Proceedings of Meetings on Acoustics

Volume 19, 2013 http://acousticalsociety.org/

ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Architectural Acoustics
Session 1pAAb: Vibration in Music Performance

1pAAb4. Recent experiences with vibration of stage and audience floors in concert halls

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Vibration of (wood) surfaces plays a significant role in concert hall acoustics, as confirmed by musicians and music lovers. Many acoustic engineers, on the other hand, tend to have strong reservations against vibrating surfaces, and usually try to minimise surface vibration in order to maximise RT and airborne Strength (G) at bass frequencies. This has lead to a generally accepted preference for massive and stiff surface constructions in new halls. Problems have been known to occur when this general guideline was also applied to the design of wooden floors, in particular stage floors. Despite some good scientific research in this field, a big gap still remains between the vibro-acoustic behaviour of wooden floors and subjective preferences of musicians and audiences. This paper further explores the role of vibrations in concert hall design, and the need for balancing surface reflectivity versus vibration transmission. Recent experiences, including the new Konserthus in Stavanger and the renovation of the Bolshoi Hall of the Moscow Conservatory, will be described as well as vibration measurements carried out on a number of existing stage floors. Some implications for the design of wooden floor constructions will be discussed.

Published by the Acoustical Society of America through the American Institute of Physics

Received 23 Jan 2013; published 2 Jun 2013

1. AN INTRODUCTORY CASE: THE BOLSHOI HALL OF THE MOSCOW TCHAIKOVSKY CONSERVATORY

The Bolshoi Hall (Grand Hall) of the Moscow Conservatory is one of the best loved major concert halls in Russia. It is a 1737-seat classical shoebox hall, with lots of ornamentation on the side walls and balcony fronts, flexible oak parquet floors (both on stage and in the audience), lightly upholstered wood chairs with hard back rests and wooden benches on the rear balcony[1].

In 2009, the first author took part in a measurement session and listening test organized by Akukon acoustic consultants as part of the renovation of the Hall (carried out in 2010-2011). It was noted that subjectively the Hall has a beautiful and strong bass response, even in far seats in the rear amphitheatre. However, the Reverberation Time (RT) and Strength (G) measurements indicate lower than usual values for these parameters at bass frequencies, being lower than the mid-frequency values (leading to a "bell shaped" RT curve). This could be expected in a room with lots of wood panels, which tend to be more absorptive at bass frequencies, but in that case one would also expect a weak subjective bass sound, which is not the case as confirmed by the listening test. Figure 1 shows the measured average RT spectrum for both the unoccupied and occupied cases, confirming the "bell shape", to be avoided according to standard practice.

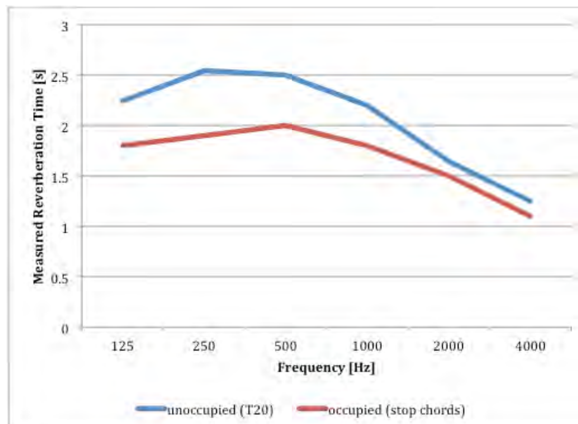

FIGURE 1. View from balcony (left) and average measured Reverberation Time (right) in the Bolshoi Hall of the Moscow Conservatory (2009).

Naturally, the question arose as to why the Bolshoi Hall can have such a good subjective bass response despite the bell shaped RT (and G) curves. A clear and complete answer could and can still not be given, but two potentially relevant observations were made at the time:

(1) When somebody walks on the stage extension, this creates slight movements of the parterre floor, which can clearly be felt ("wobbling"). This seems to indicate that a good structural connection exists between both structures (i.e. stage extension floor and parterre floor). Since "wobbling" corresponds to very low frequency components of vibration transmission (<20Hz), this seems to indicate that the structure of the auditorium and stage floors is such that there is good transmission of vibration down to the inaudible bass frequencies. As a result, vibration from the double basses, which "inject" bass vibrations directly into the stage floor through their pin, should be able to travel via the floor of the parterre (and to a lesser extent also via the floor of the amphitheatres) right up to the seats of the audience members. If these vibrations are then radiated by lightweight panels (e.g. the back panels of the benches), it could at least partly explain the strong bass sound in Bolshoi Hall.

(2) In certain locations, the double basses could clearly be "felt" as vibration in the floors and the benches. In theory, this can either be caused by airborne sound energy being locally converted to structureborne sound (making the bench vibrate), or by pure vibration transmission from stage to seat, i.e. structureborne sound from the source (never having been airborne).

The build-up of the wood floors of the Bolshoi Hall was found to be the following:

- Stage: 22mm thick oak parquet, nailed through thin cardboard layer into underfloor of pine planks (50mm thick). Double perpendicular wood understructure of 160x160mm wood joists, widely spaced (approx. 1m), resting on iron I-beam. The front part of the stage (typically carrying the double basses and cellos) is resting on large wood columns directly onto the parterre floor.
- Parterre: 22mm thick oak parquet, nailed through thin cardboard layer into underfloor of pine planks (60mm thick). Single wood understructure of 180x180mm wood joists, widely spaced (approx.. 0.8m), resting on 130mm thick concrete on top of iron beams.
- Balcony: Similar to parterre, but only 15mm thick oak parquet and 50mm think underfloor.

The stage and parterre floor surfaces are clearly thick (between 65 and 82mm), and therefore massive in comparison to many historic wood floors. However, because of the cardboard layer (1-3mm thick) between the oak parquet and the pine planks below, and the not entirely stiff connection between these two layers, it can not be ruled out that the top layer (oak) can vibrate separately to some extent from the pine planks underneath (which would explain observation 1 above). In addition, it should be noted that the stage (in particular the front part on wood feet) is mechanically well connected to the parterre floor, which partly explains observation 2 above.

The exact link with the strong perceived bass sound is not fully understood, but in any case, it was considered that the construction of the wood floors and their understructure are a delicate enough subject - with most likely a significant influence on the acoustics of the Bolshoi Hall - to not alter them fundamentally during the renovation. Although the entire stage and audience floors were fully rebuilt, no major changes occurred to the floor constructions (the use of plywood sheets replacing the pine planks in the parterre had to be fought against), and consequently the acoustic character was entirely preserved by the renovation.

The above experience in the Bolshoi Hall triggered the authors to further explore the subject, both by reflection and questioning some of the standard practice in our work of acoustic consultant and by carrying out some practical vibration measurements on wood floors. Section 2 sets out a couple of relevant theoretical considerations, while sections 3, 4 and 5 describe the conducted measurements. To conclude, section 6 highlights a number of practical implications with respect to wood floor design for stages and audience areas.

2. SOME GENERAL THEORETICAL CONSIDERATIONS

For instruments in direct contact with the stage floor (mainly double basses, cellos, piano and timpani), the following different types of sound and vibration transmission paths can be distinguished in theory:

- **Type 1 - Purely airborne paths:**
  Airborne sound radiated by the instrument body to the listener's ears; this encompasses both direct and reflected/reverberated components. This is the classic domain of room acoustics.
- **Type 2 - Purely structureborne paths:**
  Vibration transmitted via the pin of the instrument into the floor, travelling via the floor to the listener's body; in theory there are also direct and reverberated components, although the latter have been shown in the literature to be of no practical interest[4].
- **Type 3 - Structureborne-to-airborne paths:**
  Floor vibration being radiated by the floor surface. A typical example is the radiation of a tuning fork placed on a table surface.
- **Type 4 - Airborne-to-structureborne paths:**
  Airborne sound being converted to floor vibration. Linked with the damping properties of the floor, this corresponds to absorption of airborne sound energy.

These 4 types can be applied both to transmission on stage (support between musicians and to oneself) and to transmission from stage to audience. It should be noted that transmission types 3 and 4 represent interaction between the airborne and structureborne paths. Although they are presented here as separate processes, in reality they constitute a coupled system with constant interchange between the two in time, and this interchange is not limited to a certain area but rather "smeared out" over the entire solid-to-air interface. However, it is still instructive to distinguish them as separate processes, even if the physical reality is more complicated.

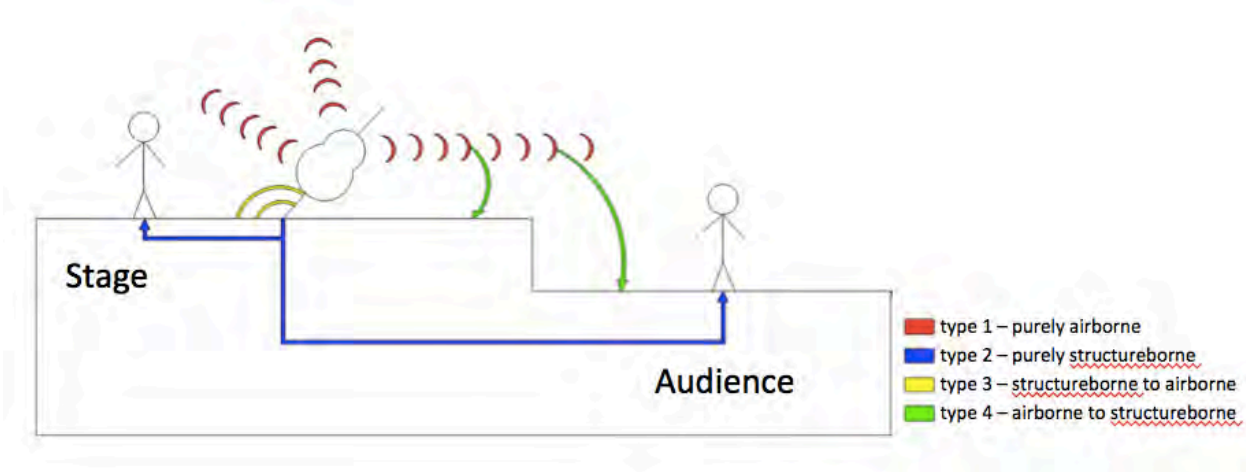

FIGURE 2. Theoretical transmission paths of sound and vibration for instruments in contact with the stage floor.

In order to maximize bass strength and reverberation of the airborne paths (type 1), acoustic consultants tend to specify heavy and stiff surface constructions in concert halls, in order to minimize bass absorption (type 4). This is undoubtedly a good approach for walls and ceilings, but if is also carried through for the stage and audience floors, transmissions types 2 and 3 will be minimized as a side effect.

It is therefore important to be aware to what extent types 2, 3 and 4 play a significant role or not in concert hall acoustics. Previous studies ([2,3]) have indicated that type 3 (radiation by the stage floor of pin induced vibrations) plays a significant role, mainly for on-stage hearing and to a lesser extent for stronger double bass sound towards (the front parts of) the audience. Fewer research has been published about the potential role of types 2 and 4, involving vibration being "picked up" by the human body, for example via the feet. The authors of this paper believe that more work is needed to better understand the importance of the latter types. In the meanwhile, they take into consideration that type 2 may play a significant and beneficial role on stage, and type 4 in the audience chamber.

Most acousticians are nowadays aware that some flexibility of the stage floor is important for on-stage communication. Bass players always express a preference for wood floors on joists, rather than wood floors bonded to concrete. However, for the floors of the audience areas (parterre and balconies) there is general tendency of acousticians specifying massive and stiff wood floors in order to minimize bass absorption.

Unlike for the purely airborne sound (type 1), no well-established equations exist to predict types 2, 3 and 4, which would help to guide the design of floors. The Sabine equation, on the other hand, clearly tells us that absorption (type 4) will decrease the reverberation time (type 1). A simple thought experiment allows a better quantification of this effect. Consider a shoebox concert hall, 20m wide, 45m long and 20m tall. The stage takes up 1/3 of the floor area, the audience 2/3. The mid-frequency RT is 2.0s; at 125Hz the RT is 2.3s. The wood audience floors are massive and stiff with an absorption coefficient of 0.05 at 125Hz. Now consider replacing the audience floors with a more flexible build-up (e.g. parquet on joists). The absorption coefficient at 125 Hz will significantly increase, say to 0.2. According to the Sabine equation, the RT at 125Hz will consequently decrease to 2.15s. This represents a measurable difference of 7% for the reverberant component of path 1, but subjectively this change at low frequencies will hardly be audible. However, paths 2, 3 and 4 – for now leaving in the middle whether they contribute positively to the hall acoustics or not - will now at least been given a chance to exist.

In other words, the question is whether it would be possible to find a more suitable balance between the 4 transmission types by fine-tuning floor constructions, rather than to place all bets (and the corresponding money) on type 1 by designing only massive and stiff floor surfaces.

3. DEDICATED VIBRATION MEASUREMENT SYSTEM

In order to carry out further investigations in this field, a measurement project was set up as part of the second author's MSc thesis. A low-cost multichannel vibration acquisition system was developed in-house, using 4 basic accelerometers (MSI ACH-01) and a multichannel audio card (M-Audio). This approach allows simultaneous measurements of the acceleration at 4 different measurement points on the floor, having the advantage that real instruments can be used as a source because there is no need for a reproducible source (as would be the case if a 1-channel system were used). The cello of the second author was used as the main source, in addition to a standard B&K tapping machine.

A set of MATLAB routines was developed to obtain acceleration levels in 1/3 octave bands, and the system was calibrated using a separate Svantek vibration level meter. In addition to the 4-channel vibration level measurement, it is also possible to listen directly to the sound picked up by the accelerometers. This "stethoscope" function allows comparative examination by listening to different stage and audience floors.

This dedicated system was used to carry out measurements both on different stage floor prototypes and on stages of three historic concert halls in Brussels, as well as in a new concert hall in Stavanger.

4. VIBRATION MEASUREMENTS OF STAGE FLOOR PROTOTYPES

A prototype sample of a typical wood stage floor on joists was tested using the above measurement system in order to find out the influence of the wood thickness and the spacing between the joists on the acceleration level after excitation (by a cello and a tapping machine). The test sample measured 1.14m x 1.03m; the tested wood thicknesses were 22mm (1 layer of pinewood), 44mm (2 layers) and 66mm (3 layers); and the joist spacing varied from 320mm to 1140mm on centers.

Other than measuring the frequency response for the two different vibration sources in various points (of which the detailed results are not presented here), the spatial and frequency average of the acceleration level was obtained for the tapping machine source. Figure 4 shows a summary of these results. It can be seen that the thickness of the wood floor has a significant influence on the average acceleration level: the thicker the floor, the lower the average vibration level, as expected. The joist spacing, however, does not correlate well with the vibration level, which is contrary to the expectations, and contrary to theoretical calculations, showing a good correlation between joist spacing and vibration level.

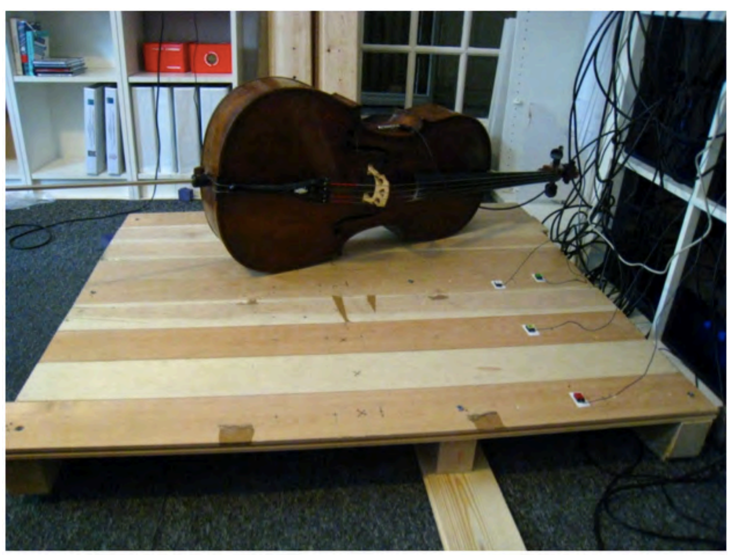

FIGURE 3. View of the tested stage floor prototype, showing the 4 accelerometers tightly mounted to the wood surface using strong double-sided adhesive tape.

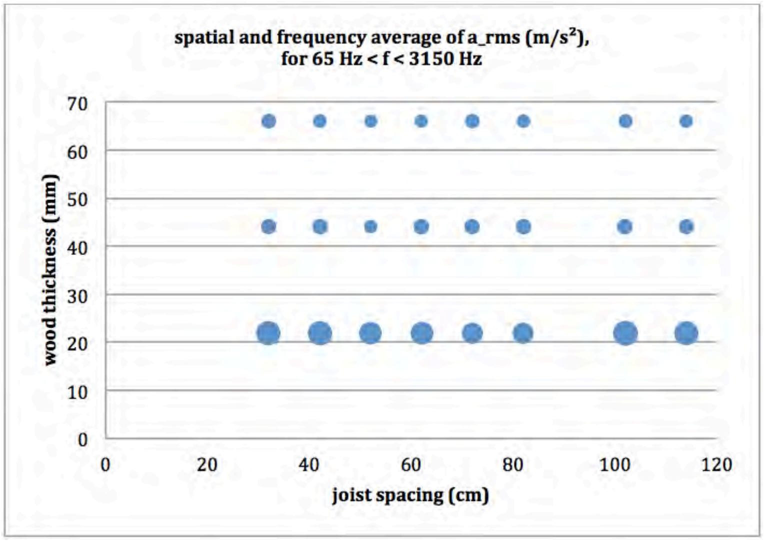

FIGURE 4. Average acceleration level (corresponding to diameter of blue dots) for different values of joist spacing (x-axis) and wood thickness (y-axis), tapping machine source.

5. VIBRATION MEASUREMENTS OF EXISTING CONCERT HALL STAGES

The same vibration measurement equipment has been used to carry out measurements on the stage and audience floors of 3 historic halls in Belgium and 1 new concert hall in Norway. The halls are listed in Table 1, together with their seat count and year of opening.

TABLE 1. Overview of the tested concert Halls

Concert Hall	City	Seat Count	Year
Royal Conservatory of Brussels	Brussels, Belgium	679	1832
Studio 4 at Maison de la radio Flagey	Brussels, Belgium	900	1938 (renovation 2002)
Salle Henry-le-Boeuf at Palais des Beaux-Arts	Brussels, Belgium	2150	1929 (renovation 2000)
Nytt Konserthus	Stavanger, Norway	1500	2012

The aim was firstly to measure acceleration levels at 4 different points on stage, following the same layout on every stage (see Figure 5A). Secondly, acceleration levels were also measured at the stage-to-hall transation (see Figure 5B). The vibration excitation was done by means of a tapping machine as well as a cello (with its pin resting on the stage). In addition, measurements have been made with a live symphony orchestra during a rehearsal at Studio 4 in Flagey.

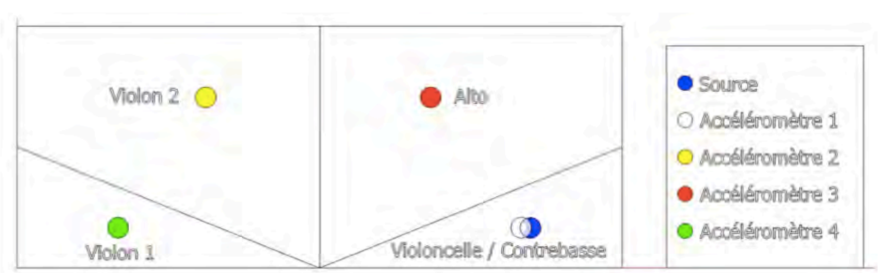

FIGURE 5A. Schematic plan showing the location of the vibration source (cello and tapping machine) and the 4 accelerometers for the on-stage measurements.

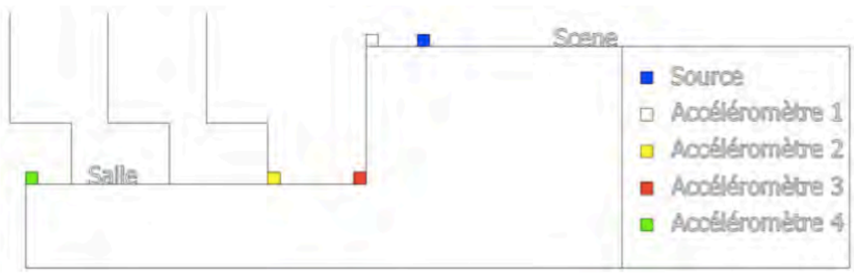

FIGURE 5B. Schematic section showing the location of the vibration source (cello and tapping machine) and the 4 accelerometers for the measurements at the transition of the stage ("scène") to the audience floor ("salle").

Some details of the stage and audience floor constructions are given as follows:

- Royal Conservatory of Brussels: Stage floor 10mm thick oak parquet glued onto 22mm thick pine planks, joist spacing approx. 300mm. Audience floor is carpeted, most likely to be wood floor on joists.
- Flagey Studio 4: Stage floor 21mm thick oak parquet onto 18mm thick plywood sheets, joist spacing approx. 550mm. Audience floor is parquet directly on concrete.
- Salle Henry-Le-Boeuf: Stage floor 13mm thick oak parquet onto 30mm thick planks, joist spacing approx. 330mm. Audience floor is parquet directly on concrete.
- Nytt Konserthus Stavanger: Stage floor 40mm thick three-ply at the front of the stage (up to 60mm at the back of the stage), joist spacing 300-450mm. Audience floor is parquet on joists.

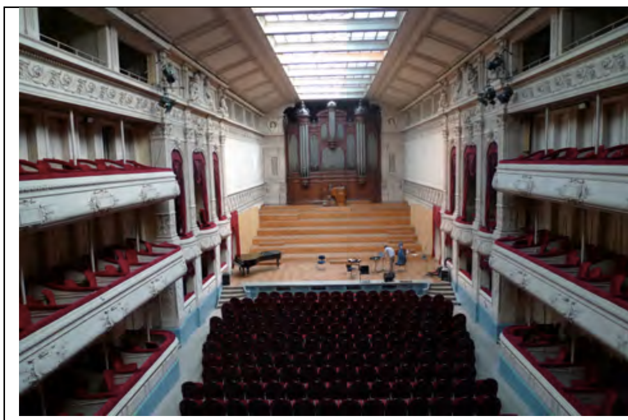

FIGURE 6. View onto stage platform of Royal Conservatory.

FIGURE 7. View below stage of Salle Henry-Le-Boeuf.

FIGURE 8. Live vibration measurements during rehearsal of Brussels Philharmonic at Flagey Studio 4.

FIGURE 9. View onto stage platform of Stavanger Konserthus.

At the time of writing (January 2013), the analysis of the measurements and the comparison between the four halls had not yet been completed. These results will be presented at the conference in June 2013.

6. CONCLUSIONS AND PRACTICAL IMPLICATIONS FOR WOOD FLOOR CONSTRUCTIONS

The full acoustic behavior of wood floors is complicated, since many physical processes take place. In addition, their role in acoustic perception of concert halls is not fully understood. Other than absorbing airborne sound at bass frequencies - which is an unwanted effect - wood floors, at least on stage, can amplify the sound of double basses and cellos. In addition, flexible wood audience floors will vibrate to bass sound, which creates a pleasant sensation for the listeners, picking up bass vibration via their feet. Although no confirmation can be given at this stage, there is some indication that the latter happens mostly via airborne sound being retransformed to vibration close to the listener, and less so via purely structureborne paths. More research is needed to better understand the underlying processes. Until then, it seems useful for acoustic consultants to consider and try to balance all different transmission paths when designing concert hall floors, in an attempt to revisit some of the acquired standard practice currently used all over the world. This could lead to even better concert halls, both for musicians and audiences.

The following guidelines for stage floors can be given:

- Wood surface should not be too thick nor too thin. 30-40mm seems like a good range, preferably thicker at the back (to minimize timpani/percussion vibration).
- Spacing between joists does not seem highly critical, but try to maximize the spacing. This is typically in conflict with modern stage load requirements of up to 750 kg/m^2, calling for narrow joist spacing (and stiff floor surfaces).
- Avoid stiff plywood sheets as underfloor, but rather use pine planks .
- Limit cuts between the various parts of the stage floor (e.g. piano lift, motorised risers).
- Avoid absorption in stage void in order to minimize unwanted broadband absorption.
- No varnishing but oiling of wood surface in order to avoid overly “harsh” high-frequency reflections.

For wood audience floors the following guidelines are proposed:

- Wood floors on wood joists seem to be preferred to wood floors directly on concrete.
- The surface weight of the wood should be of the order of 40 kg/m^2.
- No absorption in void in order to minimize unwanted broadband absorption.
- Stage-to-audience transition: try to connect the stage floor structure rigidly to the audience floor structure.

Future research should include analysis of other stages, including bad ones, and a practical method should be worked out to measure structureborne and airborne components separately.

ACKNOWLEDGMENTS

The authors wish to thank Henrik Möller of Akukon for the invitation to take part in the listening test at the Moscow Conservatory and for the subsequent good collaboration. The managements of the Palais des Beaux-Arts, Maison de la Radio and the Royal Conservatory of Brussels deserve our warm thanks for their cooperation on the measurements conducted in their halls.

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