Concert Hall Acoustics—2008*

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Concert hall acoustics has received important attention since the search described in *Concert Halls and Opera Houses: Music, Acoustics and Architecture* was published (Springer, 2004). An overview of those recent contributions that appear most useful to practicing acousticians is presented. A review of the Sabine and Eyring reverberation equations shows that if either the Sabine or the Eyring absorbing coefficients are known, the other is known automatically, provided the Sabine coefficients are allowed to exceed unity. In the context of the buildup of sound in a concert hall, the known parameters are discussed—sound energy density buildup, reverberation time T_{60}, early sound, including initial time-delay gap (ITDG), apparent source width (ASW), listener envelopment (LEV), sound strength *G,* and various subjective considerations. Measurements in chamber music halls are summarized. A new formula for calculating LEV is presented.

1 REVERBERATION

1.1 Sabine and Eyring Equations

The Sabine equation (left) and the Eyring equation (right) are

$$\frac{0.161V}{S_{\text{tot}}\alpha_{\text{sab}} + 4\text{ mV}} = T_{60} = \frac{0.161V}{S_{\text{tot}}[-2.3\log(1-\alpha_{\text{ey}})] + 4\text{ mV}}$$

where S_{tot} is the total surface area in the hall, α_{sab} is the average Sabine coefficient for that area, V is the hall volume, and α_{ey} is the average Eyring coefficient for the area S_{tot}.

When both equations predict the same reverberation time T_{60}, the following equality holds:

$$\alpha_{\text{sab}} = -2.3\log(1-\alpha_{\text{ey}}).$$

This means that for a given reverberation time, if α_{sab} is known, α_{ey} is known automatically, and the ratio can be taken,

$$\alpha_{\text{ey}}/\alpha_{\text{sab}}.$$

In a concert hall let us name three areas: the combined acoustical audience and orchestra area S_{T}, all other not highly absorbing surfaces, S_{R}, and any highly absorbing surfaces, ΣS_{i}. For both equations the total hall area is $S_{\text{tot}} = S_{\text{T}} + S_{\text{R}} + \Sigma S_{\text{i}}$. Denote the Sabine sound absorption coefficients for these areas α_{T}, α_{R}, and α_{i}, respectively, and the Eyring absorption coefficients $\acute{\alpha}_{\text{T}}$, $\acute{\alpha}_{\text{R}}$, and $\acute{\alpha}_{\text{i}}$, respectively. For the Sabine equation $\alpha_{\text{sab}} = (S_{\text{T}}\alpha_{\text{T}} + S_{\text{R}}\alpha_{\text{R}} + \Sigma S_{\text{i}}\alpha_{\text{i}})/S_{\text{tot}}$, and for the Eyring equation $\alpha_{\text{ey}} = (S_{\text{T}}\acute{\alpha}_{\text{T}} + S_{\text{R}}\acute{\alpha}_{\text{R}} + \Sigma S_{\text{i}}\acute{\alpha}_{\text{i}})/S_{\text{tot}}$. Division of one by the other gives

$$\acute{\alpha}_{\text{T}} = (\alpha_{\text{ey}}/\alpha_{\text{sab}})\alpha_{\text{T}}$$
$$\acute{\alpha}_{\text{R}} = (\alpha_{\text{ey}}/\alpha_{\text{sab}})\alpha_{\text{R}}$$
$$\Sigma\acute{\alpha}_{\text{i}} = (\alpha_{\text{ey}}/\alpha_{\text{sab}})\Sigma\alpha_{\text{i}}.$$

Consider $T_{60} = 0$ first. For the Eyring equation, $T_{60} = 0$ when the Eyring coefficient is 1.0. For the Sabine equation $T_{60} = 0$ only if the Sabine coefficient is very large. This demands that the Sabine absorption coefficient must be allowed to exceed 1.0, a fact that Sabine appeared to disregard when he stated (in 1900, 1906, and 1915) that the absorbing power of an open window, meaning a surface with no reflected sound, is 1.000. By contrast, in a 1912 paper he showed without comment an absorption coefficient of 1.26 at 1024 Hz for a felt material and, in a 1915 paper, absorption coefficients of 1.10 at 512 Hz for "upholstered settees" and 1.12 at 512 Hz for wood sheathing, 2 cm thick [1].

Consider a *very small* room (3.17 × 2.60 × 1.95 m) with all walls equally absorbing and covered with 13.5-mm glassfiber panels [2]. What are the two measured absorption coefficients as a function of frequency? Fig. 1 shows that the Sabine coefficient may rise well above unity in a small or highly absorbent room.

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Joyce [3] and others have clearly shown that if the same absorption coefficients are used in different halls, a different reverberation equation must be used for each type of hall. A different hall is also one whose surfaces have different scattering characteristics. Alternatively, if the same reverberation equation is used to predict reverberation times, the absorption coefficients in different halls must be different—for example, the audience in each shape of hall absorbs a different amount of sound energy because of the difference in the way successive sound reflections involve it and the other surfaces. In Fig. 2 the difference is shown in the audience absorption coefficient for a classical shoe-

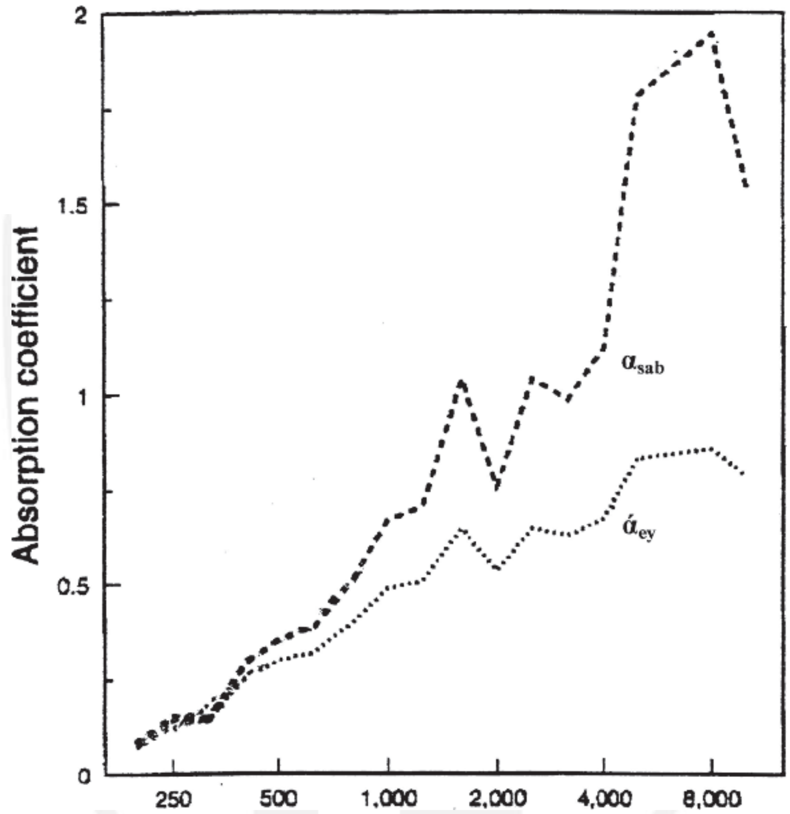


Fig. 1. Sabine and Eyring absorption coefficients calculated from measured reverberation times in a small room with all surfaces absorbing uniformly. (From Hodgson [2].)

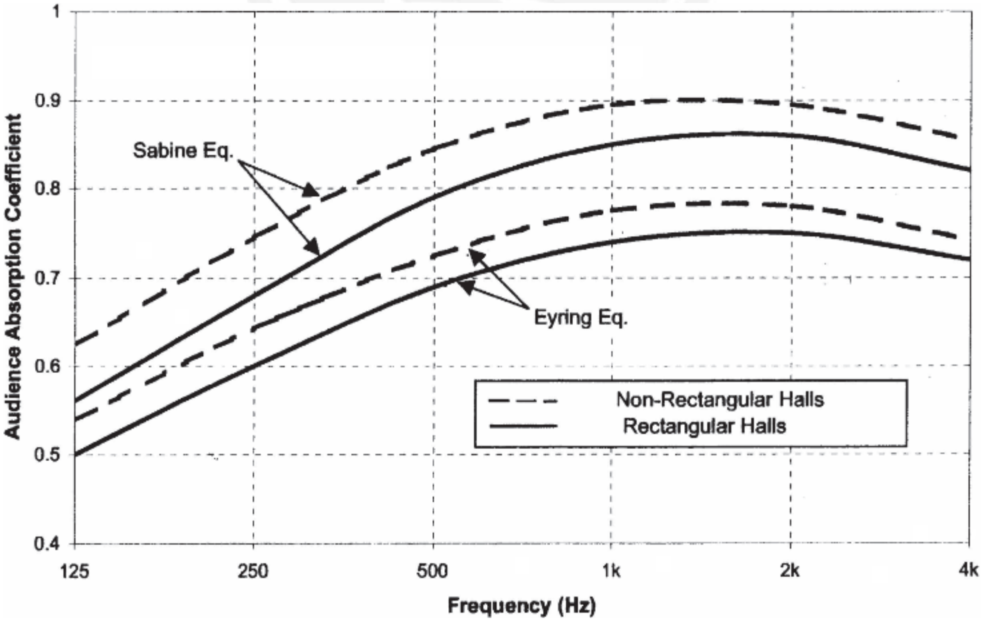


Fig. 2. Sabine and Eyring audience absorption coefficients in two different types of halls—classical rectangular (average of 9 halls) and nonrectangular (average of 11 halls).

box-shaped hall (average of 9 halls) compared to a non-shoebox-shaped hall (average of 11 halls). The absorption coefficient for the latter is 6% greater. Hidaka and Nishihara [4] show that the mean free path is greater in shoebox halls than in the other halls, meaning that if the same absorption coefficient is desired for both types of halls, the reverberation equations must be different.

Kitamura et al. [5] show that different locations of a large area of sound-absorbing material in a room result in different sound absorption coefficients for that material. For example, a given material covering the upper third of the rear wall of a test auditorium yielded an Eyring coefficient of 0.5, but when moved to the middle third, it yielded 0.35. They also find that the absorption coefficient for an area of acoustical material changes when an absorbing material is added to another surface of a room. Conclusion, when using the same reverberation equation, the absorption coefficients used should be determined from measurements in a similar shape of room in which there are similar locations of the material.

It is hoped that no one is still calculating reverberation times in a concert hall considering the audience absorption as being proportional to the number of occupants. In repeated papers the author has shown, and more recently Barron and Coleman have confirmed [6], that the absorption of an audience is proportional to the area over which it sits. This difference is serious because, for example, in the Amsterdam Concertgebouw, 1200 people sit over an area of 500 m^2, whereas in the Munich Philharmonie, only 900 sit over this area. Thus because the absorption is proportional to the area, in the Munich hall each person absorbs 33% more sound energy than in Amsterdam. Also, it must be noted that the area of an audience is greater if it is on a slope than if seated with no rake. The sloped area must be used in the calculations.

1.2 Subjective Ratings of Concert Halls

In [7] 60 concert halls were divided into three categories according to subjective ratings by conductors and music critics. Examples taken from there are given in Table 1.

1.3 Rise and Decay of Sound in a Typical Concert Hall

Fig. 3 shows the theoretical (dashed curve) and measured (irregular curve) rise in cumulative energy at 1000 Hz as heard in the center of Boston Symphony Hall. Assume that a violin plays a note 100 ms long with energy in the 1000-Hz band. The cumulative energy rises as shown by the irregular curve. If the note ceases after 100 ms, the sound will decay, as seen by the straight heavy line. If a second note is sounded just after 100 ms, its peak energy will be heard easily above the previous reverberation. But simply hearing each note is not the only measure of acoustical quality.

First, the reverberation time T_{60} must go with the music to be performed in the hall. A reverberation time of 1.9 s goes with today's symphonic music repertoire.

Second, the initial time-delay gap (ITDG) is important, the time at which the first reflection is heard after the direct sound. For Boston, ITDG ≈ 15 ms, and this is about optimum. If it is greater than 35 ms, the hall will sound like an arena, with a lack of intimacy—hall size is audible.

Third, there is the law of the first wavefront. Before about 100 ms, at a seat in the hall the azimuth location of the source is possible. Azimuth location is determined from the first wavefront, and this is an important contributor to the acoustics rating of a hall.

Fourth, during this 100-ms period the early reflections broaden the sound, called the apparent source width (ASW). ASW depends on the proportion of the early energy that arrives at the listener *laterally* and is measured

Table 1. Concert hall ratings.

	T_{60} (occup)	G_{mid} (dB)
Category 1		
Vienna, Grosser Musikvereinssaal	2.0	6.5
Boston, Symphony Hall	1.9	4.2
Tokyo Opera City (TOC), Concert Hall	1.95	5.0
New York, Carnegie Hall	1.8	—
Cardiff, Wales, St. David's Hall	1.95	3.2
Special category (surround halls)		
Berlin, Philharmonie	1.9	3.7
Los Angeles, Disney Hall	1.85	—
Category 2		
Cleveland, Severance Hall	1.6	3.5
Munich, Philharmonie Am Gasteig	1.8	1.9
Washington, D.C., JFK Concert Hall	1.7	2.5
Category 3*		
London, Royal Festival Hall	1.45	1.9
Paris, Salle Pleyel	1.5	3.9
Montreal, Salle Wilfrid-Pelletier	1.65	0.1
Buffalo, Kleinhans Music Hall	1.5	2.7
San Francisco, Davies	1.85	2.2

* The rankings and acoustical data given here precede the renovations that have been made to all of these halls in recent years.

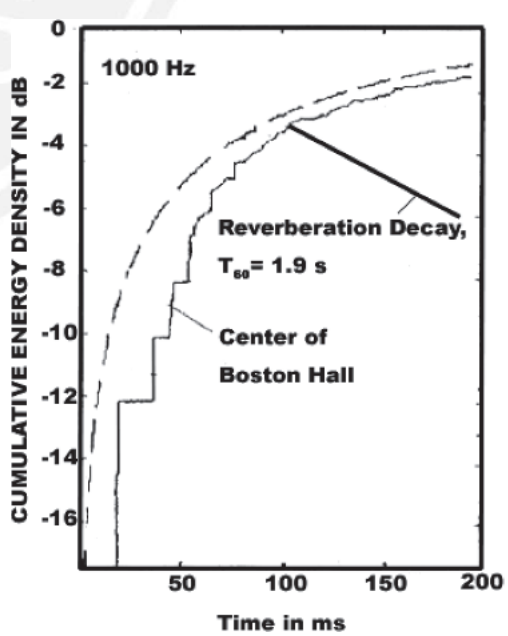


Fig. 3. Rise and decay of sound at center of Boston Symphony Hall.

by the interaural cross correlation coefficient (IACC) (microphones at two ears) or the lateral (energy) fraction (LF) function (figure-of-eight microphone). Boston Symphony Hall ranks among the best.

Fifth, after about 100 ms the listener is enveloped by the sound. The value of the listener envelopment (LEV) function must be large enough for good sound quality. Note that when LEV is experienced, the azimuth direction of the source can no longer be observed by listeners (Morimoto et al. [8]).

Sixth, Griesinger [9], [10] says that for best sound quality, the energy in the direct sound at the listener's position should be no weaker than about −10 dB below the ultimate level, as shown by the left-hand curve in Fig. 3, which is the curve that theory says should represent the buildup of sound if there were no ITDG. This −10-dB goal holds in Boston for two-thirds of the audience. But the ITDG is much shorter in the balconies, and the energies of the earliest reflections add directly to the energy of the direct sound. Hence the remaining third of the audience is still well served.

Seventh, the number and distribution of early reflections that occur before about 100 ms, that is, texture, is an important factor in acoustical quality.

These are the critical factors for judging the acoustical quality of a concert hall, at least as they are known today. Let us see how they apply to halls for which data are available.

1.4 Reverberation Time and Early Decay Time at Midfrequencies

The reverberation times at midfrequencies measured in 40 concert halls are plotted in Fig. 4 against the subjective ratings taken from [7]. It is seen that in the better halls the reverberation times lie between roughly 1.7 and 2.0 s. In the halls with lower ratings, the reverberation times fall between 1.5 and 1.7 s. These ratings assume standard symphonic repertoire.

The early decay time (EDT) measured in unoccupied halls is plotted in Fig. 5 against the rank ordering according to acoustical quality. A part of the variations in the location of points on the EDT graph is due to different

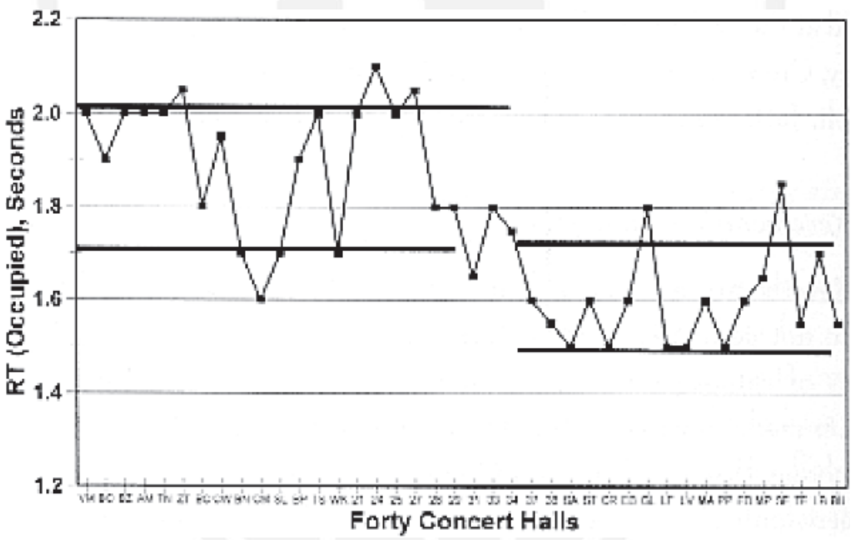


Fig. 4. Midfrequency reverberation times measured in occupied halls versus subjective ratings of acoustical quality. (From [7].)

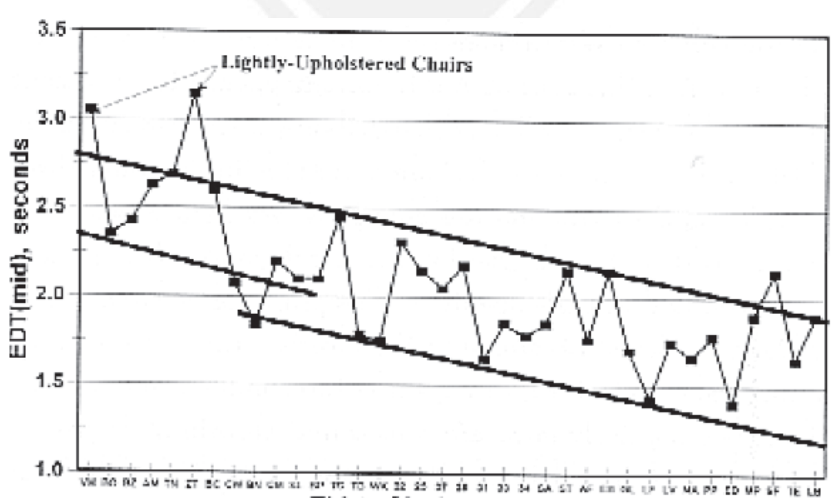


Fig. 5. Early decay times at midfrequencies in unoccupied halls versus subjective ratings of acoustical quality. (From [7].)

degrees of chair sound absorption. For judging acoustical quality it appears that the EDT, even though measured in unoccupied halls, is a better measure of sound quality than the reverberation time measured in occupied halls.

2 LATERAL FRACTION

Barron and Marshall [11] have demonstrated that subjective measurements of the apparent source width ASW correlate highly with the lateral fraction LF, the ratio of the energy measured with a figure-of-eight microphone to that measured by a unidirectional microphone. They expressed the opinion that data in the upper bands, 2 and 4 kHz, have little correlation with ASW. However, Blauert and Lindemann [12] and Morimoto and Maekawa [13] have shown that the higher frequency bands also contribute to ASW.

The graph in Fig. 6 plots the measured lateral fraction LF_{E4} versus subjective concert hall ratings. The subscript E stands for integration before 80 ms and 4 means the average of the levels in the four octave bands from 125 to 1000 Hz. Also plotted is measured LF_{E3}, where 3 means the average of the levels in the three octave bands of 500, 1000, and 2000 Hz. The low-band LF_{E4} and midband LF_{E3} curves are almost identical. Hence in the analyses that follow, the two LF averages are used interchangeably.

3 BINAURAL QUALITY INDEX

The interaural (binaural) cross correlation coefficient IACC measures the similarity of the sound at the two ears. Sound coming from the front only will be the same at the two ears; hence IACC = 1.0. The subjective apparent source width ASW is higher the greater the difference in correlation of the sound at the two ears, that is, greater values of ASW correlate with lower values of IACC. To give increasing numbers with increasing ASW, the quantity $(1 - IACC_{E3})$ is determined and is called the binaural quality index (BQI). Measured values of BQI plotted against the subjective ratings of concert hall quality are shown in Fig. 7. It appears that BQI is more closely cor-

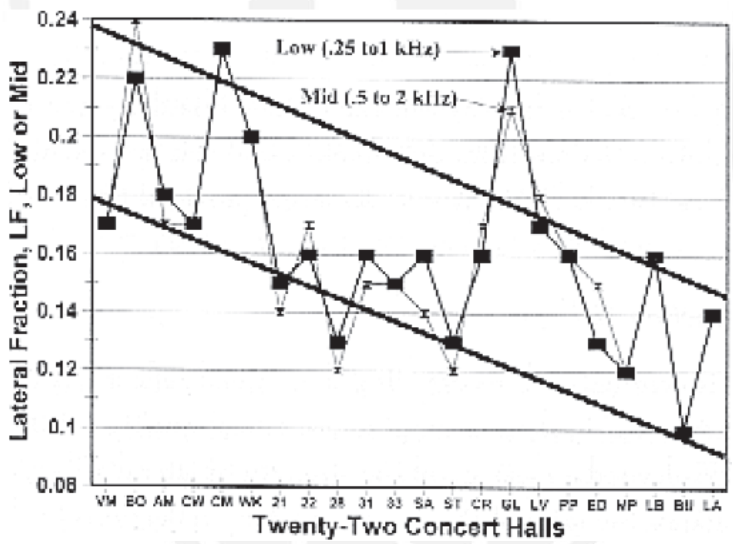


Fig. 6. Lateral fraction LF versus subjective ratings of concert hall quality. ■ average LF values in four lowest bands; × average in three highest bands. (From [7].)

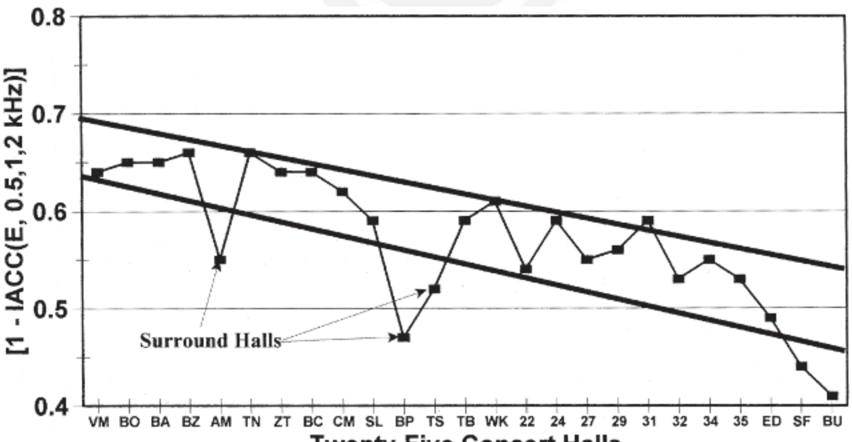


Fig. 7. Binaural quality index $(1 - IACC_{E3})$ versus subjective ratings of concert hall quality. E—integration before 80 ms., 3—average values in 500-, 1000-, and 2000-Hz bands. (From [7].)

related with subjective acoustical quality than LF, although both will separate excellent halls from less good ones.

Measured BQI values ($1 - \mathrm{IACC}_{E3}$) are plotted in Fig. 8 versus LF_{E4}. Part of the reason for the scatter of the points is undoubtedly the fact that the data were taken over long periods of time by different observers. In addition, Bork [14] reported that in five-team round-robin comparisons of three different specimens of figure-of-eight microphones (Neumann KM 86) level differences of more than 3 dB were detected between sound irradiation from the front and from the back in the free field. The difference in sensitivity of the two spatially separated capacitor-microphone capsules involved is attributed to aging. A frequent accurate calibration of the figure-of-eight and omnidirectional microphones in an anechoic chamber is essential. It will be assumed in the analyses that follow that measured BQI and LF_{E4} values are highly correlated, at least for BQI values of less than about 0.65.

4 CONVENTIONAL SHOEBOX HALLS

Boston Symphony Hall, a shoebox hall, opened in 1900. Why has this hall received high subjective ratings from conductors and music critics when so little was then known about acoustics? In part, it was a confluence of critical decisions made by the owner of the Boston Symphony Orchestra, Henry Lee Higginson, who was also the chairman of the hall's building committee, and his advisors. The architect, Charles McKim of the then famous New York firm McKim, Meade and White, had first come up with a design that was in effect a steeply raked Greek theater with a roof over it.

Higginson took the architect's sketch and drawings to Europe and showed them to prominent conductors and musicians of that time who counseled against that design and recommended that he consider instead the best liked hall in Europe, the Gewandhaus in Leipzig, Germany (destroyed in World War II) [15], [16]. The Gewandhaus was a shoebox hall, a shape that is known today to ensure rich

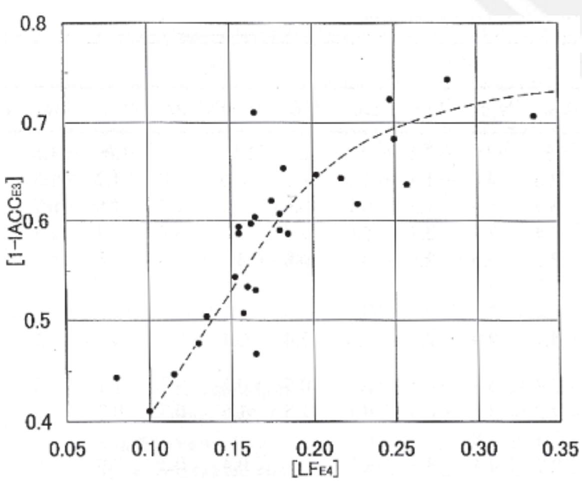


Fig. 8. Measured values of binaural quality index ($1 - \mathrm{IACC}_{E3}$) versus LF_{E4}.

reverberation and uniform coverage of the audience. For visual reasons, Higginson stipulated that the 2600-seat hall should be no wider than 75 ft (22.9 m), which we now know ensures adequate apparent source width and an optimum initial time-delay gap. The building committee demanded that the hall be fireproof—concrete block and plaster—which ensures strong bass. When McKim was informed by Higginson of these restrictions, he created three new design variations.

At this point Wallace Clement Sabine, a young assistant professor of physics at Harvard University, came into the picture. Sabine had completed a study of 11 lecture halls at Harvard and had successfully recommended acoustical renovations for an auditorium in the university's (former) Fogg Art Museum. The president of Harvard, Charles Eliot, spoke to Higginson and expressed the opinion that Sabine's experience might be helpful. Eliot immediately told Sabine that he had spoken to Higginson. Sabine asked for time to study his data and, in a fortnight, came up with a formula (the Sabine equation) for predicting reverberation time, which requires knowledge of the cubic volume of the hall and the sound-absorbing properties of the audience and the various other surfaces in a hall.

Higginson, after becoming acquainted with Sabine, gave him McKim's latest drawings and those for the Leipzig Gewandhaus. From audience absorption data that he had obtained in a physics auditorium and the sound-absorbing characteristics of plaster, carpets, and so forth measured in a Harvard test chamber, he applied his formula to the drawings of the Gewandhaus and determined from it the probable reverberation time. Selecting the design that most resembled the Gewandhaus and using his formula, Sabine determined the cubic volume, that is, the ceiling height, that would give the same reverberation time as that calculated for the Gewandhaus. This recommendation has resulted in a reverberation time, now measured as 1.9 s at midfrequencies in the occupied hall, that is considered optimum for today's orchestral repertoire. But McKim's drawings had a fault that both Higginson and Sabine felt could not be tolerated, namely, the hall was too long. They both felt the result might be a "tunnel" sound. To reduce the length, Sabine recommended balcony changes, and he designed a stage house so as to free up space on the main floor. Higginson reduced the row-to-row spacing. These changes brought the distance from the front of the stage to the farthest seat down to 138 ft (42 m). Only then did Higginson reveal to McKim that Sabine was involved in the changes. McKim was not happy.

Higginson sent Sabine to New York to talk with McKim, and after a two-hour meeting McKim's firm declared that it was placing the responsibility for the acoustical results in the hands of Sabine. (Sabine never received a fee.) After that, McKim devoted his efforts to making the hall visually beautiful, which resulted in niches and statues on the sidewalls and coffers in the ceiling. Those architectural features have created a pleasant sounding reverberation. The hall opened October 15, 1900, and its design has remained unchanged to this day (see Fig. 9).

5 SURROUND HALLS

In the late 1950s a new concert hall in Berlin to be used by the Berlin Philharmonic Orchestra was in the planning stage. Hans Scharoun was chosen as architect, and he selected as his advisor the leading acoustical consultant in Germany of that time, Professor Lothar Cremer. Sharoun wanted to make an architectural statement, and copying the well-known halls of Vienna and Amsterdam held no appeal for him. He set his mind on the concept of surrounding the orchestra by the audience. Among other things this would make the hall visually more intimate as the distance to the farthest listener could be less. He talked with the music director of the Philharmonie, Herbert von Karajan, who opined that the orchestra might even like being surrounded by the listeners.

Scharoun made preliminary drawings and showed them to Cremer, whose reply was vociferously negative. Scharoun's decision remained unchanged. To obtain a second opinion, Cremer invited Beranek to Berlin to meet with Scharoun 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 Scharoun 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 alternate place to perform.

Cremer then steered the architect toward architectural features that maximized the acoustical quality of a surround hall. He planned the cubic volume to achieve a reverberation time that approximated the values found in Europe's leading halls, 1.9 s. He knew that early reflections were important at each listener's position. To achieve this to the extent possible, he recommended that the audience be divided into blocks, that is, terraces the front edges and sides of which could reflect early sound to listeners' positions. Also, the ceiling was shaped so that it provided early reflections. Cremer also worried (needlessly) about the possibility of excessive bass, that is, boominess, and provided "boxes" in the ceiling that can be adjusted to absorb more or less bass sound.

The hall opened in 1963 to great acclaim. The architecture was judged visually fantastic. To this day tourists to Berlin are urged to go to the Philharmonie to view the outstanding work of Scharoun. But what about the acoustics? The author has attended over 15 concerts there and has sat in many different parts of the hall. The observations, stated here in first person, are the following.

> Because the audience terraces are at different heights and movement between them is not easy, there are a number of stairways. My first seat was high above the orchestra, which I got to after a search for the proper stairway. When I emerged into the hall, I was almost overcome by the view—the architecture was breathtaking. I enjoyed the concert, although the sound was somewhat different from that in Boston Symphony Hall. At my next attendance I had a seat behind the orchestra. Featured was a piano concerto. Because of the sound board on the piano, the high frequencies were almost entirely radiated to the audience in front. I only heard the bottom octave of the piano's sound, hardly a satisfactory listening experience. This same result occurred at another concert where a soprano sang. Her high-frequency registers were radiated forward—only lower frequency sounds reached my ears.
>
> At subsequent concerts I sought the best sound and found it in three locations. One location was directly in front, in about

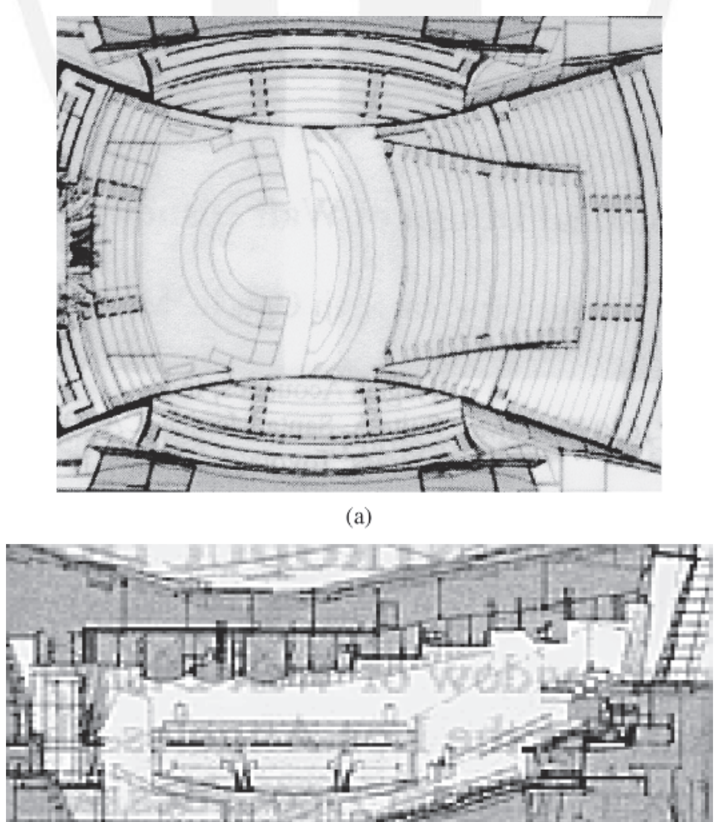
Fig. 9. Boston Symphony Hall showing stage house, irregularities on sidewalls and ceiling, and balcony designs. (Courtesy Boston Symphony Orchestra.)

> the sixth row, and another in about the tenth row. The third was in the front row of the terrace that is closest to the first violin section. Different and less good acoustics were found in several of the higher up terraces. The conclusion is that the acoustics differ from one location to another. Regular subscribers gravitate to the seats with the best acoustics. I am told by those familiar with the attendance at concerts that the hall is nearly always sold out because of tourists. I learned from Maestro von Karajan that the players enjoy being surrounded by the audience, although he commented that it is somewhat easier to play on a stage where they are surrounded by side and rear walls and a ceiling. In the Philharmonie several large nonflat surfaces hang above the stage, which helps the players hear each other.

The Los Angeles Philharmonic Orchestra had never been happy with the acoustics of the Chandler Pavilion Hall, which opened in 1964. The Walt Disney family decided to underwrite the construction of a new hall adjacent to it, and observing that the architect Frank Gehry had been celebrated for his Bilbao, Spain, art museum, he was selected. A Japanese acoustician, Yasuhisa Toyota, was chosen because his firm had been acoustical consultants for a successful surround hall in Tokyo, the Suntory Hall. The garage beneath the Walt Disney Hall was first completed, but the cost of the overall project ballooned beyond expectations, and concert space was not completed until years later, in 2003. Published plans and photographs of the Walt Disney Hall are shown in Figs. 10 and 11.

Three architectural features stand out—the surrounding of the orchestra by the audience, the curved surfaces that extend the length of the hall on either side, and the complex-shaped ceiling. These surfaces serve an important acoustical purpose, and great efforts were spent using computer and wooden models to make them supply early reflections to as many seats as possible. The acoustics are excellent at a significant number of seats, although in some places the acoustics differ where the texture is less good. The height of the ceiling above the stage is about 49 ft (14.9 m) and the midfrequency occupied reverberation time is 1.85 s, both parameters being near optimum. The average signal strength G in the hall is about 2 dB less than in Boston and 4 dB less than in Vienna's Musikvereinssaal. As in the Berlin Philharmonie, the orchestra had to become accustomed to playing without side and rear walls. This difference demands that the players pay closer attention to the conductor. The listening experiences of the author, in first person, are as follows.

> I obtained tickets for two different seats in each of three concerts, which were performed on three successive days with the same conductor, the same program, and the Los Angeles Philharmonic. Two of the seats were relatively near the stage—one directly in front and the other at a front side. At these seats the acoustics were excellent, just as reported by music critics, who generally are seated in these areas. My one seat at the rear of the orchestra had the same problems as discussed for the Berlin hall: those instruments facing for-



(a)

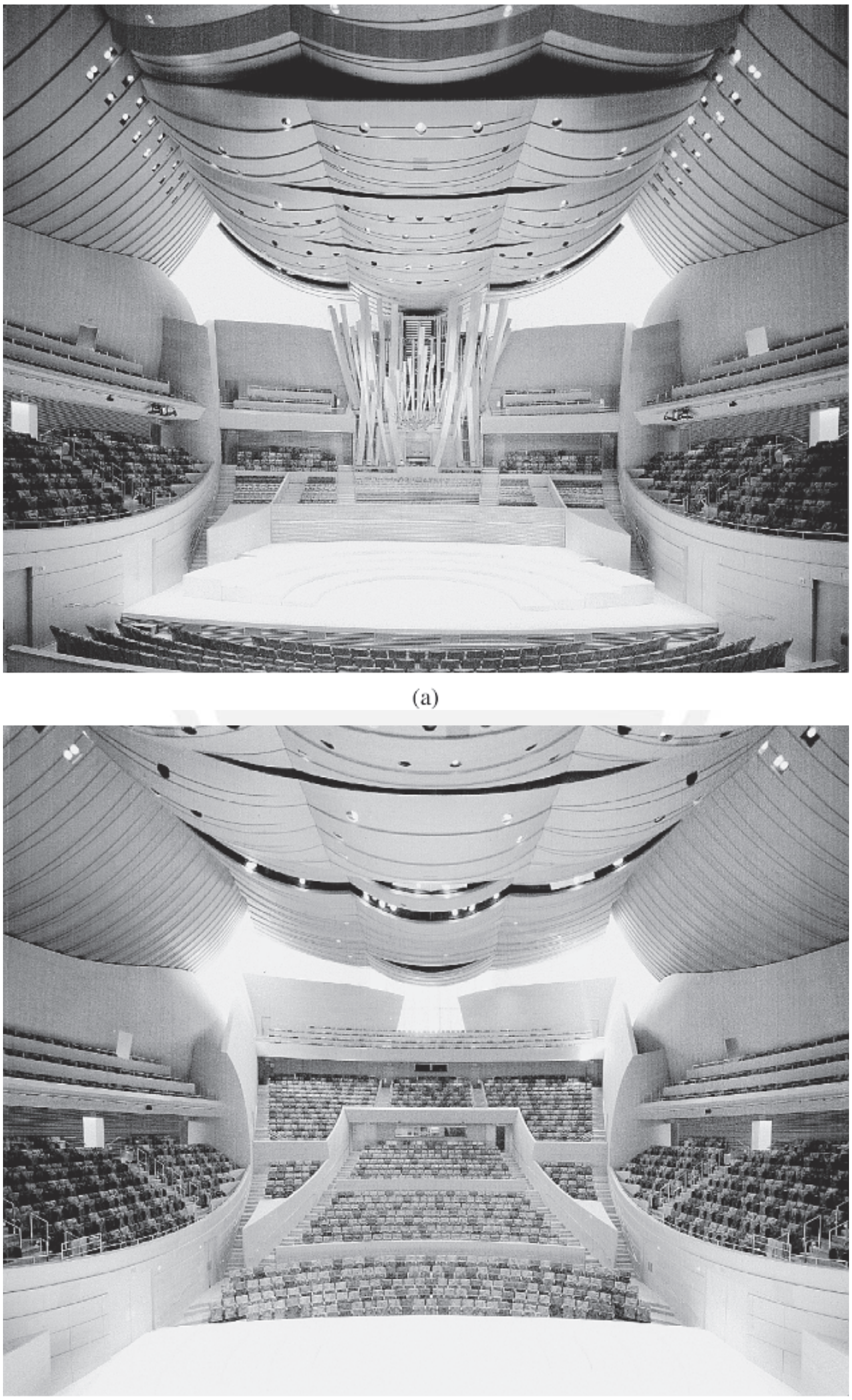
(b)

Fig. 10. Walt Disney Hall, Los Angeles, CA. (a) Plan. (b) Longitudinal section.

ward—piano, trumpets, and trombones—do not come across naturally. However, at this seat the conductor's face and motions are interesting to observe, giving one the feeling that he is seated with the players.

In one seat in the main part of the hall, three-quarters of the way back, the strength of the first violin section seemed amplified, which made the bass sound weak. The person next to me, who was an architect from Los Angeles whom I did not know, remarked: "I could see the basses and cellos bowing vigorously, but they were almost inaudible." At another seat in this area the sounds of the first violins seemed to come, in part, from the curved surface on the right. My sixth seat was in the fourth row of the seating area behind the left-hand curved surface, just opposite the row of first violins. The sound there was excellent, and several attendees around me expressed their opinion that this location was choice.

It was interesting to me that the programming during the inaugural week's concerts emphasized contemporary music, limiting traditional classical music to one symphony—in fact, one opening-week's concert was devoted to the music of Hollywood film scores. I am tempted to ask: "Is contemporary music better adapted to performance in a contemporary surround shaped hall?"



(a)

(b)

Fig. 11. View of Walt Disney Hall. (a) Looking toward stage. (b) Looking out from stage. (Courtesy L.A. Philharmonic Orchestra.)

6. PERCEIVED LOUDNESS IN HALLS AT DIFFERENT DISTANCES FROM THE STAGE

In 2001 Zahorik and Wightman [17] performed a carefully executed experiment designed to determine whether the subjective loudness of the music decreased as a listener moved back in the hall farther from the stage. In their experiment the music was produced by a loudspeaker. A person with blocked ear canals was equipped with two microphones, one at the entrance to each ear canal. As the loudspeaker was moved to successive positions in the hall, away from the person, the outputs of the microphones and the strength of the sound (the sound level) were recorded. In the next phase of the experiment, listeners, blindfolded, were seated in a cubicle and the recorded sounds were played back to their ears, binaurally, through earphones. Each listener was asked to judge the loudness of the music that had been recorded at each of the different distances between the listener and the loudspeaker. The results were amazing. The listeners reported that the loudness of the sound was the same at all positions, even though the measured sound levels decreased as the separation distance was increased. Zahorik and Wightman concluded that the loudness must have been determined by the reverberant sound, the strength of which does not vary appreciably throughout a hall. (Averaged measurements in many typical concert halls—$V = 20\,000$ m^3 and $T = 2$ s—show that the overall sound strength G falls off about 5 dB for source–receiver distances of between 10 and 40 m, while the reverberant field falls off about 2 dB for these separations.)

In 2007 Barron reported a similar study [18], except that in his experiment the listeners made their judgments of loudness while looking at the stage and moving back in the auditorium—no recordings, except for the sound level, were necessary. Apparently unaware of the 2001 paper [7], Barron concluded: "Assessment of subjective loudness indicates that the listeners' *loudness* judgment is almost *independent of distance* from the stage." His explanation for this result was: "This suggests that listeners are compensating their judgment of loudness on the basis of visual information." Barron then gives advice to hall designers. He says, this result suggests that ideally the sound strength *G should be planned* to decrease with the distance from the stage by about the same amount as it decreases in Boston Symphony Hall.

This is an important discovery, even though it is not known to what extent listeners' judgment of loudness in a hall is based on the strength of the reverberant field or on the vision of the distance of the source—probably on both.

7 CHAMBER MUSIC HALLS

Hidaka and Nishihara sought general design guidelines for chamber music halls based on studies of 11 European halls and 7 Japanese halls [19]. The occupancy of the former ranged from 336 to 844 and of the latter from 252 to 767. If halls with seating under 339 and multipurpose are excluded, the occupied-hall midfrequency reverberation times range from 1.5 to 1.7 s. Opinions of musicians with experience in halls with occupancies of between 500 and 600 seats were that these reverberation times are excellent. For those particular halls, the midfrequency (unoccupied) clarity factor C_{80} lay in the range of −1.0 to +2.0 dB, as compared to −3.0 to −1.0 dB for classical shoebox halls, indicating greater clarity in chamber music halls.

For the European halls the unoccupied-hall average sound strengths at midfrequencies G_{M} ranged from 9 to 13 dB and the low-frequency strengths G_{L} (125/250 Hz) from 9 to 14 dB. In the modern (mostly Japanese) halls these values were 3 and 5 dB less, respectively. The initial time-delay gaps measured at midfloor were 20 ms or less in the best halls. For the best halls the binaural quality indices [$\mathrm{BQI_{MID}} = (1 - \mathrm{IACC_{MID}})$] integrated over 80 ms were more than 0.68, and integrated over 50 ms they were more than 0.58.

8 CALCULATION OF LISTENER ENVELOPMENT

In this section a new formula is presented for the calculation of listener envelopment, (LEV). It has as its basis a paper by Soulodre and coworkers of the Communication Research Centre in Ottawa [20]. Their work is definitive and very important. In the presentation that follows the formula they deduced is changed in detail in order to permit the use of data available in the literature [7].

Before proceeding to their work, we note that it has been believed until now that the most important component of listener envelopment is the late energy arriving from lateral directions at a person's ears. Furuya et al. [21] found from extensive subjective measurements of listener envelopment that late vertical energy and late energy from behind, respectively, affect listener envelopment by approximately 40 and 60% of the lateral energy. It must be concluded that total late energy is a better component of LEV than late lateral energy. This finding is confirmed in the study by Soulodre et al.

In the experiments performed by Soulodre et al. a listener was surrounded by the sound from five loudspeakers, one frontal, two at ±30°, and two at ±110°. The sound stimulus was a 20-s segment of anechoic music (Handel's Water Music). Direct sound came from the forward loudspeaker. Early reflections and reverberant sound came from the other loudspeakers. The reverberant sound and some of the early reflections were varied as well as the strength G and the reverberation time. The subjects were asked "to rate only their perception of being enveloped or surrounded by the sound." They measured in octave bands 1) the late lateral energy fraction $\mathrm{LF_L}$ (measured with a figure-of-eight microphone and integrated after 80 ms), 2) the late total energy G_{L}, and 3) the reverberation time.

Note: They found very little change in perceived listener envelopment for reverberation times of between 1.7 and 2.0 s, common for concert halls. (But it must be noted that they and Morimoto et al. [8] found that the listener envelopment is diminished when the reverberation time is low in any frequency region, whether low, middle, or high.) The derivation that follows is valid for this range of reverberation times only.

An important conclusion in Soulodre's paper: "The results are fairly independent of how the various octave bands are grouped." They even found slightly higher correlations between the results of their subjects' responses using the 500- and 1000-Hz bands for averaging their measured data rather than using the four 125–1000-Hz bands. They decided to average their results over the four 125–1000-Hz bands, saying only that they wanted to use a larger number of bands.

As a by-product they found that for the 125-, 250-, and 500-Hz bands the transition time between ASW and LEV is substantially longer than the 80 ms customarily assumed. For the 1000- and 2000-Hz bands it is about 100 ms. Because at midfrequencies their 100-ms transition time is close enough to the 80-ms value, which has been used for nearly all of the data in the literature [7], and because of the information in the previous paragraph, the derivation that follows uses the 500/1000-Hz bands for averaging.

Directly from Soulodre et al., but with the modifications mentioned, their formula for calculating listener envelopment LEV, which correlates highly with their subjective judgments, is

$$\mathrm{LEV}_{\mathrm{calc}} = 0.5G_{\mathrm{late,mid}} + 10\log \mathrm{LF}_{\mathrm{late,mid}} \quad \mathrm{dB}.$$

For many halls in the literature the strength factor G (overall) and the clarity factor C_{80}, which measures the ratio of early to late energy, are published. From these two quantities the late strength factor G_{late} can be found with

$$G_{\mathrm{late}} = G - 10\log(1 + \log^{-1}C_{80}/10).$$

It was shown in Fig. 8 that (1-IACC) is highly correlated with the lateral fraction LF. Hence $(1 - \mathrm{IACC}_{\mathrm{late}})$ can be substituted for $\mathrm{LF}_{\mathrm{late}}$, so that their formula, revised to use widely available data [7], becomes

$$\mathrm{LEV}_{\mathrm{calc}} = 0.5G_{\mathrm{late,mid}} + 10\log(1 - \mathrm{IACC}_{\mathrm{late,mid}}) \quad \mathrm{dB}.$$

Using data from [7], the listener envelopment $\mathrm{LEV}_{\mathrm{calc}}$ for 10 well-known halls is given in Table 2.

Table 2. Listener envelopment for 10 well-known halls.

Hall	$\mathrm{LEV}_{\mathrm{calc}}$
Vienna, Musikvereinssaal	2.0
Amsterdam, Concertgebouw	1.4
Berlin, Konzerthaus	1.2
Tokyo, TOC Hall	1.0
Tokyo, Suntory Hall	0.4
Boston, Symphony Hall	0.3
Berlin, Philharmonie	−0.2
Baltimore, Symphony Hall	0
Sapporo, Kitara Hall	−1.5
Buffalo, Kleinhans Hall	−2.2

Anyone who has listened to music in these halls will agree that the degree of listener envelopment is greater in the upper group of four halls than in the lower group of four halls. Boston is appreciably lower than Vienna because, as shown in Table 1, the measured sound strength G is lower.

A question needs answering: "Is this measurement $\mathrm{LEV}_{\mathrm{calc}}$ unique, or is it highly correlated with other common measures?" Fig. 12 shows plots of $\mathrm{LEV}_{\mathrm{calc}}$ versus total strength G_{mid} and total room absorption $(S_{\mathrm{tot}}\alpha_{\mathrm{sab}}) \times 10^{-3}$. For all but the Buffalo hall the correlation is high. Buffalo has both exceptionally low G_{mid} and low $(1 - \mathrm{IACC}_{\mathrm{late}})$.

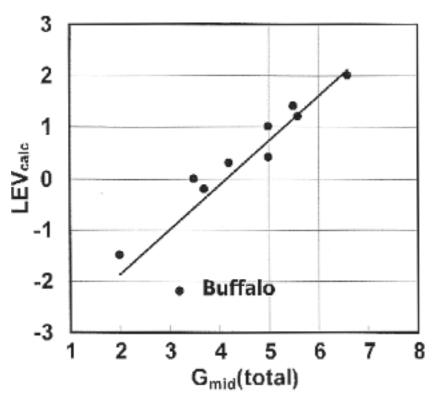
9 SUMMARY

1) Sabine absorption coefficients should be allowed to go above 1.0, and, if so, there is always a definite relation between Eyring and Sabine coefficients.

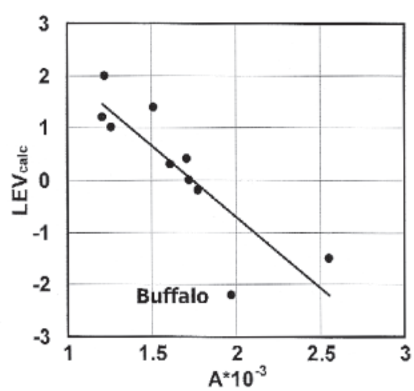
2) When calculating reverberation times, the sound absorption coefficients used must have been determined in rooms of nearly the same shape and size, with the absorbing surfaces in the same locations. Audience area and not audience count should be used in determining audience absorption, and the slope of the audience should be used to determine its area.

3) There is a high correlation between measurements of the low-frequency lateral fraction LF and the midfrequency binaural quality index (1 − IACC).

4) Listeners determine the direction from which the sound is coming during the first 100 ms, after the direct sound arrives. At about 100 ms the upper limit of the first



(a)



(b)

Fig. 12. (a) $\mathrm{LEV}_{\mathrm{calc}}$ versus total strength G_{mid}. (b) $\mathrm{LEV}_{\mathrm{calc}}$ versus total room absorption $(S_{\mathrm{tot}}\alpha_{\mathrm{sab}}) \times 10^{-3}$.

wavefront is reached. Also, early reflections before about 100 ms act to widen the apparent source width ASW.

5) Listener envelopment LEV occurs only after the upper limit of the first wavefront is reached, and then the direction of the sound source is no longer apparent.

6) Listeners judge the loudness of an orchestra in a hall to be the same in remote seats as in front seats, even though the measured strength *G* decreases with the distance from the stage.

7) Listener envelopment LEV can be calculated by a new formula that includes the sound strength G_{late} and the late lateral energy as measured by (1-$IACC_{late}$), where "late" means after about 80 ms. Data for LEV_{calc} are averaged in the 500–2000-Hz octave bands.

8) For most halls, calculations of LEV are highly correlated with the overall *G* (not late) and the total room absorption $S_{tot}\alpha_{tot}$, except when either or both are weak.

10 POSTSCRIPT

Since the Heyser Lecture, Hidaka et al. [22] have completed a comparison of shoebox and surround halls based primarily on the growth of sound in the first 200 ms after the arrival of the direct sound (like the irregular curve in Fig. 3), measured at a number of seat locations in each of the unoccupied halls. They also measured the sound levels versus the distance from the stage. The average sound levels in the 125/250-Hz bands fell off by about 2 dB in classical shoebox halls at a distance of between 10 and 40 m from the source on stage, and by about 4 dB in surround halls. In the 500/1000-Hz bands the levels decreased by about 3 dB in the former and by 5 dB in the latter. The growth-of-sound curves determined at many seats in each hall were plotted on one graph. The range of the sound levels between the highest and lowest of these curves for the 125-Hz band was found to be approximately 12 dB for a surround hall and 6 dB for a classical hall. However, if one rules out the curves for about 25% of the seats in a surround hall where the deviations were greatest, it is found in both types of halls that the curves for the growth of the sound in the first 200 ms at 125 Hz had nearly the same shape and nearly the same spread of levels, namely, 6 dB. However, the mean level for the best behaved 75% of the seats in the surround halls was about 7 dB lower than the mean level for 100% of the seats in the shoebox halls. In addition, a new technique for looking at texture was presented, and it indicated somewhat better textures in shoebox than in surround halls. In summary, these data show that there are significant differences in the sound in 25% of the seats in surround halls, but that in the remaining 75% the sound quality is about the same as in shoebox halls, except for about a 6-dB difference in levels and some texture differences.

11 ACKNOWLEDGMENT

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