IN SEARCH OF A NEW PARADIGM: HOW DO OUR PARAMETERS AND MEASUREMENT TECHNIQUES CONSTRAIN APPROACHES TO CONCERT HALL DESIGN?

Larry Kirkegaard and Tim Gulsrud
Kirkegaard Associates
801 W. Adams
Chicago, Illinois 60607
and
954 Pearl Street
Boulder, Colorado 80302

Introduction

Concert hall design is known to be part art and part science. While the development of the science side of concert hall design has brought real and significant progress to the field especially over the last 50 years, the quest to reduce concert hall acoustics to a set of parameters has also narrowed our vision and range of enquiry from what is truly required to achieve excellent acoustics. In this article we take a critical view of the current scientific paradigm for concert hall design, explore some of its shortcomings, and offer suggestions for new ways to approach this complex subject in a more holistic and multidisciplinary manner. Real progress in concert hall design will require not only building on the scientific understanding already achieved, but also making closer connections to the art forms being performed there.

> *"Our computers can collect terabytes of data at blazing speeds, but those data must be guided by artful listening, with deep conviction that there is much more that we need to learn."*

The problem is not that scientifically developed parameters are incorrect, but that they are insufficient for the task of designing acoustically superior concert halls.

What do the parameters miss?

Acoustics researchers have contributed to the development of parameters that many acousticians use in their design of concert halls and other performance spaces. While these parameters have been helpful in focusing designers' attention to important acoustics qualities, rigorous application of these parameters does not guarantee excellent acoustics.

A wide range of acoustics parameters is found in the literature. A good example is the ISO 3382 international standard, which includes a helpful summary of the most widely used parameters in room acoustics.[1] In addition to the classic reverberation time, this standard divides parameters into other categories including sound strength, early decay time, balance of early and late energy, and early lateral energy. Table 1 below summarizes and describes the subjective definition of these basic room acoustics parameters, along with some other widely used ones.

Notwithstanding the apparent validity of these parameters, we maintain that they are insufficient. They simply do not address all the acoustical qualities that are critically important to achieving great concert hall acoustics. During our interactions with musicians and other critical listeners in concert halls, we regularly hear comments such as:

Clarity measurements are in the correct range, but the sound is muddled and unclear…
The sound is unbearably harsh above a *mezzo forte* dynamic…
The bass sounds emasculated and lacks impact…
The celli are strong, but I cannot hear the double basses…
The core of the tympani sound is missing…
I cannot hear the soloist above the orchestra…
Some instruments sound disembodied, like their sound is coming from the wrong direction…
The balance between winds and strings is not right…
I cannot hear my colleagues across the orchestra…

These of course are just a few examples of the many comments we encounter in our consulting practice. But, they illustrate how very real acoustics issues tend not to fit very

Table 1. Summary of frequently used room acoustics parameters

Category	Parameter	Subjective Definition
Room decay time	T_{30}, T_{60}	Lingering of sound when music stops
Early decay time	EDT	Sense of reverberance
Sound strength	G	Loudness
Early/late energy balance	C_{80}, D_{50}, T_s	Clarity, definition, balance between clarity and reverberance
Early lateral energy	LF, IACC	Spatial impression, apparent source width
Onstage hearing	ST_{early}, ST_{late}	Musicians' hearing of selves and others

neatly into typical parametric categories.

The imbalance among different instrumental sections of an orchestra is one example of the shortcomings of our existing parameters. There is no widely accepted parameter to describe orchestral balance, probably because it is influenced by such a large number of factors including accuracy of acoustics at the conductor's position, musician placement, riser configurations, instrument directivity, musician playing technique, repertoire, and specific sound reflection paths in the room. In a situation as complex and subjective as this, it seems unlikely that any single parameter for orchestral balance could emerge. Yet the issues remain critically important. We suggest that significant new progress in concert hall design will require delving into complex and multidisciplinary issues such as these.

When has 'average' ever described something of extraordinary beauty?

Another problematic aspect of our room acoustics parameters is that they tend to be excessively averaged over space, time, and frequency. While making measurements at a limited number of seating positions is a practical reality in the consulting world, it is too easy to assume that the room is "well-characterized" even if the number of measurement positions greatly exceeds those outlined in the ISO 3382 standard. Understanding the differences among various seating locations may be even more important than their averaged values. The Swiss Alps would be of little interest if we observed only average values—a high plateau covered with rocks, pine needles, and alpine flowers under a thin layer of snow and ice.

Parameters that depend strongly on direct sound and early reflection structure can be especially misleading if averaged over seating locations, since the most interesting and significant qualities of these parameters are often *how* they vary within the room. The variation of Early Decay Time (EDT) in a hall with deep under-balcony areas is a good example of this.[2] A single room-averaged EDT value, as typically reported, would entirely miss the relevant, and perhaps obvious, point that a listener will feel disconnected from a full sense of enveloping reverberation if seated under a deep overhang.

Unoccupied vs. occupied data

Acoustics characteristics in halls change when musicians and audience are present. Yet the vast majority of room acoustics data available for performance spaces is based on unoccupied measurements.[3] While some data for occupied halls is available, not enough is known about the influence of an audience and/or orchestra on the acoustics parameters, especially on those other than reverberation time. All parameters that are influenced by the strength of direct sound are rendered inaccurate if they do not account for the fact that audience heads obscure listeners' access to that sound.

Modern multi-channel measurement systems make it feasible, however, to acquire impulse response data efficiently and simultaneously at multiple positions in an *occupied* concert hall. With careful planning, the audience and musicians need to remain quiet only 20 to 30 seconds while the test signals are played and recorded in many positions in a hall. In our experience, audiences find this measurement process to be entertaining, especially if there is a very brief explanation of their role in changing the acoustics and the reciprocity of noise transfer from the audience to the stage. Crinkling a candy wrapper in front of a very quiet audience dramatically demonstrates that if gentle *pianissimo* sounds of the orchestra are heard everywhere in the hall, the quiet sounds of opening a cellophane-wrapped candy are also perfectly audible everywhere in the hall. Such brief moments provide unique opportunities for outreach and education to the general public. When concertgoers and musicians are engaged in the measurement process, we acquire much needed acoustical data for occupied halls. Moreover, audiences become engaged directly in meaningful research aimed toward making real improvements for both the audience and the musicians.

A different measurement approach

We believe that a useful approach for concert hall acoustics investigations is to focus on understanding the specific phenomena that determine the character of a hall, rather than focusing on a hall's statistical characterization. Within this framework, we first listen to music carefully in the room—ideally during a rehearsal—and note the good, not-so-good, and bad acoustical/musical qualities throughout the space. After listening to music, we explore the unoccupied room with a steady-state full spectrum sound source placed on the stage. This greatly facilitates listening for timbral balance, evaluating evenness of sound distribution, and identifying particular (sometimes anomalous) reflection paths. Since a steady-state sound source does not easily reveal arrival time of reflections, listening also to a loud, sharp-clicking metronome is very useful for understanding time domain characteristics. Only after we develop a full grasp of the various subjective qualities and variances of a space do we pursue instrumented measurements. Those measurements seek first to unravel any mysterious observations before documenting what may be a 'typical' condition. To the extent possible, such observations and measurements are ideally made in both the unoccupied and occupied hall.

The goal through all this is to understand the space as a whole as well as the assemblage of its parts. When we identify particular seats that are notably good, bad, or just 'unusual' acoustically, we measure room impulse responses at those locations often with a highly directional listening and recording device to discover and help extract the most valuable information in the data—perhaps a late-arriving reflection, a series of reflections with limited frequency response, or an area of grossly uneven sound distribution.

A curious example

An anecdote from recent experience in a well-known opera house may serve as a useful example of this phenomenological, rather than statistical, approach to acoustics. In this case, we had been made aware of concerns about the sound of the orchestra in the pit being overly loud at certain

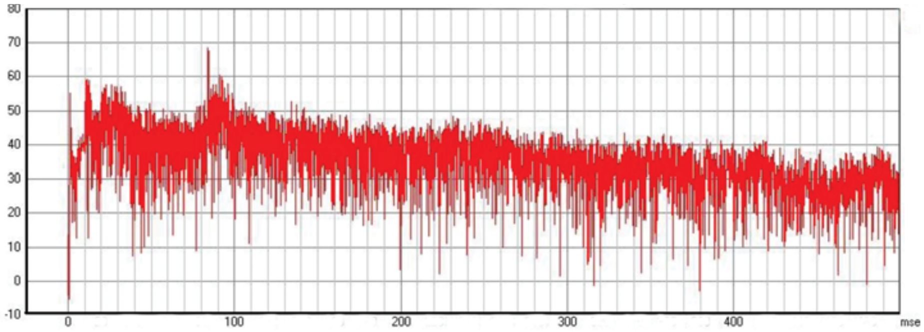

Fig. 1. Room impulse response measured on the main floor of an opera house with a loudspeaker sound source in the pit.

positions on the main floor. We began by listening to music in the space during a rehearsal to become familiar with the space as a whole, and to understand in particular the complaints on the main floor. We noted a strong upward shift in the aural image of the pit orchestra. The strength of this upward shift was caused by a long radius dome covering most of the ceiling in front of the balcony. Clearly this was one of the sources of instrumental/vocal imbalance. Were there others?

After the rehearsal, we placed an ILG fan[4] in the pit. With this venerable, yet underutilized, constant sound-power source we were able to quickly identify those areas of the main floor that received strong reflections from portions of the concave ceiling overhead. In this case, the reflections were clearly audible without any special listening device, and did not require "golden ears" to detect. Stagehands and administrators joined us in the exploration and easily could hear the effects of the focusing geometry. With a loudspeaker sound source in the pit, we then measured the room impulse response illustrated in Fig. 1.

Figure 1 shows the direct sound arriving at 0 ms, but at a low level since there is no line-of-sight to the sound source placed in the pit. The "interesting" feature of this particular impulse response is the strong single reflection at about 83 ms followed by a cluster of slightly-less-strong reflections that all arrive between 83 and 100 ms. These arrival times correspond to path lengths from the elliptical dome ceiling in this hall. The combination of these focused ceiling reflections is the loudest sound heard at this position, and the measurement clearly demonstrated the upward image dislocation and balance issues that we had experienced during the rehearsal.

The subjective experience caused us to make the objective measurement, but this phenomenon might have been missed if our measurements had been based only on parameters averaged over many seat positions or if the impulse response had been integrated over time to calculate an energy-based parameter. The concentration of energy in this time region was not about total loudness or clarity, but rather about confused clarity, displacement, and imbalance, none of which are addressed by typical parameters!

Most importantly, this approach gives primacy to actually listening in concert halls, and if implemented more widely in the room acoustics community, we hope will result in new parameters that relate more closely to the acoustical problems and issues encountered in concert halls, rather than our current parameters that tend to limit and constrain our view of concert hall acoustics.

Imperfections of the "perfect" omnidirectional sound source

The vast majority of acoustics parameters used by room acousticians are based on the use of omnidirectional sound sources. An omnidirectional source is understandably attractive from a theoretical point of view, since it should most easily allow different spaces to be compared. After all, if two different rooms are excited by the same sound source emitting equally in all directions, then should this not clearly reveal the aural differences between the two halls? This is not necessarily so…

Musical instruments are generally highly directional, with their sound radiation patterns varying with frequency in complicated ways.[5] Loudspeakers used in amplified performances are not omnidirectional by design. Listeners perceive aural phenomena in concert halls that are influenced strongly by the sound directivity of the source. For example, a rear wall echo is a simple acoustical phenomenon that can be experienced even by casual listeners in an auditorium, and is, at times, considered to be a room acoustical defect. Rear wall echoes are most noticeable with highly directional sound sources, such as a trumpet or directional loudspeaker aimed at the rear wall. If measured with an omnidirectional sound source, however, an echo may not be especially noticeable—even to a discerning eye studying the energy decay curve—simply because there is not enough sound energy concentrated into the direction of interest.

The dodecahedral loudspeaker, or "dodec," commonly used for room acoustics measurements is not truly omnidirectional across its usable frequency range. These measurement loudspeakers begin to exhibit pronounced lobing above approximately 1 kHz,[6] and the influence of this directivity on measured room impulse responses and parameters is not well understood. This also calls into question how easily high frequency data taken in different halls can be properly compared, since a slight re-aiming of the loudspeaker might significantly change the results.

While we would not argue that dodecs should be eliminated completely from the room acoustician's toolbox, we do propose that our toolbox should be expanded to include other types of sound sources so that conclusions drawn from them might have closer connections with the acoustical phenomena we experience as listeners. One needs only to walk around a dodec while it is emitting pink noise to realize that its distribution pattern is a bit like an acoustical mirror ball!

Recent measurements we have made with small directional loudspeakers have proven to be useful for documenting particular reflection paths and highlighting surfaces of interest.[2] It is especially interesting to note that the reverberation time is largely independent of source directivity, while other parameters that depend heavily on the direct sound and early reflection sequence (e.g., Early Decay Time, Early/late Energy Balance, Loudness) vary strongly with source type. Perhaps this characteristic could be exploited to develop a set of "directivity dependent parameters" that would more closely resemble those experienced by listeners in a hall. Other recent work has explored the possibility of using multichannel loudspeaker arrays to simulate the sound directivity of musical ensembles.[7, 8] The aim of this work has been to develop sound sources that excite a room in a more realistic way than the dodec.

Why do we squeeze our frequency range of interest?

No pianist would be content if asked not to venture lower in frequency than the octave below middle C (i.e., fundamental frequency of approximately 125 Hz) on the keyboard, just as no recording engineer would consider limiting musical recording to frequencies below 4 kHz! (See Fig. 2.) Why then, have we in the room acoustics community limited our frequency domain to the octave bands between 125 Hz and 4 kHz?

The answer probably lies in the limitations of the equipment historically used for room acoustics measurement. The typical dodec, probably not coincidentally, has a usable frequency range between about 100 Hz and 5 kHz. A large portion of the available room acoustics data has been collected using this sound source.[3] Another major factor is that laboratories used for sound absorption measurements are not typically qualified at lower and higher frequencies,[9] and so we do not have reliable data for building materials outside the standard frequency range.

Despite this, loudspeaker technology with significantly wider frequency bandwidth is readily available today. Technology will hopefully result in a greater proliferation of data measured in concert halls that extends below the 125 Hz octave band.

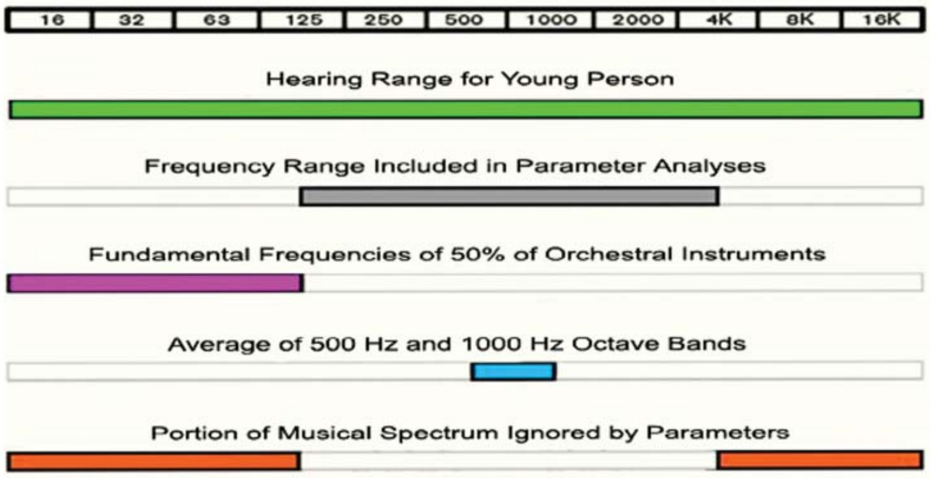

Fig. 2. Comparison of frequency ranges.

What is bass, really?

It is apparent from Fig. 2 that many orchestral instruments have important sound energy below 100 Hz. The low frequency fundamentals of pianos, double basses, contrabassoons, bass saxophones and bass clarinets, tympani, and bass drums all occur in this frequency region. One of the most frequent complaints heard in concert halls is that these instruments sound weak, and that the hall therefore has "poor bass response." In the amplified music realm, subwoofers are used to reinforce or reproduce sound energy between approximately 30 and 100 Hz. Concertgoers and mix engineers alike know this as sound that is felt as much as it is heard.

Based on these considerations, we suggest that room acousticians have largely neglected "real" bass, and any parameter or measurement that does not take into account energy below 100 Hz has little hope of being a proper measure of bass response.

In our consulting practice and listening experience in concert halls throughout the world, we have observed the important role that heavy building materials play in providing deep, rich, palpable bass. Old concert halls often have strong bass response not because they are old, but because they were constructed with heavy masonry walls that reflect long wavelength sounds efficiently.

As an example, London's Royal Festival Hall was originally designed with an interior lining of thin wood paneling to provide low and low-mid frequency sound absorption.[10] The resulting reverberation time spectrum in this hall unfortunately lead to complaints of poor bass response by musicians, listeners, and critics. Correction of this issue was a major factor leading to the acoustics renovation completed in 2007.

The bass response improvements to Royal Festival Hall required removal of all the thin wood paneling from the upper and lower side walls and then infilling the voids with massive materials to form a bond back to the heavy concrete and brick structural walls of the original building. The other low frequency improvement was the replacement of the 35 mm shredded-wood/plaster ceiling with solid 100 mm thick plaster. Reverberation time data for this hall are shown in Fig. 3.

In Fig. 3, it is clear that low frequency reverberation times increased significantly after the renovation, and the improvement to bass response is profoundly appreciated.

While the reverberation data for the 63 Hz octave band in Fig. 3 seems to correspond well with our subjective impressions in this instance, we suggest that reverberation times may not ultimately be the best measure of bass response. Sound levels at low frequencies (i.e., below 100 Hz), or perhaps

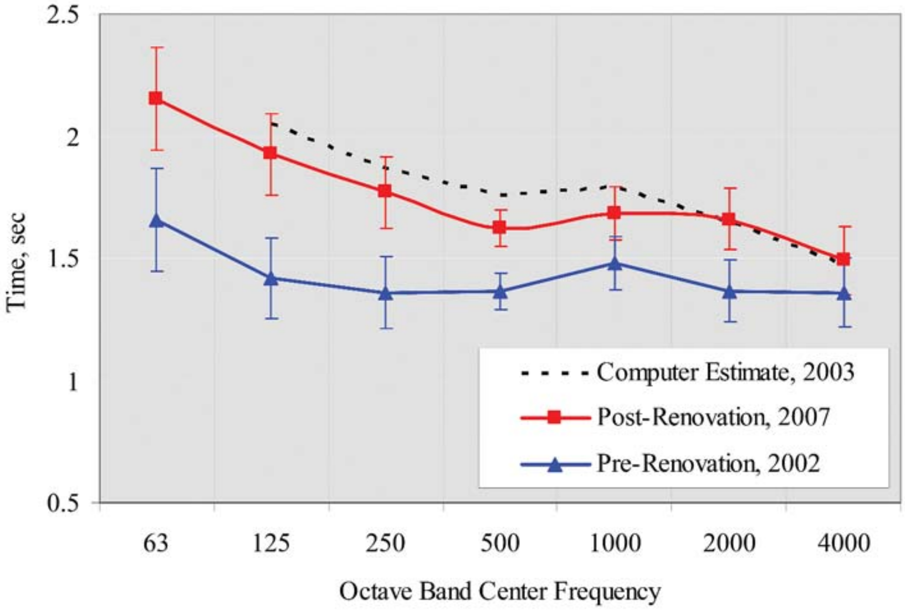

Fig. 3. Reverberation Times (T_{30}) measured and calculated by Kirkegaard Associates in Royal Festival Hall, London. Error bars indicate the standard deviation of the measurements, which were made with an orchestra seated on the stage and full audience.

sound build-up curves, could be considered as alternative methods of analyzing the level and time behavior of low frequency sound.

In fact, the bass ratio, a traditional measure of bass response, has fallen out of favor as a predictive parameter for bass response in concert halls. Most researchers appear to be more focused now on the overall strength of low frequency energy, rather than its duration. This leads to parameters like G_{80}(125)[11] instead of a ratio of reverberation times, which probably is a move in the right direction, but still does not take into account energy below 100 Hz. A recent study of venues for amplified music in Denmark has emphasized the importance of reverberation times in the 63 Hz octave band, in that case as a measure of suitability for rock music performance.[12]

High frequency brilliance versus harshness

The high end of the frequency spectrum deserves greater attention as well. Reverberation times tend to fall off at high frequencies in any room because the air absorbs high frequency sound more efficiently than low frequency sound. This may be a reason why room acousticians have tended to neglect high frequency information above 4 kHz or so. Despite this, high frequency sound plays a vital role in some of the more subtle qualities that distinguish good concert halls from great concert halls. While a "brilliant" sound quality is desirable, an over-abundance of high frequency sound can result in harshness.

Figure 4 illustrates portions of the spectrum of a violin that relate to subjective qualities of violin tone.[13] It is interesting to note here that the 'F' region, which extends above 4 kHz, and therefore beyond the reach of standard room acoustics parameters, is related to a sharp or harsh tone quality. The regions 'D' and 'E' are associated with brilliance. Perhaps a new high frequency room acoustics parameter that somehow relates the relative levels of these portions of the spectrum could be developed to distinguish between brilliance and harshness in a concert hall? We suggest that the degree of attenuation between the 'E' and 'F' portions of the spectrum may be significant in addressing this question.

Another aspect of harshness we have observed in our consulting practice is the tendency of a room to sound harsh as the dynamic level is increased. An orchestra playing at a *pianissimo* or even *mezzo-piano* dynamic may sound lush and beautiful, but increasingly harsh and strident at *forte* and *fortissimo* dynamics. While this effect begins with the instruments themselves, it would be useful to explore the role that

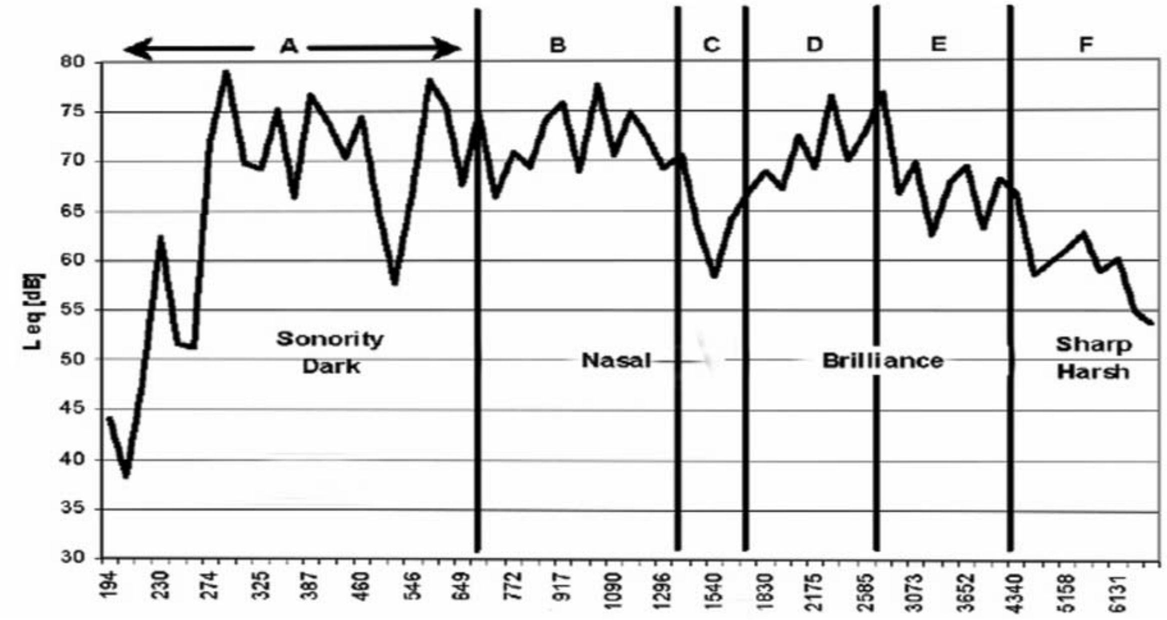

Fig. 4. Plot of a violin sound spectrum[13] (With permission of A. Buen).

Fig. 5. Fabric panels in place over the lower "sawtooth" walls in the Concert Hall at the Sydney Opera House.

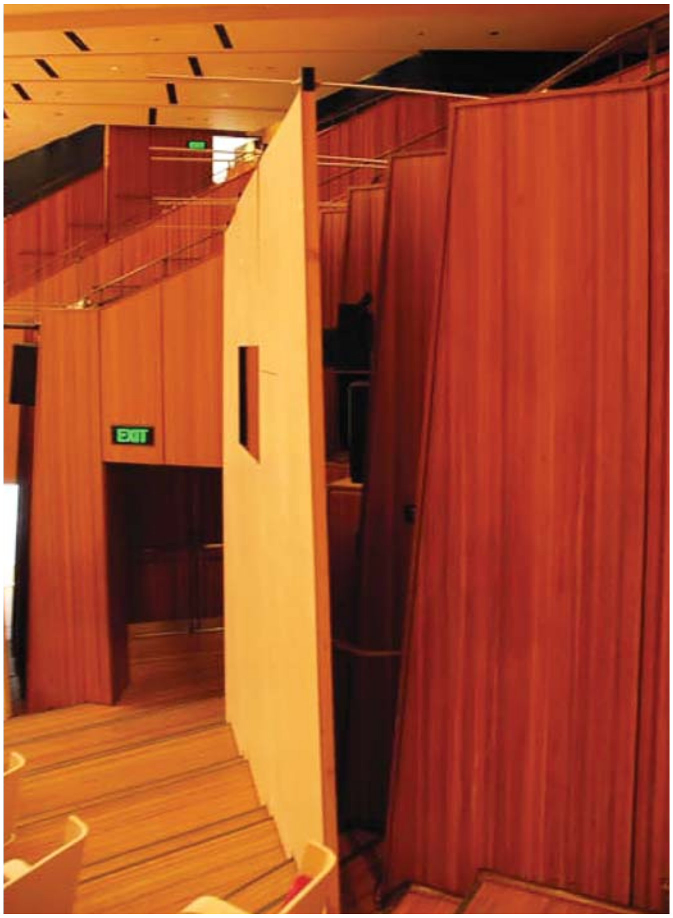

Fig. 6. One of the adjustable medium density fiberboard (MDF) panels covering the lower sawtooth walls during the 2009 acoustics trials in the Concert Hall at the Sydney Opera House.

the room might play in this phenomenon. One common thread we have noted is that rooms with large amounts of fine and medium-scale sound diffusing shaping on the walls and ceiling tend to have this undesirable quality of harshness at high dynamic levels.

One illustrative example of this is from the Concert Hall at the Sydney Opera House. Harshness in the stalls level seating and on stage was acknowledged as a serious acoustical defect in this hall in a number of independent studies conducted between 1996 and 2003.[14] Our own studies of this issue concentrated on the acoustics impact of the "sawtooth" shaping of the lower sidewalls flanking the stage and stalls seating.

This wall shaping was presumably intended to provide diffused lateral reflections to improve listening conditions, but the sound reflected by the sawtooth paneling was harsh and abrasive for audiences listening in the stalls seating as well as to musicians on stage. Musicians felt they could not make a beautiful sound in the hall, and audiences concurred. Careful listening pointed to the sawtooth walls as the source of the harshness, and as a simple means of demonstrating this to listeners and musicians, we suggested a mock-up with fabric hung in front of the saw tooth walls, pictured in Fig. 5. The fabric made a dramatically positive contribution to the quality of the musical sound even though it diminished the loudness and enveloping quality one would desire from these side-arriving reflections.

The temporary fabric was installed in 2007 and has remained in place for three years awaiting funding to replace it with timber paneling, which would provide sidewall reflections rather than absorbing them.

As proof of the timber paneling concept, and for public as well as stakeholder encouragement in this iconic space, we prepared a second demonstration in 2009 that replaced the fabric in front of the sawtooth walls with sealed medium density fiberboard (MDF) panels. The MDF panels were designed to be adjustable to allow experimentation and optimization of wall angles as can be seen in Fig. 6. Over the course of the trials, the orientation of the panels was optimized in plan and section. Improvements were clearly noticeable to musicians onstage, but the improvements were most significant in the stalls seating, borne out by consistently positive comments from both audience and musician surveys.[15]

This experience was one of several that have convinced us that a better understanding of the positive and negative influences of sound diffusion is essential for progress in concert hall design. In the case of the Sydney Opera House Concert Hall, less diffusion from the essentially flat MDF panels was clearly preferred. Unfortunately, this acoustics trial did not reveal the precise mechanisms at work here. Is it low level edge-diffracted sound from the points of the sawtooth shaping? An imbalance between high and mid-frequency sound levels? "Smearing" of the reflection structure in the time domain? Perhaps some combination of all these effects?

A new paradigm?

As room acousticians, we are at a pivotal moment in our field. Our computers can collect terabytes of data at blazing speeds, but those data will not truly progress the science of concert hall acoustics unless guided by artful listening, with deep conviction that there is much more that we need to learn. The great concert halls of the world remain an invaluable resource for critical listening and investigation, but we should not approach them merely as technicians. Instead, we should approach them with eyes and ears wide open, guided by the wisdom of those who have pioneered our field. Our vocabulary needs to be increased to include parameters that relate better to the music performed in concert halls, and must grow and change as those musical art forms evolve. Does this amount to a paradigm shift? Yes!

A new paradigm for concert hall design is needed in which we approach buildings in an ears-first, multidisciplinary way that properly focuses on listening to what spaces and performers can tell us that inform, enrich, and temper our work.**AT**

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[3] L. L. Beranek, *Concert Halls and Opera Houses: Music, Acoustics, and Architecture*, 2nd ed. (Springer-Verlag, New York, 2006).

[4] The ILG fan is a reference sound source consisting of a centrifugal fan wheel driven by a ¼ HP motor, manufactured by ILG Industries, Inc. It has usable sound output down to approximately 50 Hz, is more omnidirectional than a dodec, and we find it more pleasant to listen to than pink noise from a loudspeaker!

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When a wise man advised "find a career around what you most enjoy doing," Larry Kirkegaard listened to the advice and continues to listen—to clients, to performers, and especially to spaces to discover the secrets of great acoustics. He thrives on the collaborative challenges of designing wonderful spaces that enhance the joys of listening and performing.

Pursuit of excellence drew Larry to Harvard College as an undergraduate and then to Harvard's Graduate School of Design for studies in architecture and acoustics. He interned at the acoustics firm Bolt, Beranek, and Newman while completing his MArch degree in 1964. These steps began the journey that has led to working on many of the world's most notable performing arts facilities and to earning a place among the world's leading acousticians.

The firm he founded in 1976 embodies the same pursuit of excellence with enthusiasm, dedication, spirit of collaboration, and extraordinary talent. The firm is privileged to work with passionate clients on extraordinary projects, collaborating with visionary architects, and professional colleagues… All who listened to the same wise career advice!

Tim Gulsrud is a Senior Consultant with Kirkegaard Associates, based in Boulder, Colorado. He received a B.S. in physics from the University of Oregon and a M.S. in physics from the University of Colorado, Boulder. During his work at Kirkegaard Associates he has been involved in several key projects including the Royal Festival Hall in London, the Sydney Opera House Concert Hall, the San Francisco Conservatory of Music, and currently the Studio Towers Renovation Project at Carnegie Hall in New York City. He has research interests in a wide variety of architectural acoustics issues including the use of computer modeling in consulting practice, room acoustics measurements, sound source simulation, and auralization. He is also active as a recording engineer and church musician, and was recently appointed Lecturer for the Recording Arts program at the University of Colorado, Denver.