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Concert halls – conveyors of musical expressions

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Abstract:

The first question of an acoustician regarding a new concert hall is too often: What is the reverberation time? Such tradition has historical reasons as reverberation time and sound strength have been considered the most important objective measures of concert halls. However, although they are indeed important—music should be loud enough and reverberated to sound good—they do not tell much on the multidimensional acoustical conditions of a hall. This paper collects the recent research to understand concert hall acoustics beyond these traditional measures. The results indicate that a concert hall is considered exceptional if it renders music expressive, i.e., conveys the subtle nuances of music from the stage to the audience as well as possible. In other words, a concert hall is preferred if it renders proximate sound with large dynamics and wide frequency range. This paper links together musical acoustics, room acoustics and human spatial hearing to highlight recent findings in concert hall acoustics research.

Keywords: auditorium acoustics, music, concert halls, dynamics

Concert halls – conveyors of musical expressions

1 Introduction

The audience gathers to concert halls to listen to music in favorable acoustic conditions. The hall conveys the sound waves from the stage to the audience areas. The reverberation of the hall ties consecutive notes together and provides continuity to the music. In addition, the reflections from room boundaries make the sound stronger. Moreover, the concert hall isolates the music from distracting noise leaving room for full dynamics that an orchestra provides. In short, a concert hall can be considered as a conveyor of music from the orchestra to the audience. In communication acoustics, such a process is often described with a source-medium-receiver model [1], illustrated in Fig. 1 in the case of a concert hall.

Research on concert hall acoustics is often focused on the medium part of this communication chain. Objective room acoustics research is performed with measured or modeled impulse responses. Such an impulse response completely describes this linear and time-invariant communication channel from one source to one receiving position. Typically, the linear and time-invariant assumption is indeed valid, as the temperature is not changing and there are no currents in the air. The ISO3382-1:2009 standard [2] defines that the impulse response should be measured with good quality transducers that have flat frequency response to all directions, i.e., an omnidirectional point source (usually a special loudspeaker) and an omnidirectional measurement microphone. However, in an orchestra there are no omnidirectional sources as all musical instruments have frequency dependent radiation patterns [3, 4]. In addition, receivers–human listeners–have two ears and human spatial hearing has frequency dependent characteristics [5]. In the standard [2], there are a few parameters that are computed from impulse responses captured with directional devices, such as a figure-of-eight microphone or a dummy head, to better mimic the spatial aspects of human hearing. However, the standard falls short of linking the subjective impressions and objective measurements completely [6, 7, 8].

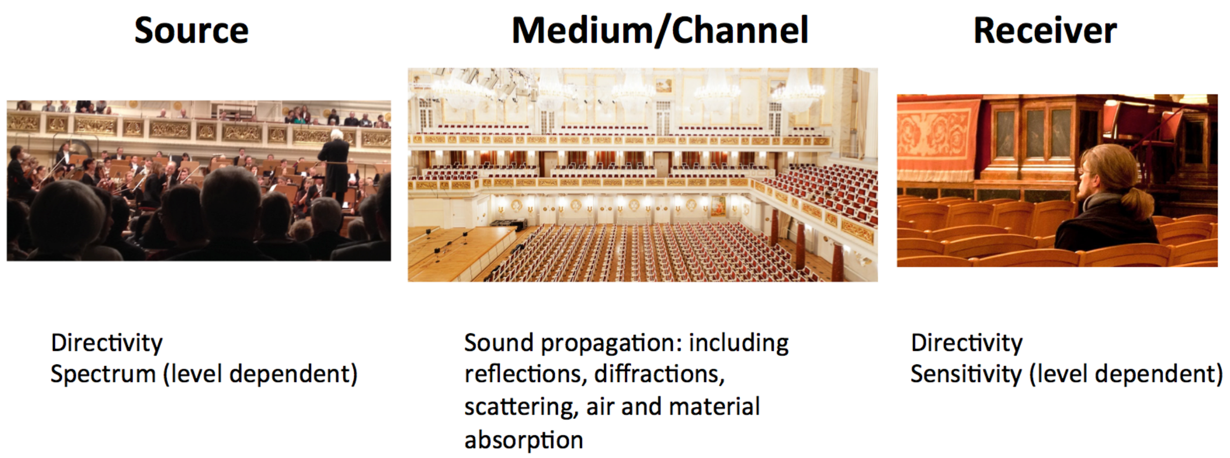

Figure 1: **Source - Medium - Receiver communication chain in the case of a concert hall.**

One aspect which is totally ignored in the ISO3382 standard, and indeed often in concert hall acoustics research, is that both the source and the receiver have level dependent effects. Therefore, the studies restricted to room impulse responses are inadequate, as both the source signals and human hearing have non-linear characteristics. As indicated in Fig. 1 the spectrum of the source signal is level dependent, meaning that the spectrum of the orchestra is different in different playing dynamics, even if the same instruments would play the same notes [9]. In addition, human hearing has level dependent sensitivity, which is generally known in the form of Equal Loudness Contours [10], but again this phenomenon is not taken into account in concert hall acoustics research. Thus, the communication chain has a non-linear source, a linear medium, and a non-linear receiver, making the interpretation of the measured impulse responses very hard. More importantly, these non-linearities affect strongly how a concert hall renders the music. This paper addresses one of these level dependent issues.

2 Music – expressions of composers

A concert hall is a dedicated space for a music performance, which is carried out with acoustic, non-amplified instruments. The music itself expresses the ideas and feelings of a composer who has chosen the instruments and notes they played. Generally speaking, the music consists of tempo, harmony, rhythm, timbre, and accents to name a few. In symphony, these features form the music and can wake up emotions in the listener, when the composer has been successful and the performing artists master their instruments and ensemble playing. As said above, the role of a concert hall is to render music so that the message by a composer is delivered as well as possible to the audience. The message often includes emotional passages and in the best case the hall supports the played music making it warm, bright, dynamic, and intimate.

In traditional research on concert halls these aspects are mainly ignored. The research is concentrated on analysis of room impulse responses and such parameters as strength, reverberation, clarity, auditory source width, and envelopment have been considered important [2]. All these measures are computed from the decay of room reverberation and they do not tell much on timbral (warmth and brightness) or level dependent (dynamics) aspects. However, some papers have noticed, e.g., the importance of lateral reflections to spatial impression [11, 12, 13, 14], but clear connection between music and room acoustics has been missing. Two years ago the first article [9] linked the whole communication chain (Fig.1) together, by explaining why some concert halls produce larger perceived dynamics than the others. In that article, it was shown that in *fortissimo* playing the instruments emits much more harmonics, i.e., high frequencies than in *pianissimo*. Moreover, the form of a human head strengthens these high frequencies for the sound coming from the side, thus showing the benefit of lateral reflections instead of reflections from the ceiling.

3 Level dependent spectra of a source and a receiver

The importance of high frequencies for large dynamics has been recently discussed [9, 15, 16], but the origins of warm and strong bass sound has not received much attention. As well known, the warm sound is related to the strength and quality of low frequencies, but the measurements are usually done only at 125 Hz octave band [17], which is clearly not sufficient. There are many instruments that emit a lot of sound below 90 Hz and this frequency region is extremely important for warm and emotional sound.

Figure 2 illustrates the spectral differences of *piano* and *fortissimo* of a full orchestra. The data are analyzed from 29 recordings of Bruckner's 4th Symphony (bars 19-26, III movement). This passage is good for such analysis as the orchestra plays a long crescendo practically without changing the played notes, see more details in [9]. In Fig. 2 the spectra at different dynamics are aligned so that they overlap at 1 kHz. It can be clearly seen that in *fortissimo* there are relatively more low frequencies. What is relevant here is that when the overall level increase is removed, we can see that in *fortissimo* both low and high frequencies are pronounced. In other words, the change in level is not the same at different frequencies, i.e., the spectrum changes its shape. Thus, as indicated in Fig. 1 the spectrum of the excitation signal in a concert hall is level dependent.

Another level dependent phenomenon is related to human hearing, i.e., the receiver in a concert hall. The sensitivity of human hearing at different levels is illustrated on the right in Fig. 2. Again, the spectra of equal loudness contours are aligned to match at 1 kHz, and such illustration shows that the higher the level is the flatter the equal loudness contour is.

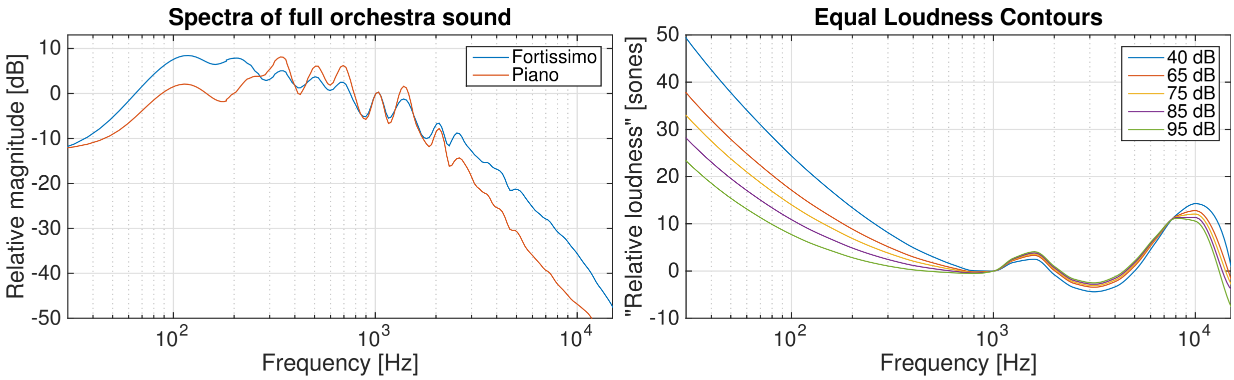

Figure 2: **Left: The spectra of a full orchestra sound in different dynamics. Right: Relative magnitude responses of equal loudness contours. Note that in both figures the curves are shifted to overlap at 1 kHz.**

When these two level dependent effects are combined together, the result is quite interesting as shown in Fig. 3. In this figure, the spectrum of *piano* level has been added to the equal loudness contour of 40 dB and the spectrum of *fortissimo* level has been added to several higher level equal loudness contours, and finally the plot shows differences between these curves. The figure illustrates that when an orchestra plays in *fortissimo* the low frequencies below 200 Hz and high frequencies above 3 kHz are substantially pronounced in comparison

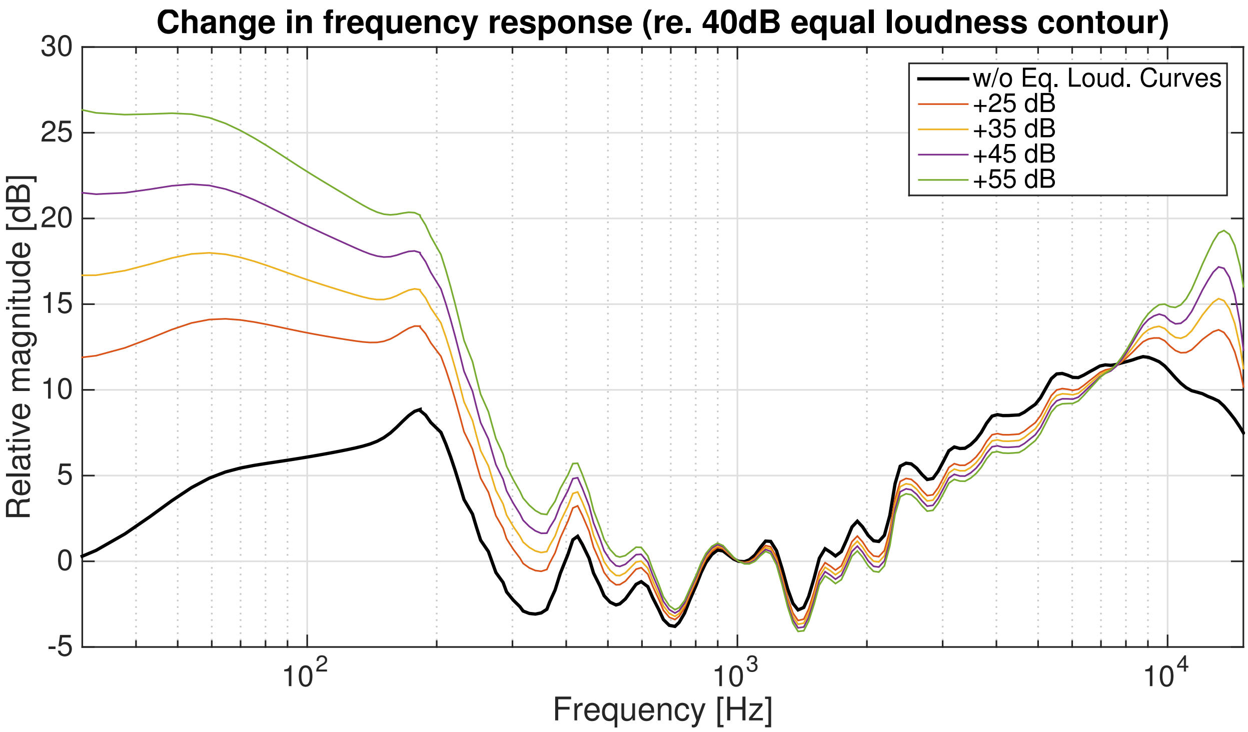

Figure 3: **Illustration of how the relative magnitudes of different frequencies change when an orchestra plays the same notes in *fortissimo* and in *piano*. The black curve is the difference without the effects equal loudness contours. If the spectra in *piano* and in *fortissimo* would be the same then the result in this illustration would be a flat line at 0 dB.**

with *piano* passages. Nevertheless what is the effect of a concert hall, as a linear transfer path of sound when these level dependencies are always present?

If a hall attenuates strongly either the low or the high frequencies, then the perceived frequency response is different and in such a case human perception follows different curves of Fig. 3 at different frequency regions. In fact, there are two distinct features and the other one is related to the directivities of sources [18] and receivers [5]. The directivities affect mainly high frequencies and the perceptual consequences have been explained in another article [9]. At low frequencies both sources and receivers are more or less omnidirectional, and only the level dependent features matter.

4 Perceived bass in concert halls

Figure 4 shows measured frequency responses from 10 European concert halls. The plotted responses are averages of 25 source positions, thus they represent an orchestra well as a source. The plots reveal that there are level differences of as high as 10 dB at low frequencies below 200 Hz. In the light of these differences, Fig. 3 could be interpreted so that a hall that emphasizes 10 dB more the low frequencies, the perceived increase is not 10 dB, but

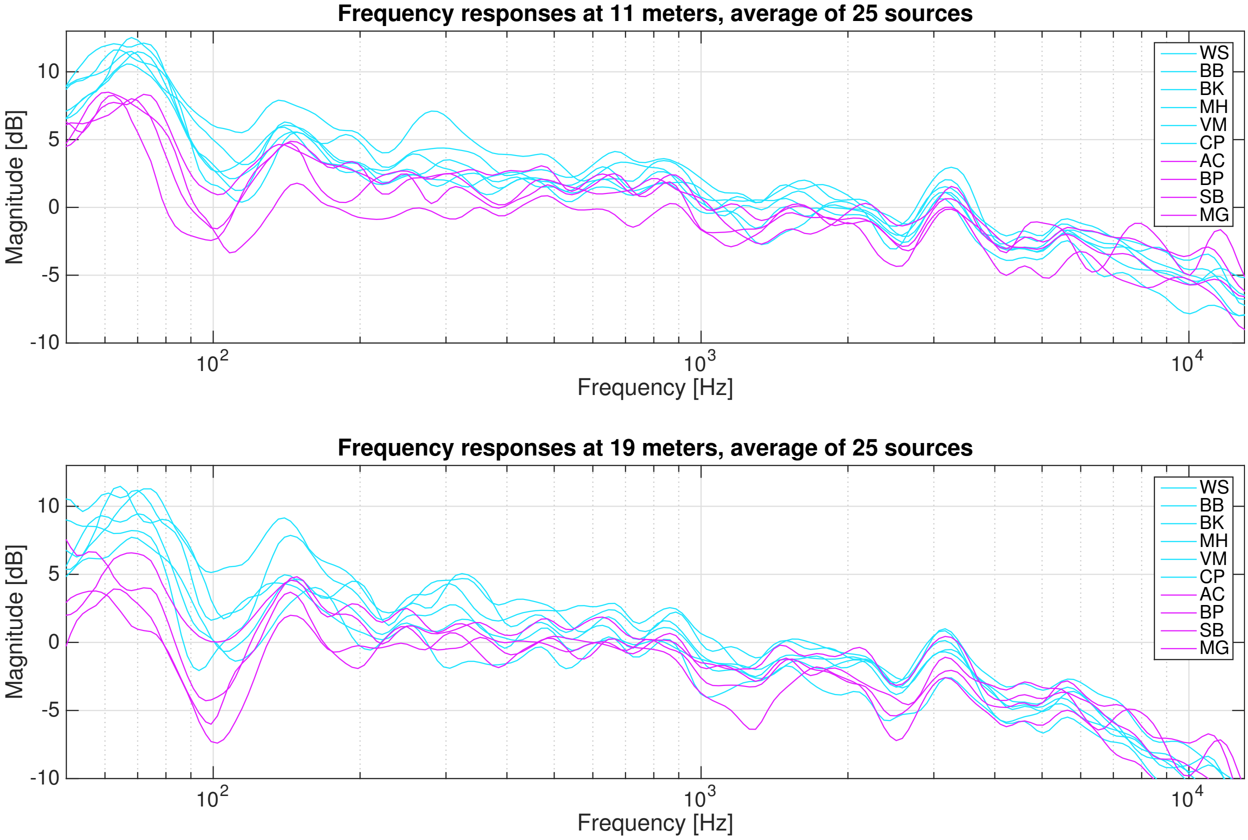

Figure 4: **Frequency responses of 10 different concert halls, measured with the loudspeaker orchestra in two different receiver positions.**

it is about 13 dB. This 3 dB increase in perceived bass is the consequence of flatter equal loudness contours at higher levels. Our experience is that in halls with weak low frequencies the bass lacks strength while in halls with strong low frequencies the bass instruments sound powerful and intense. Moreover, in large *crescendo* and *fortissimo* passages the compositions often includes bass drum, timpani, tuba, and double basses, which all produce warm sound when they are clearly audible.

The reasons why some concert halls render much more powerful low frequencies are outside the scope of this article, but they are discussed in the accompanying paper [19].

5 Conclusions

This article contributes to concert hall acoustics research by addressing the level dependent features of the sources and the receivers. These aspects are well known in psychoacoustics, but research on concert halls usually ignores these fundamental issues. In addition, it is shown that when an orchestra plays in different dynamics, not only the overall level changes, but the shape of the frequency spectrum changes. Low and high frequencies are pronounced much more than mid frequencies, resulting in the enhancement of brightness, brilliance, and warmth of the music. It is also evident that these timbral aspects have a key role in making music more intimate and expressive.

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