CONSIDERING THE BASS RATIO IN ACOUSTICALLY OUTSTANDING CONCERT HALLS

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1 INTRODUCTION

Certain shortcomings may be worth a discussion before auditorium acoustics engineering reaches the level of maturity proclaimed in the present call for papers. Experts seem to agree that acoustic quality mainly depends on the direct sound emitted from the sources and the early reflections from the room´s boundaries (walls, ceiling, reflectors). Numerous quality criteria were thus derived, yet due to lack of resources and time in most projects for music and speech the reverberation time T(f) is left as the only criterion and regrettably all too often just that at medium frequencies f. As this statistical parameter (as an indigent image of the total sound absorption incorporated in a room) has a very special meaning at the lower frequencies, these will be addressed here.

For larger rooms some propositions are at variance with a common belief that low-frequency reverberation would be necessary to create ´volume´, ´warmth´, and ´envelopment´ in performances and that therefore e.g. co-vibrating wooden paneling should mostly be avoided. One may argue that a bass ratio BR > 1 could somehow compensate for a) the weaker sound emission of instruments and voices, b) the lower sensitivity, and c) faster fading of loudness and reverberance in human hearing. This purely energetic view should, however, be confronted with that of destructive wave interference effects of the direct with early laterally reflected sound at low frequencies. These may affect the clarity of music and definition of speech and hence call for a BR ≤ 1.

Architectural and acoustical design of concert halls often favor a *´shoebox´* shape and mostly take the *Musikvereinssaal* in Wien (opened 1870) as a kind of golden model. Its reverberation characteristics with typically around 2 s at medium and up to 3 s at low frequencies also served as the generally accepted guide for the (then revolutionary) *´vineyard´* structured *Berlin Philharmonie* (of 1963), *Elbphilharmonie* in Hamburg, and *Pierre-Boulez-Saal* again in Berlin (both 2017). The first *"has become one of the models of successful acoustical designs … A number of terrassed surround halls have been built, though none have been as acclaimed as the Berlin Philharmonie"* according to *L.L. Beranek* [1, p. 297 and 500]. The second, according to its resident conductor, *T. Hengelbrock*, *"differs from all the others … as a phenomenal wonder".* Two of these designs, however, clearly (unfortunately or favourably?) missed the goal of a bass ratio BR > 1 that the acousticians in charge had planned or strived for. The failure (or lucky coincidence?) in these two spectacular projects may be due to an underestimate of the absorption at several bounding surfaces. The almost flat frequency response (BR ≈ 1) of the *´Elphi´* may account for the stunningly *"clear, transparent, and powerful"* sound experienced and praised by a large majority of professional musicians and conductors like *K. Nagano*. And this has in fact to do with the heavy, curiously structured inner gypsum shell (*´Weiße Haut´)*, but presumably not in the way so mysteriously propagated by its inventors. In a striking contrast to the other two, *Pierre-Boulez-Saal* exhibits a BR = 1,6 (occupied), for obvious reasons and as clearly intended by *Y. Toyota* but probably not for the benefit of its acoustics. Anyway, a comparison with T(f) characteristics of renowned historical concert halls like *Symphony Hall* in Boston and *Concertgebouw* in Amsterdam may be informative.

2 REVERBERATION TIME AS UNIVERSAL ROOM ACOUSTICS INDICATOR

In contrast to noise control in buildings no equally binding regulations and standards exist for the planning of room acoustics. A large variety of subjective criteria are used instead, more than forty of which may be looked up in [2]. In a very vivid plea for ´aural architecture´ and ´spatial acoustics´ the authors of [3] regret that "*architects almost exclusively consider the visual aspects of a structure. Only rarely do they consider the acoustic aspects".* When reading some of the published statements during and after the construction of the *Elbphilharmonie* as cited in [4] one may get the impression that the acousticians and architects in charge relied on aesthetic parameters rather than on any calculations or measurements, just as if the aural performance of a room were not an issue for specific engineering tasks but rather an unpredictable chance or miraculous wonder to which musicians and listeners mainly have to get accustomed and to adapt their hearing.

A long time ago, however, *W.C. Sabine* [5] has ingeniously defined a very clear and substantial physical parameter and introduced it into his design of *Symphony Hall* in Boston, which is *"an excellent hall, there is none better"* [1, p. 47]. From then on the reverberation time became *the* room acoustic parameter, the spectral characteristics of which may be found for the majority of named halls in standard textbooks, e.g. about 100 alone in [6]. For a large consulting company it goes without saying to publish these data as minimal ´business cards´ of their projects, just about 50 documented in [7]. In [8] one reads: "*This standard continues to specify room acoustic quality by reverberation time alone … T is related to the* physical properties of the auditorium … *The frequency range should include the octave bands from 125 to 4000 Hz … In concert halls the 63 Hz octave band should be added".* For other quantities like early decay time EDT, strength G, clarity C_{80}, definition C_{50}, center time $T_{S,}$ and lateral fraction LF, meant to be subjectively relevant according to a (merely informative) Appendix A in [8], a much more restricted range between 500 and 1000 or 2000 Hz is normally considered. In this context *L. Kirkegaard* [9] may be cited: *"I am convinced that we need to work with the whole spectrum of human hearing – we must not ignore the universes of very high and very low frequency sound that are presently unattended in our data gathering and analysis. Half the instruments of our orchestra have their fundamental pitches below 125 Hz. We need to design for strength in the fundamental sounds of those instruments. Fundamental pitches of low frequency instruments support intonation and bloom for the full orchestral sound. Fundamentals are fundamental!"* And an experienced tonmeister suggests that *"recognizing the musical structure and architecture in the contra- and sub-contra ranges is just as important as doing it for the formants"* [10, p. 279].

In the old days sound engineers had problems in measuring and calculating T(f) in s and providing equivalent absorption areas A(f) in m^2 at the low frequencies. Today the appropriate instruments, tools, and a variety of sufficiently broadband sound absorbers have become available [11, Chap. 4-10]. It is now possible to perfectly lay out, check and control the intended reverberation time spectrum according to

$$T(f) = 0.16 \frac{V}{A_S(f) + A_E(f) + A_P(f) + 4V\, m(f)} \tag{1}$$

where the room volume V is in m^3, m stands for the energetic attenuation coefficient in m^{-1}, A_S for the absorption at the room´s boundaries, A_E that for its furniture, and A_P that for its occupants.

3 DESTRUCTIVE WAVE INTERFERENCE EFFECTS

In churches, drama theaters, opera houses, and concert halls sound waves travel across relatively large distances between sources on the stage and listeners in the auditorium (Figure 1). One knows that, due to a ´precedence effect´ named after *H. Haas* [13] the first wave front (Dir in Fig. 1) which hits both ears of an attentive listener plays a dominant role in perceiving, locating, and analyzing a source. It is also generally agreed upon that ´early reflections´ (A, W … D´ in Fig. 1) can contribute a lot to the intelligibility of speech and clarity of music (in what follows called ´transparency´ of sound in performances, recordings and reproductions). The transition from early to late reflections (perceived as reverberation) may vary between Δt = 50 and 160 ms depending on the volume of and absorption in the room. The upper value 160 ms according to [3, p. 232] means that any specular reflections from all boundaries of a larger hall are superimposed with different amplitudes and phases at a certain position in the auditorium in either a constructive or destructive manner to form the respective aural sensation evoked in a listener there.

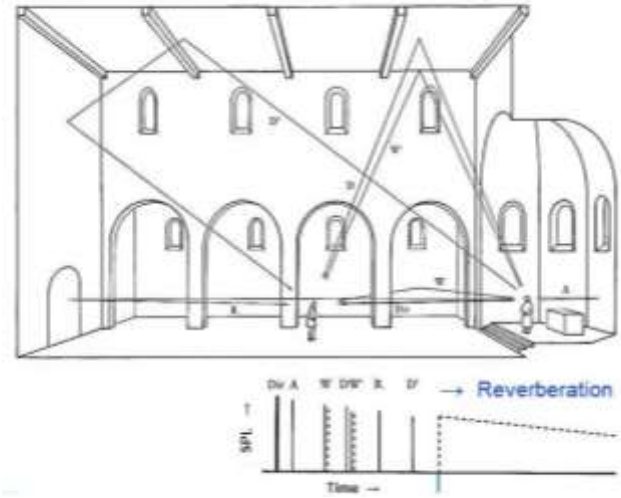


Figure 1: Composition of the sound field in a larger room by direct and early reflected sound waves plus reverberation after *J. Meyer* [12, Fig. 2.6]

Table 1: Time delay Δt respectively path difference Δx in relation to the period T_f and wave length λ of the direct and reflected sound waves at different frequencies f [14]

f [Hz]	λ [m]	T_f [ms]	Δx [m] / Δt [ms]	1 / 2.9	2 / 5.8	4 / 12	8 / 23	16 / 46	32 / 92
				$\Delta t / T_f = \Delta x / \lambda$					
16	22	63		0.05	0.09	0.18	0.37	0.73	1.5
31	11	32		0.09	0.18	0.37	0.73	1.5	2.9
63	5.5	16		0.18	0.37	0.73	1.5	2.9	5.9
125	2.8	8		0.37	0.73	1.5	2.9	5.9	12
250	1.4	4		0.73	1.5	2.9	5.9	12	23
500	0.7	2		1.5	2.9	5.9	12	23	46
1k	0.3	1		2.9	5.9	12	23	46	92
2k	0.2	0.5		5.9	12	23	46	92	184
4k	0.1	0.25		12	23	46	92	184	368

Table 1 indicates three different situations related to the delay parameter

$$\frac{\Delta t}{T_f} = f \frac{\Delta x}{c} = \frac{\Delta x}{\lambda} \qquad (2)$$

with the path difference Δx, the time delay Δt = Δx/c (c = sound velocity) and the period $T_f = 1/f$:

a) At frequencies f ≥ 1000 Hz (lower lines in Table 1) path differences Δx ≥ 1 m correspond to several wavelengths λ and to time delays Δt > (2 to 3) T_f – sufficient for two human ears to identify and localize the respective source before the arrival of any reflected waves. Later arriving waves have lost more and more of their energy and coherence with the direct sound but may reinforce the latter plus the reverberance perceived. For mid and high frequencies one may thus argue and calculate on a purely energetic basis, as is commonly done when applying computer aided design CAD programs for parameters like G, C_{80}, and C_{50}. For f < 1000 Hz the situation remains similar, when considering Δx ≥ 2 m and Δt ≥ 5,8 ms, see green numbers in Table 1. For larger Δx the level differences, for simplicity assuming a spherically radiating point source with

$$\Delta L_x = 20 \lg \frac{x + \Delta x}{x} \qquad (3)$$

become so large (e.g. for x = 10 m and Δx = 18 m yielding ΔL_x = 9 dB), that such a superposition of sound waves cannot have any negative effects on the reception and localization of sound. These, together with all later reflections, contribute to the reverberant, more or less diffuse field. For human voices and musical instruments with, especially at the higher frequencies, a pronounced directivity characteristic, the respective source/receiver configuration would come into play when estimating the corresponding level differences ΔL_x.

b) At the lower end of the frequency scale and for relatively small values of Δx and Δt, i.e. with large reflecting surfaces near the sources, these are known to primarily act as a mostly favorable amplification (equivalent to almost doubling the strength or number of the sources!), see lines 1 to 3 in Table 1 for f = 16 – 63 Hz with gradually decreasing favorable path differences Δx = 4 to 1m, see blue numbers in Table 1.

c) Between the above discussed parameter ranges which basically tend to support the important direct sound field, albeit in completely different ways, a so far underrated intermediate range may be identified in which sound waves can interfere with each other in always a very destructive manner (see red numbers in Table 1): Time delays Δt of less than 2 to 3 periods T_f do not allow to identify a source prior to a coherently reflected sound wave which may instead blur the information contained in the directly transmitted wave by a discrete superposition in amplitude and phase, even if it arrives at the listener with a somewhat lower level. The resulting interference phenomena closely resemble those best known from ´comb filter´ effects which are discussed in [15, chapters 6 and 7] as a steady state phenomenon in which a distortion of the wave amplitude A according to something like

$$A \sim \cos\,(\pi\, f\, \Delta t) \;=\; \cos\,(\pi\; f\; \frac{\Delta x}{c}) \qquad (4)$$

is indicative of the rather complicated interference effects alluded to above.

One may thus conclude from these simple considerations that high-frequency sounds tend to be in fact positively supported by early reflections in full accordance with the quality criteria defined as G, C_{80} and C_{50}. On the other hand, fundamental sounds of a lower frequency tend to be blurred by early reflections. The destructive interference effects potentially weaken the fundamental bass textures and give rise to the muddy sound that so often conceals the genuine sound, diminishes clarity and intelligibility of music and speech, respectively. One might argue that later reflections (Δt > 100 ms) could enhance the bass, but these may never recover what has been lost during the earlier arriving reflections. The authors of [16] consequently conclude: “*The perceived strength of bass sounds is not* (positively) *influenced by* (excessive) *low-frequency reverberation time.”* If the hypothesis of destructive interference phenomena holds true, it is not recommendable to raise reverberation time towards the bass. Installation of as much as possible bass absorption on the relevant lateral surfaces in the room is here recommended instead.

Bass absorption may be vital for both the early as well as the late reflections for an improved acoustical transparency in a room. The intermediate range in Table 1, in particular, should gain more attention in room-acoustic designs, for both music and speech. The common energetic approaches are more to the purpose at and above 500 Hz. Or as stated in [10, p. 278]: “*It is important to know that a ‘slim’ hall helps to ‘read’ the fundamental structures which are so essential in the bass range for all compositions of value. A space with great bass-reverb´, however, will rather hamper the desired transparency in the low ranges, although unassuming concert goers may be happy with the voluminous but unstructured ‘bass-clouds’ they can have in such halls. This second variety is more frequent, because until very recently there was no scientific knowledge to judge room acoustics in any other but a purely quantitative manner, just considering the amplitudes”*.

4 BASS RATIO AS ACOUSTIC QUALITY CRITERION

E. Skudrzyk demands (in a translation from the German) “*that the reverberation time at low frequencies should not be much greater than at medium and high tones*” [17, p. 675] and he explains his stand very convincingly in relation to stereophonic recording and reproduction: ”*It does not matter whether the bass drums can be located on the right and the trumpets on the left, but* *rather that they can be heard spatially in different positions, ... that the overall sound impression of the reproduction also has spatial breadth and depth and that one perceives, corresponding to the particularity of the piece, the sound leaping vivaciously and spatially from instrument to instrument … One will therefore, contrary to the traditional approach, have to try to weaken the low frequencies of the reverberation in order to prevent them from masking the low-frequency transient processes of the musical instruments and in this way impair spatiality.*" Likewise, *G. von Békésy* [18] also recommends "*a frequency-independent reverberation time as most favorable*" and demonstrates that decisive for the distance impression at the human ear so important in direct and indirect listening are the low-frequency initial transient processes of the sound sources.

On the other hand, when looking through the later literature, one may find statements which sound very logical, though only from an energetic point of view:

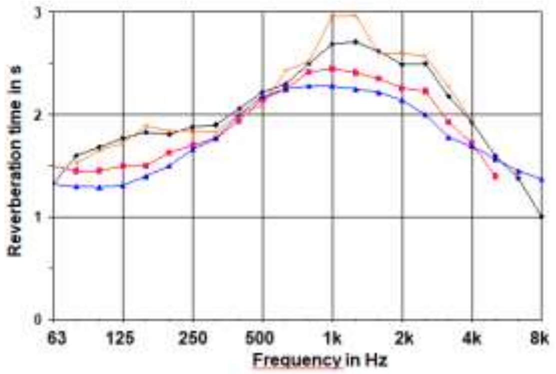
- All human voices and musical instruments, including a full orchestra sound, radiate a long-time averaged sound spectrum that *drops* toward low frequencies. Therefore somewhat stronger reflections from the room boundaries should be beneficial for its low frequency part and hence for the fullness and warmth of the sound.
- The human ear is less sensitive, respectively the hearing threshold is higher toward low frequencies, in fact the more so, the less loud the performance is. For this reason, it should be expedient, particularly in large rooms, to support the lf sound by means of a stronger reverberation.
- Curves of equal loudness move closer and closer together toward low frequencies. In order for all frequencies to remain audible equally long during pauses, the sound level decay should be delayed by a longer reverberation of the low than of the high frequencies.

Consequently, *L.L. Beranek* defined a corresponding bass ratio

$$BR = \frac{T_{125} + T_{250}}{T_{500} + T_{1000}} , \quad (5)$$

with reverberation times at 125 and 250, respectively 500 and 1000 Hz (in an occupied hall) as an acoustical quality criterion [19]. Accordingly, this should assume values between 1,1 and 1,5 for rooms with a generally high, respectively low mean reverberation time T_m : *"If the surfaces of the walls or ceilings or seats absorb the low frequencies, the full orchestra may sound deficient in basses and cellos … A hall lacks warmth when the reverberation times are lower at low frequencies (75 to 350 Hz) than at mid-frequencies (350 to 1400 Hz), i.e. low BR"* [6, p. 37]. However, in his numerous and elaborate investigations of ´orthogonal acoustical attributes´ that relate to the acoustic quality of concert halls he finally *"found unexpectedly that it is immediately apparent that BR does not correlate strongly with the rating categories"* [1, p. 512]. In a second attempt to prove its positive relevance, *the same author* considered the difference of the strengths (G_{500} + G_{1000}) and (G_{125} + G_{250}) but he had to resume: "*When this was tried for 38 concert halls, the conclusion was that it also was not a useful measure*". In a review paper *J.S. Bradley* [20, p. 6] concludes that his investigations *"indicated that the perceived strength of bass sound was not related to the low frequency reverberation times"* and *L.L. Beranek* assents: *"Recent studies have shown, that the reverberation time at low frequencies is less important than the strength of the sound there"* [21, p.2].

Contemporary composers, if given the choice, would certainly prefer to have their works performed in spaces which render all the details and finesse of their composition acoustically transparent. The present author is fully aware of his own plea for BR ≤ 1 still being ´at odds´ with the views of most acousticians dealing with auditoria, as one of the reviewers of [14] pointed out. The issue is obviously one to stimulate further discussions and requires more fundamental research. In the meantime, however, it may be worthwhile to have a closer look at several prominent examples of auditoria with a pronounced ´bass drop´ reverberation characteristic, the acoustics of which have gained a widespread approval by musicians and sound engineers, experts as well as laypersons. Such a place that – by a lucky coincidence rather than by concrete alternative planning and design – comes close to that 'ideal' is the *Jesus-Christus-Kirche* in Berlin (Figure 2) as documented in more detail in [11, Sect. 11.12] and [14]. It was built in 1931 and became world-famous after the war as a recording space for countless symphony orchestras, music ensembles, choirs and soloists.



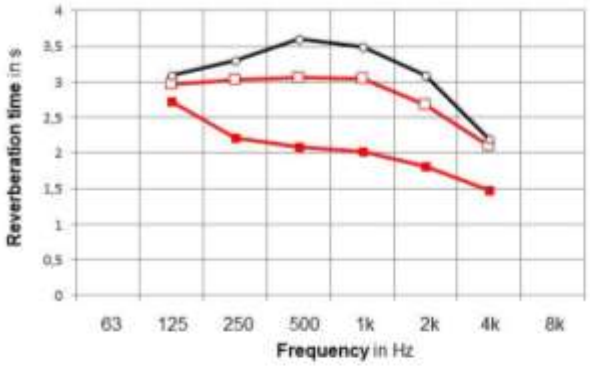


Figure 2 (left): Reverberation times measured between 1952 and 1963 in the *Jesus-Christus-Kirche* (V = 7900 m^3) when occupied by varying music ensembles

Figure 3 (right): Reverberation times measured in the *Musikvereinssaal* (V = 15000 m^3) unoccupied with old seats before 1960 (o) resp. n = 1680 new seats (□) after [1, p. 594] and occupied with new seats (■) after [22]

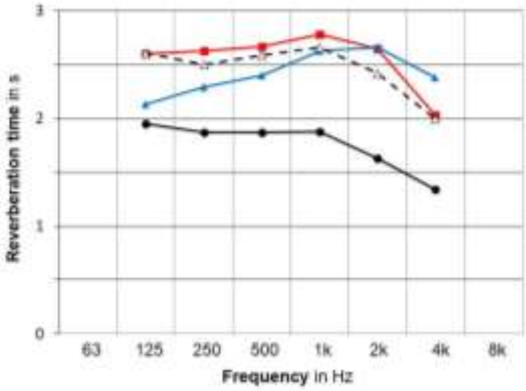
5 CONCERT HALLS WITH OUTSTANDING ACOUSTICS

5.1 *Musikvereinssaal* in Wien (1870)

Ambitious acousticians do not restrict their efforts on just the medium frequencies and take the universally praised *Musikvereinssaal* as ´golden model´ with a presumably necessary bass rise in its reverberation spectrum. They normally consider the occupied hall as decisive and hence correspondingly upholstered seats as advisable, although all audience areas, occupied or unoccupied, due to their alignment and absorption, have little impact on the decisive early reflections. If the reverberation of this model, along with its obviously high diffusivity, is undoubtedly responsible for its acoustic excellence, it may be interesting to analyze its frequency spectrum without the dominant influence of occupants and seats: This room, with moderately upholstered unoccupied seats, had its reverb maximum definitely not in the bass regime but with 3,5 and 3,6 s at 1000 and 500 Hz (BR < 0,9) and BR ≈ 1,2 when occupied, s. Figure 3 and [1]. If one subtracted in equation (1) an estimated absorption of $A_E \approx 0{,}15$ m^2 for any of these seats, the resulting $T_m > 5$ s would exhibit an even steeper descend toward the bass – just as in Fig. 2 for similar scanty seating. Only after installing in 1960 slightly more upholstered seats an almost constant absorption between 125 and 1000 Hz may be read from Fig. 3 for the unoccupied room and a steep ascend of reverb may be found for the fully occupied hall – just as later originally planned for so many other halls.

5.2 *Concertgebouw* in Amsterdam (1888) + *Boston Symphony Hall* (1900)

These two equally high rated concert halls according to [1, pp. 425 and 611 + 47 and 586] both showed a relatively high, again almost flat absorption spectrum when unoccupied (Figure 4). With *Symphony Hall,* which was modeled after the (old) *Gewandhaus* in Leipzig, *W.C. Sabine* has set a milestone on the very brink of acoustics as an engineering science. A major restoration in 1982 brought about an absorption characteristic monotonously increasing from 1000 to 125 Hz for the unoccupied hall thanks to seats with a minimum of upholstering and, equally important, large resilient inner shells at the walls and ceiling. The latter mostly consist of 12,5-25 mm thick wood paneling and 19 mm plaster on lath-work and metal-screen in front of an up to 1,5 m thick airspace [1, p. 50]. According to [1] encomiums like *“one of the world´s greatest halls”, “an excellent hall, there is none better”, “most noble of American concert halls”* are expressed about *Symphony Hall* by players and leaders. It is noted here that none of the above mentioned halls lost their excellence when varying their seating for the reasons discussed in the preceding chapters.



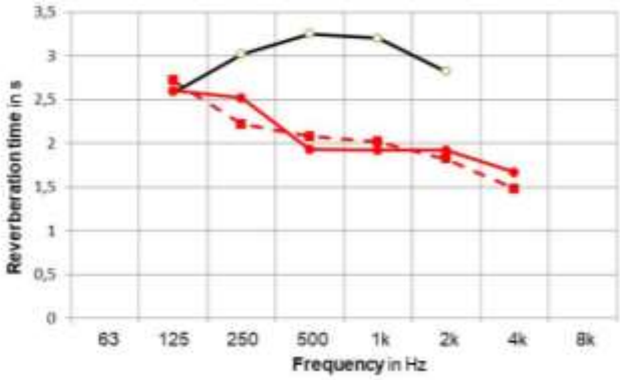


Figure 4 (left): Reverberation times in the *Symphony Hall* (1900, V = 18750 m^3, n = 2625), unoccupied before 1982 (■) resp. after 1982 (▲) and occupied (●) and in the *Concertgebouw* in Amsterdam (V = 18780 m^3, n = 2037) unoccupied (∆)

Figure 8 (right): Reverberation times in the (old) *Berlin Philharmonie* (1888, V = 18000 m^3, n = 1960) unoccupied (o), occupied (●) and *Musikvereinssaal* occupied (■) after [22] and [25]

5.3 (Old) *Berlin Philharmonie* (1888) + (New) *Berlin Philharmonie* (1963)

After the acoustical and visual virtues as well as certain inconveniences of shoebox-, horseshoe-, cylinder and other more or less directional architectures have been tested and optimized for concert halls and opera houses between around 1750 and 1950, an ingenious designer, *H. Sharoun*, found it was time to revive the classical surround structure for a novel large music venue. According to [23] he felt that *"the normal placement of the orchestra in back of a proscenium at one end of the hall blocked the audience from participating in the creative act on the stage. Only by having the audience close to the musicians, even surrounding them, could the two communicate as freely and intensely as they should"*. [24] reports that *"Sharoun made preliminary drawings and showed them to Cremer (his acoustician), whose reply was vociferously negative. Sharoun´s decision remained unchanged. To obtain a second opinion, Cremer invited Beranek to Berlin to meet with Sharoun and him. Being a devotee of the Boston Hall and knowing that music of the great composers was planned for performance in rectangular halls, Beranek concurred with Cremer´s statement that the acoustics of a surround hall represented a serious gamble. But Sharoun persisted and the building committee concurred. Cremer stated his position publicly and so frightened the orchestra that it leased a nearby hall for the year after the opening so that if the public outcry about the acoustics was great enough, they would have an alternative place to perform. Cremer then steered the architect toward architectural features that maximized the acoustical quality of a surround hall"* and the architect, luckily, was "*willing to do everything to further his idea*" according to [26, p. 93].

In a first step, the volume was raised to about 26000 m^3, i.e. 11 m^3 for each of the n = 2340 seats, with dimensions around 60 x 55 m and a height of 22 m above the orchestra (Figure 5). The reverberation spectra (Figure 6) estimated from data in [22, Fig. 7) depict a) the unavoidable absorption due for instance to 2200 air conditioning outlets under the seats plus the upholstered seats, b) plus the audience and c) plus all the low-frequency absorbers according to plan (thin wood paneling, partly perforated, over a shallow air space on wall areas at the perimeter of the room plus 135 *Helmholtz* resonator boxes under the ceiling, see Figure 7. According to [24] *"Cremer worried (needlessly) about the possibility of excessive bass"* and according to [23] *"reverberation time in the bass should be longer than the mid-frequency time to give the hall ´warmth´, but if the bass time is too long, says Cremer, it will have a hollow, booming sound"*. In fact, *L. Cremer* had planned a bass ratio BR ≈ 1,2 comparable to that he cited from the *Musikvereinssaal* and the old *Philharmonie*, see Figure 8. The actually measured data d) in Fig. 6 indicate, however, that a strong ´bass rise´ finally turned out to be avoided, most likely due to the light resilient suspended ceiling (see Fig. 5) made of a wire netting with 12-15 mm roughcast plaster. In a certain analogy to what happened with the famous *Jesus-Christus-Kirche* [11, section 11.12], a hidden bass absorber (mainly in the ceiling) was again (very luckily!) overlooked and helped to achieve an almost flat reverberation characteristic, for which *L. Cremer* (unnecessarily!) sought an excuse, even suggesting possible modifications to the timber claddings, in [25]. The light ceiling obviously vibrates with incident sound waves; actually so much that in 1988 parts of it came down and made it necessary to restore and stabilize the whole ceiling. Measurements now indicate an average of 2,1 s at 125 Hz according to [1, p. 603]. Unfortunately, measurements below 125 Hz are, as so often, not available.

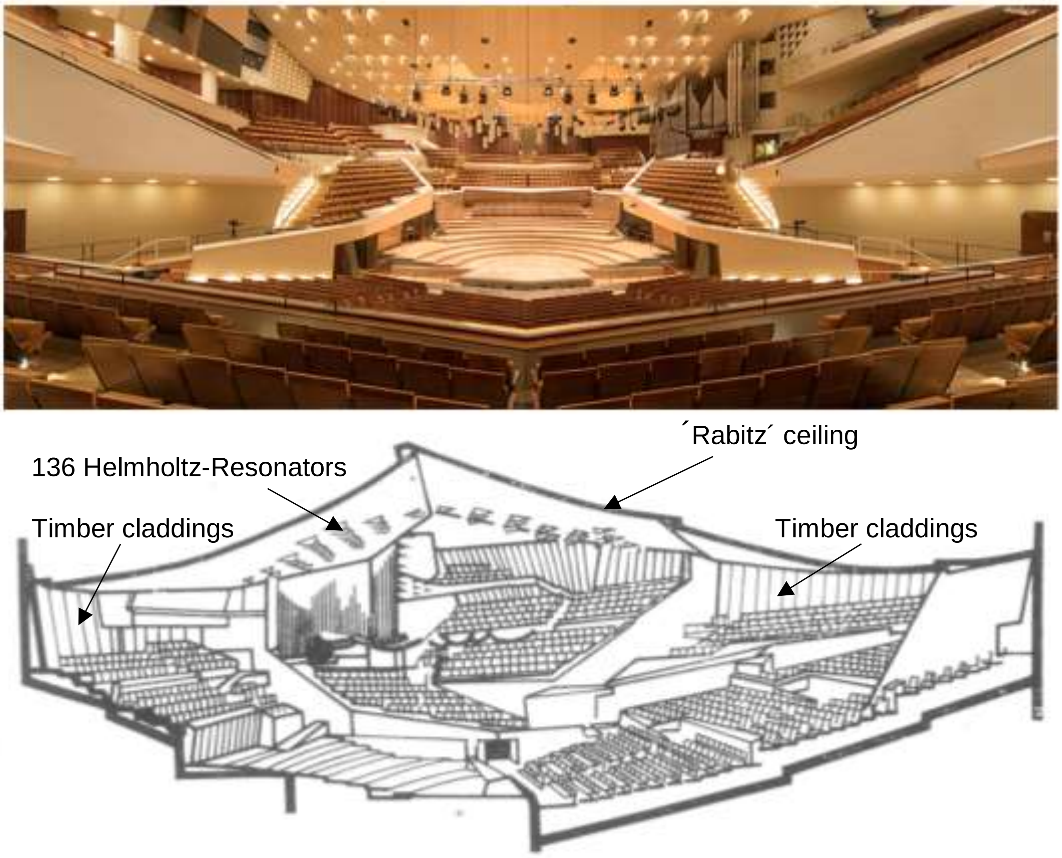
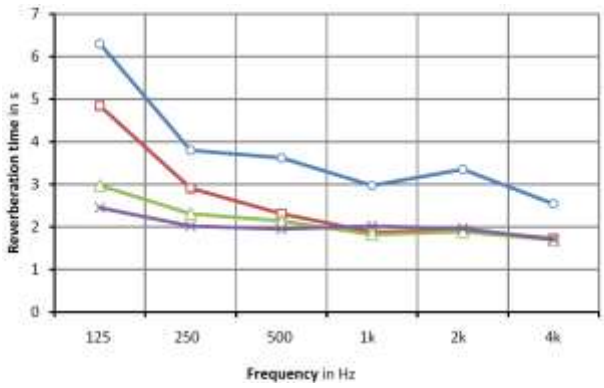


Figure 5: View and Cross section of the ´vineyard´ style *Berlin Philharmonie* (1963, V = 26000 m^3, n = 2300) with several low-frequency sound absorbers intentionally installed on walls and ceilings



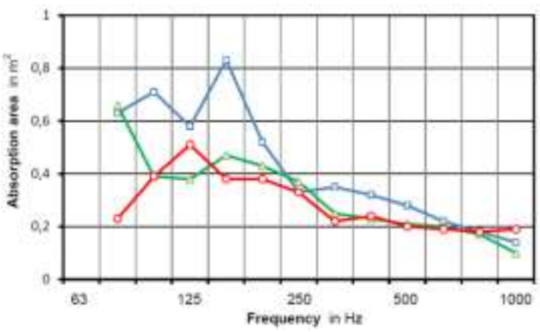


Figure 6 (left): Estimated reverberation times in the hall of Fig. 5 taking into account a) unavoidable absorption plus 2300 upholstered seats (○), b) plus audience (□), c) plus bass absorber elements to be installed (Δ), and d) measured (x), data taken from [22, Fig. 7]

Figure 7 (right): Absorption area of various Helmholtz resonator ´pyramids´ under the suspended, slightly resilient ceiling as part of the acoustic treatment in the *Berlin Philharmonie* [22, Fig. 5]

5.4 *Elbphilharmonie* in Hamburg (2017)

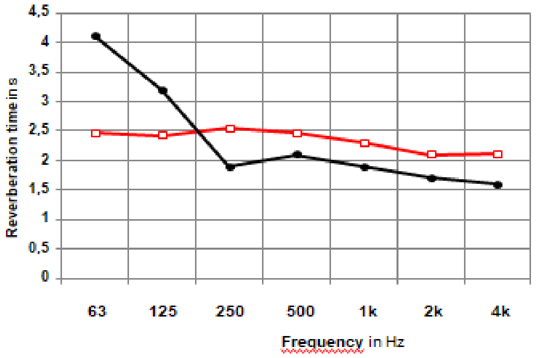
Figure 9: Large Hall of the *Elbphilharmonie* (2017, V = 23000 m^3, n = 2100) with its impressive ´White Skin´ made of multi-layered fiber reinforced gypsum board sculptured in a seashell motif pattern (Fotos: Elbphilharmonie / I. Baan (left) / J. Arlt (right))

A louder echo may never have been evoked in popular media by a new concert hall venue before and after its opening. In contrast to their own habits with other such spectacular projects, here the acousticians in charge did publish just a medium reverberation time of T_m = 2,4 / 2,3 s (unoccupied / occupied) with comments like: „*Critical assessments and judgements about the excellence or failings of a concert hall´s acoustics do not come from people reading data sheets with reverberation time and other numerical measurements of physical properties. Ultimately, individuals seated in audience seats listen to performers playing music on the stage and the audience, by listening to the music, evaluates and judges the acoustics"* [27]. That left ample room for unusually enthusiastic responses from musicians and conductors. The counter tenor of the opening concert, *P. Jaroussky,* reports: *"The sound is very warm and clear … here I feel I have a very voluminous voice … it is unbelievable!"* Some audio experts and music critics judge that the sound be clear, light, transparent, and direct so as if the full score of the music lay open before the listener.

The reason for such subjective impressions for many remains an incalculable miracle like acoustics as a whole. A closer look onto the ´White Skin´ and its substructure may therefore be informative: It spans about 6000 m^2 of the walls and ceiling (Figure 9). The 10287 individually prefabricated gypsum plates with an average weight of 125 kg/m^2 were made extra heavy, "*because we needed these panels to have sufficient weight to effectively reflect sound even at low frequencies"* [27]. An expensive surface micro-shaping by about a million exactly calculated indentations should *"create a visual design with a seashell motif and serve the role of promoting acoustical diffusion for the hall´s acoustics".* With a depth of only 10-90 mm and an average width of 80 mm of the corrugations this goal, however, could only be scored at most in the higher kHz range. Much more important may be

Figure 10: Substructure carrying the ´White Skin´ of the hall in Fig. 9 (Fotos: Peuckert GmbH)

an inspection of the steel substructures onto which the ´White Skin´ is mounted (Figure 10). Its local resilience probably provides the spring elements that, together with the mass of the gypsum plates, may form mass/spring systems which could be excited by impinging low-frequency sound waves and thus act as broadband bass absorbers. In addition the large air volumes between the inner shells and the outer solid structure of the building may similarly be excited through slits in the shells inevitably left open. These huge resonators may have prevented a BR = 1,3 as intended and caused an almost flat frequency response according to Figure 11. For T > 4 s at 63 Hz one may have assumed an absorption coefficient of 0,1 for all reflecting boundaries. Retaining this value just for the 2500 m^2 not covered by the ´White Skin´, eq. (1) yields an absorption area of 1250 m^2 for the latter. A corresponding absorption coefficient of 0,2 could well compare with that commonly assumed for windows or parquet on laths.



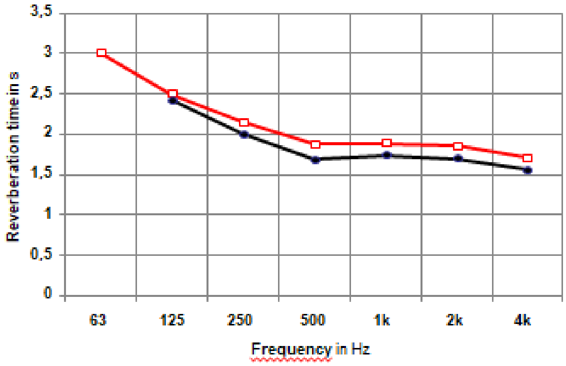


Figure 11 (left): Unconfirmed reverberation times in the venue depicted on Fig. 9; estimated for the occupied hall (●), measured in the unoccupied hall (□)

Figure 12 (right): Reverberation times in the venue according to Fig. 13; measured in the unoccupied hall (□), measured in the occupied hall (●) [28]

5.5 Pierre-Boulez-Saal in Berlin (2017)

A bass rise in reverberation is almost exclusively characteristic of the many concert venues accounted for by *Nagata Acoustics.* The corresponding data in Figure 12 for the *Pierre-Boulez-Saal* (Figure 13 a) were frankly published, but could not differ more from those in Figure 11. Again it may be interesting to discover the different result: In contrast to the filigree enclosure of *Elbphilharmonie,* the Berlin hall had to be inserted into an existing solid construction. As the height (14 m) of its massive ceiling was found too high, a light suspended (by 3 m) ceiling was first considered. Following the same concept as in Hamburg, however, it was finally decided to add the weight of 27 tons of concrete to it (max. 100 kg/m^2) in order to avoid any absorption by this element. The same was obviously achieved by thick gypsum claddings (with an attractive wood image) directly affixed to all solid walls. As the explicitly intended result the reverberation time culminates to 3 s at 63 Hz.

a 

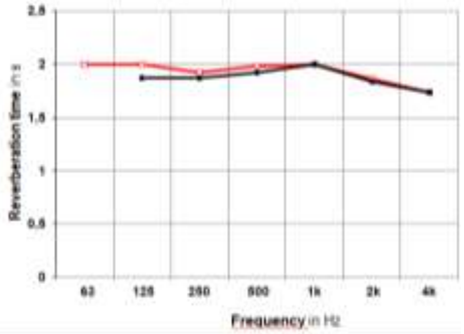
b 

Figure 13: *Pierre-Boulez-Saal* [28] (V = 7615 m^3, n = 682) with very attractive, fully reflective walls and ceiling (a) and a vividly resonating floor (b) (Fotos: Lindner KG / M. Scheithammer)

The audience sitting extremely close to the musicians on the floor undoubtedly experience an unusual ´intimacy´, ´presence´, and ´proximity´ [2]. At some distance in the upper circles, however, a booming low-frequency sound is perceived. This may be provoked e.g. by the wooden floating floor (parquet on laths, Fig. 13 b) being excited by any footsteps, percussion- or bass-instruments.

5.6 *Jinji Lake Hall* in Suchou (2017) + *Neues Gewandhaus* in Leipzig (1981)

For a third concert hall project opened last year, *Jinji Lake Hall* [29] (2017, V = 9600 m^3, n = 509), the same consultants published another reverberation spectrum equally flat between 1000 and 63 Hz as in Hamburg (BR ≈ 1, Figure 14). Similar as in the *Elbphilharmonie*, the sound waves again impinge on gypsum panels with an obscure surface structure mounted on an unknown substructure at the walls. The hall´s response resembles that of the occupied *Neues Gewandhaus* in Leipzig [1, p. 604] (1981, V = 21000 m^3, n = 1900), see Figure 15. This much larger hall, when unoccupied, exhibits a broad hump at medium frequencies. The strong absorption at the lower frequencies, is due to a large portion of the walls all around being covered by plywood and steel panel resonators. According to *L.L. Beranek* [1, p. 309] the acoustic quality of this surround hall was marked ´very good´ or ´good´ by a group of 50 subjects, chosen in equal numbers from music professionals, concertgoers, and acousticians. And he remarked that he *“was surprised to sense that the early sound energy predominated over the later reverberant sound energy. Only in fortissimo passages and after musical stops did the reverberation seem to take an active part in the music”* (sic!).



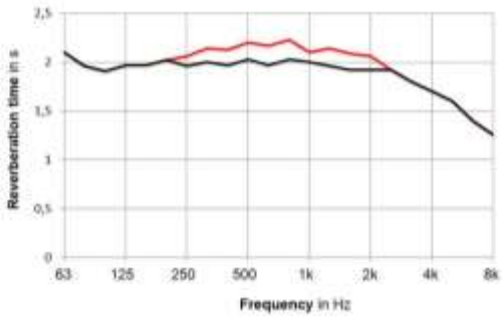


Figure 14 (left): Reverberation characteristic achieved in the *Jinji Lake Hall* ; unoccupied (□), occupied (●) [29]

Figure 15 (right): Results published for the *Neues Gewandhaus*; unoccupied (red), occupied (black)

6 Summary and CONCLUSIONS

5 ´shoebox´- and 5 ´vineyard´-structured halls are here discussed which are predominantly praised by experts for their acoustical quality. None except one of them shows a bass ratio BR > 1 in its reverberation characteristic when it is empty or furnished with weakly sound absorbing seats and unoccupied. For some of the more famous halls described in the literature one finds a moderate ´bass rise´ when these are occupied or equipped with an upholstery normally designed to equally absorb the medium frequencies which are so vital for the production and sensation of music and speech. Early reflections from the walls and ceiling are considered as key parameters for the design of a hall. They normally support all sound at high and medium frequencies. At the lower frequencies, however, they cause destructive interference effects with the direct sound waves. A long bass reverb cannot compensate for what is lost through earlier bass affecting phenomena. Rather should all relevant boundaries absorb low frequencies as much as possible to leave the direct sound clear and unadulterated throughout the venue. A purely quantitative consideration may suffice for the bulk of the sound energy emitted from the stage. But the transparency of music should not be affected by disturbed fundamental and transient sounds. These are simultaneously emitted and are equally important in forming a firm bass foundation. A spectrum with BR ≤ 1 is identified as a reliable indicator of how well this goal is met - quite independent of the medium reverberation time T_m and other relevant acoustic parameters. The author can refer to opinions long laid down in [9, 10, 17, 18] for his general plea of BR ≤ 1 for all rooms and uses. But he feels particularly indebted to his honored teacher *L. Cremer* in how courageously he tackled and frankly discussed the tremendous problems and risks in the (at that time) revolutionary new *Berlin Philharmonie* with a clear vision of its reverb characteristic: *“The ceiling will be absorbent for lower frequencies. In addition, numerous surfaces of walls and steps, covered with wood panels, will have the same effect”* [30]. From his knowledge about the (old) *Gewandhaus* in Leipzig he derived a

reverberation time of 2 s +/- 5% between 100 and 2000 Hz as most desirable for concert halls [31], well knowing how ambitious and difficult to achieve in practice this aim was (and still is!).

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