T_{60} Slope Ratio Thesis

Reverberation vs Frequency Guidelines for Modern Architectural Acoustic Environments

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Abstract

The T_{60} Slope Ratio - symbolically $T_{60}SR_6$ or TSR - is a proposed standard for condensing six octaves (63 Hz – 2 kHz) of reverberant decay data into a singular-quotient, qualitative score for indoor performance, worship, and entertainment facilities.

It is a defining metric for scoring and grading the proportional relationship (i.e. ratio) between the longest and shortest of six reverberation (T_{60}) time values - measured or predicted - and applied to fully enclosed venues employing full range sound reinforcement systems.

In practice, legacy Bass Ratio and modern TSR goals are conflicting concepts. Bass Ratio goals and calculations were developed to support the idea that acoustic instruments and voices need a little extra assistance, via longer reverberation times in the lower frequency ranges.

TSR goals and calculations support the notion that those same low frequencies do not require extra reverberant support, but rather they need to be well contained. Longer low frequency reverberation is not needed, nor desirable, when a full range sound reinforcement system is used.

The TSR thesis is offered to advance and define a room's acoustic design objectives, and provide a simple *scoring* scale, and MOS (mean opinion score) grading vocabulary, from which acoustical design specifications can be initiated and evaluated.

1 The TSR Enigma

Modern loudspeakers are designed and optimized to perform as flat, or nearly flat, audio output devices. Therefore, shouldn't acousticians be designing the same nearly flat reverberant timbre into the rooms in which these loudspeakers operate?

Put another way: We have standards and design goals for speech intelligibility, but there are currently no universally defined standards for music clarity, nor acoustic performance goals for venues offering amplified music.

2 Background

Even before Sabine,[1] and the subsequent developments in the field of architectural acoustics, it was believed a concert hall's ability to support and sustain low frequency reverberation was desirable, yet at times difficult to achieve. Why was this important? Because low frequency (LF) and very low frequency (VLF) sounds - produced by acoustic instruments and voices - are weak and difficult to propagate into large rooms.

In the context of this backdrop much of the existing body of architectural acoustics design literature focuses on classical music, and the need to properly support acoustic instruments and voices. Yet today, there are many more performances of popular music, including rock, pop, and country. Classical orchestral music, opera, and ballet are no longer the mass-market entertainment draws they once were.

Fast forward to the 21st-century. Like it or not, live music, supported by powerful full-bandwidth sound reinforcement systems, sells tickets.

The quantitative expectations of today's audiences are higher than ever and easily met with the right equipment. However, one key reason the qualitative expectations aren't easily accommodated is poor room acoustics: specifically excessive LF and VLF reverberation and resonances.

In place of traditional concert halls, we now have multi-purpose performing arts theaters, strip mall and warehouse worship centers, casino ballrooms, sports arenas, and gymnatoria. Introduce thousands, if not tens of thousands of Watts of subwoofer amplification, and you can easily find yourself in a thunderous cacophony.

If we're lucky, such venues have installed some form of variable acoustic treatment, or at least some mid frequency (MF) and high frequency (HF) sound absorbing materials. The obvious examples are carpet, padded chairs or pews, fiberglass wall or ceiling panels, drapes, and maybe a little architectural shape for scattering and/or added modal complexity. Still, it's rare that any attention is paid, or treatment specifically assigned, to absorb modal and reverberant energy below 125 Hz.

Consequently, the problem is often compounded because MF and HF absorption - whether it comes in the form of soft finish materials and/or people - causes a dramatic imbalance in the reverberant character of a room. It's not uncommon to encounter an “acoustically treated” facility with T_{60}s that are two or three times longer at 63 Hz than at 2 kHz.

To further complicate things, ISO 11654, which defines absorption classes, does not even reference the 125 Hz octave band. This is possibly part of the fundamental problem, as many manufacturers don’t feel the need to test for or show absorption coefficients at or below 125 Hz.

In a recent study Margriet Lautenbach et. al., of Peutz BV concluded, “At least as important as the actual reverberation time is a flat reverberation spectrum, from at least 63 up to 4,000 Hz. Special attention has to be paid to the absorbing efficiency at low frequencies, i.e. the 63 and 125 Hz octave bands.

If the reverberation level at low frequencies is high, a soup of sound 'swallows' all higher frequencies and kills the definition. In order to achieve a clear and perceivable bass rhythm, in balance with the mid- and higher frequencies, the reverberation time in the 63 and 125 Hz octaves may not exceed the average RT (reverberation time) by more than 10%.”[2]

Note: While the T_{60} Slope Ratio thesis was developed independently, and without any prior knowledge of the works of Peutz, Niels W. Adelman-Larsen,[3] and others, the TSR guidelines correlate well with their findings.

3 The Challenge

As Leland Roth points out in his book, *Understanding Architecture*,[4] “Reverberation is frequency dependent: The length of the decay, or reverberation time, receives special consideration in the architectural design of spaces, which need to have specific reverberation times to achieve optimum performance for their intended activity.”

Our present-day challenge is that many if not most contemporary performance, worship, and entertainment venues cannot dissipate the massive amounts of LF and VLF sound energy as quickly as they are being produced, nor as quickly as the mid and high frequencies are produced and absorbed.

Dr. Niels W. Adelman-Larsen of Flex Acoustics in Denmark summarizes the problem this way: "Surveys among professional musicians and sound engineers reveal that a long reverberation time, at low frequencies, in halls featuring reinforced music such as pop and rock, is a common cause for an unacceptable-sounding event. Mid and high frequency sounds are seldom the reason for a lack of clarity and definition.

Calculations indicated a standing audience in a rock or pop concert venue will absorb five to six times the sound energy in mid/high frequency bands compared to low frequency bands. This indicates that if a venue has a disproportionately long reverberation time in low (bass) frequencies when empty, the difference between reverberation times will be even greater when it is filled with an audience.

Lower frequency sounds are, within the genre of popular music, rhythmically very active and loud, and a long reverberation leads to a situation where the various notes and sounds cannot be clearly distinguished."[3,5]

4 $T_{60}SR_6$ Defined

Submitted for consideration is the T_{60} Slope Ratio thesis, represented symbolically as $T_{60}SR_6$ or TSR. It is a new metric for scoring and grading the reverberant timbre of a room.

- T_{60} is the acronym for reverberation time, in seconds.
- SR_6 is the calculated Slope Ratio using the two extreme time values selected from the six octave centers, between 63 Hz and 2 kHz.

Frequencies above 2 kHz are intentionally excluded. Because of air absorption, naturally short T_{60} values, above 2 kHz, disproportionately skew the ratio. Similarly, while T_{60} measurements below 63 Hz are possible with modern dual FFT technology, implementing effective treatment in the 31.5 Hz octave band and below is currently an unreasonable expectation for most.

5 TSR Target Goals

The focus of this thesis is the decay time ratio of naturally occurring reverberation and resonances found in fully enclosed, unoccupied buildings. Again, the primary application is directed toward live performance venues, using sound reinforcement systems.

It is suggested here that to achieve an *Optimal* grade, the TSR score must fall between 1.11 and 1.20. See Figure 1 below for a complete listing of the various scores and grades.

$T_{60}SR_6$ Scoring & Grading Scale	
≤ 1.10	Good
1.11 - 1.20	Optimal
1.21 - 1.30	Good
1.31 - 1.50	Fair
1.51 - 1.70	Poor
Above 1.70	Bad

Figure 1: The Proposed TSR Scoring & Grading Scale

Regardless of a venue's mid-band T_{60} time or requirement, it is implied that the TSR guidelines remain a consistently viable metric. For example: In some traditional house of worship settings a T_{mid} (the average of the T_{60}s at 500 Hz and 1 kHz) of 1.50 seconds might be desired and appropriate. More contemporary houses of worship may require a 1.00 second T_{mid}. Given that, or most other T_{mid} prerequisites, the TSR goals and objectives do not change.

One general caveat: The TSR metric is best applied to rooms requiring a T_{mid} in the vicinity of 1.50 seconds, or less.

6 TSR Scoring & Grading

Much like the subjective MOS scoring that is applied to %ALcons or STI grading scales for speech intelligibility, the proposed TSR scoring and grading scale is defined by six numeric scoring tiers, and five grading adjectives, which most people can easily understand. Until more exhaustive testing is done to update the Figure 1 table, these denotations are proposed to describe the measured or predicted reverberant profile of a room.

Critics may say the goals are too aggressive. The author suggests they are not. Consider outdoor concert venues. When outdoor rock, pop, blues, rap and country events operate in free field conditions, no one seems to have a problem with the flat, near-zero T_{60}s. In many cases, these are the best conditions for high SPL sound reinforcement.

Why not strive for an *Optimal* objective between outdoor free-field acoustics, and tight, well defined indoor acoustics?

7 Application Limits

It would be great if the TSR protocol could be applied to all rooms; it can't. There are some practical limitations - guided by the true nature of reverberation. These defining guidelines should be factored into the TSR application and calculations:

A. Room Size – Not too big or small for true reverberation.

For best results, it's necessary to consider the room volume. Anything less than about 45,000 f^3 (~ 1,274 m^3) is too small for reasons related to the Schroeder frequency, which are outlined below. For reference: A room with interior dimensions of 61' x 37' x 20' (LWD) is 45,140 f^3

This guideline ensures the possibility of a diffusive reverberant field at 63 Hz. In other words, a room needs enough volume to support reverberation at this frequency.

Likewise, a room may be too big for meaningful analysis. Prescribing a specific threshold for what's too large is nearly impossible. The author suggests anything exceeding about 1,500,000 f^3 (~ 42,475 m^3) might be too large. Such large room volumes may not support a true reverberant field because the mean free path is becoming too long for a homogenous reverberant field to develop.

Expressed another way, rooms with seating for 7,000 to 10,000 or more may be approaching the upper size limit for true reverberation.

Important note: Rooms that are larger or smaller than those described above may have excess, non-diffusive, VLF resonant energy that needs mitigation. This energy is better identified in terms of *decay* time - caused by modal resonance(s) - rather than reverberation time.

B. Sound Pressure Level – Not too loud or soft

The emphasis of the TSR thesis leans toward powerful, extended-range sound reinforcement systems. When deployed, these systems are often capable of delivering much more than 100 dBc levels to an audience.

When sound levels increase, our ear's sensitivity at different frequencies changes dynamically.[6] The TSR scoring guidelines are based on mean sound pressure levels (SPL) between 80 and 105 dBc.

As audio levels get louder, the need for a low TSR score becomes even more important. Levels below 80 dBc are generally less and less problematic and can be given a little more latitude in scoring and grading.

C. Schroeder Frequency

The Schroeder frequency (F_s) delineates the approximate boundary between reverberant *ray* behavior above this point, and discrete room modes demonstrating *wave* behavior below it.[7] In other words, F_s identifies the frequency at which there is insufficient modal density to sustain diffusive reverberation, at or below the calculated frequency.

Per Schroeder's 1954 paper: Within the half-power (-3 dB) bandwidth of 63 Hz, a minimum of 10 Eigenfrequencies (a 10-fold overlap) should surround the target frequency. See more on modal density below.

F_s is also influenced by reverberation time. See Figure 2. Example: A 45,140 f^3 room (~1,278 m^3), with a T_{mid} of 1.25 seconds, will have an F_s of 63 Hz. If the same room has a 1.8 second T_{mid}, the Schroeder frequency moves up to 75 Hz.[8]

The *transition zone* includes frequencies between F_s and $4F_s$.

As stated above, F_s defines the initial (lowest) frequency, beyond which all lower sounds behave like waves. Once we know F_s it's necessary to multiply that frequency by four (4) to determine the upper limit of the transition zone ($4F_s$). $4F_s$ establishes the approximate point at which all higher sounds behave like light rays.

The transition zone consists of frequencies with ambiguous behavior; neither fully resonant/modal, nor completely diffusive reverberation. This is not a hard transition but a gradual one that occupies about two octaves of sound and includes all frequencies between F_s and $4F_s$.

D. Modal Density

The Bonello factor looks at how many modes exist in any third-octave band. According to the *Bonello criteria*, this function should be strictly increasing, per each 1/3-octave band, to reach a good distribution of modes.[9]

The 45,140 f^3 room cited above has 35 modal Eigenfrequencies in the third-octave band centered at 63 Hz. 35 is reasonably good density.

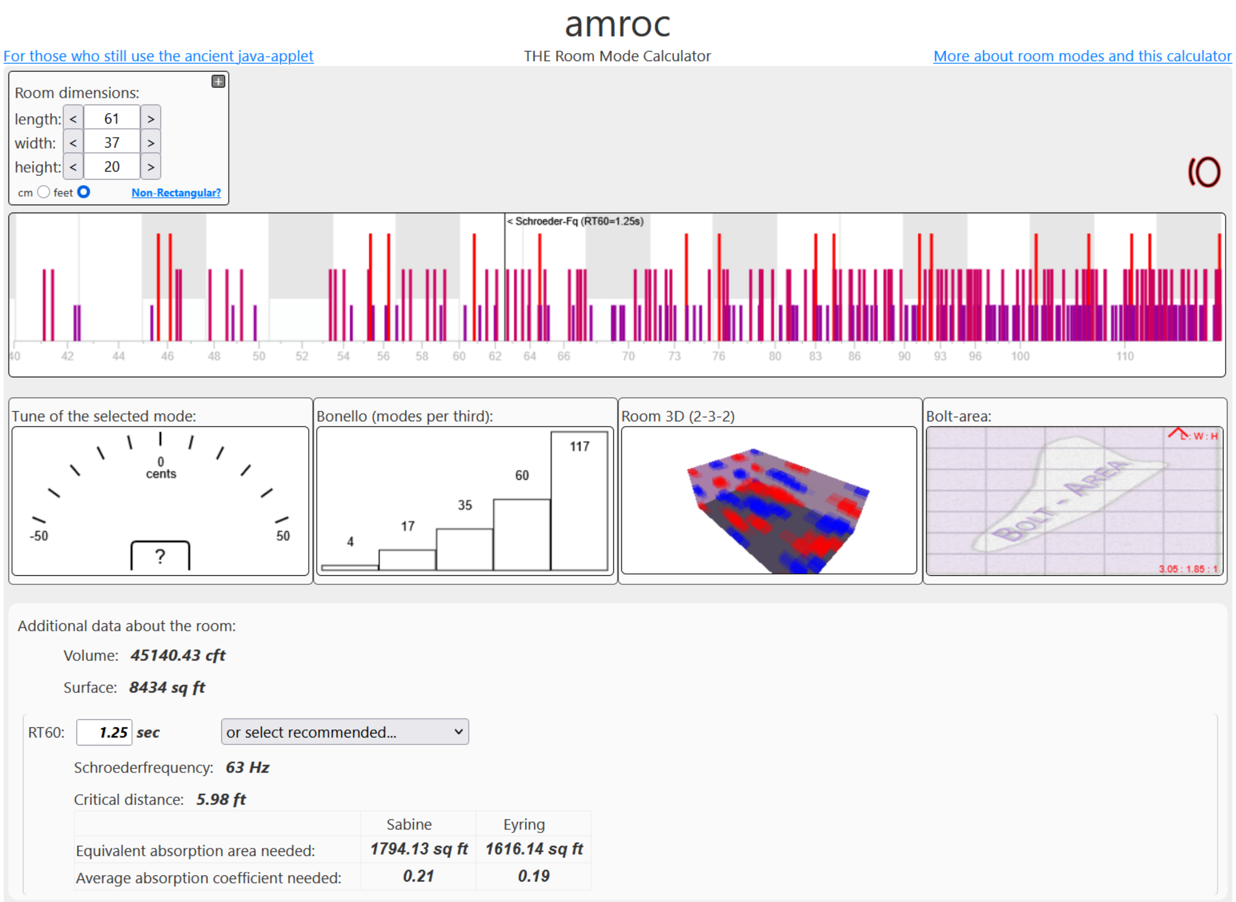

Figure 2: A screen shot from the AMcoustics room mode calculator 8 for a rectangular room. Note the room dimensions in the upper left corner and the corresponding room volume, Schroeder frequency, and Tmid target in the lower left corner.

8 Slope Asymmetry

It is common that T_{60} times gradually descend from longest to shortest, starting with the longest at 63 Hz. See examples in Figure 3 below. But this is not always the case.

The phrase slope asymmetry implies the longest or shortest times may occur at any of the six octave centers, not just the lowest and highest frequencies. As shown in Figure 4 below, a room may have a 1.78 second T_{60} at 63 Hz and a 1.39 second T_{60} at 2 kHz, but an even longer 1.96 second T_{60} at 125 Hz. If we only look at 63 Hz and 2 kHz the TSR score is 1.28 or *Good*. But, the longest T_{60} appears at 125 Hz, therefore the math needs to be applied using 1.96/1.39, which equals a score of 1.41, or only a *Fair* grade.

The takeaway is that specific *parametric*[10] room treatments should be applied to rectify this type of asymmetry.

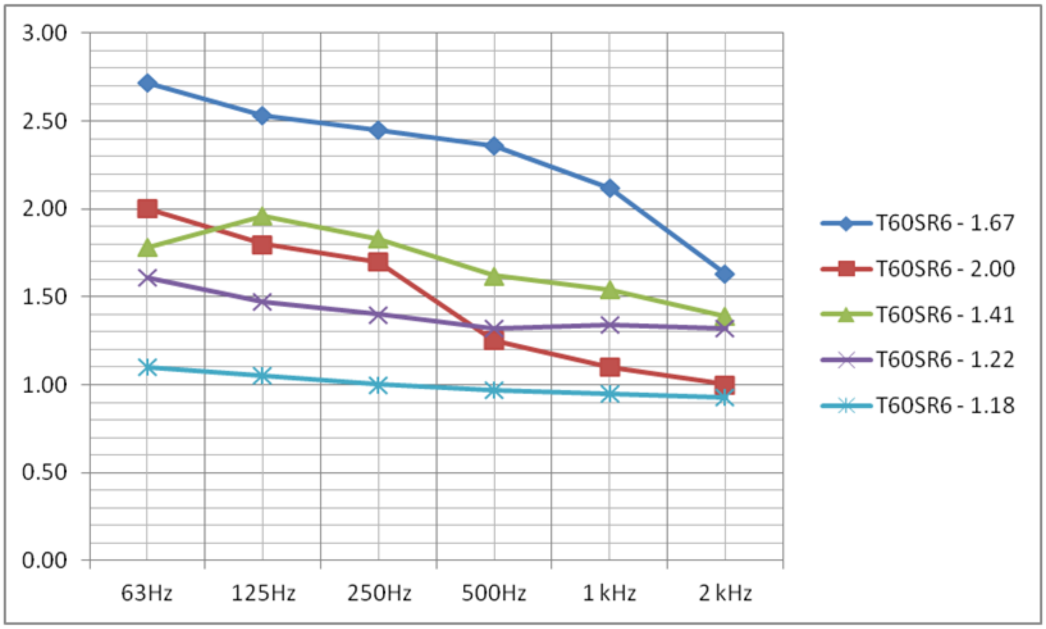

Figure 3: Examples of real world and hypothetical TSR curves and *Scores*. As shown in Figure 4, each *Score* displays one of the five *Grades*. Note the green line above, which is an example of an asymmetrical slope.

Seconds

Frequency						$T_{60}SR_6$ Score	Comments	Grade
63Hz	**125Hz**	**250Hz**	**500Hz**	**1 kHz**	**2 kHz**			
2.72	2.53	2.45	2.36	2.12	1.63	**1.67**	Recently Measured RIR	Poor
2.00	1.80	1.70	1.25	1.10	1.00	**2.00**	From Graph 1 BR Chart	Bad
1.78	1.96	1.83	1.62	1.54	1.39	**1.41**	Predicted Goal	Fair
1.61	1.47	1.40	1.32	1.34	1.32	**1.22**	Recently Measured RIR	Good
1.10	1.05	1.00	0.97	0.95	0.93	**1.18**	Targeted Goal	Optimal

Figure 4: A tabular representation of Figure 3 T_{60}s.

9 The Math

The TSR math is very simple. To find the slope ratio, divide the longest T_{60} by the shortest T_{60}. Use the two time-value extremes, regardless of frequency, between 63 Hz and 2 kHz. Note: Third-octave resolution can also be used if necessary.

Example: If a 63 Hz T_{60} of 1.90 is divided by the 2 kHz T_{60} of 1.20, the resulting ratio is 1.58:1. The TSR score is the ratio quotient, without the ":1" constant.

To put this example into further perspective, the 63 Hz T_{60} lasts 1.58 times longer than the 2 kHz T_{60}, which is a *Poor* result.

It is also proposed that the optimum time deviation between any two adjacent octave centers be limited to +/- one tenth (0.10) of one second.

10 Case Study

Because this thesis posits very new thinking, there is only one documented case study: a 3,000 seat, Southern California mega church - offering a very contemporary worship experience.[11]

During the planning phase, the client and author agreed to target goals of reducing the 63 Hz band T_{60} by approximately 1 second, while also reducing the T_{mid} to be as close to 1.25 seconds as budget, aesthetics, and logistics would allow.

By specifically targeting the 63 Hz band for custom treatment, along with large amounts of various broadband treatments for the mid and high frequencies, a TSR score of 1.22 was achieved.

Figures 3 & 4 above show this venue’s before and after T_{60} RIR (room impulse response) testing results. The before TSR score was 1.67, which was considered subjectively *Poor* to the client. After treatment, the room achieved a score of 1.22, which gets a *Good* grade.

We only have the anecdotal evidence of the professional audio staff, the facility manager, some regularly booked musicians, and various congregants - all of whom indicated the room was greatly improved. Their collective opinions (MOS) clearly moved the acoustical grade from *Poor* to *Good*.

While the author has pursued similar goals and treatment plans for many years prior to this case study, this project was the immediate precursor to the development of the formalized T_{60} Slope Ratio thesis.

11 Are There Other Useful Standards?

Do current standards exist to define and quantify the critical T_{60} times at each octave between 63 Hz and 2 kHz? It is suggested here that they do not. Examples:

A. Bass Ratio: Leo Beranek developed the concept of the Bass Ratio (BR), and recommended it be applied to classical concert halls. BR is the ratio obtained by dividing the average T60s of the 125 Hz and 250 Hz octave bands by the average T60s of the 500 Hz and 1 kHz octave bands.

In practice, BR and TSR objectives are conflicting concepts. Further, the BR calculations only factor four octaves of data. It is suggested here that four octaves are insufficient given modern musical genres and technologies. A BR T_{60} plot might look something like Figure 5 below.

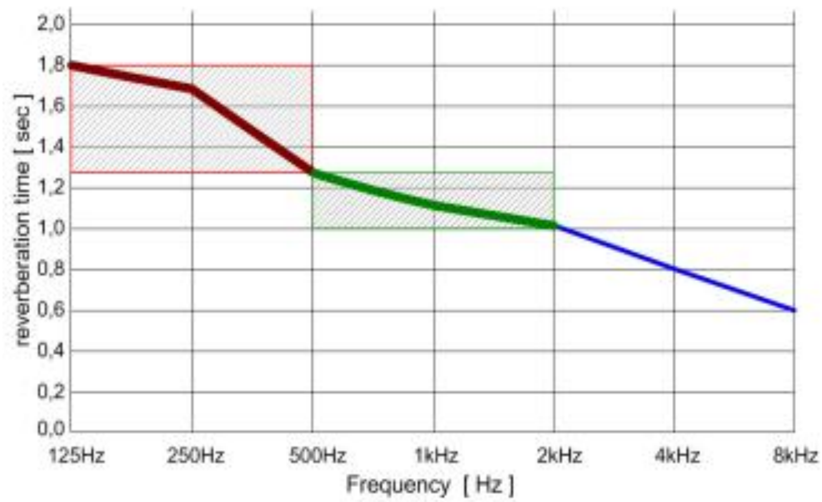

Figure 5: Example of a Bass Ratio histogram chart[12]

Using Figure 5 above, the BR works out to be 1.49:1 (1.75/1.175). Using the same chart, the TSR score could easily be 2.00:1, if we extrapolate up to a 2.0 second T_{60} at 63 Hz. A TSR score of 2.00 is considered *Bad*.

When the extrapolated BR chart above is laid over an *Optimal* TSR chart, and matched at 2 kHz, you get what is shown in Figure 6 below.

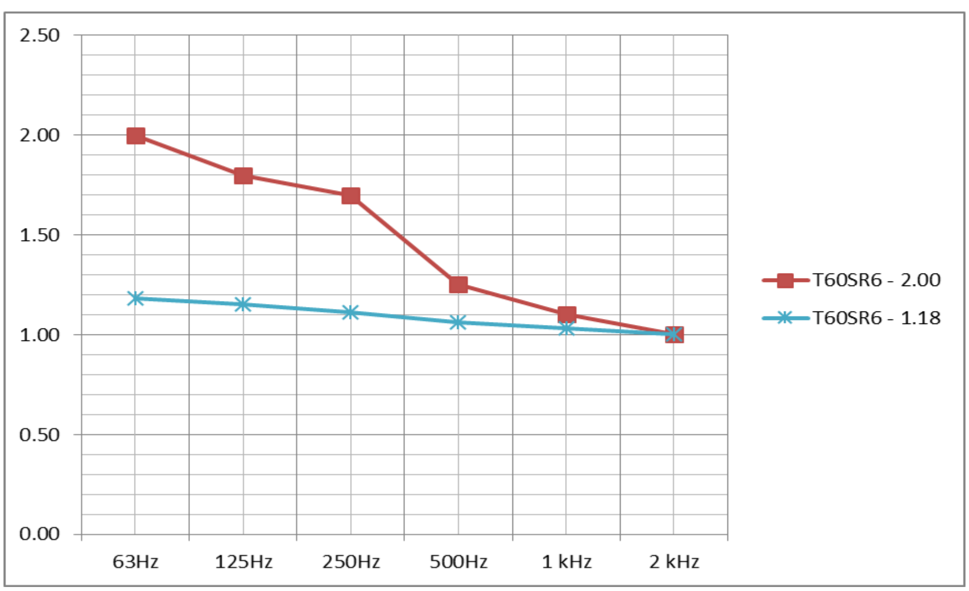

Figure 6: Notice the substantial time disparity in the bottom 3 octaves. Unfortunately, this is not an uncommon scenario.

B. ICA DIN 18041: This standard falls short for multiple reasons, but primarily because it states, "… that the standard should not cover concert halls, churches, studios and other rooms of high acoustic quality."

C. The Norwegian Standard 8178: This standard recommends specific acoustic conditions for music rehearsal and performance rooms. But again, falls short because the standard is not intended to be applied to "large, specialized concert halls, opera venues, and similar spaces designed for concerts and performances."

D. ISO 3382: This is mainly a procedural reference for measuring reverberation. It addresses nothing below 125 Hz, nor does it provide any qualitative guidance related to acceptable, temporal tolerances - across a broad range of frequencies.

E. Variable Acoustics (VA): If you're using VA, are you able to shorten the T_{60} at or below 125 Hz? VA systems cannot remove excess reverberation and/or resonances.

F. Or maybe nothing at all because no one has asked for anything other than an ill-considered, mid-band T_{60} target?

Conclusion: None of the standards above adequately address T_{60} goals or guidelines at 63 Hz, or are applicable for modern, high-quality, performance venues.

12 Modern Applications

The following are some obvious applications for the TSR metrics.

A. Performing Arts Venues: These facilities need to accommodate many disparate, artistic productions. An *Optimal* TSR grade will benefit most, if not all musical productions using amplified sound.

B. Contemporary Worship Facilities: From the perspective of their audio, video and acoustic requirements, these are essentially performing arts venues.

C. Recording Studios and Sound Stages: Most would benefit from an *Optimal* TSR.

D. Rooms with electro-acoustical enhancement systems, also known as electronic variable acoustic (EVA) systems. See more on this in Section 14. Prior to implementation, such systems tend to require a T_{mid} of about 1 second. However, a simple 1 second T_{mid} does nothing to describe what's happening at each octave center between 63 Hz and 2 kHz. An Optimal TSR grade should further maximize the options and capabilities of any EVA system.

E. Large Rehearsal Rooms: Recent European studies, such as those used to support the Norwegian Standard, have shown that rehearsal rooms should closely match performance space acoustics.

F. Also consider most other indoor settings that feature both amplified music & speech.

13 VLF Acoustic Treatment Options

Retrofitting VLF absorption treatment can be quite difficult. It is usually more cost effective if such treatment is factored into a structure during the initial design and construction phases.

Treatment techniques such as deep slat panel enclosures; diaphragmatic absorbers; and Helmholtz resonators can be built into an architectural plan. However, these are usually custom solutions.

Currently, effective, commercially available VLF absorption products are not easily found. The folks at Flex Acoustics[5] in Denmark, and at RealAcoustix[13] in the USA, are perhaps the leaders in today's market, with few other companies (known to the author) engaging in solutions for mid- to large-size venues.

There appears to be at least three reasons for the scarcity of VLF acoustic products:

A. The lack of ISO standards and testing criteria below 125 Hz.
B. There are very few testing facilities large enough to do true reverberation testing in the 63 Hz range and below.
C. Until the late 20th century there was little need or demand for such standards and products.

The author suggests those hurdles are no longer acceptable reasons to ignore the obvious problems that exist in venues with *Fair*, *Poor* or *Bad* TSR grades.

14 Electro-Acoustic Enhancement Systems

It is well known and understood there are no electronic systems capable of removing reverberation; it can only be added. Modern electro-acoustic (EVA) systems such as Meyer’s Constellation; LARES from E-coustic Systems; Yamaha’s AFC; Muller-BBM’s Vivace; and others rely on implementation in buildings with a very well-controlled acoustic profile.

Prior to implementation, such systems require a room with a T_{mid} of about 1 second. However, a simple 1 second T_{mid} does nothing to describe what's happening at each octave center between 63 Hz and 2 kHz. The author suggests that a room's TSR should be evaluated and, if necessary, be properly treated to achieve an *Optimal* grade, or as close as possible. If any other T_{60}s are much longer than the desired mid-band target, an EVA system can do nothing to compensate.

Also, consider this: In some situations, a venue with a good reverberation profile may now be viewed to be nearly as limiting as one with too much or too little reverb. Ideal, classical music T_{60}s only compliment a narrow range of 21st century music, entertainment, and production. Like it or not, modern economics requires venues that are built to support the widest possible range of offerings.

15 Testing Standards and New Treatment Options

There is a glut of companies that sell absorption products for treating low-, mid-, and high-frequency reverberation. But even today, LF and VLF testing standards and pre-made treatment options are lacking. Therefore, the author believes the next major wave of invention and development in Architectural Acoustics should be focused on two fronts: Standards and Manufacturing.

The author calls on the ANSI and ISO organizations to develop new guidelines and standards for testing VLF absorption products and integration (mounting) options.

It is further suggested that manufacturers make the development of new, moderately high Q (bandwidth of one to two octaves) LF and VLF absorption products a priority.

Summary

In his paper, *Reverberation and the Art of Architectural Acoustics,*[14] Robert Sekuler notes that the father of architectural acoustics, Wallace Clement Sabine, had this to say about concert hall acoustics. "Sabine realized that the total acoustic disturbance produced by any ensemble's instruments must be intense enough to overcome the concert hall's tendency to absorb sound. Otherwise, the hall will *soak up* much of the available sound, leaving little for the audience to hear, and causing the audience to complain that the music lacks *body*."

Sabine's comment was made more than one hundred years ago. Musical styles, venues, technology, and consumer tastes and expectations have advanced far beyond anything relevant to Sabine's concern.

It is offered here that reverberation decay times, in the six octaves of sound outlined above, are fundamentally critical when evaluating a room that has or may require a powerful, extended-range sound reinforcement system.

The author believes the best way to make a building's acoustic *character* adequately flexible for the widest range of events is to start with a reasonably short T_{mid}, blend in an *Optimal* slope ratio, then design and install an electro-acoustic enhancement system that can be applied when needed.

The T_{60} Slope Ratio thesis is offered to help quantify a room's current conditions, or proposed reverberation objectives, and provides a simple scoring scale and grading vocabulary from which acoustical design specifications can be initiated and/or evaluated.

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