ARCHIVES OF ACOUSTICS
Vol. **38**, No. 1, pp. 13–18 (2013)

DOI: 10.2478/aoa-2013-0002

Research Papers

Music-Induced Vibrations in a Concert Hall and a Church

Sebastian MERCHEL, Mehmet Ercan ALTINSOY

Chair of Communication Acoustics, TU Dresden
01062 Dresden, Germany; e-mail: sebastian.merchel@tu-dresden.de

(*received June 22, 2012; accepted September 25, 2012*)

Sound and vibrations are often perceived via the auditory and tactile senses simultaneously, e.g., in a car or train. During a rock concert, the body vibrates with the rhythm of the music. Even in a concert hall or a church, sound can excite vibrations in the ground or seats. These vibrations might not be perceived separately because they integrate with the other sensory modalities into one multi-modal perception.

This paper discusses the relation between sound and vibration for frequencies up to 1 kHz in an opera house and a church. Therefore, the transfer function between sound pressure and acceleration was measured at different exemplary listening positions. A dodecahedron loudspeaker on the stage was used as a sound source. Accelerometers on the ground, seat and arm rest measured the resulting vibrations. It was found that vibrations were excited over a broad frequency range via airborne sound. The transfer function was measured using various sound pressure levels. Thereby, no dependence on level was found. The acceleration level at the seat corresponds approximately to the sound pressure level and is independent of the receiver position. Stronger differences were measured for vibrations on the ground.

Keywords: auditory-tactile music perception, room acoustics, transfer function measurements.

1. Introduction

This paper addresses sound and vibration during real-life situations. A typical example is the vibration perceived during an organ performance in a church. The following questions come to mind: Can vibrations be perceived even in a conventional classical concert hall during a concert performance? Do the acceleration levels exceed the perception threshold? Which dynamic range can be expected? Is there a linear relationship between the sound pressure level and the acceleration level for whole-body vibrations? How does the vibration intensity vary depending on receiver location? To answer these questions, comprehensive sound and vibration measurements were undertaken in two exemplary locations: a classical concert hall and a church.

2. Literature

The interest in multimodal reproduction has increased in the audio community over the recent years (Rumsey, 2010). Especially, the field of auditory-tactile perception has gained importance in the context of virtual environments (Altinsoy, 2012) or audio hardware (Merchel *et al.*, 2012). However, only a few studies have been published that involve vibration measurements in a musical context. Daub (2003) measured sound and vibrations in two different venues using musical instruments as sound generators. It was therefore difficult to separate the contribution of the sound source from the transfer characteristics of the room.

A study by Simon *et al.* (2009) reported audio-induced vibrations in a car generated by a music sequence, which was played back via the automotive audio system. They found that high vibration levels between 50 Hz and 75 Hz were excited in the seat and floor. However, it is not clear whether this characteristic results from the spectral content of the source material. They also reported a relatively linear relationship between sound and vibration in this frequency range (a 4.5 dB increase in the bass level resulted in an approximately 4.5 dB higher acceleration level).

Abercrombie and Braasch (2010) measured structural impulse responses on different stage-floors, which were excited using a sledgehammer. They found that the acceleration level decreases and the propagation time increases with increasing distance from the source (maximum 4 m measured). Both were strongly dependent on the stage construction. Unfortunately, it is not possible to separate air- from structure-borne vibrations in their measurements and to predict resulting vibrations in the auditorium.

For this reason, vibro-acoustical measurements in the auditorium of the Semperoper Dresden and the Lutherkirche Radebeul have been conducted.

3. Concert hall

This section discusses the relation between sound and vibration for frequencies up to 1 kHz in the Semperoper Dresden (Fig. 1). Therefore, the transfer function between sound pressure and acceleration was measured at different listening positions.

Fig. 1. Auditorium of the Semperoper Dresden with a lifted orchestra pit.

3.1. Setup

A dodecahedron loudspeaker (Outline, Globe Source with Subwoofer) was used as the sound source. It was placed on the lifted orchestra pit 4 m from the edge of the stage and 1.5 m to the side of the middle axis. Six receiver positions were selected, three in the parquet (R1–R3), one in the loge (R4) and two in the balconies (R5 and R6). This is illustrated in Fig. 2. To measure room impulse responses, a measurement microphone at ear height (B&K, 4188), a spherical microphone array and a Kemar dummy head with blocked ear canals were used. The last-mentioned recordings can be used to reproduce the opera house virtually in the lab, e.g., using wave field synthesis or binaural reproduction, to conduct perceptual experiments. In this study, only the data from the measurement microphone are used as a reference.

The measurement could only be made at night in the empty concert hall. However, compared with a situation when two-thirds of the seats are filled, the reverberation time below 2 kHz was only prolonged by 0.5 s, which resulted in an approximately 3 dB increase in the sound pressure level averaged over the receiver

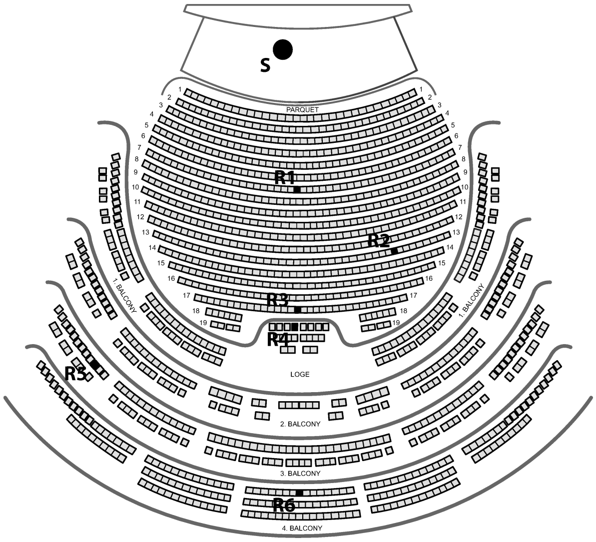

Fig. 2. Seating plan of the Semperoper Dresden with receiver position R1 to R6 and position S of the sound source.

positions R1 to R6 (Kraak, 1984). Typically, the stage is narrowed for orchestral concerts using moveable wall elements to build a concert dome. Because this dome was not available, the measurements were taken with the safety curtain closed. The reverberation time in both situations is very similar (Kraak, 1984).

White noise was used as a measurement signal and reproduced via the loudspeaker. However, the sound source shows some coloration. Magnitude spectra of the resulting sound pressures at all receiver positions at ear height are shown in Fig. 3. A homogeneous energy distribution over all receiver positions can be seen. However, a strong increase toward lower frequencies is observable, which results mainly from the characteristics of the sound source. This characteristic does not distort further results because the transfer function between the sound pressure at ear height and the acceleration at different surfaces will be calculated. The influ-

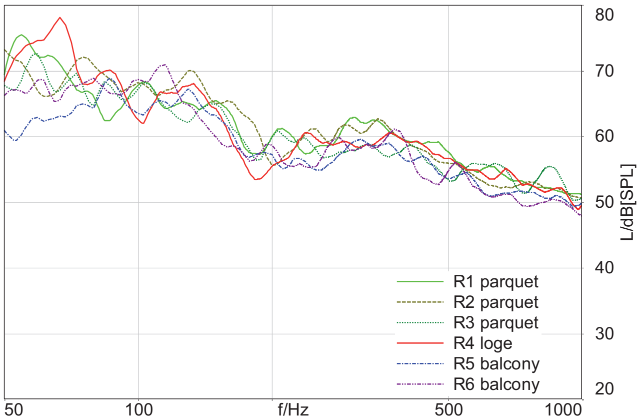

Fig. 3. Magnitude spectra (FFT 65536, 1/24th octave intensity averaging) of the sound pressure at ear height for all receiver positions.

ence of the overall sound pressure level on this transfer function will be discussed later.

To measure the vibrations at different surfaces, accelerometers (Kistler, 8636C10) were mounted to small metal plates with a 10 cm diameter and placed on the ground, on the seat and on the arm rest (see Fig. 4). The measurement position was then loaded with a person (80 kg). It should be noted that all other seats were unoccupied. The influence of a larger audience on the measured vibrations cannot be assessed easily. However, the presence of a second person in an adjacent seat did not change the results of a test measurement specifically.

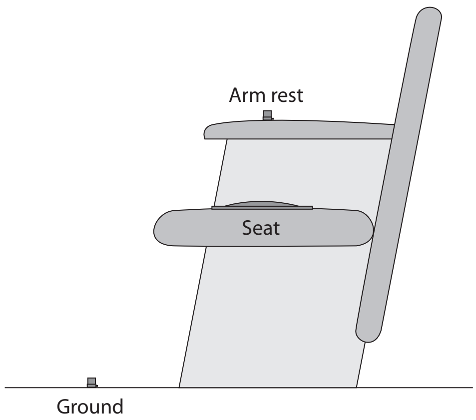

Fig. 4. Measurement setup with accelerometers on the ground, the seat and the arm rest.

3.2. Results

Figure 5 shows the transfer function between the acceleration on the ground and the sound pressure at ear height for the same measurement position. This corresponds to the difference between the acceleration level and the sound pressure level $L_{\mathrm{acc}} - L_{\mathrm{SPL}}$. A horizontal line at 0 dB represents equal levels for sound at ear height and vibrations on the ground. The overall sound pressure level at each measurement position was approximately 90 dB. It can be seen that higher acceleration levels were measured in many cases, especially in the parquet (R1–R3) for frequencies below 200 Hz. Interestingly, this location-dependent difference disappears at the seat surface (Fig. 6). The frequency response is relatively homogeneous over a broad frequency range with a slight decrease toward lower frequencies. Only a few positions showed isolated resonances (e.g., 100 Hz at receiver position R4).

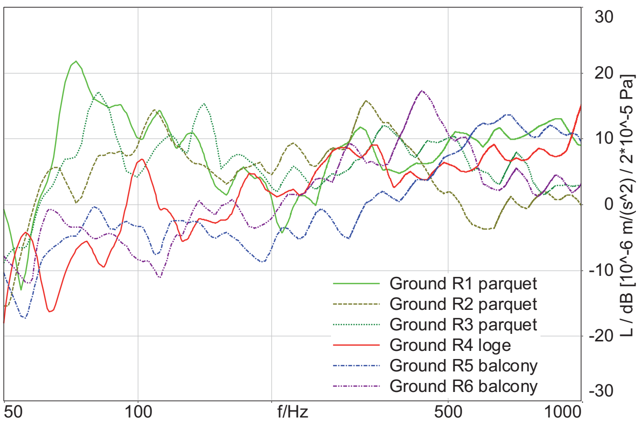

Fig. 5. Transfer functions (FFT 65536, 1/24th octave intensity averaging) between acceleration on the ground and the sound pressure at ear height at all receiver positions.

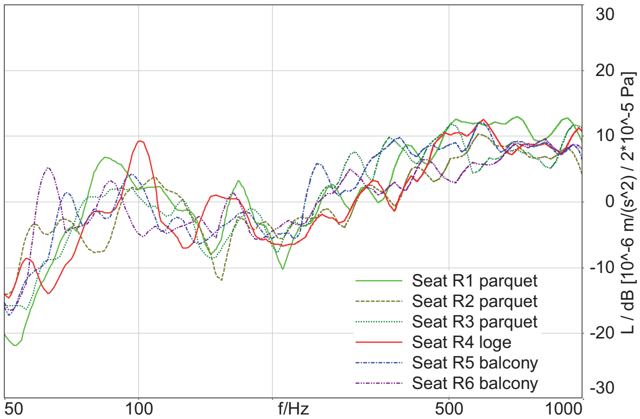

Fig. 6. Transfer functions (FFT 65536, 1/24th octave intensity averaging) between acceleration on the seat and the sound pressure at ear height at all receiver positions.

No distinct dependence of the overall level on the distance between the receiver and source was observed, e.g., there was not much difference between the accelerations at positions R1 and R3. This indicates that the vibrations are not transmitted via the ground from the loudspeaker to the seat. It is hypothesized that the airborne sound excites the surface near the listener. To test this hypothesis, the loudspeaker was decoupled from the stage floor using a sheet of foam (55 cm × 45 cm × 16 cm). The vertical resonance frequency of this system was measured to be approximately 8 Hz, resulting in effective vibration isolation in the interesting frequency range above 50 Hz. The exemplary transfer functions at position R4 (seat) in Fig. 7 show no considerable difference with and without the isolated loudspeaker. This finding supports the hypothesis that the vibrations are excited via air-borne vibrations in the auditorium. Air-borne transmission could also explain the lower levels on the ground for positions R4–R6 due to the smaller floor areas in the balconies.

If the sound pressure level rises, the excited vibrations should grow accordingly. However, it is not clear whether there is a linear relationship between both levels. Therefore, a few measurements were taken at different sound intensities. Figure 8 shows two exemplary transfer functions at position R4 (seat) with a 30 dB difference in the sound pressure level. Both curves are

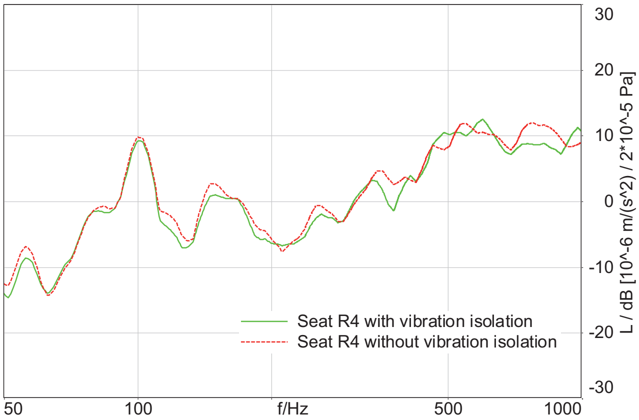

Fig. 7. Transfer functions (FFT 65536, 1/24th octave intensity averaging) between acceleration at the seat and the sound pressure at ear height at the receiver position R4 with and without vibration isolation of the sound source.

almost identical. This proves a linear relationship between the two physical variables, which is a prerequisite for meaningful transfer functions.

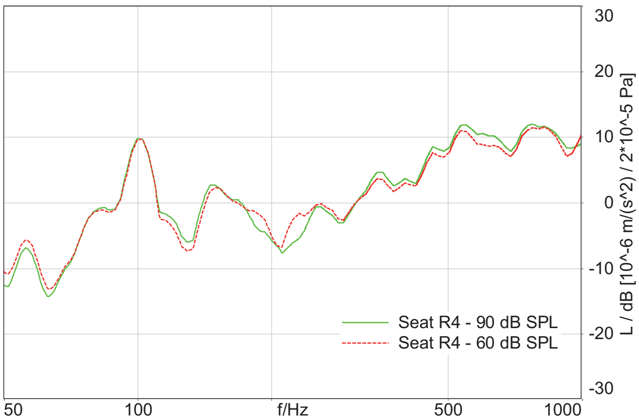

Fig. 8. Transfer functions (FFT 65536, 1/24th octave intensity averaging) between acceleration at the seat and the sound pressure at ear height at the receiver position R4 for different sound pressure levels.

3.3. Discussion

Typical sound pressure levels in a concert hall for fully orchestrated passages are between 80 dB and 90 dB (forte), depending on the instrumentation and the room (Meyer, 2009). The fortissimo can reach average sound pressure levels approximately 10 dB higher (Weinzierl, 2008). For example, there have been measurements in the Semperoper with L_{AI} from 96 dB to 98 dB for themes from Wagner's Lohengrin (*Kraak*, 1984). The peak level at low frequencies can reach even higher values. Taking into account the perception threshold for sinusoidal seat vibrations, which is approximately $L_{\mathrm{acc}} \approx 90$ dB for frequencies below 150 Hz (Merchel *et al.*, 2011), the above measurements indicate perceivable vibrations for the forte and fortissimo parts of orchestral music. However, these vibrations might not be perceived separately because of the integration of the tactile sense with the other sensory modalities into one multimodal concert event. During subsequent concert visits to the Semperoper, the author paid special attention to music-induced vibrations and could clearly identify them during a classical concert and a jazz concert. Interestingly, other concert visitors, who had been unaware of music-induced vibrations in the concert hall before, did confirm these findings.

The measurements suggest that differences between positions and the influence of local resonances should be clearly perceivable because they are considerably larger than the perceivable difference in the acceleration level, which is approximately 1.5 dB (Forta, 2009). In addition, the dynamic range for vibration perception is quite small, which results in strongly perceived vibration intensity differences even for small changes in acceleration level. It is expected that these differences increase further between different venues. Therefore, a second measurement series was taken in a church.

4. Church

This section discusses the relation between sound and vibration in the Lutherkirche in Radebeul, a typical church build in 1892 with massive bearing walls and a stone floor. An outline of the church can be seen in Fig. 9. An organ loft is located in the back of the

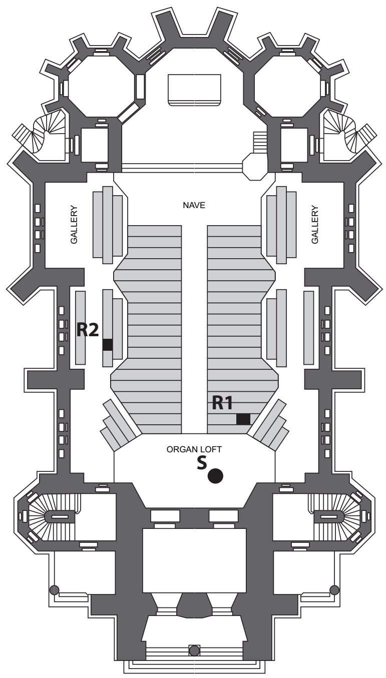

Fig. 9. Floor plan of the Lutherkirche Radebeul with positions of the receivers and the source.

church. Wooden pews can be found in the nave and on the wooden galleries. Again, transfer functions between sound pressure and acceleration were measured at different exemplary listening positions.

The same method and equipment was used as in the concert hall measurement described above. The dodecahedron source S1 was placed in the organ loft to simulate organ stimulation. Various measurement positions have been selected, but only two exemplary receiver positions (R1 in the nave and R2 in the gallery) will be discussed here.

4.1. Setup

Again, different microphone setups were used to record various room impulse responses. Additional vibration impulse responses were measured on the ground, foot rest, seat and back rest of the wooden pews using accelerometers (Kistler, 8636C10). This is illustrated in Fig. 10. The measurement position was then loaded with the same person (80 kg) as before.

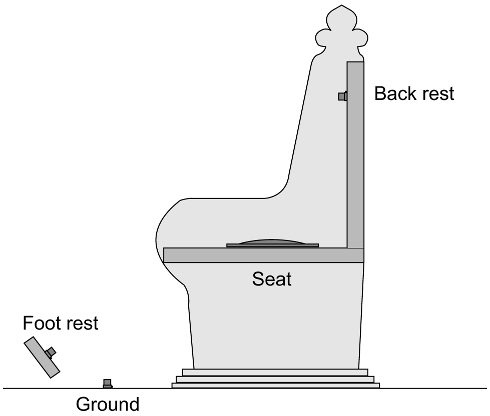

Fig. 10. Measurement setup with accelerometers on the ground, foot rest, seat and back rest.

4.2. Results

Figure 11 plots the transfer function between acceleration on the ground and the sound pressure at ear height for the same position. The acceleration on the ground, which is excited by the sound, differs significantly between positions, due to the massive stone floor in the nave and the wooden construction of the gallery. Again, a broad vibration spectrum is excited with a slight roll-off toward lower frequencies.

This frequency spectrum differs completely for measurements at the foot rest, a long wooden board which is mounted only at its ends. Figure 12 shows strong resonances for foot rest vibrations at both receiver positions. This resonance pattern is also dependent on the position of the accelerometer along the board, which is not plotted here. The acceleration level varies considerably with frequency; however, the overall level is similar in both conditions.

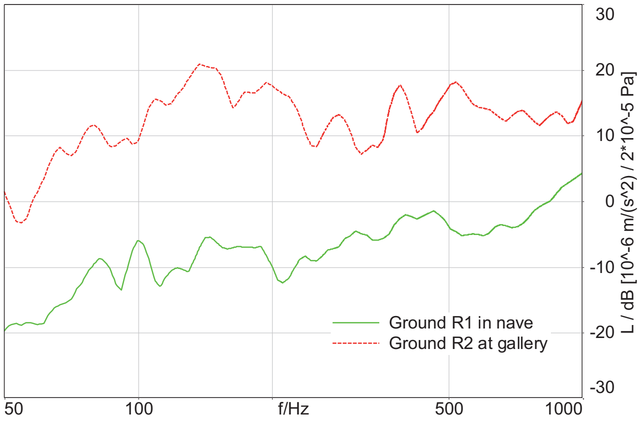

Fig. 11. Transfer functions (FFT 65536, 1/24th octave intensity averaging) between acceleration on the ground and the sound pressure at ear height in the nave and in the gallery.

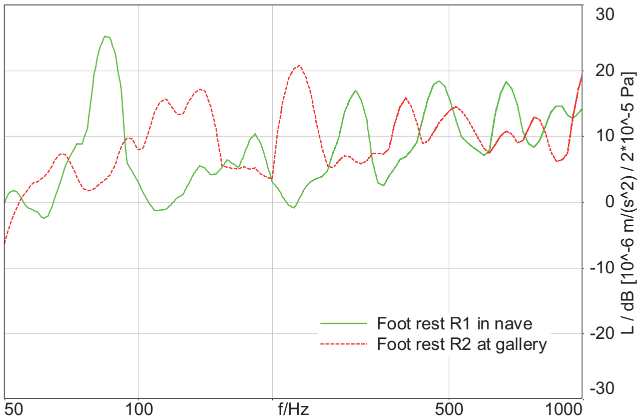

Fig. 12. Transfer functions (FFT 65536, 1/24th octave intensity averaging) between acceleration at the feet and sound pressure at ear height in the nave and in the gallery.

Comparable levels at both positions were also measured at the seat (see Fig. 13) and back rest. Compared with the concert hall, the overall acceleration level at

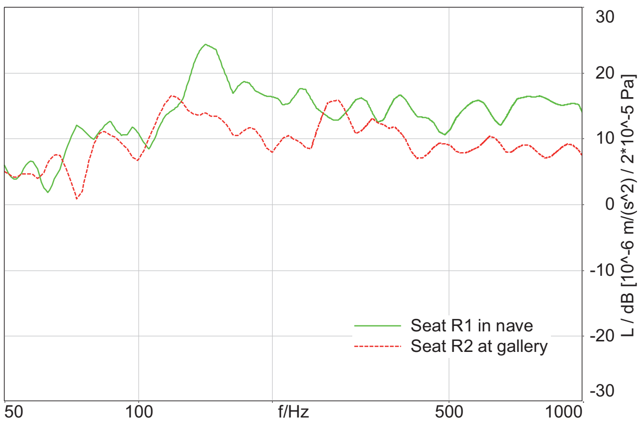

Fig. 13. Transfer functions (FFT 65536, 1/24th octave intensity averaging) between acceleration at the seat and the sound pressure at ear height in the nave and in the gallery.

the seat is significantly higher. This might be due to the missing seat upholstery and the large continuous surfaces, which can be excited by the sound more intensively.

Similar to the concert hall, no change of the transfer function was found when the subwoofer was decoupled from the ground, supporting the hypothesis of the dominance of airborne vibrations in the auditorium. There was also no dependence on the overall sound pressure level, confirming the linear relationship between sound pressure and acceleration discussed before.

4.3. Discussion

Organ-generated sound pressure levels in a church can be quite high. A sample sequence with a significant low-frequency content (Max Reger, Introduktion d-Moll) performed by organ player Gottfried Trepte in the Lutherkirche Radebeul reached sound pressure levels of 90 dB(A) at both receiver positions. Clear-to-strong vibrations (100 dB) were excited most of the time in a broad frequency range.

5. Conclusions

It was shown that sound can excite perceivable surface vibrations. It can also be seen that our experience with audio-induced vibration can vary heavily. Even within one venue, the vibration intensities and frequency spectra are strongly dependent on the listener position. However, the measured sound-induced vibrations are only exemplary in nature.

The measurements reveal nothing about the perceived quality of such music-induced vibrations. No ideal sound-to-vibration transfer function can be deduced. To identify which vibrations are favorable, comprehensive listening tests are necessary, such as those described by Merchel and Altinsoy (2008) and Merchel and Altinsoy (2009). If an ideal sound-to-vibration transfer function exists, it might be possible to improve the concert experience by modifying vibrations through architectural changes or artificial generation. The latter case is especially interesting for audio reproduction systems but could improve the music experience even in a classical concert. It is expected that vibrations have a strong influence on the listener's presence or envelopment – parameters which are of vital importance for the quality of concert halls (Cerdá *et al.*, 2012).

Acknowledgments

The authors wish to thank the responsible people at the Semperoper Dresden and the Lutherkirche Radebeul for permission to conduct measurements in the respective venues.

Part of this work was presented at the 59th Open Seminar on Acoustics (Poland, Boszkowo, September 10–14, 2012).

References

1. Abercrombie C., Braasch J. (2010), *Auralization of audio-tactile stimuli from acoustic and structural measurements*, J. Audio Eng. Society, **58**, 10, 818–827.
2. Altinsoy M. E. (2012), *The quality of auditory-tactile virtual environments*, J. Audio Eng. Society, **60**, 1/2, 38–46.
3. Cerdá S., Giménez A., Cibrián R. M. (2012), *An objective scheme for ranking halls and obtaining criteria for improvements and design*, J. Audio Eng. Society, **60**, 6, 419–430.
4. Daub M. (2003), *Cross-modal correlation – relationship between musically produced whole-body vibrations and auditory perception* [in German], Diploma Thesis, Institute of Communication Acoustics, Ruhr-University, Bochum.
5. Forta N. G. (2009), *Vibration intensity difference thresholds*, Ph.D. Thesis, Institute of Sound and Vibration Research, University of Southampton.
6. Kraak W. (1984), *Report on the acoustical testing of the Semperoper Dresden* [in German], TU Dresden.
7. Merchel S., Altinsoy M. E. (2008), *5.1 or 5.2 Surround – Tactile enhancement of surround sound* [in German], DAGA, Dresden.
8. Merchel S., Altinsoy M. E. (2009), *Vibratory and acoustical factors in multimodal reproduction of concert DVDs*, HAID, LNCS 5763, Springer, Berlin.
9. Merchel S., Altinsoy M. E., Stamm M. (2011), *Equal intensity contours for whole-body vibrations compared with vibrations cross-modally matched to isophones*, HAID, LNCS 6851, Springer, Berlin.
10. Merchel S., Altinsoy M. E., Stamm M. (2012), *Touch the sound: audio-driven tactile feedback for audio mixing applications*, J. Audio Eng. Society, **60**, 1/2, 47–53.
11. Meyer J. (2009), *Acoustics and the performance of music*, originally published in German by Edition Bochinsky, Springer, Berlin.
12. Rumsey F. (2010), *Audio in multimodal applications*, J. Audio Eng. Society, **58**, 3, 191–195.
13. Simon G., Olive S., Welti T. (2009), *The effect of whole-body vibrations on preferred bass equalization of automotive audio systems*, 127th Conv. of AES, pp. 1–18, New York.
14. Weinzierl S. [Ed.] (2008), *Handbook of audio technology* [in German], Springer, Berlin.