MEASURING IMPULSE RESPONSES IN A FULLY OCCUPIED CONCERT HALL USING A TAILOR-MADE ELECTRONIC MUSICAL COMPOSITION – PROOF OF CONCEPT –

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1 INTRODUCTION

Since the beginning of concert hall acoustics research it is quite difficult or almost impossible to find or arrange an opportunity to do extensive measurements with audience present, shortly before the beginning of a symphonic concert or during a break. It is always a trade-off between time, type of signal, number of measurements and measurement quality, while the ISO 3382-1 standard ('Measurement of room acoustic parameters') demands a certain minimum amount of measurement positions and a certain minimum quality of measurement results (minimum decay ranges) depending on hall dimensions, number of seats, stage dimensions (presence of an orchestra pit) and parameter type.[1] In the past there have been many successfull and unsuccessfull attempts to obtain room acoustical parameter values in occupied concert halls with and without orchestra using gun shots, balloon pops, noise bursts, etcetera. This type of signal is perceived as annoying and irritating (loud impulsive sounds and the smell of sulfur when using blanks) to both the audience and the orchestra. It disturbs the concentration of musicians and conductor before a performance, while the audience tends to react, producing additional sound. To circumvent this problem it is often attempted to use stop chords or loud impulsive fragments during a live performance of a symphonic orchestra. This was first done in 1935 by Meyer and Jordan during a symphonic concert in the occupied concert hall of the former 'Berliner Philharmonie' (Beethoven Coriolan-overture, Op. 62).[2] To use this technique and reach a certain minimum acoustical quality of stop chords and impulsive sounds (time shape and spectrum) Jan Masséus (1913-1999) a Dutch composer and music pedagogue was contracted in 1973 to compose a symphonic piece of music for testing the acoustics of a fully occupied concert hall.[3] He incorporated 'measurement signals' and the subsequent silences in a piece of symphonic music that was acceptable to the audience, which delivered better measurement results. However, the responses obtained from all above-mentioned measurements were mainly used to obtain an indicative value of the reverberation time. In a room acoustic study of Hidaka et al. in 2001 seven concert halls with and without audience could be measured using the ISO 3382 standard but 15 other halls with audience could only be measured using stop chords recorded during concerts with audience.[4] It was found that the stop chord method has about twofold spreads to the ISO method. This means that very careful examinations are necessary when musical stop chords are used to obtain the reverberation time of a hall. In a study of Cox *et al.* it is described how to extract the room reverberation time from speech, using artificial neural networks.[5] In his study, Kendrick describes the Maximum Likelihood Estimation (MLE) method.[6] This statistical technique enables acoustical measurements in an occupied room, using only passively recorded speech and music signals.

The purpose of the experimental study described in this paper is to obtain measured room acoustical parameters in accordance with the ISO 3382-1 standard for three occupancy rates in a concert hall. First the unoccupied situation (without audience and without musicians), secondly with occupied stage only (without audience and with 80 musicians) and third with fully occupied concert hall (with an approx. 1000 person audience and 80 musicians). To ensure that nothing changed (between the measurement sessions) concerning 'furnishing', orchestra and measurement positions, the measurements where conducted on the same day within 8 hours.

2 MEASUREMENT CONDITIONS

2.1 Introduction

The measurements (as a proof of concept) for this study were carried out during one of the events of ‘The Dutch Design Week’ (DDW) in October 2014. The DDW is a nine-day annual event about Dutch design with exhibitions, workshops and seminars at around 80 venues in Eindhoven, The Netherlands with more than 250,000 national and international visitors. One of the events, called ‘Architectural Acoustics: How Buildings Sound’, took place in the large concert hall of ‘Muziekgebouw Frits Philips’ (MFP) in Eindhoven. It was an event with music performances and lectures about concert hall and stage acoustics design, supported by controlled lasers. One of the performances was a fully occupied room acoustic measurement according to the ISO-3382 standard, using a dummy orchestra of 80 ‘musicians’ on stage and a piece of electronic music with a ‘hidden’ measurement signal, composed especially for this purpose. Before playing the signal (composition) the visitors were informed about the research goal and were asked to enjoy and listen attentively to the composition and the response of the concert hall on the signal. Figure 1 shows an impression of the ‘Architectural Acoustics’ event.

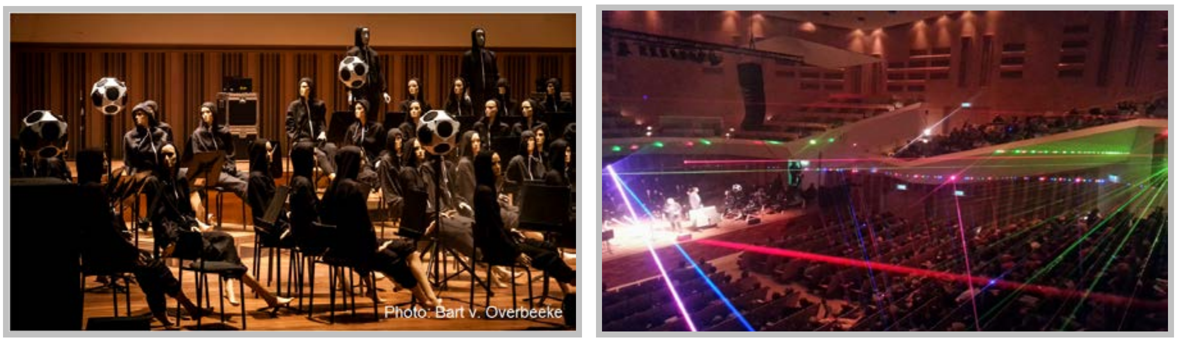

Figure 1. The Architectural Acoustics event during the Dutch Design Week. Left picture: dummy orchestra with omnidirectional sound sources; Right picture: Concert hall during the event.

The recorders were running during the whole event and the 8 microphone positions were marked with striking blue coloured LEDs. The chairs on both sides of the microphones were occupied by dummies, so everyone in the hall knew exactly where the recordings took place, while minimizing the background noise around the microphones. The dummy orchestra, part of the ongoing research of Wenmaekers *et al.* was a reliable substitute of a real orchestra.[7] Figure 2 shows two microphone positions.

Figure 2. Microphone position (R3 and R4) between two dummies in the audience area.

2.2 Hall Description, Occupancy Rate and Indoor Climate

The Room Impulse Response (RIR) measurements were performed in the large concert hall of ‘Muziekgebouw Frits Philips’ (MFP). The volume of this hall is approx. 14,400 m^3 and the shape of the horizontal cross-section is a stretched octagon with a length of 45 and a width of 33 m. The

stage floor, surrounded by Schroeder diffusors (intended for a uniform sound distribution), covers an area of approx. 200 m^2. The total number of seats is 1260 corresponding with a seat area of 670 m^2. The number of seats of interest (in front of the stage edge) is 1070, divided in 480 seats in the centre part of the hall and 780 at the balcony locations. Three situations have been measured: 1) completely unoccupied; 2) occupied stage only; 3) occupied stage and occupied audience (seat) area. In this study the seating area behind the stage at the position of the concert organ (65 chairs), normally used for a choir, is left unoccupied for all situations. In fully occupied state the occupancy rate exceeded 80% (about 1000 persons) in accordance with the ISO 3382 standard. The orchestra consisted of 80 dummies. For an equal distribution of temperature, relative humidity and air velocity, the MFP hall has a special HVAC system, whereby the conditioned air is blown into the hall through the backside of the chairs. This also ensures a stable temperature and humidity under different hall conditions. During all room acoustic measurements the indoor climate kept substantially constant and consequently had negligible impact on the results: the temperature was between 21.3 and 21.9 °C and the relative humidity was between 55 and 58 %, measured at one position on stage.[8] The average A-weighted background noise level, obtained from the recordings (microphones at audience positions) was 27 dB(A) in the empty hall, 39 dB(A) in the fully occupied situation (shortly before the performance) and 35 dB(A) during (shortly before applause) the performance (measurement). The total sound level during the performance was 75 dB(A)
.

2.3 Measurement Positions

Figure 3 gives an impression of the hall and presents a schematic floorplan with the source positions S1 through S8 as indicated and the microphone positions R1 through R8, equally distributed over the audience area (in front of the stage edge) where R1 and R2 are receiver positions in the lower central part of the hall and R3 through R8 on the balconies. The microphone height was 1.20 m and because of the use of stage risers, the sound source height ranged from 1.40 m (S1, S3 and S6) via 1.65 m (S2, S7 and S8) through 1.90 m (S4 and S5).

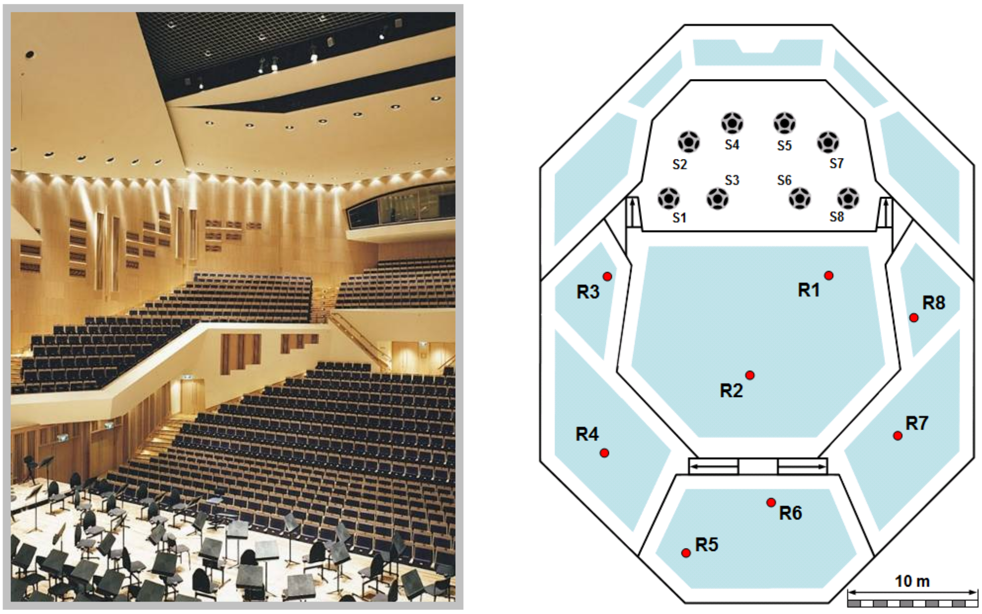

Figure 3. Impression of the ‘Muziekgebouw Frits Philips’ and schematic floorplan with source and receiver positions.

2.4 Measurement Method

To minimize the effective measurement time, the measurement set consisted of 8 omnidirectional sound sources (dodecahedrons), one for each source position and 8 microphones one for each receiver position. Each microphone was connected to a digital sound recorder. For safety reasons the use of long microphone cables during the fully occupied performance was not allowed. Therefore an asynchronous measurement technique was used. During the measurement all sound sources were generating the same measurement signal, but with different time shifts, thereby not 'affecting' each other. The room impulse responses (RIR's) were obtained by deconvolving the recorded signal with the measurement (input) signal.

2.4.1 Asynchronous measurement

Impulse response measurements based on deconvolution techniques normally require a connection between the stimulus generator and the response recording device. This is inconvenient for long distance measurements and for situations where the use of long cables is not allowed. Playing the excitation signal from an arbitrary playback device generally introduces errors due to a clock speed mismatch between the signal player and the response recorder. In a previous study we have shown which speed differences are to be expected and how common room acoustic parameters will be affected[9]. To remove any clock speed error between transmitter (input signal sound source) and receiver (digital recorder), time stretching by resampling was used prior to deconvolution of the recordings. For all devices the nominal sample frequency was set to 48 kHz.

2.4.2 Measurement equipment

The measurements were carried out as asynchronous measurements using 8 omnidirectional sound sources and 8 digital sound recorders, one for each measurement position. The end result was a recording for every receiver position of an overlapping set of 8 sweeps, where each separate source produced one sweep. In the composition the signal was repeated once. Figure 4 shows the setup with all its components (device name, manufacturer and type code) for the 8-channel asynchronous measurement.

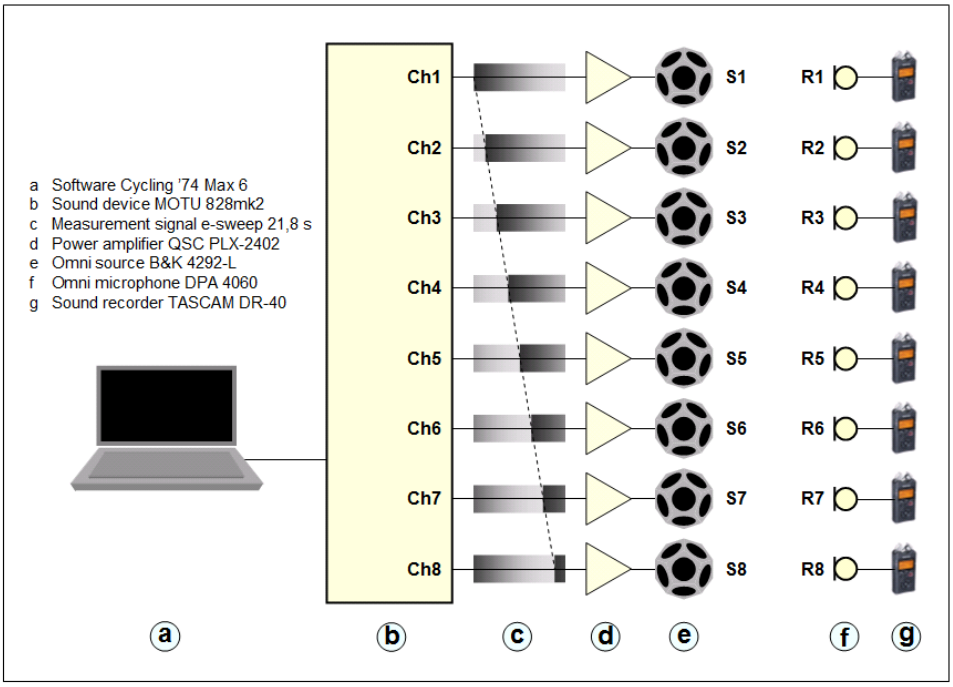

Figure 4. Setup for the 8-channel asynchronous room acoustic impulse response measurements.

2.4.3 Measurement signal and analysis

The room acoustic measurement was a part of the event (mentioned in 2.1) and was introduced with a lecture about room acoustics related to the actual concert hall, accessible for a broad public (in age and background). All acoustical details in that hall such as reflectors, diffusors and absorbers were brought to attention and explained using a 'laser show' with corresponding attributes (such as mirrors and haze) to simulate wat happens with incoming sound rays. To obtain sufficient high quality impulse responses, without boring the audience ('keep them quiet'), the signal used for the real room acoustic measurement was embedded in a special piece of electronic music, "a composition for 8 omnidirectional sound sources". Using a musical composition instead of a continuous repetition of the traditional measurement signals like impulsive sounds, noise bursts, MLS or sweeps, keeps the attention of the audience. This prevents a high background noise level and time variance during the measurement. This is important in order to reach a certain minimum impulse response decay range value needed for accurate room acoustic parameter value calculations.[10] Using sweeps as measurement signals and the deconvolution technique enables to overlap measurement signals when using multiple sound sources. This can save a lot of measuring time, certainly in this case using 8 sound sources. For a theoretical decay range of 60 dB the delay or rotation shift should at least equal the reverberation time. Previous measurements show that the longest reverberation time in the empty MFP hall for the lower octave bands is approx. 2,5 s. This results in a minimum sweep length of (8 x 2.5 =) 20 s. Using DIRAC software for analysing the recorded signals, the minimum sweep length became 21.8 s (2^{20} / 48k). This implies a time distance between the successive calculated responses of (21.8 / 8 =) 2.73 s with a small correction for time delay differences caused by the different source distances. Because of the character of the composition, the used e-sweeps were reversed, resulting in a spatially 'endless' downward sweep of 43.7 s, the so called 'Shepard tone'.[11,12] This sweep was the mid-portion of the presented composition with its total length of 3:40 minutes

Listen to the composition "Angry Balls" for 8 omnidirectional sound sources by clicking on this play button ► (this requires adobe Flash player to be installed). This dummy head recording, made on stage with dummy orchestra and without audience, is best heard over headphones.

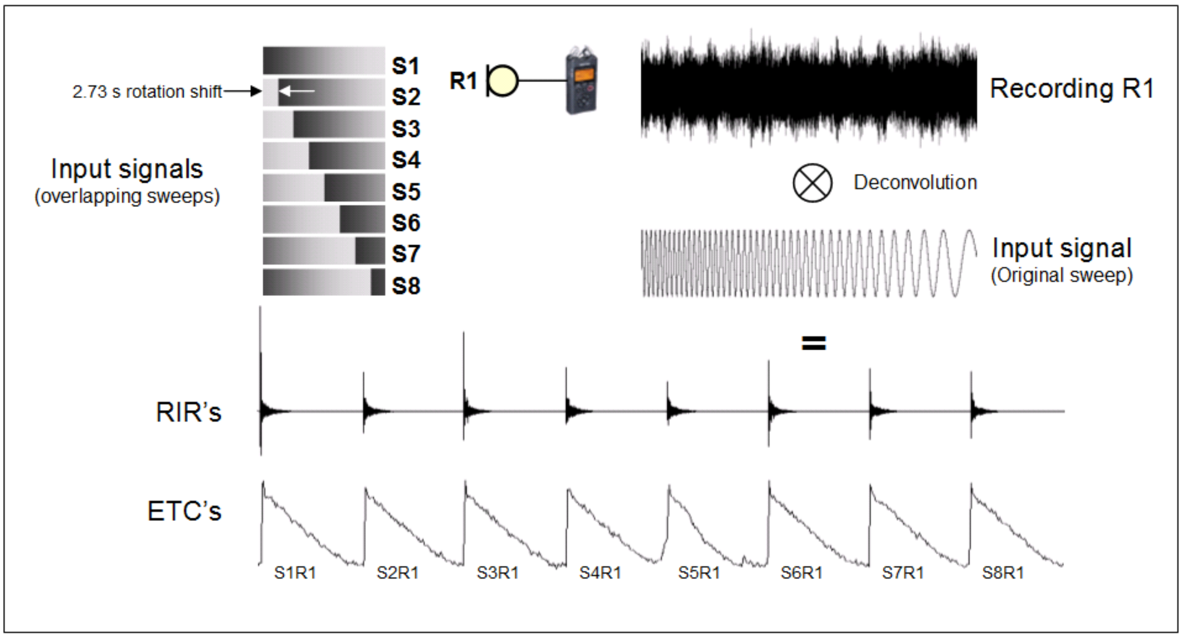

Figure 5. Signal analysis for one digital sound recorder (receiver position R1). Deconvolution of the recorded signal with the original downward e-sweep results in a response train. Each Room Impulse Response (RIR) or its derived Energy Time Curve (ETC) represents one sound source position.

The recorded signals were deconvolved by the original (21.8 s) downward sweep resulting in 8 new sound files consisting of 8 RIR's. These RIR's were analysed separately in accordance with the ISO 3382 standard. Figure 5 shows a schematic explanation of the signal analysis.

3 RESULTS AND DISCUSSION

3.1.1 Measurement quality

After deconvolution the end result was a set of 64 RIR's obtained from the recordings in an empty hall (4 persons only), a set of 64 RIR's with dummy orchestra only (80 dummies) and a set of 56 RIR's with orchestra and audience (80 dummies and approx.1000 visitors). The quality of a RIR is indicated by its decay range and can be represented using the INR (Impulse Response to Noise Ratio) expressed in dB. All ISO 3382 room acoustic parameters derived from impulse responses need a certain minimum decay range (INR) to reach a certain accuracy.[1,10] Figure 6 shows all decay ranges in ascending order for the three situations (empty, with orchestra only and with orchestra and audience). Figure 7 shows the average decay range and the number of usable RIR's for the three situations.

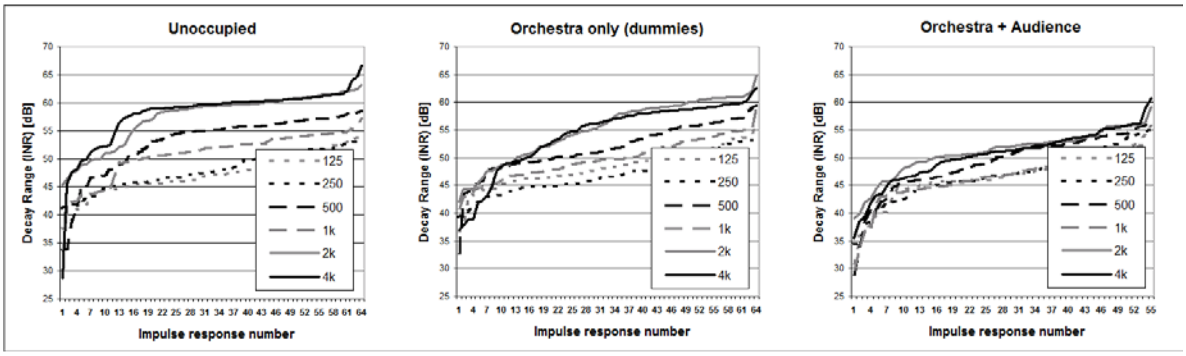

Figure 6. Decay ranges in ascending order for the three situations (empty, with musicians only and with musicians and audience).

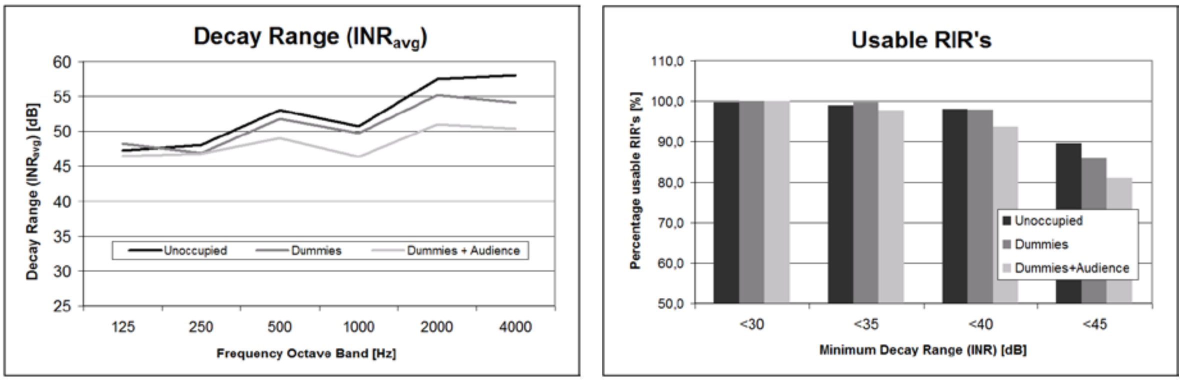

Figure 7. Average decay range (left) and usable RIR's as a function of decay range and occupation.

For this study the calculated room acoustic parameters are the Early Decay Time (EDT), the Reverberation Time (T_{20}), the Clarity (C_{80}) and the relative sound pressure level (L_{rel}). The Just Noticeable Differences (JND's) for these parameters are respectively 5%, 5%, 1 dB and 1 dB. For accurate room acoustic parameter value calculations a certain minimum RIR decay range is necessary. The minimum decay range value for EDT, T_{20}, C_{80}, and L_{rel} has been set at 35 dB (INR) as described in the ISO 3382 standard and our previous.[10] Almost 100% of all measured RIR's comply with this requirement. This means that all parameter values can be determined within the accuracy of 1 JND. Using a more stringent requirement of 45 dB (INR), more than 80% of all RIR measurements can be used for calculating the parameter values with an accuracy of 0.5 JND for the T_{20} and 0.1 JND for the other parameters. During the whole event, the sound power levels of the omnidirectional sound sources were kept at the same level and the direction of the loudspeaker cable connectors did not change, which also made it possible to compare relative sound pressure levels L_{rel} instead of absolute (normalised) G values. New insights on sound source calibration in laboratory or in-situ concerning to level related parameters and uncertainties are presented in our last mentioned study in the reference list.[13]

3.1.2 Measurement results

Although this study/experiment it is not meant to include an extensive discussion of the absolute parameter values, the measurement results for all parameters (EDT, T_{20}, C_{80} and L_{rel}) are given as a function of the octave band frequency. This is done for all occupation situations and presented in Figure 8. In the journal paper by Hidaka, Nishihara and Beranek, about the relation between room acoustic parameters with and without audiences in concert halls, the authors show room acoustic parameter values for 6 occupied concert and opera halls.[4] These values were obtained from accurate measurements and prediction using the regression equation:

$$RT_{occ} = a - b \cdot e^{-RT_{unocc}} \tag{1}$$

where RT_{occ} is the reverberation time with and RT_{unocc} the reverberation without audience. The values a and b are frequency dependent regression coefficients corresponding to the reverberation times measured in six halls. According to the authors[4] this equation is more accurate than conversion schemes that appeared earlier in the literature as long as it concerns “halls that do not have peculiar shapes or unusual frequency characteristics”. Despite the fact that it is therefore somewhat arbitrary, it seems to be useful for the (traditional) halls with a more or less shoebox or fan shaped horizontal cross-section. The MFP hall (described in section 2.2) has a stretched octagon shape. It is therefore interesting to also calculate the ‘occupied room acoustics’ using the measurements done in the unoccupied situation, according to Hidaka *et al.* In Figure 9 the T_{20} measurement results for the occupied situation are compared with the T_{20} results obtained from prediction using the unoccupied T_{20} values and formula 1. The average deviation per octave band between fully occupied and ‘orchestra only’ is 6%, which is just above the JND of 5%.

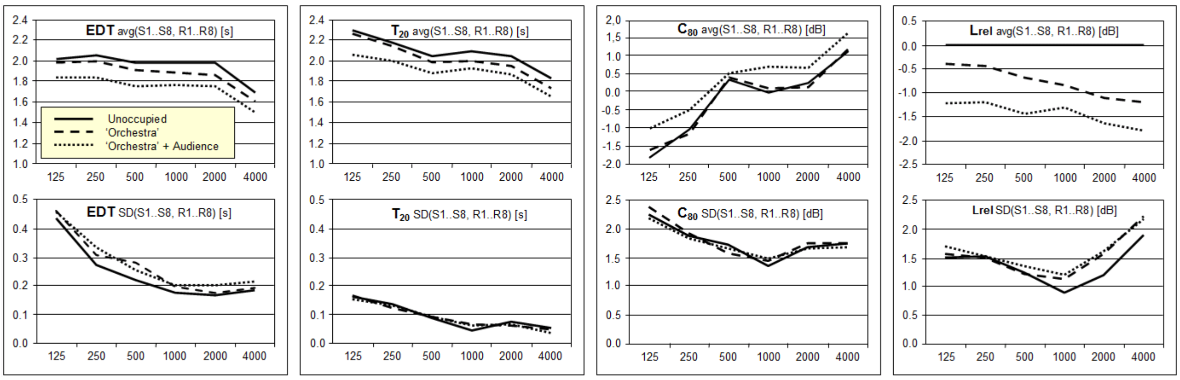

Figure 8. Average and standard deviation over all sound source and microphone positions for all measured parameters.

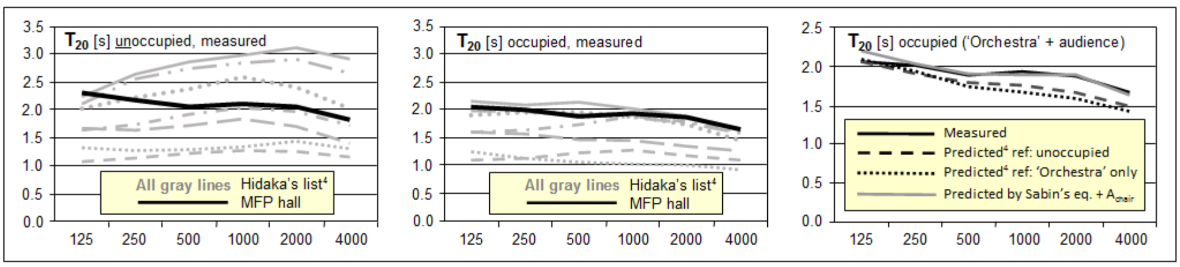

Figure 9. Measured and predicted values for T_{20}. Left: measured T_{20} values for 8 unoccupied halls (Hidaka’s list and MFP); Middle: measured T_{20} values for the same 8 halls, occupied; Right: Measured and predicted T_{20} values for MFP hall using Hidaka’s regression equation and Sabin’s equation combined with laboratory measurement values of the current chair absorption.

In the graph on the right in Figure 9 it is shown that the predicted values are (in contrast with Hidaka's halls) rather different from the measurements, with an average deviation of 7% for the unoccupied reference and 10% for the 'orchestra only' reference. Although not presented in this paper, this also applies to the other parameters. From previous global measurements in the MFP hall (during the first concert 25 years ago, using a blank pistol, presented in an internal report only) it is known that there was a small difference between the reverberation time with and without the audience for all frequency bands. In the meantime the old chairs have been replaced by new ones without changing the typical characteristic of this hall, confirmed by the accurate measurements of this study, that therefore may not fit in the Hidaka's list of 'non-peculiar' halls. Finally, using the sound absorption values of the current chairs, with and without persons, obtained from laboratory measurements, the last result shows a prediction within 1% deviation of the measured occupied T_{20} value when using Sabin's equation as suggested by Hidaka *et al.*, which confirms that the measurements are reliable. This last result is depicted as a solid gray line in the right graph of Figure 9.

4 CONCLUSION

Based on existing literature and the authors own experience we found that:

- Accurate impulse response measurements in occupied (occupancy rate of more than 80%) concert halls according to the ISO 3382 standard remains difficult using the described traditional measurement techniques.
- In most cases it is very difficult or even impossible to reach the impulse response quality or the sound source directivity as required in the ISO 3382 standard when using alternative measurement techniques like real impulses or stop chords and the advanced technique using running speech or music, where the sound sources have a natural directivity that is not described in the standard.

After preparing of, composing for, performing and measuring during and analysing and evaluating after this *proof of concept* it can be concluded that:

- It is still necessary to measure occupied halls because prediction methods for occupied concert halls have a limited accuracy.
- It is shown that in addition to the reverberation time, it is also possible to obtain other accurate room acoustic parameter values from impulse responses measured in a more than 80% occupied concert hall without using annoying and/or deafening measurement signals like repeated gunshots, noise bursts or swept sines.
- In the framework of extensive room acoustic studies (with audience) where several concert halls are required, the concept of embedded or 'hidden' measurement signals in a composed piece of (modern, electronic) music (incorporated in the concert hall program/agenda) to obtain impulse responses, is an accurate, well workable and audience-friendly alternative for the standard measurement methods in occupied situations. This concept (to obtain high quality impulse responses under occupied conditions) requires some extra effort in terms of organization, equipment handling, 'signal design' and post processing, but generates a large amount of accurate measurement results.

5 ACKNOWLEDGEMENTS

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