figure 1 Floor plans of the measured concert halls. Receiver positions are denoted with R1-R5. Sources S1-S4 are denoted with filled circles. Unnumbered sources on the stage show the loud-speaker orchestra setup.

Majority of the earlier research has concentrated on the development of the seat dip effect during the few milliseconds after the arrival of the direct sound. This paper aims to compare and analyze, first, the frequency response of the direct sound in five existing halls with 20 identical source-receiver combinations. Second, the development of the frequency responses over time with measurements from a wide stage area are investigated. The results are discussed with regard to the informal listening experiments with the studied halls.

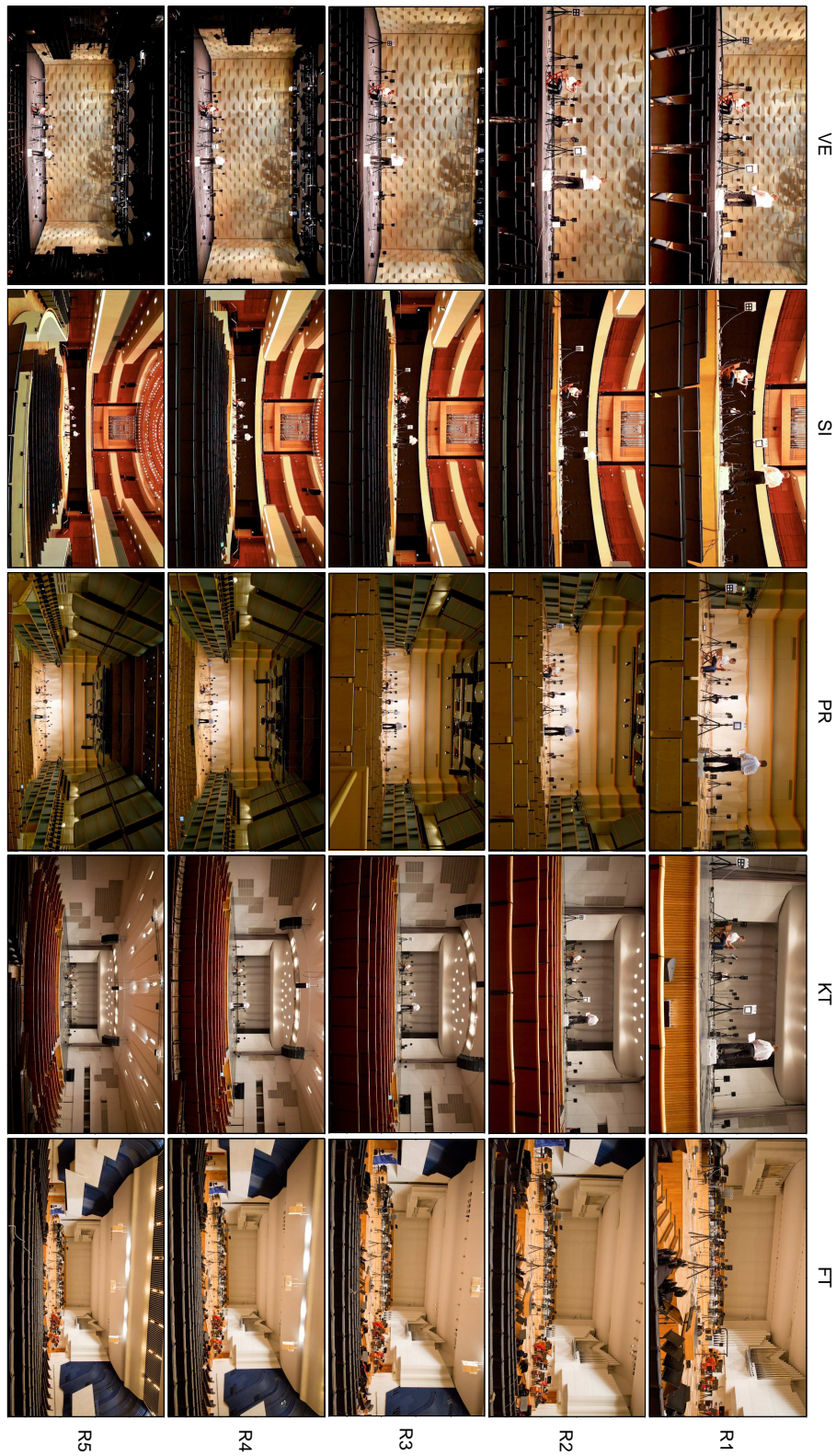


Figure 2 Photos from the halls at different receiver positions. Photos in VE are taken with a longer focal length, resulting in a slightly tighter framing.

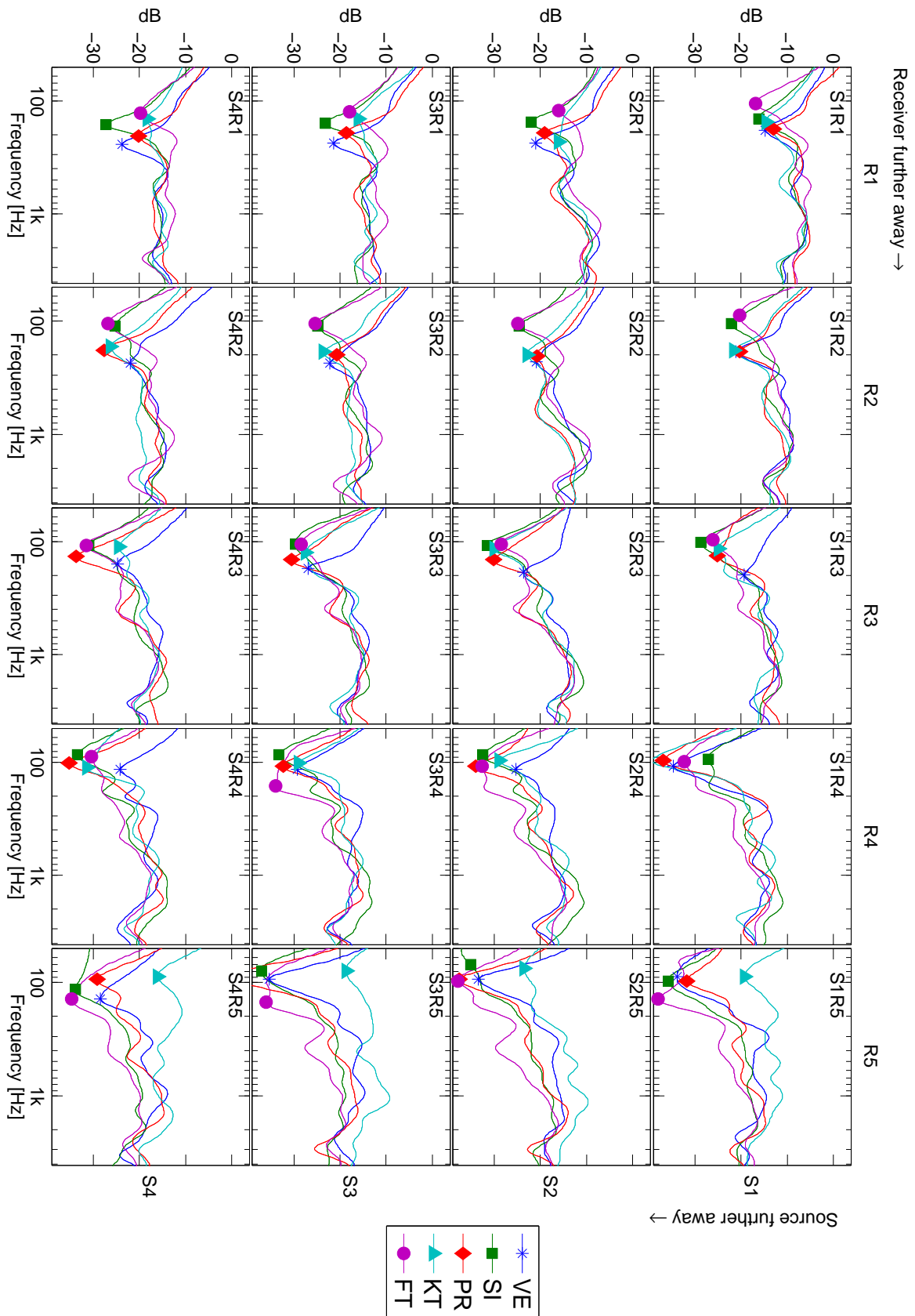


Figure 3 Seat dip behavior of 20 measurement pairs in five halls with a 20 ms window. The markers indicate the current minima of the seat dip attenuation.



## 2 HALL MEASUREMENTS

Five unoccupied concert halls of various sizes were investigated. The plans of the halls are shown in Fig. 1. The halls are denoted with VE, SI, PR, KT, and FT, and their seating capacities are 700, 1100, 860, 1390, and 1700, respectively. Halls VE, SI, and PR are medium-sized shoebox-shaped halls, and KT and FT are fan-shaped halls. Photographs of the investigated halls from each receiver position are shown in Fig. 2. VE has six rows of loose chairs on a flat floor, and the rear stalls with lightweight seats are moderately inclined. The stalls in SI have a very slight inclination with an increasing angle, and it is surrounded by a curved concrete wall. The seat structure in SI is moderately heavy. The stage in SI differs from most typical concert halls by having an absorbing surface behind the stage. In PR the middle part of the hall has a nearly flat floor surrounded by highly diffusing side walls that are shaped as MLS-sequences. The seats are rather lightweight. Hall KT is very wide with flat stalls and removable lightweight seats at the front, and a steep inclination at the rear with similar but non-removable seats. The inclination in FT is constant throughout the stalls, and all the seats are massive.

A loudspeaker orchestra<sup>11</sup> was used as the source in the current investigations. 33 two-way loudspeakers were positioned on the stage, representing a symphony orchestra. The layout is seen in Fig. 1. Thick bars indicate a 1 m distance. Distinguished sources S1-S4 used for the seat dip analysis are marked with filled circles. Receiving positions are denoted with R1-R5. It should be noted that the distance of the receiver positions from the loudspeaker orchestra remained unchanged between halls.

Two-way loudspeakers, such as the applied Genelec models 1029A, 8020A and 1032A, are not omnidirectional as stated in the ISO3382-1 standard<sup>1</sup>, but they are practically omnidirectional up to near 1 kHz. In order to improve the high frequency radiation with the string instrument positions, two loudspeakers were applied to a single channel. They are shown with thin lines between two loudspeakers in Fig. 1. One loudspeaker was directed to the audience, and the second was laying on the floor pointing upward. Such combined loudspeakers have been found to closely represent the radiation of the actual string instruments. Swept sinusoid excitation was used as the measurement signal, and the responses were measured with a GRAS 3-D measuring microphone at 1.18 m height above the floor.

## 3 SEAT DIP ANALYSIS

The seat dip effect is investigated in the five measured halls in combinations of four source and five receiver positions in line in different distances. Figure 3 presents the magnitude responses from a 20 ms window after the initial direct sound with one-third octave smoothing. Such a window approximates the hearing integration time<sup>12</sup>, allows the seat dip to form<sup>7</sup> in varying distances, but aims to minimize the possible reflections in the window. The symbols mark the frequency and magnitude at the maximum attenuation. In most cases the main seat dip attenuation occurs between 100-200 Hz. In the nearest receiving position the magnitude of the seat dip diminishes slightly with the further sources. Instead, with further receiver positions, the attenuation increases more rapidly than the overall sound level by  $1/r$ -law. Moreover, the attenuation bandwidth increases. This corresponds to the findings by Davies and Lam<sup>7</sup>.

The seat dip effect in the closest position R1 is mostly visible as a narrow-band attenuation. The strongest attenuation is noticed in SI, which accommodates the most seat rows in front of the receiver position. While in VE there are also several rows in front of R1, the seat dip condition is not as prominent, as the attenuation bandwidth or magnitude are small. The seats in VE are lightweight, removable chairs with ample space in between and under the seats. The open seats correspond to a half-wave resonator, which yields an octave higher seat dip center frequency compared to similarly sized closed seats<sup>3</sup>. In addition, we consider such seats to contribute to the flatter response. The frequency response in halls VE and KT benefit possibly a reflection from the wall behind the source S4 (see Fig. 1).

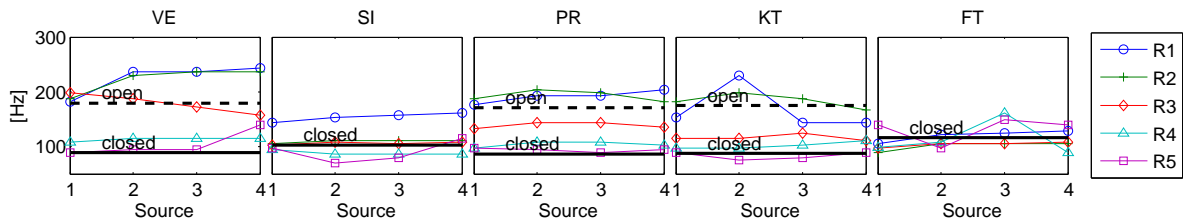


Figure 4 Comparison of the observed frequency of the maximum seat dip attenuation indicated in Fig. 3 and the equation for the seat dip frequency with varying seat height<sup>3</sup>. Theoretical frequency is indicated with solid and dashed lines for closed and open space under seats, respectively.

The receiver positions R3 are 14 m away from the nearest source. At such a distance, the increasing effect of the seat dip is visible generally as a more wide-band attenuation, compared to the narrow-band behavior in R1 and R2. The seat dip effect already affects to frequencies up to 1 kHz. In VE the inclined stalls in R3 result in a wider angle of incidence. Hence, the absence of seats near the propagation path provides the direct sound a better frequency response than in other halls.

In the position R4, the seating area in KT is inclined similarly to VE, and they present either the attenuation having the smallest magnitude or the narrowest bandwidth. The best direct sound frequency response is found in KT position R5. The strongly inclined rear stalls and lightweight seats result in a negligible seat dip attenuation. In PR, the two last receiver positions are on the balcony, where the attenuation is already strong despite having only three seat rows in front of the receiver position R4. The furthest positions R4 and R5 in FT and SI have the least floor inclination and the heaviest seats. They appear to suffer the most from the seat dip effect that causes a large decrease in the direct sound level in a wide frequency band up to 2 kHz. The receiver position R5 is elevated above the source in all halls, and the frequency response improves slightly with further sources. This is predicted to result from the increasing angle of incidence.

The frequencies of the maximum attenuation are compared against the equations for wavelength-dependent resonator. Figure 4 shows the observed maximum seat dip frequencies with the equations for open and closed seats<sup>3</sup>. The seats in positions R1-R3 in VE, PR, and KT have over 0.2 m of free space under unoccupied seats. Such positions R1 and R2 follow best the equation for a half-wave resonator. For all other positions there is 0.1 m or less unobstructed free space, and they are found to correspond to the quarter-wave equation for closed seats.

Statistical properties of the seat dip attenuation were investigated with ANOVA. The frequencies of the maximum attenuation have significant differences with regard to the receiving position ( $F(4, 99) = 105.22, p = 0$ ) and halls ( $F(4, 99) = 56.79, p = 0$ ). Also the differences in the measured seat dip mean magnitudes are significant ( $F(4, 99) = 43.15, p = 0$ ).

The relations for the seat dip frequency and magnitude for the increasing receiver distance are calculated for positions R1-R4. Receiver positions R5 are temporarily excluded due to the large hall-to-hall differences in that position. Linear fits to the seat dip frequency and magnitude yield a rate of -6 Hz/m for the frequency, and attenuation increases by -0.7 dB/m. No significant differences are present between the source positions on the stage, but the seat dip magnitude shows a decrease 0.76 dB/m when the source is moved toward the back of the stage. The findings are in line with earlier research on the vertical clearance over the seats<sup>4,7</sup>.

Overall, the removable chairs and lightweight seats and a strongly rising rear stalls in VE provide the most narrow-band seat dip effect with often the least attenuation. In contrast, halls FT and SI with heavy, fixed seats exhibit strong and wide-band seat dip attenuation.

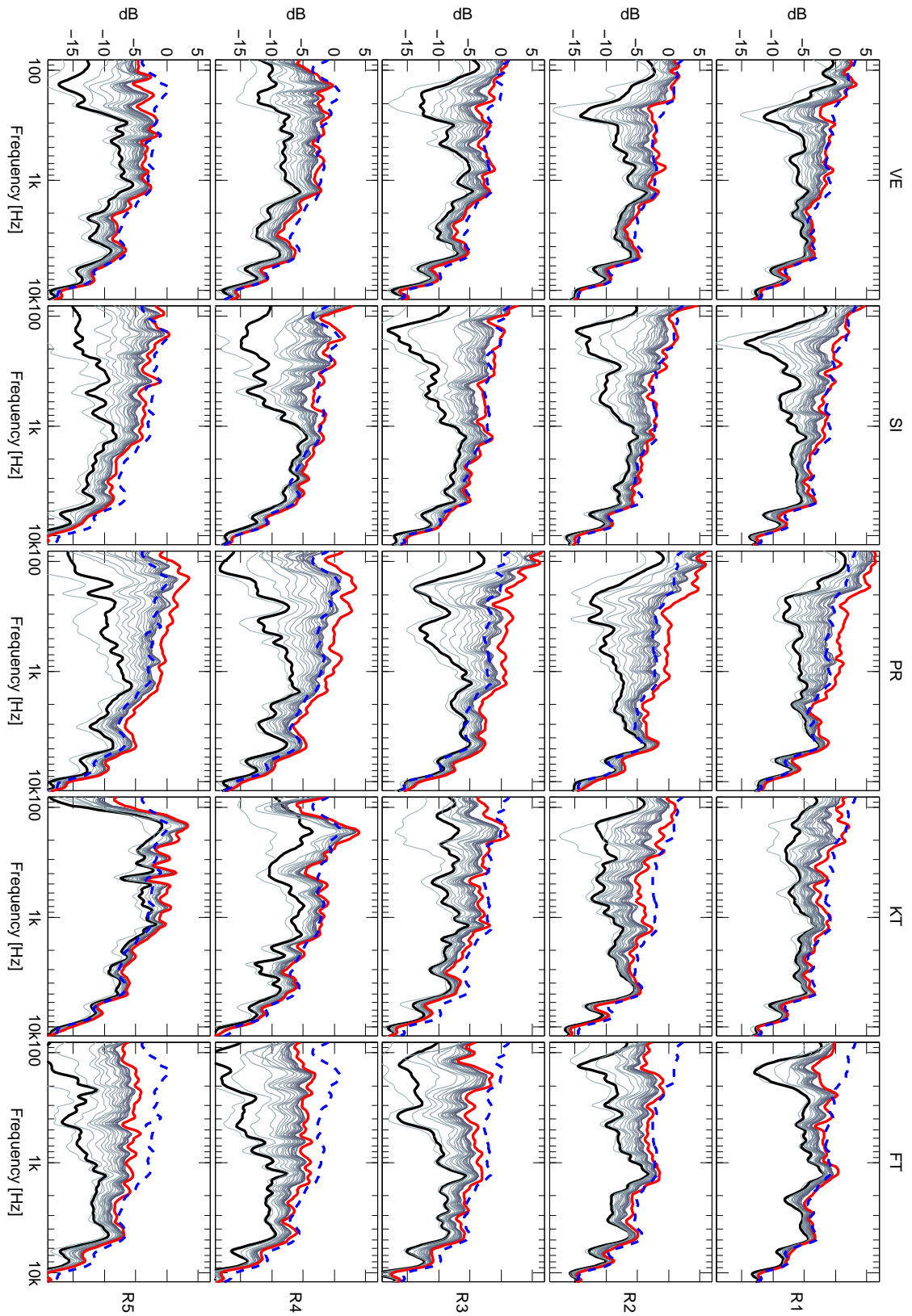


Figure 5 Frequency responses in time with 10 ms time window increments. Black, red, and blue curves show the 30 ms, final, and average final responses, respectively.

## 4 FREQUENCY RESPONSE DEVELOPMENT OVER TIME

So far we have established a behavior of the seat dip effect in five halls. Next, we investigate the development of the frequency response, taking into account the reflections arriving after the direct sound. Figure 5 shows the time-dependent frequency responses in the measured halls in positions R1-R5, averaged over the 33 sources on the stage (see Fig. 1). The thin line curves indicate the responses within a time window from the initial direct sound up to 20-200 ms in 10 ms increments. The black solid curve present the response after 30 ms - an approximate hearing integration time for music and speech. Red curves represents the final frequency response of the whole impulse response, that is, relative strength (G). The average of the total responses in the corresponding receiver positions is plotted in dashed blue curve. The relation of the lowest thin curves are of particular interest, as they show the development of the frequency response in the hall. The varying source-receiver distances in the curves are not compensated for. Informal listening was applied in order to subjectively evaluate the acoustic impression. This was achieved by convolving windowed impulse responses from the loudspeaker orchestra with multi-channel anechoic orchestral recordings of Bruckner's Symphony no. 8<sup>13</sup>.

In the R1 positions the direct sound is strong in relation to the early reflections. Hence, the curves are not spread very much. The seat dip effect is clearly present in VE, SI, and FT. In SI the direct sound is the most impaired by the seat dip, as found previously. However, the seat dip attenuation near 200 Hz is recovered within the first 70 ms from the initial direct sound. Similar effect is noticed in FT. The late reflected sound in the fan-shaped halls KT and FT has little contribution to the response after the first 40-50 ms. The late reverberation in PR, shown as the space below the red line, is stronger than in other halls.

In the position R2 and further, the importance of the reflected sound increases. In SI the frequency response is again the prominently improved during 30-60 ms after the direct sound, correcting the already wide-band attenuation between 100-1000 Hz. This suggests strong early reflections. Other halls do not exhibit similar effect as strongly. The later response develops very moderately in SI. With informal listening, the direct sound in a 20 ms window in halls VE and KT is considered the best, having adequate strength and uncolored timbre, which corresponds to the most narrow-band attenuation in the curves. SI and FT are regarded weaker.

Also in the receiving position R3 the SI direct sound with a nasal tone is among the worst with PR and FT, correlating with the visualized responses. The curves for SI show again a dramatic contribution from the reflected sound, causing the strong seat dip effect to be entirely corrected after 50 ms. This repeating phenomenon is particularly interesting for the following reasons. The ceiling reflections do not reach the receiving position within the 50 ms window. Hence, the strong, correcting reflections inside the time window can arrive only from the closest lateral surfaces, that is, the smooth concrete wall surrounding the front stalls. This is seen visually in Fig. 2. Similar improvement takes place also in VE. In PR, however, the shape of the frequency response does not change considerably during the first 100 ms, and only the overall gain increases gradually.

In positions R4 the development of the low and middle frequencies is generally slower than in R3. However, in SI the position is still inside the concrete wall, providing strong reflections. In PR the receiver position R4 is in the front of the rear balcony. The weak low frequency response is corrected near to the final shape during the first 100 ms. The subjective impression on the R4 direct sound is better than in R3.

With informal listening the strong initial 20 ms window from the positions R5 KT is easily regarded the best with negligible seat dip attenuation. In contrast, the last positions in FT sound weak and distant with all time windows. In SI the frequency response development is slowed down in R5, as the supporting strong reflections from the concrete wall are absent. After 50 ms the perceived frequency response is generally near to its final state, and mostly the low frequencies gain additional warmth. This is in line with the seat dip phenomenon losing its effect, as seen in the figures. Furthermore, the



50-100 ms region can be associated mostly with the bass strength in all positions. This is beneficial for the improved warm and deep sound.

Prominent differences in perceived clarity are found when convolutions with 20, 50, and 100 ms windowed impulse responses are compared. In PR position R2 the initial 50 ms clarity is lower than in the identical positions in other halls. While the frequency response in PR sounds natural after 50 ms, transients of the brass and timpani are smeared in comparison to halls SI and VE with the most similar sizes. The muddiness is increased yet more with 100 ms time window in PR R3, while other halls still sound much clearer. In contrast, the position R3 in SI provides clear and vigorous bass despite of the notably weaker 20ms direct sound.

## 5 DISCUSSION

The effect of the distance, height, and type of the seat rows has been presented in the literature. Here, the total seat dip effect is found the least pronounced in positions where the seats in front are of easily removable type (positions R1-R3 in halls VE and KT), or the angle of incidence is sufficient. The least favorable seating configuration according to the measurements and informal listening is the heavy, solid seats in a constant slope. Such a seating gradually decreases the incident angle over the seat backs, thus, enhancing the seat dip attenuation. The seats in the renowned halls, such as Boston Symphony Hall, Concertgebouw, and Musikverein are open, lightweight seats, which raise the seat dip frequency. Moreover, the stages above the flat stalls provide a wider incident angle, which decrease the affected bandwidth.

The perceived clarity was observed to differ between different halls during the first 50 and 100 ms windows. Comparing halls SI and PR in positions R2-R4 in Fig. 5, the development of the frequency response is very different. The perceived clarity is better in SI, where the weak direct sound is recovered quickly at the seat dip frequencies. Considering the differences in the acoustical design of the halls, the objective seat dip attenuation, and the subjective bass clarity in these halls, we propose the following theory.

In the seat dip effect, part of the direct sound diffracting to between the seat rows is absorbed and part is reflected from the floor. The seats in SI are heavier, absorbing more of the diffracted sound. With the more simple seats in PR, the seat dip frequency band is more reflected from the seat rows toward the hall ceiling. The lower height of PR, in addition to the tilted wall panels, reflect that sound back to the audience. Being too strong and too early to be considered as late reverberation, this reflected sound creates muddiness to the low frequencies. This does not happen SI, as the hall is higher, and the heavier seats absorb more seat dip frequencies. The concrete wall provides reflections that correct the seat dip, since it is, first, slightly higher than the audience area. Hence, the sound propagates over the seat backs with sufficient clearance in order to avoid a strong seat dip effect. Second, the lateral angle over the stalls is different than with the direct sound, thus varying the seat dip frequency. The reflecting wall is sufficiently large for reflecting also low frequencies, and the reflection arrives to the receiver from the side, avoiding further seat dip effect. Finally, the attenuation in the direct sound is compensated in a short time window. This does not compromise the low frequency clarity. Furthermore, the highly diffusing side walls in PR spread the important reflections temporally and spatially, and thus contribute to a muddy sound. However, this hypothesis cannot be proved by the currently applied methods. Hence, computer simulations for modeling the seat dip phenomenon is left for a topic in future research.

Regarding hard concrete walls, Beranek has stated<sup>14</sup> that such surfaces cause unsatisfactory acoustic "glare", and diffusing surfaces should be preferred instead. Our findings speak for the opposite, as well-defined early reflections are observed to contribute to a clear, lively sound<sup>15</sup>. It has been suggested earlier that the seat dip attenuation can be compensated with reflections from the ceiling, instead of lateral reflections<sup>4</sup>. However, the current observations prove otherwise.

## 6 CONCLUSIONS

Impulse responses from five concert halls were measured using a large number of loudspeakers distributed in a constant pattern, representing a symphony orchestra. Five identical receiver positions were used in each hall to analyze the properties of the seat dip effect. Furthermore, the development of the frequency response along time was investigated with increasing-length time window. Informal listening with convolutions of the measured impulse responses and anechoic orchestra music was used to support the observed phenomena.

The results from the seat dip analysis indicate that the seat dip attenuation is the worst in halls with moderately rising audience area and massive seat rows with high seat backs. The investigations on the developing frequency response revealed differences in perceived clarity, when multi-channel anechoic orchestra music was convolved with a short segments of the initial impulse responses. This suggests that the perceived clarity in concert halls depends on more intricate properties than the energy relation before and after 80 ms in the impulse response. With the differences found here only within a 100 ms window, standardized C80 values have little meaning.

As a conclusion, we first propose the seat dip effect should be minimized in the first place with careful seating design. Hard surfaces that provide reflections soon after the direct sound can be used to recover the seat dip attenuation. Corrective reflections arriving too late render the sound muddy. Second, higher level of late reverberation is not detrimental for the clarity, if the frequency response of the early sound field is not impaired. Third, the sound is perceived fuller the sooner the frequency response from the seat dip attenuation becomes corrected.

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