Influence of "omnidirectional" loudspeaker directivity on measured room impulse responses

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Measured room impulse responses (RIR) strongly depend on the directivity of the sound source used for the measurement. An analysis method is presented that is capable of pinpointing the influence of the loudspeaker's directivity on a set of RIRs. Taking into account the rotational symmetries of a dodecahedron loudspeaker, it detects the effects that the changing directional pattern induces in the RIR. The analysis of RIRs measured in completely different acoustical environments reveals that the influence of the loudspeaker's directivity can still be observed in the very late part of the RIR—even in very reverberant rooms. These results are presented and the consistency with general room acoustical theory is revised and discussed. © *2013 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4824334]

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I. INTRODUCTION AND PREVIOUS WORK

Measurements are needed to quantify the acoustic conditions in rooms. These measurements, however, are prone to measurement uncertainties. One of these uncertainties originates from the directivities of different types of sound sources used for such measurements. This article addresses the uncertainties introduced by the loudspeakers' directivity and presents a novel method of analysis that is capable of detecting the influence of the loudspeaker's directivity in measured room impulse responses.

While initial research on the reproducibility of room acoustical measurements was driven by the goal to generally assess the validity of measurements (see Pelorson *et al.*[1] or Bradley *et al.*[2]), the aspect of source directivity was also discussed. The results of these works led to the introduction of source directivity requirements in ISO 3382:1997.[3] Quantitatively, the requirements were chosen on pragmatic grounds and reflect the slightly adopted requirements from the relevant building acoustic standards. Current research on measurement sound sources' directivities—now with years of experience using ISO 3382:1997—appears to approach the question of whether these quantitative requirements are stringent enough. Barron[4] starts this discussion and recognizes difficulties with omnidirectional measurement sound sources. While he seems primarily concerned with the difference of directivities between musical instruments and measurement loudspeakers, he points out a lack of research aimed at studying the influence of the measurement source's directivity.

Addressing this lack of research, one of the authors of this article collected data (Ref. 5) showing how auditorium measurements are affected by the directivities of sound sources in detail. Various dodecahedron loudspeakers were successively rotated between sets of repeated measurements. It was shown that a stronger deviation of radiation patterns is reflected in a stronger deviation of acoustical quantities calculated from the measured room impulse responses. In an offshoot of this survey, additional measurements were conducted in different auditoria in Spain.[6] These results confirm the initial findings and allow a closer look at how these effects occur in different auditoria. Further results show that the early part of the impulse response is most significantly affected by the directivity of the sound source. For subsequent research, San Martin[7] used commercial geometric room acoustic simulation software to determine the influence on acoustical quantities calculated for various receiver positions. He recognized the initial-time-delay-gap as a predictor to identify critical receiver positions.

Despite the good idea to use simulation results to generate a statistically sufficient foundation for an in-depth discussion, it needs to be considered that most ray tracing simulation methods rely on stochastic models to represent some aspects of sound propagation in rooms, e.g., sound scattering. Therefore, additional accuracy requirements must be met in order to ensure that subtle effects prevail over the stochastic noise of repeated simulations. Given the information provided in Ref. 7, it is remarkable that many simulation tools still provide little information on the accuracy of their results and, hence, make it difficult to understand how such influences have been considered and whether results can be reproduced independently.

The form of analysis presented in this article does not rely on room acoustical simulations, but merely on measurements in real auditoria. It is capable of identifying the influence of a sound source's directivity directly in the room impulse response and not just in acoustical quantities. This exceeds what previous studies[5–7] have discussed. The line of argument is divided into three parts. Initially, the tangible concept behind the method is presented. In part two, measurement series to provide input data for the analysis method are described. Central parts include a detailed description of the method of analysis and discussion of the results. As the

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findings might not appear completely intuitive, the coherence with general room acoustic theory is discussed. This article concludes with remarks on the general applicability of the presented method.

II. MOTIVATION AND CONCEPT

In order to determine the influence of loudspeaker directivity on the room impulse response (RIR), it is crucial to first be able to recover the directivity of the loudspeaker from a measured RIR. A way of doing this is to determine a certain characteristic of the loudspeaker's directivity, which can also be detected in a measured RIR. This enables one to pinpoint the influence of the directivity in the RIR. The aim of this work is to find such a characteristic property of the directivity and then to detect it in the RIR as well. However, before that, the directivity of a dodecahedron loudspeaker needs to be characterized. For the sake of simplicity all of the following considerations will focus on a specific, arbitrarily chosen frequency band, i.e., the third-octave band around 2 kHz.

The measured directivity of a given loudspeaker (sound intensity level relative to mean radiated intensity) at this frequency band is shown in Fig. 1. Due to the dodecahedron shape of the loudspeaker, the directivity shows certain rotational symmetries with respect to the vertical axis. In this example, a threefold symmetry can easily be observed. In a thought experiment in which the loudspeaker is rotated around the vertical axis, this symmetry leads to periodically repeating directivity patterns. At every 120° turn, the directivity of the loudspeaker looks almost the same. This is due to individual loudspeakers of the same kind with very similar properties that are built into the dodecahedron housing. When conducting repeated room acoustical measurements in between which the sound source is stepwise rotated around its vertical axis, it will radiate a very similar distribution of energy into the room every 120° turn, thus leading to similar RIRs every 120°. This can be used to detect the loudspeaker's directivity in a RIR. If an analysis of RIRs reveals that a certain property shows the same periodic change with respect to the rotational angle of the sound source, this change would clearly originate from the directivity of the loudspeaker. It is very unlikely that any other property of the room (e.g., the room temperature) changes with that exact periodicity (every 120° turn of the loudspeaker) during the course of the measurements. The 120° periodicity is a characteristic property of the dodecahedron speaker at this given frequency.

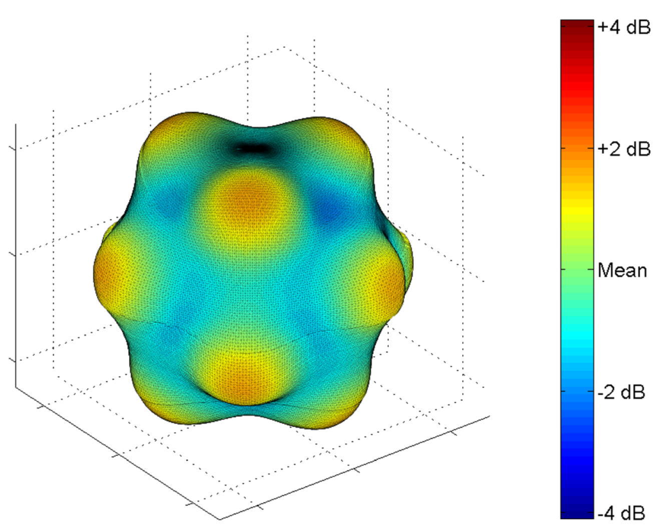


FIG. 1. (Color online) Measured directivity of a dodecahedron loudspeaker at 2 kHz (1/3 octave). The directivity shows a threefold (120°) rotational symmetry when rotated around its vertical axis.

Detecting periodic patterns in the properties of measured RIRs can help to identify the influence of the loudspeaker's directivity within the RIR. In order to find out where to look for such periodic changes in the RIRs, it is helpful to focus on what happens in a room when a sound source is rotated. Since rooms that are usually acoustically surveyed are auditoria with low Schroeder frequencies (<300 Hz) and the directivities of typical measurement speakers do not begin to show any predominant directions until fairly high frequencies are reached (>1 kHz), a sound path based model for sound propagation can be applied for the following considerations. In a certain time interval $[t\ t\ +dt]$ after the sound was emitted by the sound source at $t = 0$, a number of sound paths with the lengths $[ct\, c(t + dt)]$ lead from the source to the receiver. Each of these paths carries a certain amount of energy depending on the absorption of the walls and on the directivity of the loudspeaker. When the sound source is rotated, the directivity changes while the sound paths geometrically remain exactly the same (note that this is true not only for specular reflections but also for scattered sound energy, as scattering is a deterministic process as well). The only thing that is changed by the rotation of the loudspeaker is the energy that is introduced into each sound path due to the source's directivity (as shown in Fig. 2). These amounts of energy are scaled with the periodic patterns of the loudspeaker's directivity and are then carried by the different sound paths to the receiver. So if these periodic patterns can be detected within the energies arriving at the microphone, the influence of the loudspeaker can be identified in the RIR.

III. MEASUREMENTS

Various rotating loudspeaker measurements were carried out in four rooms with different acoustical characters (see Table I) to verify this assumption. In each of the rooms, the same ISO 3382-1:2010 compliant dodecahedron loudspeaker was used. The directional deviations of the source from omnidirectionality in dB as defined in ISO 3382-1:2010 are shown in Fig. 3. The ISO 3382-1:2010 conformity is based on measurements in the equatorial plane that were conducted in a 1° resolution. For the measurements in different rooms, the source was placed on an electronic turntable and turned in 5° steps conducting a measurement for each angle. A number of microphones were distributed at arbitrary positions in the room and a room impulse response was recorded with each one of them. The same measurements were conducted for different source positions. Exponential sweeps were used for the excitation. Air conditioning, heating, and other ventilation systems were adjusted to maintain a constant room temperature during the

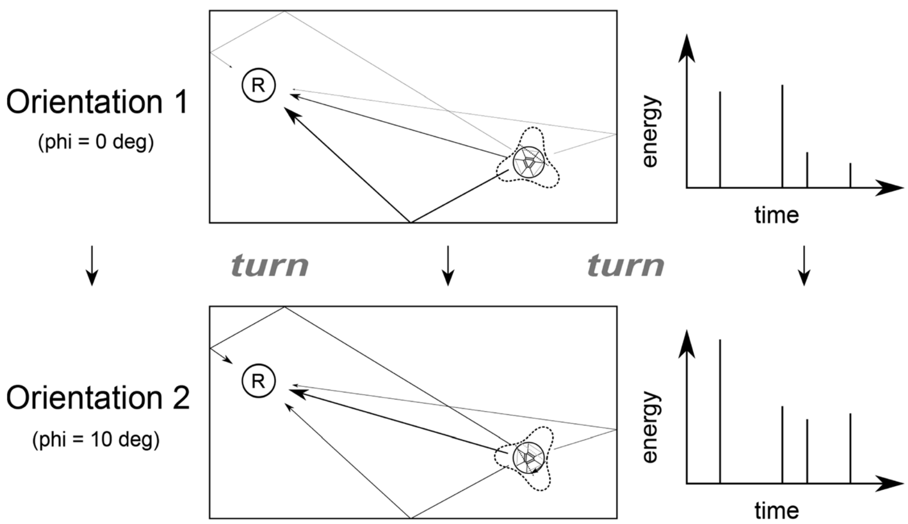


FIG. 2. Sound paths in rooms. When rotating a loudspeaker during a measurement, the energy carried by different sound paths is scaled by the directivity of the speaker; the sound paths themselves remain the same. Only the amplitude, but not the position, of the individual reflections changes in the echogram.

measurement sequence. After the last person exited the auditorium, the room was left for about 30 min to stabilize before the actual measurement sequence started. A period of 15 min was determined to be sufficient by Vorländer *et al*.[8] when studying the requirements for measurements to determine the scattering properties of samples in reverberation rooms.[9] Due to the larger size of the surveyed auditoria compared to reverberation chambers, the period for the room to stabilize was doubled. The relaxation process of the room was monitored by means of repeated measurements in which the setup of the room remained unchanged. The sets of rotation measurements were conducted via a fully automated process so that nobody was inside the room during the measurements. All these precautions were taken in order to keep the room as stable as possible in between different measurements. The directivities of the different dodecahedron speakers used for the measurements were measured before in an anechoic room.

IV. ANALYSIS

A. Data processing in time domain

The results of the measurements described above are sets of 72 RIRs. Each RIR corresponds to one rotational angle, ϕ, of the loudspeaker. In order to better analyze the energies arriving within certain time slots, the measured RIRs are processed and turned into "time binned RIRs."

TABLE I. Acoustical properties of investigated rooms. The critical time t_0 denotes the time after the impulse start when the measured signal of the room impulse response falls below the 10 dB level above the noise floor.

Room name	Volume V [m^3]	Surface A [m^2]	Reverberation time T_{40}[3] at 2 kHz [s]	Critical time t_0 at 2 kHz [s]
Seminar room, Aachen	140	180	1.3	0.8
Aula I, Aachen	5800	2300	1.5	1.1
Philharmonie, Berlin	21 000 (Ref. 10)	~4000	2.0	1.8
Reverberation chamber, Aachen	123	178	3.8	4.5

(1) As a first step of data processing, all nonlinearities at the end of the RIRs were cut off.[11] To automate this step some precautions have been taken as part of the measurement design. In detail, the excitation signal—including the stop margin after the sweep—has a length that is at least twice the RIR-signal-length before it falls below the measurement noise. An excitation signal of proper length ensures that the second half of the measured RIR only includes background noise and nonlinearities, allowing for automated trimming. In a second aspect, it is ensured that the impulse responses excited by the harmonic distortions decay quickly enough to have negligible influence on the primary impulse response. This is achieved by a sufficiently slow sweeprate (in octaves/s) and a low amplification. In a third aspect, it is ensured that measurements are conducted in an environment with a constant noise level. This is necessary to avoid a difference in noise between the end and the beginning of the RIR after trimming, which would be detrimental for the cyclic deconvolution.

(2) Afterward, each set of RIRs was time shifted as a whole so that the earliest direct sound in the set was positioned at $t = 0$. This type of time shifting is important to make

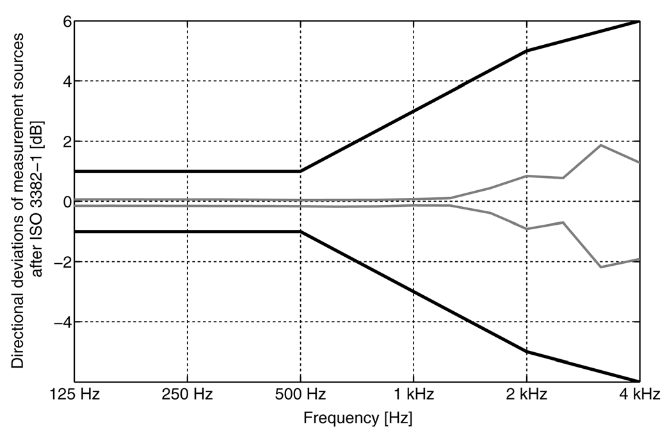


FIG. 3. Measured directional deviation of the used dodecahedron sound source. The gray line shows the equatorial deviation from omnidirectionality in third octave bands as defined by ISO 3382-1:2010. The black line indicates the standardized maximum allowed deviations.

the sets measured in different auditoria or at different source-receiver combinations comparable to each other, as they will have the same time code. This operation has no influence on the temporal relations of the different impulse responses within one set, as all RIRs of a set are shifted by the same amount. In addition, the time shifting has no influence on the delay of any reflection to the direct sound as each RIR is shifted as an entity.

(3) After the time shifting, the RIRs were band-filtered in third-octave bands.[3]

(4) The filtered signals were time windowed with overlapping Hamming windows. The windows had a length of 10 ms with a 5 ms rise and fall time. The overlap was chosen as 50% of the window time, resulting in a delay of 5 ms between two adjacent windows. The choice of 10 ms window lengths satisfies two conflicting demands on the windowing process. On the one hand, a high temporal resolution of the resulting signal is required. Larger windows quickly approach the length of integration ranges of room acoustic single number quantities (e.g., C_{50}, etc.), but the discussion is aimed at how the impulse response as such is affected. The mere analysis of room acoustic single number quantities would provide few new findings, compared to previous studies. On the other hand, very short window lengths lead to an unwanted distortion of the results because they augment the influence of varying measurement conditions. As laid out in Sec. III, the temporal positions of the individual reflections in a RIR are expected to remain the same, independent of the loudspeakers' orientation. However, because of the way the measurement setup is laid out, each individual RIR is measured at a different time. Changes in the speed of sound between these measurements shift the temporal position of the individual reflections. If very short window lengths are used, a significant part of the energy carried by one of the reflections might be shifted to a different time window. The resulting differences between two measurements might mainly originate from the changing room properties instead of the loudspeakers' orientation.

(5) An energy average was calculated for each window. The overlap of the window ensured that the total energy of the RIR is preserved.

The resulting signal is an energy-over-time signal with a time sample every 5 ms corresponding to the sound energy arriving at the receiver within the given time interval in the given frequency band. The data for each source-receiver-combination was processed independently.

B. Fourier transform

Having processed the data in time domain, it is possible to focus on a given time interval and analyze how the energy arriving within that certain time interval changes for every orientation of the source. This can be done by selecting the same time sample in each of the RIRs of a set and monitoring its progress throughout the set. The signal obtained by this kind of analysis is an energy-over-angle signal and will be referred to as an *angular signal* in this article. An example of such a signal with its obvious periodic character is shown in Fig. 4.

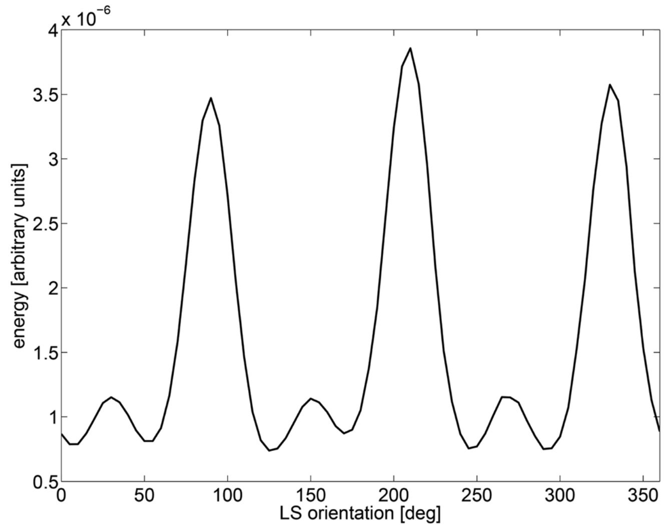


FIG. 4. Angular signal of the first 10 ms of a set of RIRs at 2 kHz (1/3 octave). The energy arriving at the microphone during a certain time interval clearly shows the periodic character of the directivity when plotted over the different rotational orientations of the measurement speaker.

As suggested by the theoretical considerations, the signal shows a three-fold (or 120°) periodicity originating from the sound source's rotational symmetry. Furthermore, some higher order periodicities (e.g., 60°) and an amount of energy independent of the loudspeakers orientation can be observed. In order to better display the different periodicities of this *angular signal*, a further processing step is conducted. A discrete Fourier transform and normalization is carried out according to

$$\Psi_\Phi = \sum_{n=0}^{N-1} \phi_n e^{-i2\pi n/\Phi N}, \quad \text{and} \quad \sum_\Phi \Psi_\Phi = 1. \tag{1}$$

In this notation, the index identifies the running variable; ϕ_n denotes the angular signal of energies over the rotational angle n, N is the total number of samples/angles of the angular signal, and Ψ_Φ is the rotational spectrum of periodicities, Φ. The normalization of the rotational spectrum on the right-hand side of Eq. (1) allows for displaying the fraction of total energy carried by each of the periodicities.

In comparison to the classical time-frequency Fourier transform, Eq. (1) does not transform from a time to a frequency domain, but from an angular domain to a reciprocal angular domain of "rotational frequencies." To facilitate an intuitive interpretation of the data, the discussion of "rotational frequencies" (in reciprocal angular domain) is waived in favor of rotational periodicities, Ψ_Φ. The latter clearly show the period of the angular signal in units of degrees. To give an example, the coefficient $\Psi_{\Phi=60^\circ}$ carries the energy of the angular signal that repeats itself every 60°, and therefore has six repetitions over a full 360° rotation of a set of measurements.

The rotational spectrum of the angular signal shown in Fig. 4 is displayed in Fig. 5. The "infinite degree" periodicity, i.e., the constant component, is omitted as normalized

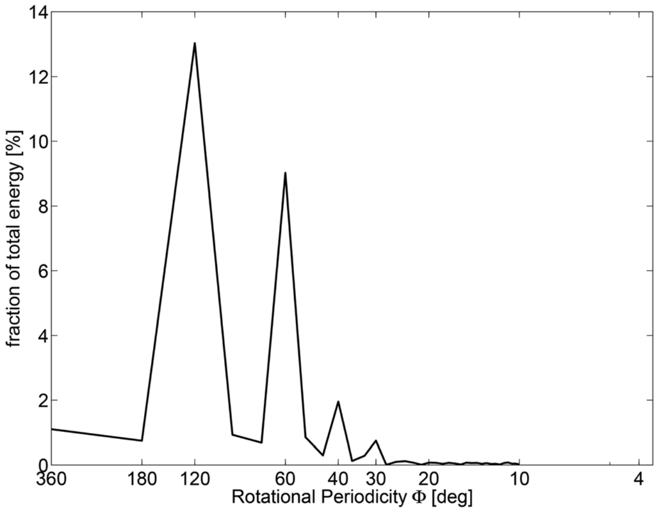


FIG. 5. Rotational spectrum of the angular signal shown in Fig. 4. A Fourier spectrum of the angular signal helps to better display the distribution of energy among the different periodicities.

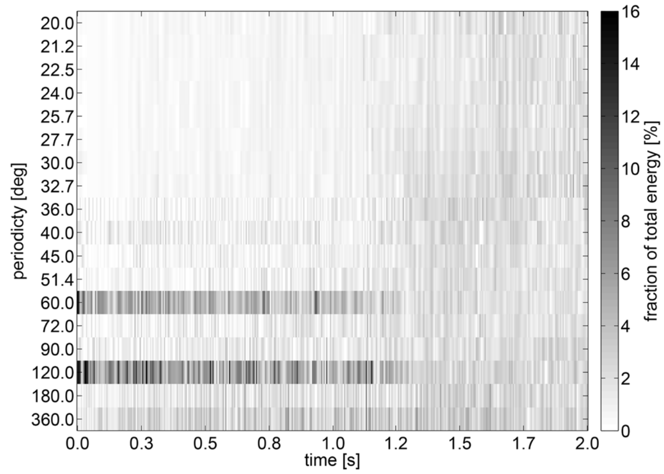


FIG. 6. Periodicities of a measurement in Aula I at 2 kHz (1/3 octave). The characteristic periodicities of 120° and 60° carry considerably more energy than the non-characteristic periodicities (e.g., 360°, 180°, or 90°).

data [see Eq. (1)] is presented. For further considerations, only the relative/normalized energy distribution within the periodicities is of interest.

In the rotational spectrum (Fig. 5), it can be observed that the 120° periodicity contains most of the energy followed by a 60°, 40°, and 30° periodicity. All of these (360/3 n) periodicities correspond to rotational symmetries that can be found in the directivity pattern of the loudspeaker at that frequency band, and are therefore called *characteristic periodicities* (CPs). The other periodicities such as 180° or 90° correspond to rotational symmetries (e.g., two- or fourfold), which cannot be found in the directivity of the sound source. Therefore, these periodicities are called *non-characteristic periodicities* (nCPs). In the example shown in Fig. 5, it can clearly be observed that the nCPs do not carry nearly as much energy as the CPs.

The domination of CPs over nCPs in the example shown is not really surprising considering that the observed time interval ranges from 0 to 10 ms after the arrival of the direct sound, and mainly contains the energy of the direct sound. More interesting is an investigation of how this changes throughout the later parts of the RIR as the density of reflections increases and the sound field turns diffuse. For this reason an analysis of the whole RIR is conducted in which each time interval is transformed and normalized separately.

V. RESULTS

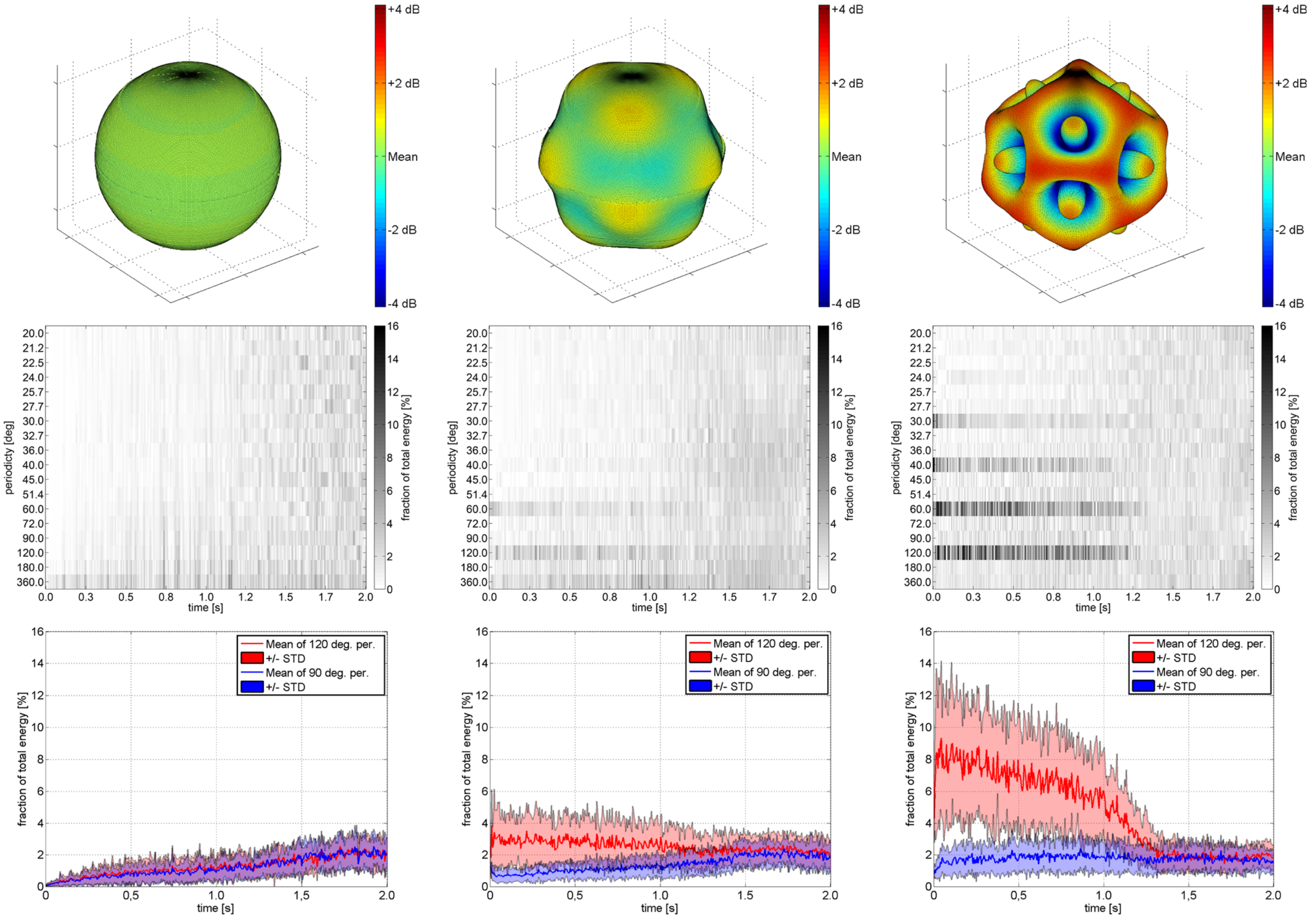
A. Influence of the source's directivity

The result of an analysis of the whole RIR is shown in Fig. 6. The presented range is limited to periodicities greater than 20° to improve the display. This can be justified because in none of the measurements the accumulated energy of all periodicities smaller than 20° exceeds 10% of the total energy. Again, it is clearly visible that the CPs, such as 120°, 60°, and 40°, dominate the nCPs.

Comparing the rotational spectra at different frequencies with each other shows how the prominence of individual periodicities changes (Fig. 7). At low frequencies [e.g. 500 Hz in Fig. 7(a)], the directivity of the source is still almost perfectly omnidirectional, not favoring any specific rotational symmetry; in other words, all possible rotational symmetries are equally represented. From 1.5 kHz on, the loudspeaker starts to show the first lobes and predominant directions, thus losing its complete rotational symmetry and favoring a threefold rotational symmetry [Fig. 7(b)). At 4 kHz, many smaller lobes arise leading to even higher rotational symmetries [six- and twelvefold; Fig. 7(c)]. This change of symmetries is clearly reflected in the change of the corresponding periodicities in the RIRs. At very low frequencies it can even be observed that all of the periodicities carry less energy than the statistical average that they reach when the signal itself is submerged in noise at approximately 1 s. The omnidirectionality of the directivity along with the normalization [see Eq. (1)] "suppresses" the periodicities.

The advent of first deviations from omnidirectionality at 1.6 kHz is easily detectable in Fig. 7(b) in both the balloon plot and the respective periodicities. In Fig. 3, however, the minuscule increase in the standardized equatorial directional deviation at this frequency would hardly be detectable, if it were not for the information available in Fig. 7. In a side note, without wishing to anticipate any other conclusions, this suggests that it might be worth re-evaluating whether the ISO 3382-1:2010 requirements for sound sources are sufficient. In two steps, one would have to explore if the directivity induced measurement uncertainty is significant, and then this result needs to be cross-checked for congruence with the existing requirements. If necessary, a modification (e.g., to the maximum allowable deviations or the extent of the gliding arc to average over) should then be discussed.

A central, but rather surprising, observation is that the domination of the CPs (i.e., the influence of the loudspeaker) can still be observed in the very late part of the RIR (see Fig. 6). In order to quantitatively display the temporal trend of the influence of the loudspeaker in the course of the RIR, Fig. 8 (and for comparison at other frequencies shown on the bottom row of Fig. 7) shows the 120° periodicity over time as a representative for all the CPs. Since the detailed



(a) 500 Hz (b) 1.6 kHz (c) 4 kHz

FIG. 7. (Color online) Measured directivities of speaker, corresponding spectrum of periodicities in RIRs, and temporal trend of 90° and 120° periodicities in RIRs at different third octave bands. The change of the directional pattern in the loudspeaker's directivity is reflected in the measured periodicities of the RIRs (measured in Aula I).

geometry of the room is not of interest, the temporal course of the 120° periodicity is averaged over all measured combinations of speaker and microphone positions. The obtained signal is a more general result solely depending on the main acoustical characteristics of the room—such as volume, free mean path, and reverberation time. The signal of the averaged 120°periodicity at 2 kHz (Fig. 8) can roughly be divided into three parts. At the very beginning of the impulse response there is a strong drop-off (here, until about 50 ms). From here on, the signal remains at about the same level, only slightly decaying until it starts dropping to the noise level at the end (in the example of Fig. 8 at about 1.1 s). Comparing the temporal behavior of the 120° periodicity with an untreated RIR of the same measurement (Fig. 9) reveals that the final drop to noise level does not start before the signal of the actual room impulse also has dropped down to only about 10 dB above noise level. From this critical time t_0 on (here, $t_0 \approx 1.1$ s), the noise has significant influence on the character of the signal,[3] which implies that the entire clean RIR is influenced by the directivity of the speaker.

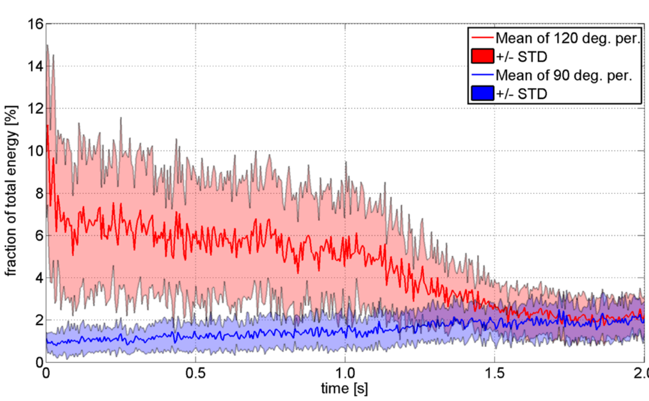


FIG. 8. (Color online) Averaged 120° and 90° periodicities over all source and receiver positions measured in Aula I at 2 kHz (1/3 octave). The mean of the 120° periodicity can be used as a representative for the CPs, and the 90° periodicity for the nCPs when focusing on the temporal developing of the periodicities.

This influence of the speaker's directivity on the entire RIR was not only detected in a single measurement or room, but in all rooms that were studied. Figure 10 shows a comparison of the averaged 120° periodicity as measured in different rooms. It seems that only the reverberation chamber with its very special characteristics differs significantly from the other three auditoria. However, even in the reverberation chamber the influence of the speaker can be detected at the

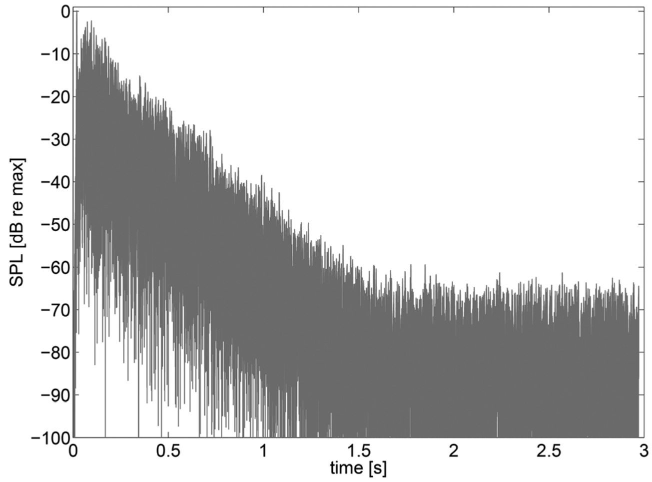


FIG. 9. Exemplary RIR measured in Aula I at 2 kHz (1/3 octave). The signal energy drops below the 10 dB level above the noise floor at about 1.1 s. After this point, the influence of the noise is not negligible anymore.

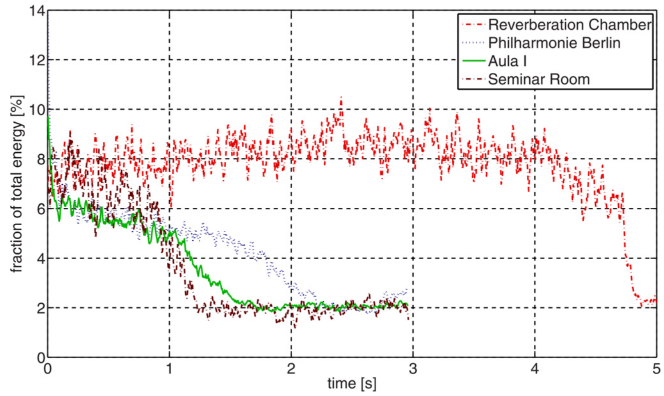


FIG. 10. (Color online) Averaged 120° periodicities of different rooms at 2 kHz (1/3 octave). Comparing the temporal trend of the averaged 120° periodicities, it can be observed that the CPs remain prominent until the very end of the signal in all of the investigated rooms.

very end of the RIR (at about 4.5 s). The final drop-off in all of the signals correlates very well with the critical times, t_0, in the respective measurements (compare Table I).

VI. DISCUSSION

A. Reliability of results

Although not shown in the presented data, it should be mentioned for reasons of completeness and critical review that on rare occasions some measurements showed, apart from the regular CPs, a single nCP (i.e., 180°) carrying more energy than the statistical average (i.e., approximately 1.5% of the signal's entire energy). In contrast to the CPs, such nCP did not depend on frequency, but carried the same amount of energy in all frequency bands of an affected measurement. This nCP occurred due to an unpreventable variation of other properties of the room during the measurement (possibly such as temperature, etc.). Although careful precautions were taken to minimize such effects, they still are generally unavoidable. Nevertheless, it is reasonable to assume that they have no influence or negligible influence on the line of argument pursued. As we focus on the 120° periodicity, any known or unknown acoustic property of the auditorium would have to vary with exactly three periodic cycles during the entire measurement sequence in order to have an impact on the results. It is understood that this is generally possible, but rather unlikely. A linearly changing speed of sound, for example, results in a stronger prominence of the lower-order periodicities (especially 360°), but hardly influences higher-order periodicities like the CPs. Furthermore, if a certain nCP stands out in a given set of measurements and it is observed in all frequency bands at the same time, it can be argued that this is not related to the sound source, but to some general property that changed during the measurement. The prominence of the 360° periodicity in many of the measurements is caused, for instance, by a minimally inclined (not perfectly upright) loudspeaker stand on the turntable. This leads to an equally miniscule imbalance when the speaker is rotated.

To further ensure that the CPs are related to the loudspeaker's directivity and not to the measurement procedure, another measurement was conducted in exactly the same manner as the rotating loudspeaker measurements. In this case, however, the sound source was not set on top of the turntable, but next to it in a non-rotating position. The results showed no CPs at all. All these observations strongly suggest that the CPs correlate to the directivity of the sound source and their dominance over the nCPs represents its influence on the RIR.

B. Coherence with general room acoustic theory

The fact that the loudspeaker's directivity affects the RIR even in its very late part and even in reverberant environments might seem surprising at first and contradicts intuitive expectations, but it is perfectly consistent with room acoustical theory even when assuming a perfectly diffuse sound field. One of the properties of the diffuse sound field is that there is no net energy flow at any given point. This concurs with the observation that the amount of energy arriving at this point from a certain solid angle integrated over the whole duration of the sound decay is independent from the orientation of that solid angle. Therefore, in a diffuse sound field it can be assumed that the sound paths in a room are evenly distributed and well mixed.

Let us consider a source and a receiver with omnidirectional directivities. Applying the reciprocity principle to this sound field would only change the signs of the propagation vectors and, hence, imply that the originating trajectories of the sound paths on the source are also evenly distributed. This argument holds true for any room geometry in which a diffuse sound field can exist. Since the paths along which the sound propagates are solely geometry-dependent, introducing a directivity to the sound source sound will not change these geometric paths. Instead, each of the sound paths carries energy scaled by the directivity of the speaker (see Fig. 2). When the source is rotated, the exact rotational signal of each sound path strongly depends on the directivity (as a function of frequency) as well as the originating trajectory from the source, e.g., a sound path originating from the very top of the loudspeaker will hardly show a periodic character when the source is rotated around the vertical axis at any frequency. In contrast to that observation, two sound paths originating from the same latitudinal ring of the loudspeaker (i.e., their originating directions have the same elevation or theta angle) may differ because they may have different rotational phases (i.e., different starting points on the loudspeaker concerning the rotation and thus different rotational offsets). Although this shows that all sound paths arriving at the receiver are technically related to each other by the sound source and its directivity, the different rotational signals and their rotational phases associated with these sound paths may still be considered uncorrelated to each other as the distribution of the originating trajectories from the source is uniform.

When the focus is put on the later part of the RIR, it can be observed that the energy arriving during a certain fixed-length time interval originates from an increasing number of different sound paths, since the density of reflections in a RIR increases with the square of time.[12] Therefore, the energy arriving during this time interval consists of many periodic angular signals with uncorrelated phase relations. This might lead to the conclusion that a kind of mixing occurs due to an increasing number of different reflections, and as the significance of individual reflections declines the periodic character in the sum cannot be detected in the late part of the RIR.

The measurements, however, show a different result. The periodic character of the speaker's directivity is still present in the late part of the RIR. This can be explained better when first focusing on a single periodicity. Since the base functions of the Fourier transform [Eq. (1)] and thus the periodicities are linearly independent—just like the frequencies in a time-frequency transformation—a detached observation is possible and the whole signal can later be restored by a superposition of the different periodicities. The focus on one single periodicity reduces the problem to the mathematical problem of a sum of uncorrelated periodic signals with random phase relations, random amplitudes, but the exact same frequency (here, periodicity). The sum of these signals will always contain only that exact frequency innate to the summands. There is only a singular case in which all signals have a specific phase relation so the sum of the signals is identical zero. For uncorrelated signals, however, this case can be excluded from a probabilistic point of view.

Furthermore, in a statistical average, the energy of the resulting signal will increase with every additional signal contributing to it. When considering sound pressure signals, it is widely accepted that adding uncorrelated signals with a single frequency, f, and energies, E_i, on a statistical average leads to a signal with the total energy, E_{tot}, which is merely the sum of the energies of the contributing signals

$$E_{tot} = \sum E_i. \quad (2)$$

When applying this concept to the angular signals and focusing on a given time window and periodicity, it becomes clear that no matter how many reflections arrive during that time window the periodicity never disappears due to any kind of mixing or averaging effect, instead the total amount of energy with this periodicity will even be enhanced with every additional reflection which arrives and carries energy in that periodicity. This might lead to the conclusion that the characteristic periodicities even gain prominence throughout the RIR, but not only the characteristic periodicities augment with every additional reflection, also the non-characteristic ones do. And since in the single signals of the incoming reflections the CPs already carry more energy than the nCPs, and the energies of the periodicities of the incoming signals can simply be added (see above), the CPs will also dominate the nCPs in the resulting signal. That means that although it might be unexpected, the fact that the speaker's directivity has an influence on the entire RIR even in very reverberant environments is not only measurable, but also explicable by general room acoustical theory.

C. General discussion

The presented findings shed new light on the results presented by San Martin *et al*.[6,7] First and foremost, it is positive to see that the strong effect of the directivity on the early part of the impulse response can be confirmed independently. Figure 8 shows the same result. Furthermore, the specialized method presented here that is used to analyze the impulse response shows that the entire RIR is affected by the directivity of the loudspeaker. To the authors' knowledge this result is new and has not been shown previously. One of the important aspects of the theoretic framework discussed here is that sound propagation in rooms is a deterministic process. Hence, it would now be interesting to see whether the influence of a source's directivity can be detected in RIRs that have been generated using geometric models which include stochastic approaches to model sound scattering or the directivity of sound sources.

Given this perspective, studies on detailed modeling might be a subject for future research. The method of analysis presented here is more sensitive to source characteristics than the simple analysis of acoustical quantities and is able to clearly identify effects of the sound source directivity. Future research should therefore determine if the discovered effects can be modeled with the required accuracy and, in a second step, consider whether the presented findings are of significant magnitude to affect room acoustic single number quantities. Ultimately, the practical significance of the results will also depend on the effect's perceptibility, which needs to be investigated.

Although results from measurements with dodecahedron sound sources have been used and discussed, it should be noted that the presented line of argument is also viable for other types of sound sources. Without prior knowledge of the detailed directivity, at least a twofold (180°) rotational symmetry around the source's vertical axis is required to distinguish between characteristic and non-characteristic periodicities. This is due to the mere geometrical symmetry of the loudspeaker's physical shape. In case of a twofold symmetry, for example, all even periodicities $[360/(2\,n)]$ are characteristic of the sound source. All uneven periodicities are non-characteristic and the same line of argument can be applied.

In case additional information on the source's directivity pattern is available, the requirement of rotational symmetry may be relaxed. Generally, a simple single membrane boxed loudspeaker, for example, cannot be used for the discussed analysis as all periodicities are potentially characteristic ones. If, however, the detailed directivity is known and it can be established that specific periodicities do not exist in the directivity of the source, this given set of periodicities cannot be "excited" by the source and, hence, may be considered as non-characteristic. A distinction of non-characteristic and characteristic periodicities again allows for an analysis as described in this article.

VII. SUMMARY AND CONCLUSION

The influence of the directivity of the loudspeaker used for measurements of RIR needs to be of concern for a general prediction of uncertainties in room acoustical measurements. To be able to predict and model the uncertainties caused by different directivities, it is crucial to have methods to detect their influence in a RIR. A very sensitive method of analysis was developed. It is capable of detecting the directivity's influence in such measured RIRs using the rotational symmetries of a dodecahedron speaker. Measured RIRs were analyzed and the influence of the dodecahedron speaker's directivity on the RIRs was proven in all of the measurements. Its influence was even evident in the very late part of RIRs of very reverberant environments. Although this observation might come as surprise, it is completely consistent with general room acoustical theory and provides the basis for the construction of a model that is capable of predicting the uncertainties of room acoustical measurements caused by the directivity of a loudspeaker.

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