Recent studies on the seat-dip effect: Analysis and perception

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1. Introduction

The seat-dip effect (SDE) is a collection of phenomena whereby the sound arriving at grazing angle to the seats reflects and diffracts from the seating structure, causing a series of waves that interferes destructively and constructively with the direct sound [1]. The seat-dip attenuation forms 5–7 ms after the direct sound and reaches its minimum within the first 15–20 ms after the direct sound. The seat-dip attenuation can be characterized by the frequency of the main dip, its amplitude, and the width of the attenuation band [2]. The frequency of the main dip corresponds approximately to four times the seat backrest height, and the frequency falls typically between 80–300 Hz [3,4]. The effect was first discovered in the 1960s in a hall with reduced reflected sound energy [3,4], which suggests that with insufficient reflected sound energy the SDE becomes perceivable. The topic was picked up again in the 1990s by several researchers focusing on the mechanism, perception, and simulation of the effect (see for example the references in [2]). Yet, the question remains what are the important design features in concert halls when it comes to the perception of the SDE. The recent work of the author analyzed the influence of seat type on SDE in several performance spaces with the help of a loudspeaker orchestra. Additionally, a scale model measurements were run to verify some of the effects found in the concert hall measurements. Moreover, the influence of the audience presence on SDE was studied. Finally, the work shed more light on the perceptual significance of SDE with listening tests.

2. Effect of seat type and hall geometry

2.1. Measurements in a concert hall

The SDE has typically been studied with a single source-receiver pair, but in fact many orchestra instruments have fundamentals in the frequency range influenced by SDE. Therefore, measurements with a loudspeaker orchestra that consists of many sources [5], were analyzed in order to study averaged nature of the SDE. The results in twelve European concert halls show that SDE can be roughly classified into two categories as shown in Fig. 1 narrowband attenuation with the main dip at about 100 Hz (closed seats on raked floor) and asymmetric wideband attenuation with the main dip at around 200 Hz (open seats with flat floor) [2].

Furthermore, the measurements in Fig. 2 show that in halls where the attenuation dip is corrected, the spatial sound

energy distribution between 30–120 ms after the direct sound is very omnidirectional. This suggests that non-grazing angle reflections arriving at 30–120 ms after the direct sound are beneficial for leveling off the attenuation dip with time.

2.2. Scale model measurements

Because the effect of seat type and concert hall geometry could not be studied separately in the concert hall measurements, a scale model was constructed with adjustable floor raking and seat underpass height. Figure 3 shows the results of the scale model measurements at 20 ms after the direct sound. It can be seen that the open seats have a higher level than the closed seats below 100 Hz, except when the steps due to floor raking fully block the underpass. Therefore, the increase of low frequencies can be attributed to the underpass, which supports the speculation by both Ishida [6] and Davies [7]. Furthermore, the attenuation width seems similar across seat types, but differs across floor raking. The wide attenuation band can be attributed to the reduced positive diffraction from the adjacent seats with decreasing floor inclination.

3. Presence of audience

The earlier research on the influence of the presence of audience on SDE has been inconclusive. In measurements with closed or blocked seats and not fully occupied halls, the influence of the audience has been found to be negligible [1,3,4]. However, in halls with open seats, the audience is shown to have an effect on the seat-dip attenuation [6,8]. The analysis of the measurements in three different venues by the present author [8] with unoccupied and fully occupied seat conditions is shown in Fig. 4. The results support the analysis of Ishida presented in his thesis [6]: legs are likely to block the underpass when the underpass is small, which reduces the low frequencies below 100 Hz. Furthermore, if shoulders extends beyond the seat back rest, the frequency of the main dip is lowered.

4. Presence of audience

Published research on the perception of the SDE comprises one paper [9], in which the reverberant conditions of the simulated halls corresponded to fairly dry halls, and one abstract [10] that suggests that the seating array can influence the perception of bass. Additionally, there is some indication that seat-dip attenuation present in lateral reflections could harm spatial impression, but in the listening tests only two lateral reflections were included in the simulated sound field [11].

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Fig. 1 The 1/3-octave filtered magnitude responses of the measured concert halls at 20 ms and 1 s after the direct sound, individual (top), averaged by hall/seat type (bottom).

Fig. 2 Spatial energy distribution shown in four time frames: 20, 40, 80, and 2,000 ms and three planes for Berlin Philharmonie (BP) and Vienna Musikverein (VM). The dashed line indicates the energy of a source in free field at 10-m distance. The impulse responses are low-pass filtered at 1 kHz, and the frequency responses of all sources on stage are averaged. A 3-deg sliding average is applied on the histograms. The concert hall sketch is indicative, and not to scale.

In a recent work by the present author, the two different seat-dip profiles observed in the concert hall measurements were studied together with a reference free-field sound in a listening test in anechoic room with a spatial sound reproduction system with two shoebox-type halls and two vineyard-type halls [12]. The first 15 ms of the sound (here referred to as direct sound), was replaced with three versions: free-field, wide attenuation, and narrow attenuation. Their magnitude responses are shown in Fig. 5 for two different concert halls.

The results of the discrimination study show that less than half of the population could discriminate between the three different direct sound versions (see Fig. 6). The results of the preference study show that in vineyard-type halls, the uncoloured, free-field direct sound is preferred over any seat-dip-filtered direct sound (Fig. 6).

5. Conclusions

The recent work of the present author shows that seat design from the perspective of the seat-dip effect may not be crucial in concert halls with sufficient reflected energy. This energy should arrive from all over the upper hemisphere of the listener rather than at distinct direction on the ceiling or walls. In halls with insufficient reflected energy, the preference of the seat-dip effect points to the direction of narrow band attenuation, which is generally obtained by closed seats. However, in this research, the grazing angle reflections were not modified, so this topic requires further study with seat-dip-filtered reflections included. Furthermore, the work shows that seats with underpasses have an increased low frequency response compared to closed seats. It can be speculated however that some of that low frequency boost will be lost at least in some cases, as the underpasses are blocked by the legs of the audience.

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Fig. 3 The magnitude responses at 20 ms after the direct sound for seats with two different underpasses (10 cm and 24 cm) and closed seats (00) at different floor raking angles.

Fig. 4 The effect of audience on the seat-dip effect in a concert hall, scale model, and acoustically treated room in one of the analyzed receiver positions at 20 ms after the direct sound.

Fig. 5 The magnitude responses of three different direct sound versions in two of the studied concert halls (Amsterdam Concertgebouw and Helsinki Music Center).

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Fig. 6 Discrimination (a) and preference (b) results between freefield, narrow- and wide-filtered direct sound.

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