CTA Bulletin

Home Theater Recommended Practice: Audio Design

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Foreword

This guide outlines recommendations for the audio design of high performance home theaters. CEDIA and its certified Electronic Systems Contractors (ESCs) follow these practices, where applicable, to deliver high value to dedicated home theater environments, helping ensure full performance potential for the equipment and the room.

Home Theater Audio Design provides a baseline for the design and installation of residential spaces to be used for home theater or multi-channel music playback. While the focus of these two applications is home theater audio design, many of the practices are applicable to multi-purpose, two-channel and other acoustic spaces.

CEDIA recommendations are assembled from its ESCs' years of experience and cumulative wisdom. Industry standards, practices and recommendations published by other relevant bodies, as well as commonly accepted commercial practices now regarded as "de facto standards" in the audio industry, are also represented in this document.

Standards include those from:

- Society of Motion Picture and Television Engineers (SMPTE)
- Audio Engineering Society (AES)
- International Telecommunications Union (ITU)
- European Broadcasting Union (EBU)
- International Electrotechnical Commission (IEC)
- International Organization for Standardization (ISO)
- American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE)

Accepted commercial practices include those from:

- Dolby Laboratories, Inc.
- THX, Ltd. (THX)
- Imaging Sciences Foundation (ISF)

Table of Contents

Introduction

Home theater rooms are gathering spaces with one main purpose: watching movies. These rooms can also have other uses like listening to and performing music, entertaining, gaming, or simply lounging. It is important that the professionals who deliver the home theater experience be aware of the precise set of video and audio standards by which film content is created. *Home Theater Audio Design* outlines the various design parameters relevant to the proper design of a home theater that meets relevant industry guidelines. Additionally, these practices ensure that a home theater supports other media uses such as music, gaming, and broadcast TV.

Whether used as a dedicated space or a multi-purpose space, a properly executed home theater should be able to faithfully reproduce the picture and sound content. That's because the film director and the entire crew working alongside the director carefully craft the content to create an emotionally engaging story that can transport the audience to far away lands in far away times. The best way to ensure that an ESC's projects are successful and that customers are satisfied is simply adhering to movie technical production standards.

As is evident from the length of this document, when designing a home theater, many factors come into play. Several are interdependent and interactive, and the design process will invariably be iterative. This means that every step will need to be revisited and altered, continuing around the circle of decision points multiple times until the work is finished. Some compromises are inevitable. For example, the picture screen and front speakers will compete for space since they need to be in the same location. Of the several ways to deal with that issue, some yield better overall results than others. Ultimately, the best sounding and best looking home theater is the one with the most intelligent set of compromises!

Performance Objectives for Audio

The most important performance objectives for the home theater audio design are:

- **No coloration** — Reproduced sound should not be audibly colored, and should be tonally similar from all loudspeakers in the system, fronts and surrounds.
- **A continuous, smooth sound stage** — The frontal sound stage should be continuous and smooth from the left to the center to the right speaker, and not biased to one side or the other.
- **Envelopment** — The playback system should be capable of providing a sense of envelopment—the impression of being immersed in non-directional sounds, as in the reverberation heard in large rooms, halls, and corridors, crowds in stadiums, environmental sounds and so on. Atmospheric and mood-setting music is another example. Ideally, all of this should be done without listeners localizing the surround loudspeakers except when sound effects are directed to a channel/loudspeaker for that deliberate effect.
- **Dialogue intelligibility** —The listening room should not degrade dialogue intelligibility.
- **No perceptible distortion** — The system should be able to play loud without audible (annoying) distortion.
- **Consistent performance** —Audio performance should be as consistent as possible over the seating area. Best performance is expected at the prime listening location.
- **Low-frequency accuracy** — Low frequency performance of the audio system should be capable of fully supporting all audio content, consistently from seat to seat, without sounding distorted or boomy.
- **No background noise** — Background noise levels should be low enough to either be inaudible, or at least not intrusive.
- **Isolation** — Under normal circumstances noise originating outside the theater should be inaudible inside the home theater. Similarly, noise originating inside the home theater should not be audible in sensitive adjacent spaces or loud enough to disrupt normal activities in any room in the house.

A Procedure for Achieving the Performance Objectives

Several loudspeakers, several listeners and a room comprise a complicated system that cannot be completely separated into its parts. Achieving a satisfactory result might require some design iterations, a measure of trial and error. Before embarking on the project it may be useful to understand the underlying logic and issues as outlined in the guidelines that follow.

The details of room dimensions and seating locations are interactive. They should be determined together, with the result depending on how much flexibility the situation allows.

- **Prime listening location –** Industry guidelines for arranging front and surround loudspeakers are based on the position of the prime listening location. Under ideal circumstances, the prime listening location provides the optimum viewing angle for the video display. The prime listening location experience provides the basis for determining the number of surround channels to employ. Therefore, determining the prime listening location is fundamental; this will be an interactive decision process, driven by the physical, decorative and budgetary restrictions of the specific job.

- **Number of seats –** Two factors determine how many seats can be accommodated, and their arrangement:
  - Viewing angles and sightlines, and
  - Quality and seat-to-seat uniformity of bass.
- **Room size –** You should first reach agreement with the customer on the size of seats to be installed and the space required to provide access during a performance, including considerations whether extra space is needed. In an existing room, the room defines what seating arrangements are possible. In a new room design, the seating arrangement can help determine the room size and shape. In either case, it is much easier if the room has a rectangular shape.
- **Acoustical treatment –** Once the room dimensions, loudspeaker locations and seating have been decided, the interior acoustical treatment can be designed. The first requirement of that design is to ensure that dialogue intelligibility is not degraded by excessive reverberation and that tonal errors are not introduced by speaker/boundary interactions. Acoustical treatments can be designed to meet multiple purposes as required, including:
  - Assisting the front channels in providing a good soundstage
  - Providing localized sounds through the surround channels and
  - Providing immersion or envelopment.
- **Loudspeaker selection –** You can then select loudspeaker for front, surround and subwoofer applications capable of delivering high sound quality to all members of the audience, at the sound levels required for credible movie and music experiences.
- **Interior design and appearance –** Matters of interior design are of great importance, and there may be circumstances where appearance prevails over acoustical requirements. Flexibility is important, and it is good to understand what is needed and why so that trade-offs can be made intelligently. The guidelines here in *Home Theater Audio Design* are sufficiently detailed to insure that all such decisions are informed choices.

Loudspeaker Layout

Loudspeaker Layout Objectives

- **Determine the multi-channel configuration to be used**
- **Identify the approximate loudspeaker locations**

Once these two choices have been made, overall room design can progress. (Details of loudspeaker location and mounting will be discussed in "Audio System Component Location and Installation," pg. 28.)

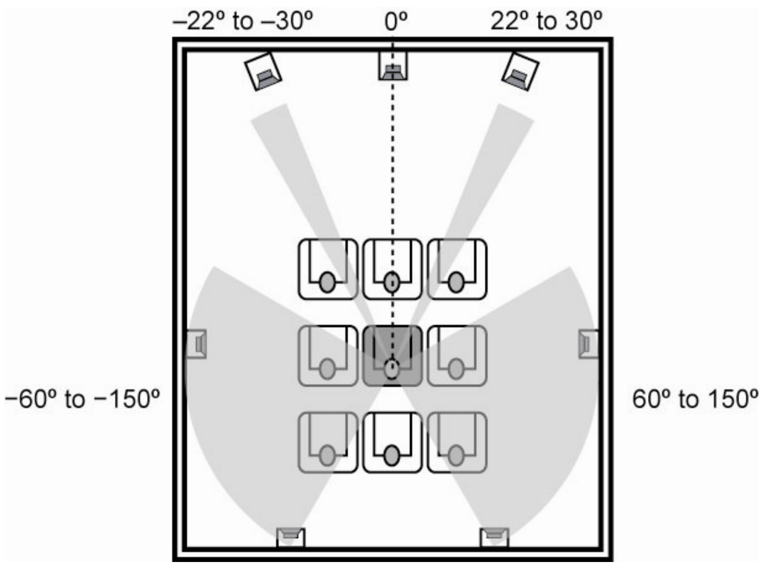


Figure 1 –
A simple diagram showing the angular ranges within which loudspeakers should be located relative to the prime listening location.
The locations of the front loudspeakers follow guidance at www.dolby.com. The angular range for surround loudspeakers is the recommendation in ITU-R BS.775-2 (2006)©.

Loudspeaker Layout Guidelines

- **Loudspeaker layout is defined from the perspective of the prime listening location .**

  In the example in Figure 1, the prime listening location is in the center of the seating area; this is obviously not a requirement. If there is to be only one pair of surround loudspeakers, as in a 5.1-channel system, they should be placed within the angular range ±110º to ±120º. If there are four surround loudspeakers, as in a 7.1-channel system shown here, the side loudspeakers can be placed symmetrically within the angular range spanning ±60º to about ±100º, and the rear loudspeakers within the angular range spanning approximately ±135º to ±150º. A 6.1-channel system could obviously have a single center-rear loudspeaker, but it is recommended that the signal be split between two rear loudspeakers.

- **Use additional surround loudspeakers for large audience areas and in large rooms.**

  Loudspeakers should be spaced by equal angles within the angular range shown in Figure 1.

Seating Layout

Seating Layout Objectives

- **There should be at least one prime listening location**

  Rooms engineered for high quality presentation should always have at least one prime listening location where the minimum possible design compromises are made.

- **Replication of the prime listening location**

  Other seats should recreate the prime listening location experience as closely as possible. It should be noted that many of the performance objectives listed above can be substantially met by proper configuration of the seats with respect to the room and to the installed loudspeakers.

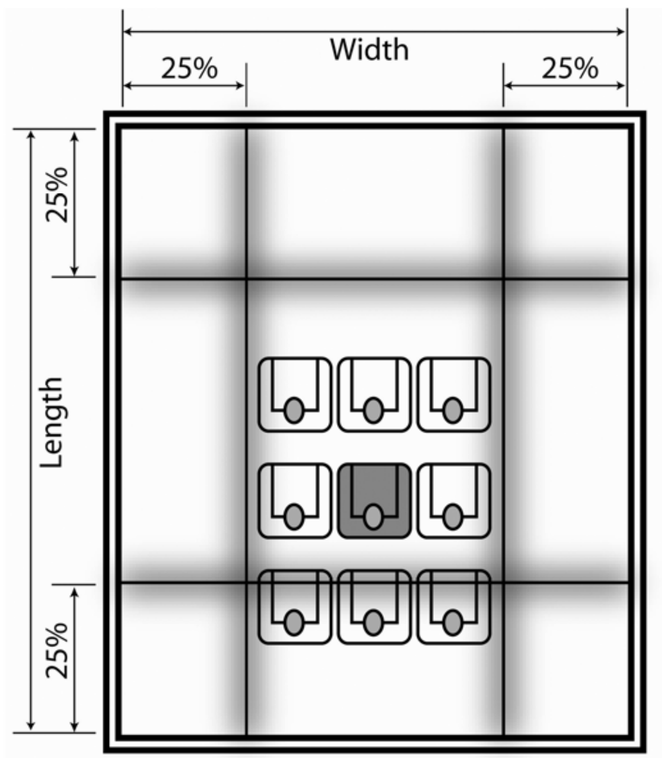


Figure 2 – *This floor plan shows locations of the pairs of nulls for the 2nd order axial (width and length) room modes. The shaded areas indicate that the designer should locate chairs such that listener's ears are more than 18" away from the nulls. Unshaded areas show acceptable locations for seats.*

Seating Layout Guidelines

Seating layout guidelines assume the room is rectangular and that wall constructions are reasonably uniform. Seat locations should meet requirements for image projection.

- **A central prime listening location**

  In a rectangular room layout with reasonably uniform wall construction, the prime listening location should be at the geometric center of the loudspeaker array, as shown in Figure 1. Other excellent seating locations are on the central front-to-back axis.

- **Centerline seating**

  Avoid aisles in the center of the room. Keep the centerline location free for seats between the left and right loudspeakers. The use of multiple subwoofers eliminates the odd-order room modes that otherwise would be problematic at these locations.

- **Maintain seat distance from speakers**

  Avoid putting seats too close to any one loudspeaker, as this will result in an unbalanced sound stage, loss of envelopment, and distracting localization to the nearby loudspeaker.

- **Avoid null points**

  Avoid putting listener's heads at or near the null points of the low-order (1st, 2nd and 3rd order) axial length and width standing waves (also called room modes). Listeners at these locations will not hear certain bass frequencies. The 1st order modes are particularly bothersome because they cut through the prime listening area.

Appendix 1 explains that certain arrangements of two or four subwoofers reduce the problem to the 25% null lines shown in Figure 2. If these subwoofer configurations are used, seats should be arranged to place the heads not less than about 18 inches (50cm) from these null lines.

Low Frequency Room Optimization

Obviously it matters greatly if you are working within fixed room dimensions or with room dimensions that you are able to choose. If those dimensions describe a rectangular room, it may be possible to find a seating layout that provides good bass for multiple listeners. At the very least, these procedures make it possible to identify which seats are likely to be good, and which are likely to be less good.

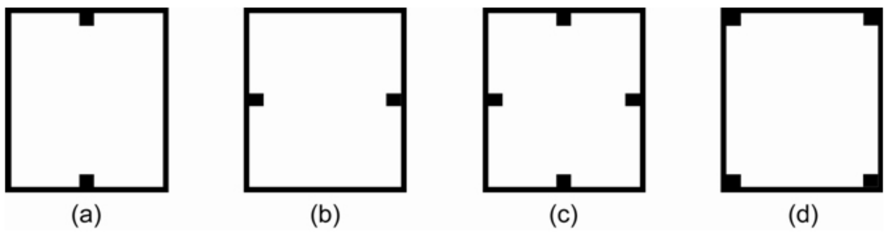


Figure 3 – *Arrangements of two or four identical subwoofers, driven by the same signal, that simplify the standing-wave patterns in a rectangular room to the one shown in Figure 2. This allows seating locations or room dimensions to be adjusted to avoid problems, or to identify those seats that have less than ideal performance. Note that arrangement (c) is significantly less acoustically efficient than the other options (requiring larger/more subwoofers and amplifier power for similar sound levels). Arrangements (a) and (b) require double subwoofers at each location to equal the sound levels of (d).*

Low Frequency Room Optimization Objective

- **Consistent bass across all seats**

  The spectral content and overall level of bass should be consistent across all seats, with no audible resonances.

Low Frequency Room Optimization Guidelines

- **Minimize seat-to-seat differences**

  Because of standing waves no two seats are likely to experience the same bass response. Equalization can improve the sound quality, but the seat-to-seat differences remain unless multiple subwoofers are employed in a manner that simplifies the standing-wave patterns in a room.

- **Optimize bass through room management**

  The use of full-range loudspeakers at the front- and surround-channel locations cannot deliver optimum bass to multiple listeners. Neither can a single subwoofer or LFE channel. Optimum bass is possible only when all low frequencies are combined through bass management and then delivered to multiple subwoofers arranged in specific patterns.

Figure 3 shows arrangements of subwoofers *in a rectangular room*. Of these, arrangements (a), (b) and (d) are preferred because they result in higher overall system efficiency, with only slightly decreased seat-to-seat uniformity. Double subwoofers at the mid-wall positions in (a) and (b) result in acoustical output comparable to that of arrangement (d). The subwoofers should be identical, mounted similarly with respect to the room boundaries, connected in the same polarity and set to the same output levels.

Alternative Methods for Low Frequency Room Optimization

One alternative low frequency room optimization method requires no specific room shape, subwoofer, or listener locations. It does, however, require specific acoustical measurements and signal processing. Similarly, yet another method is discussed in Appendix 1. It also assumes that the room is rectangular, but requires that the seating area be reasonably centered in the room. For each of several subwoofer arrangements, the alternative methods allow users to identify the room dimensions that minimize seat-to-seat variations in bass. These two methods can be used separately or in conjunction with each other.

A SUMMARY OF THE PROCESS

1. **Select optimal combination of subwoofer layout and room dimensions.**

   If room dimensions are fixed, select optimal subwoofer layout for that set of dimensions. Refer to Figures 2 and 3, and Appendix 1.

2. **Use at least two subwoofers at different locations.**

   In rectangular rooms, the arrangements of Figure 3 are preferred.

3. **Damping of low-frequency room resonances is always desirable**

   This may be achieved by using certain forms of wall construction, but only if it does not interfere with requirements for sound isolation. Techniques that result in high sound transmission loss also tend to result in massive and stiff inner wall surfaces. In those cases, it will be necessary to use specially-constructed low-frequency absorbers. In general these will be of the diaphragmatic, membrane or panel type, and they should be located in high-pressure regions of the standing waves—corners are ideal locations.

4. **Choose designs which allow further optimization during calibration**

   Designs which allow control of individual subwoofer level and delay are particularly helpful in optimizing non-rectangular or otherwise non-trivial room designs. Judicious variation of levels and delays between multiple subwoofers can reduce audibility of resonances.

5. **Include a high-resolution parametric equalizer in the design, dedicated to the subwoofer**

   The equalizer should be able to place the filter's center frequency with a resolution of 2 Hz or better, and have at least 6 independently adjustable filters. Separate equalization channels for each subwoofer can be useful as well. *Final equalization should be made at the prime listening location with all subwoofers operating simultaneously.*

   Additional analysis using modal calculators is possible, for example the method available at `http://www.harman.com/xls/Room/Mode/Calculator.xls`. The objective is to place the subwoofers so that they do not couple excessively into any mode which causes variation in sound levels in the seating area, and/or place the seats so that they do not sit in the dips of any modes. The accuracy of this approach may be affected by factors such as non-ideal wall construction, low-frequency absorption from upholstered furniture, etc., which is not accounted for in simple modal calculators. If the room is substantially non-rectangular, it is much more difficult to optimize. Steps 2-5 above are still recommended. Refer to Appendix 1 for a more detailed discussion of low-frequency optimization of the room.

Sound Isolation

Sound isolation is required for two purposes:

1) To prevent external noise from compromising the carefully engineered low background levels in the theater space; and
2) To prevent high sound levels inside the theater from being audible outside the space.

Sound isolation is achieved, in part, by partition construction for three levels of room sensitivity: typical, sensitive, and non-critical. The recommended partition construction depends on the nature of the rooms adjacent to the home theater.

- **Standard Construction**

  Typical, non-acoustically rated construction is adequate for rooms adjacent to the home theater where the noise level is low, and the adjacent room is not noise sensitive. This would be appropriate for rooms such as storage rooms, hallways, basements (assuming no loud machinery operating), etc. Typical STC is 34.

- **Isolation Level 1 Wall Construction**

  This is recommended for rooms adjacent to the home theater where the noise level is moderate, or the adjacent room is moderately noise sensitive. This is the typical situation, and includes rooms such as kitchens, dining rooms, etc. Typical STC is 52.

- **Isolation Level 2 wall construction**

  This is recommended for rooms adjacent to the home theater where the noise level is significant, or the adjacent room is noise sensitive. This is the typical situation, and includes rooms such as living rooms, dining rooms, bedrooms, etc. Typical STC is 60.

- **Isolation Level 3 wall construction**

  This is recommended for rooms adjacent to the home theater where the noise level is high, or the adjacent room is very noise sensitive. This would include noise sensitive rooms such as bed rooms, and noisy areas such as gaming rooms, kids' playrooms, etc. Note that extreme measures may be required if very noisy areas, such as a shop area, are located next to the home theater. Special care should be used for rooms with exterior exposure to traffic, airports, railway lines, night clubs, concert venues or other sources of high-level noise. The services of a competent acoustical consultant are recommended in such cases. Typical STC is 70.

Table 1 – *Transmission Loss values and typical construction for four classes of wall construction. The wall construction is classified in terms of "STC", though it is the TL values, particularly below 500 Hz, which are most important. Pay particular attention to the numbers in the 63 and 125 Hz bands as these are very relevant for film soundtracks with loud bass.*

Wall class	Recommended Minimum Transmission Loss (TL) (dB at each octave band)							General description of wall construction
	63	125	250	500	1000	2000	4000	(*See Appendix 2 for drawings*)
Standard Construction (STC 34)	6*	15	24	32	41	38	43	• 2x4 studs 16" o.c. • One layer 5/8" sheetrock • One layer 5/8" sheetrock (*Source*: NRC #66)
Isolation Level 1 (STC 52)	15*	33	44	47	56	52	64	• 2x4 studs 16" o.c. • Two layers 5/8" with visco-elastic damping compound • One layer 5/8" sheetrock
Isolation Level 2 (STC60)	23	42	55	61	64	61	69	• 2x4 studs 16"o.c. • Two layers 5/8" sheetrock with visco-elastic damping compound on isolation clips • R13 fiberglass insulation / Two layers 5/8" sheetrock (*Source*: Riverbank Reports RAL-TL02-40)
Isolation Level 3 (STC75)	42	54	63	74	84	92	90	• Double row of 2x4 studs 24" o.c. on separate plates spaced 3" apart. • One layer 1-1/8" sheetrock composite with visco-elastic damping • 3.5" fiberglass insulation • 3.5" fiberglass insulation • One layer 1-1/8" sheetrock composite with visco-elastic damping (*Source*: NRC B3433-1W)

* This number is extrapolated from available data.

Sound Isolation Objectives

- **External noises should not be audible in the home theater at any time**

  External noises should not prevent the recommended background noise levels from being met (see pg. 27). These noises can be caused by outdoor vehicle traffic, adjacent rooms, machinery, sump pumps, footfalls and/or plumbing noise, etc. Rooms which might be considered sensitive to noise intrusion include bedrooms, guest rooms, etc.

- **Sounds originating in the home theater should not be audible in adjacent rooms**

  Home theater sounds should not disturb adjacent spaces. Outgoing sounds may be just audible in less sensitive and/or noisy spaces (dining room, kitchen, bathroom etc.). Noise in seldom-unoccupied, noisy, or otherwise non-critical spaces (storage room, laundry room, etc) is not critical.

Sound Isolation Guidelines

The acoustical transmission loss (TL) of walls is commonly rated using a standardized rating called Sound Transmission Class (STC), a single number rating calculated from measurements made over the frequency range 125 to 4000 Hz. The STC rating is intended for evaluation of speech privacy, and makes no claims whatsoever about acoustical performance outside of that frequency range. This is a problem, especially at low frequencies, where home theaters generate very high sound levels.

The STC rating of any door or window should come as close to the designed STC of the wall structure, windows being avoided entirely when STC-75 is a required construction target. Although it is reasonable to use STC ratings as a guide, it is wrong to think that a high STC number is an assurance of effective sound isolation at subwoofer frequencies

Wall Construction Guidelines

Sound isolation is achieved through a combination of multiple factors:

- **The mass of the inner and outer wall surfaces**

- **Constrained-layer or other damping of either or both of those surfaces**

- **Mechanical isolation of those surfaces**

  Support each surface on a structurally independent frame or provide resilient mounting for one or both surfaces, or both. Resilient decoupling devices should be installed with care to ensure that their function is not negated by screws or nails that bridge the gap between the surface being isolated and the underlying structure.

- **Air gaps**

  The larger the distance between the inner and outer surfaces, the greater the transmission loss, especially at low frequencies. Several inches to a foot is not an excessive separation if space permits.

- **Acoustical damping**

  Use flexible batts of fiberglass or mineral wool in the space between the inner and outer surfaces.

- **Surface integrity**

  The inner and outer surfaces should be continuous, without perforations of the kind created by thoughtless installation of electrical boxes or in-wall loudspeakers. Be careful to avoid accidental mechanical connections between the inner and outer surfaces created by plumbing, electrical conduits, HVAC and the like. The sound inside the room should stay within the room and any vibrations within the inner surface should not be communicated to the outside surface—and vice versa.

- **Enhancements to theater-facing surface construction**

  Additional layers of sheetrock, resilient isolators, damping materials, etc. should be added to walls or ceilings facing into the theater space, helping avoid flanking path opportunities.

- **Construction site vigilance**

  Most builders and contractors are totally unaware of the care necessary to construct home theater spaces. All trades operating on site should be monitored and coached.

Flanking Path Guidelines

Care should be taken to ensure that flanking paths and/or inadequate installation of the specified partition construction does not compromise the required transmission loss:

- **Use appropriate door construction and installation**

  All doors into the theater area should be a minimum 1¾" (50mm) solid core door with rubber weather stripping and sealed thresholds. Use of the following hardware is suggested:

  – Specialty door thresholds
  – Astragals
  – Sound sealing around the entire jam

  For the STC-75 wall class, an acoustically rated door with a minimum STC-62 rating, preferably with a TL of 40 dB or more at 125 Hz, is recommended. Products rated using an independent accredited laboratory (e.g., Riverbank) are preferred.

  An alternative to the acoustically rated door would be to include an entryway or anteroom with at least one 90 degree turn, a minimum of 8’ separation between the anteroom entrance and the home theater room entrance, and with acoustical treatment and carpet. The 1¾" (50mm) solid core door with rubber weather stripping and sealed thresholds is still required. Figure 4 shows one acceptable layout.

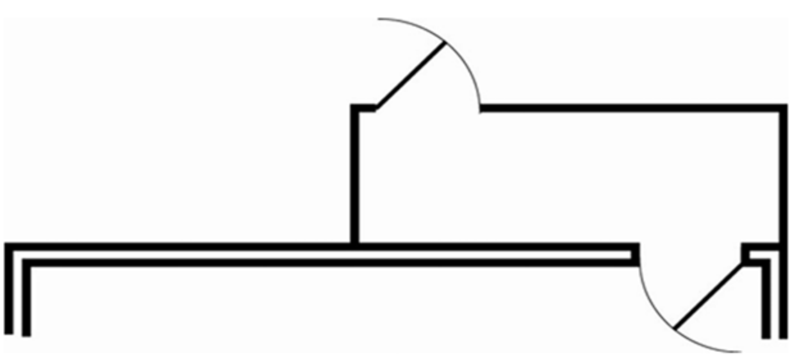


Figure 4 – *Example of entrance to home theater using an anteroom and two 1¾" solid core doors instead of a single STC-62 rated acoustical door.*

- **Use appropriate windows**

  The windows should all be of sufficient minimum rating to meet the sound isolation requirements of the room and wall class, with STC 60 for typical applications. If windows are required in the STC-75 class wall (try to avoid this), they should be acoustically rated, and have a minimum STC-58 rating, preferably with a TL of 40 dB or more at 125 Hz. Products rated using an independent accredited laboratory (e.g. Riverbank) are preferred.

- **Completely caulk and seal all joints in any common wall(s)**

- **Prevent penetrations from contacting the drywall**

  Any penetrations through the theater walls by electrical outlets, wire penetrations, HVAC ducts or plumbing should provide a ¼" gap around the penetration to prevent contact with the drywall. Gaps should be thoroughly sealed with a 50-year flexible caulking material.

- **Control break-in noise from exposed HVAC ducts**

  Enclose exposed ducts or add silencer units before the supply register in the room. Use of half round duct where noise can break into or out of a duct may be required. Refer to the 2007 ASHRAE Handbook, Chapter 47 for TL data on half round duct.

- **Control flanking paths between adjacent rooms**

  Failure to mitigate even one significant flanking path can negate all other sound isolating efforts. Flanking paths can be:

  - **Electrical outlets**
    Where outlets are located on both sides of a wall, stagger their location by at least one stud width so that they are not opposite each other.
  - **Gaps in walls, ceiling floor structure and/or ventilation systems**
    Seal all gaps with acoustically rated resilient caulking or other approved material.
  - **Ductwork**
    Ducts with a direct path from the home theater to an adjacent room or any room with expected high noise levels should include mitigation such as a silencer, duct lining and multiple 90-degree turns, lined plenum, or other (refer to CEDIA HVAC RP document, or 2007 ASHRAE Handbook, Chapter 47).

Interior Acoustical Treatment of Rooms

Interior acoustical treatments provide for the optimal reproduction of music and movies in stereo and multi-channel formats, as well as for relaxed conversation. Their use is guided by two parallel requirements: reverberation time, and enhancement of sounds delivered by the loudspeakers — or, at the very least, does not detract from that delivery while achieving reverberation time objectives.

Traditionally, the first concern in room acoustics is to achieve a suitable reverberation time (RT). The RT is primarily determined by the amount of absorbing material in the room, its effectiveness, and where it is placed. A secondary influence is the amount of scattering or diffusion of sound that is caused by large objects in the room, such as chairs and tables, by ornamental surface irregularities on walls and ceilings, and by manufactured devices created for that purpose.

In large performance spaces RTs are typically in the range 1.5 to 3 seconds, depending on the kind of music being performed. However, in small listening rooms and home theaters it is a much less critical factor because the reverberation that is important to the music or movie is included in the recording. What is added by small rooms is really the decay of early reflections arriving at our ears from specific directions determined by the number of loudspeakers and where they are located relative to the listeners and the room boundaries. It is not the "statistical", high-diffusion, situation that exists in large reflective performance halls and auditoriums.

In fact, if the room is normally furnished, with typical amounts of carpet, drapes, upholstered furniture, bookcases and cabinets, it is possible that nothing additional needs to be done. Commonly, values of mid-frequency RT in such rooms fall in the range 0.2 to 0.5 seconds, but these can vary in different geographical regions because of structural, cultural or decorative trends and traditions. In a custom theater, acoustical materials should be installed to achieve these numbers and, because it is a custom design, expectations of excellence are higher.

Reverberation Time Objectives

- **Mid-frequency (500 Hz octave band) reverberation time in the range 0.2 to 0.5 seconds**

- **Dialogue intelligibility**

  If dialog intelligibility and voice quality are unsatisfactory, entertainment in any form suffers. In general, keeping RT below about 0.5 s will ensure that intelligibility is not impaired. If RT is too low, say below about 0.2 s, the room will sound artificially "dead" and muffled. Conversations within the room will be less relaxed, because vocal effort should be elevated and it may be necessary to face each other for clear communication. The effects of excessively low RT on movies and music depend on the specific program, but in no case is it flattering. You may end up with poor integration of front and surround sound fields and a generally uninvolving experience.

Reverberation Time Guidelines

- **Simple approximation of RT**

  Assume that the floor is covered with clipped-pile carpet on felt underlay. Combined with absorbers covering about 25% of the wall area, if they are well distributed around the room, this will yield a satisfactory RT in most situations.

- **Calculate Reverberation Time Using the Classic Sabine Equation**

  For those unfamiliar with the technique, it is described in detail in Appendix 2, page 42.

Acoustical Materials Placement Objectives

The front and surround loudspeakers perform different tasks, and early – especially the first – reflected sounds from each of them need to be handled differently.

- **Front loudspeakers do the important work**

  Front Left, Center and Right (L,C,R) speakers perform multiple tasks:

  - Creating a soundstage
  - Providing dialogue and effects to accompany movie action on the screen
  - Providing a spatial portrayal of a band or orchestra.

  For these loudspeakers there can be a small benefit from lateral reflections created by reflective portions of the front side walls. The benefit is most noticeable when the front loudspeakers are operating alone, especially when sounds are "hard panned" to one of them. The effect is generally beneficial in stereo listening. In movies and television, the center channel operates alone much of the time, so a certain amount of spatial "softening" can be pleasing.

  When multiple channels are operating simultaneously, the sounds from the loudspeakers are the dominant factors, masking the less energetic room reflections. The effects of reflective side walls therefore range from neutral to slightly beneficial.

- **Side-surround loudspeakers provide localizable sound and envelopment**

  Localizable sounds include effects in movies and stable locations for musicians in "middle-of-the-band" recordings, requiring require strong direct sounds from the surround loudspeakers to be delivered to all of the listeners in the room. The majority of the time, however, their task is to envelop the audience with mood-setting music, atmospheric sounds and acoustical ambiance associated with what is happening in the front soundstage, or on the screen. Envelopment is the sense of being in a different space or of being surrounded by sounds having no specific direction. This perception is created when delayed versions (recorded reflections) of the front sounds arrive at the listeners' ears from the sides.

  Combining these guidelines into a graphical description, Figure 5 below shows the general placement of acoustical materials and devices for a dedicated home theater.

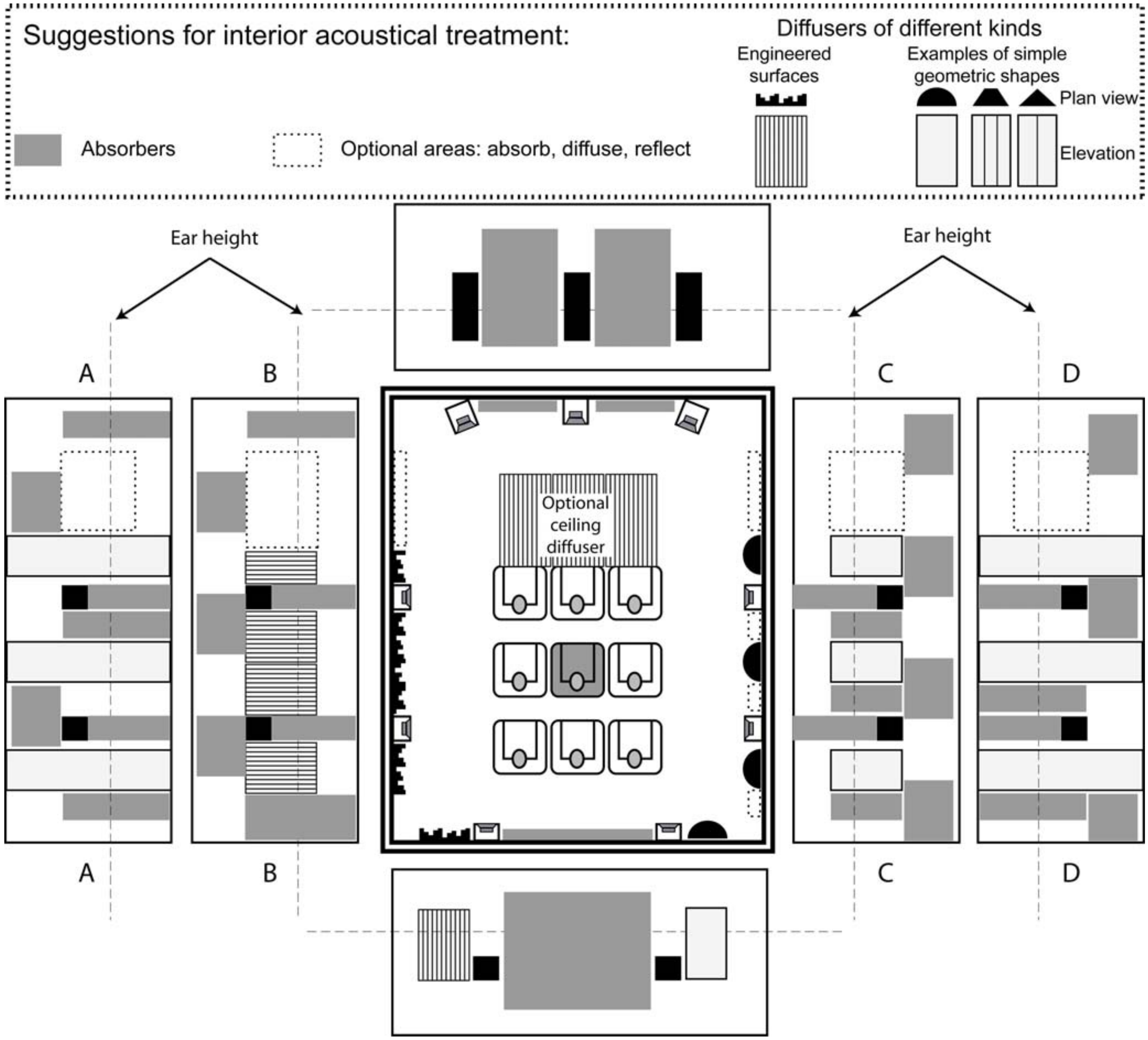


Figure 5 — *A few of the many possible ways to combine acoustical materials within a home theater, it shows a floor plan with walls folded down to show how materials might be arranged on them. The shaded seat in the middle is the prime listening location. Wall B shows a continuous array of engineered diffusers in a band around ear level. Wall C shows a version that uses semi-cylindrical geometric shapes intermixed with reflecting surfaces and absorbing panels. Walls A and D show mirrored treatments in which the diffusing shapes have been extended floor to ceiling. Absorbing panels have been placed to avoid flutter echoes. Many artistic variations are possible. The dashed lines that identify the ear height of seated listeners should be adjusted to follow the floor contours of tiered seating. If fabric is used to cover any of these treatments, be certain that it is acoustically transparent.* (*Toole, Floyd E., "Sound Reproduction", Focal Press 2008*)

Acoustical Materials Placement Guidelines

- **Wall-to-wall carpeting**

  The floor should be covered with wall-to-wall carpet on felt underlay.

- **Appropriate use of scattering and diffusing devices**

  Acoustical materials placed in the center portions of the front and rear walls should be mostly absorbing, with scattering devices towards the sides of the rear wall. All absorbers, wherever they are located, should be not less than 3 to 4 inches (75-100mm) deep.

  The side walls use a mixture of reflection, absorption and scattering/diffusing devices. Diffusers designed to scatter the sound horizontally should be located in the region about one foot below and about three feet above ear level.

  Diffusers can be of the engineered-surface type, that are attached to or built into the walls, or they can be simple geometrical shapes that can be attached to walls or constructed on site using conventional building materials. To assist the illusion of immersion or envelopment, these devices should be effective at lower middle frequencies meaning that engineered surfaces should be not less than about 8 inches deep, and geometric shapes not less than about a foot (300mm) deep.

  Almost any curved or multifaceted convex geometric shape will scatter sounds, so considerable artistic freedom exists. For visual effect it may be desirable to have the geometric shapes extend floor to ceiling, imitating columns. Engineered diffusing surfaces can be arranged side-by-side to cover an area, as shown in B, but geometric shapes should be separated, as in A, C and D. Both types can be mixed.

- **Avoid flutter echoes**

  Absorbing material and blank reflecting areas should be arranged so that walls facing each other do not present opportunities for flutter echoes (in the drawing walls A and D, and B and C are designed with staggered areas of absorption and reflection). The total amount of absorbing material in the room should be sufficient to meet the reverberation time criterion discussed in earlier in this section (see pg. 20-21; Appendix 2).

- **Use geometry or a mirror to determine the best location for the optional diffuser on the ceiling**

  It should scatter sounds from the front loudspeakers that would normally be reflected to the head locations of audience members. This is most effective if it is an engineered surface designed and positioned to scatter the sound towards the sides of the room.

- **The locations of the first side-wall reflections at the front of the room are specified as areas for optional treatment**

  Leaving these areas as flat wall surfaces provides an open and spacious soundstage for those customers who listen in stereo. In television and movies these reflections will “soften” the image of the commonly dominant center channel. Well-designed wide-dispersion front loudspeakers will sound better. When multiple channels are operating simultaneously, these reflections are swamped by the recorded sounds and become neutral factors. So, the effects of these side-wall reflections range from neutral to slightly beneficial. In any event, they are not large effects, so the choice can be left to the designer.

- **The corners of the room are available for low-frequency absorbers**

  These are preferably of the membrane/diaphragmatic/panel type, because they are located in high-pressure regions of the low frequency standing-wave patterns.

Acoustical Materials and Devices Guidelines

Acoustical materials located at important reflection points modify the sounds from loudspeakers. It is therefore important that devices intended to absorb, reflect, or scatter sound, be similarly effective at all frequencies above about 300 Hz. Some devices are designed to scatter sounds in multiple directions, and others are optimized to scatter sounds in a single plane, e.g. horizontally or vertically. Since our ears are in the horizontal plane, it is not surprising that the most rewarding acoustical experiences result from horizontal scattering.

- **Absorbers**

  Whether they are fiberglass or acoustic foam slabs (not sculptured) they should be not less than 3 to 4 inches (75-100mm) thick in order to be effective down to about 300 Hz. Sculptured foam devices can be used, but note that they have absorption coefficients equivalent to solid slabs that are about half the thickness. Check with the manufacturer for measured acoustical performance.

  Obviously, these materials can be used in combination to achieve greater thicknesses. An air space behind an absorbent panel increases its low-frequency performance, but it is best if the void is filled with fibrous material.

  The absorption coefficient of fiberglass is similar for all densities from soft batts through to rigid boards up to about 6 pounds per cubic foot (100kg per cubic meter). The highest density materials can exhibit some amount of reflection at very high frequencies; they are advantageous only in terms of their mechanical properties. Fabric coverings should be acoustically transparent, but even some of those specified for these purposes can reduce the absorption at high frequencies (above the highest frequency for which random-incidence absorption coefficient is normally measured).

  The performance of absorbers is normally specified as a “random-incidence absorption coefficient,” showing the proportion of sound (from 0 to 1) that is absorbed when the material is placed in a perfectly diffuse, random-incidence, sound field. In small-room sound-reproduction applications, the strong sounds tend to arrive from specific, or at lease a limited range of, directions, making such measurements less than completely useful. However, lacking more relevant data, they provide rough guidelines about the frequency ranges over which the materials are most effective.

- **Diffusing and scattering devices**

  Diffusing and scattering devices perform exactly the same duties and they come in many forms. In normally-furnished rooms, this has been the function of prominent irregularities in surfaces, such as:

  – Protrusions created by chairs, tables, lamps, cabinets and bookcases
  – Structural elements like fireplace bulges, window bays and recesses

  In designed spaces, deliberately constructed devices are used, such as:

  – Rectangular, curved, pyramidal or wedge shapes hung on walls
  – Engineered surfaces with complex shapes based on mathematical progressions.

- **Device performance measurement**

  The performance of these devices and surfaces is measured using the “normalized diffusion coefficient”, ranging from 0 to 1, a measure of how much sound is scattered in different directions and how uniformly it is scattered at different angles.

  All of these devices should have significant depth in order to be effective at frequencies down to about 300 Hz. Geometrical shapes should have a depth of about 12 inches (30cm), but well-engineered surfaces can be effective at depths of about 8 inches (20cm). Geometric shapes work very well when they are physically separated from each other, but when arranged in regular groups, side by side, their performance deteriorates substantially. When covering a large area, engineered surfaces tend to function better.

- **Engineered-surface diffusers**

  Engineered-surface diffusers also absorb sound. The absorption is small if they are directly exposed to the room but much greater if they are covered with fabric. Check with manufacturers for this data, as sound absorbed by these devices can be a major factor in determining reverberation time.

- **Fabrics**

  All fabrics used to cover wall surfaces should be Class A fire rated. When those fabrics cover acoustical materials or devices they should be specified for that purpose. This is not a guarantee that they are acoustically transparent, and it is reasonable to expect that the acoustical performance of the materials or devices behind them will be changed to some extent. When those fabrics cover loudspeakers they should be as nearly as possible acoustically transparent.

Flutter Echoes Objectives and Guidelines

There should be no audible flutter echoes at any of the listening areas of the room.

- **No large reflective surfaces**

  The room should not have large, untreated reflective surfaces that are parallel to each other. Such surfaces should be partially covered with either absorptive or diffusive materials. These materials should be effective down to below 1 kHz.

- **Bring absorption down to at least 6" (0.15m) below seated ear height.**

- **Interleave absorption areas**

  A practical solution is to interleave alternating areas of absorption across the room from each other.

Rattles Objectives and Guidelines

There should be no audible rattles in the room. A single frequency sweep at 95 dB (at the seating area) from 15 Hz to 500 Hz should reveal no audible rattles. Any audible vibrations should be damped. Following are some sources of rattles to consider:

- Metal lath wire used to suspend building elements
- Electrical wiring, conduit, screen frame and mounting hardware
- Limply suspended drywall
- Storage of loose material within the room
- HVAC diffusers and grilles
- Lighting cans, furniture, equipment cabinets, in-room bars, etc.

These potential sources should be controlled through one of the following methods:

- Tightened down loose hardware.
- Wedge resilient material (such as fiberglass or rubber pieces) into rattling metal parts where loose components are in contact.

Background Noise Objectives

Background noise should be measured using RC mk II criteria and should meet the criteria in Table 2 below.

Typical installation	Premium installation
RC mk II 30 Quality Assessment Index <25 (Neutral)	RC mk II 20 Quality Assessment Index <25 (Neutral)

Table 2 – *Background noise level objectives.*

Refer to 2007 ASHRAE Handbook, Ch. 47 for RC mk II curves and calculation method. There should be no audible hums, rumbles or buzzes.

Background Noise Guidelines

All noise producing devices should be isolated or damped to reduce ambient noise. Sources of background noise include HVAC systems, machinery, cooling fans and electric motors, etc.

- **Use oversized ducts**

  HVAC ducts to the theater should be oversized in order to allow for low noise levels. Flex duct may be used where break in/out noise is not an issue.

- **There should not be a concentration of noise energy at one frequency.**

- **Light dimmers should be specified for low noise**

  Use dimmers that prevent the steeply chopped sine waveforms of the less expensive units. Fluorescent and neon lighting can cause noise problems and should be implemented with extreme caution.

- **Acoustically treat plumbing in the surrounding area**

  Any plumbing within the walls, ceilings or floor of the theater should be acoustically treated to prevent noises or vibrations being audible in the theater or mechanically transmitted into the theater spaces.

  Any portion of plumbing pipe passing through theater walls/ceilings/floors should be wrapped with an appropriate noise barrier material.

  Piping through the theater spaces should be resiliently decoupled from the structure. Pressure regulators and check valves should be of the silent operating design.

- **Isolate sump or lift pumps**

  Sump or lift pumps should be installed on isolators, and care should be taken to ensure proper balance of the pump impeller.

- **Isolate mechanical and HVAC equipment**

  Any mechanical equipment or HVAC equipment near the theater area should not have contact with common walls, floor or ceiling elements common to the theater area and should be resiliently suspended. Mechanical equipment sharing a common floor with the theater should be mounted on resilient isolation pads. with static deflection appropriate to the load.

- **Isolate structural noise**

  Noise transmitted through the building structure (walls, floors, etc.) should be controlled by isolating the noise source on appropriate shock mounts. Additionally, a break in the structure between the noisy device and the room boundaries is highly recommended.

- **Hinges and chairs should not generate squeak or other noises**

Audio System Component Location and Installation

Audio System Component Objectives

Aural qualities of the theater should be consistent and maintained throughout the seating area for front, subwoofer, side and rear loudspeaker locations and installations.

- **A continuous, smooth frontal sound stage**

  For music playback, the frontal sound stage should be continuous and smooth from the left to the center to the right speaker, and not biased to one side or the other. For video playback, dialog should be intelligible and easily localizable to the screen.

- **All loudspeakers should exhibit a similar timbral signature**

  This can be subjectively evaluated by sitting in the prime location and turning to face the individual loudspeakers in turn as they reproduce broadband pink noise from a test disc. Do not use the band limited calibration signal, and do not face forward while the noise sequences around the room. (It is normal for sounds from different directions to exhibit timbral differences; it is part of normal hearing).

- **A sense of envelopment and sound localization**

  The playback system should be capable of providing both a sense of envelopment to the listener and sound localization. Highly localizable sources are beneficial for sound effects in movies and music playback when or musicians or instruments are:

  – Directed to individual channels
  – Panned to locations between pairs of channels.

- **Bass reproduction should be consistent across the seating area and without audible resonances**

Front Loudspeaker Placement and Installation Guidelines

In this discussion, “loudspeaker location” refers to the tweeter position; “seating position” refers to the position of the listeners head (at the prime listening location unless otherwise specified); “seated ear height” is approximately 4 feet (1.25m), but will depend on the seating used. Front loudspeakers should be set up in the following manner:

- **The three front loudspeakers should be as close as possible to the seated ear height**

  If higher, they should be no more than 15° above that plane. If the speakers are not at seated ear height, they should be angled in the vertical plane to cover the entire listening area uniformly at all frequencies.

- **An unobstructed sound path**

  All full-range loudspeakers should have an unobstructed sound path to the seating position, with distances as identical to each other as possible. This requirement does not apply to the subwoofer.

- **The center speaker should be on the center axis**

  Locate the center speaker between left and right front speakers on the center axis.

- **Correct front speaker height**

  If the front speakers are located behind an acoustically transparent projection screen, they should be no higher than 5/8 height of the picture screen. The left and right front speakers should be at equal height or no more than 5° different in height.

- **Correct speaker orientation**

  The speakers should be oriented according to manufacturer's specifications (generally vertical).

- **Correct in-wall loudspeaker mounting**

  In-wall loudspeakers should be flush-mounted in the front wall with minimal obstructions or cavities in their vicinity and mechanically isolated from the wall.

  Conventional box loudspeakers should preferably be located either in a baffle wall or at more than 3.5 feet (1m) in front of the wall. (Loudspeakers not designed for this kind of mounting will require equalization to reduce the excessive bass created by the in-baffle or in-wall mounting) Mounting locations should be selected to minimize errors in frequency response due to boundary effects. Locations in corners and equidistant to both walls and floor should be avoided. If placement has to be close to corners or walls, the response should be optimized for near wall/ceiling installation by design (i.e. distances from loudspeaker to each wall and to floor different and not multiples of each other) or by electronic equalization.

- **Correct cabinet loudspeaker installation**

  If box loudspeakers are placed inside cabinets, resonances from the cabinet cavities should be eliminated. A combination of front baffling, internal damping and perforation of the sides and rear of the cabinetry should be used to reduce the cavity resonance effects.

- **Correct distance between speakers**

  The correct distance between speakers is important to achieve proper left/right separation in multi-channel film and music reproduction, while maintaining clear phantom center images in two channel stereo music reproduction.

  While the stereo base width will become greater in larger rooms, the available picture will probably dictate the available width. A base width corresponding to angles of ± 22° to ± 30° relative to the center loudspeaker when viewed from the principal seating location is preferable. After placement is selected, the left and right speaker should be "toed in" so that their main axes meet at the main seating location.

Subwoofer Placement and Installation Guidelines

Optimized subwoofer location is critical for smoothest and clearest bass performance. Due to the extensive interaction of subwoofer placement and room acoustics (room dimensions, etc.), this is covered in the Room Acoustics section and in Appendix 1. Subwoofer installation requires care that subwoofers not be mechanically coupled to surfaces which can themselves radiate energy (possibly radiating out of phase, or otherwise producing unwanted effects such as rattles). This applies especially to in-wall subwoofers, or any subwoofer which is mounted in a wall. (See also "Baffle Mounting" section.)

Subwoofers need not be located with a line of sight to the seating area. Note that use of separate channels of equalization, level, and delay for each subwoofer is beneficial, and allows for in situ optimization, even in non-rectangular rooms. Note that this assumes the subs all have the same source signal (i.e. bass management is used).

Side and Rear Speaker Placement Guidelines

The left and right side surround loudspeakers should be located symmetrically to the main listening position on or near the left and right side walls. It is necessary to elevate the surround loudspeakers two feet above seated ear height.

In 5.1-channel systems, place the side loudspeakers within the angular range ±110º to ±120º relative to the center-front loudspeaker, as measured at the prime listening location. If the audience is large, and/or the room is long, an additional pair of side loudspeakers can be used, placing the additional units behind those just described – if possible, just behind the last row of the audience. The loudspeakers on each side are connected in parallel, in phase. In such instances, audience coverage for the "envelopment" effect is improved for more listeners, but some listeners in the rear row(s) may lose the clear rear directionality of sound effects in the sound track. For this reason, it is recommended that a 7.1-channel configuration be used, with the additional loudspeakers serving as genuine rear loudspeakers.

In 7.1-channel systems, using the prime listening location as a reference, the side loudspeakers can be located in the ±60º to ±100º angular range, and the rear loudspeakers in the ±135º to ±150º range.

Baffle Mounting Guidelines

Baffle mounting improves the smoothness of low-frequency response and provides increased sensitivity in the region below 300 Hz.

- **The baffle cutouts should be oversized**

  The loudspeakers should float in the cutouts. Nonetheless, they should be securely held in place with resilient mounting.

- **Avoid direct contact between the baffle and the speaker enclosure**

  Direct contact of the speaker enclosure to the baffles is a poor practice, since sympathetic vibrations and resonances can be stimulated.

- **The front face of the cabinet should be absolutely flush with the face of the hard surface of the baffle closest to the screen.**

- **Use foam gaskets on the speaker enclosure**

  The speaker enclosure should be gasketed into place with closed cell foam weather stripping (available in hardware stores), and the enclosures should sit on vibration isolating pads in each corner. For example, Mason West, Inc. Type Super W, neoprene waffle isolation pads, Durometer 40, cut 2" (5cm) square.

The left and right channels should typically use toe-in to ensure proper coverage of the listening area. After aiming, the enclosure should be gasketed into place with ¼" (65mm) thick neoprene of minimum Durometer 40 available in 4′×4′ (1.25m×1.25m) sheets or other equivalent gasketing material.

Additional Resources

Books

Audio Engineering Handbook, Benson, K. Blair ed. McGraw-Hill Book Company, 1988.

The Master Handbook of Acoustics, Everest, F. Alton, TAB Books, Division of McGraw-Hill Inc., Blue Ridge Summit, PA. (To order call 1-800-468-4322)

Sound Reproduction: The Acoustics and Psychoacoustics of Loudspeakers and Rooms, Toole, Floyd E., Focal Press 2008

Architectural Acoustics, Egan, David, J. Ross Publishing, 2007

Acoustic Absorbers and Diffusers, Second Edition, Cox, T.J. and D'Antonio, P., Taylor and Francis, 2008

ASHRAE Handbook (2003). Chapter 47, "Sound and vibration control"

"Architectural Acoustics", Long, Marshall, Academic Press, 2006

The Visual Handbook of Building and Remodeling: The Only Guide to Choosing the Right Materials and Systems for Every Part of Your Home, Wing, Charlie, Rodale Press, 1990

Periodicals

Residential Systems Magazine, NewBay Media, LLC
Website: www.resmagonline.com

CE Pro Magazine, EH Publishing
Website: www.resmagonline.com

Home Theater Magazine, Source Interlink Media
Website: www.hometheatermag.com

Ultimate AV Magazine, Source Interlink Media
Website: www.ultimateavmag.com

Web Content – Sites, articles

National Research Council Canada, Institute for Research in Construction
This organization's web page has extensive data on measured transmission loss of different floor and wall constructions

`irc.nrc-cnrc.gc.ca/ie/acoustics/index_e.html`

"Guide for Sound Insulation in Wood Frame Construction"
J. D. Quirt et al, Research Report RR-219, 2006.

irc.nrc-cnrc.gc.ca/pubs/rr/rr219/rr219.pdf

Appendices

APPENDIX 1:
Recommended Approach to Optimizing Multiple Subwoofers in Rooms with Multiple Seats

At low frequencies, the listening environment has a significant impact on the sound quality of the audio system. Standing waves within the room cause large frequency response variations at the listening locations. Furthermore, the frequency response changes significantly from one listening location to another; therefore, the system cannot be effectively equalized.

By using multiple subwoofers, however, the seat-to-seat variation in the frequency response can be reduced significantly, allowing subsequent equalization to be more effective. Note that by optimization, we are specifically referring to reduction of seat-to-seat variation in the magnitude response of the subwoofers from 20-80 Hz in the seating area. Making the subwoofer responses flat, or getting the last couple of dB of bass output are not directly included in this definition of optimization, though these goals may be achieved during optimization or should be easier to achieve once the system is optimized.

There are several factors to consider when selecting an optimization approach, as outlined in Table A-1 (page 35), which gives suggestions for optimization in various cases. The most relevant cases for optimization are multiple subs in a small room with multiple seats. Three broad categories of optimization are possible: positional optimization, positional/dimensional optimization and advanced optimization.

CASE	RECOMMENDED OPTIMIZATION PROCEEDURE	
	Rectangular Room	**Non-Rectangular Room**
Large Room. Large rooms, such as auditoria and theaters, etc., likely do not need to be optimized. Even at low frequencies, there will be a large number of active room modes, effectively smoothing out the response across the seating area.	**None**	**None**
Only one seat to be optimized. If there is only one seat, there is only a need to equalize the system—there is no further optimization necessary. Note that trying different subwoofer locations might be part of this equalization, but it is not optimization as we have defined it.	**None**	**None**
Only one subwoofer in room with multiple seats. In this case, optimization options are severely limited. In a rectangular room, wall midpoints are good subwoofer locations with which to start.	**Positional Optimization** Expected result: slight to moderate improvement	**Trial and Error** Expected result: slight to moderate improvement
Room with multiple subwoofers, room dimensions not known. For example, a room is not exactly dimensioned yet, but subwoofers need to be located.	**Positional Optimization** Expected result: moderate improvement	**None**
Room with multiple subwoofers, room dimensions are known or (better) can be specified.	**Positional/Dimensional Optimization** Expected result: moderate to good improvement	**None**
Existing room with multiple subwoofers, impulse response measurements from each subwoofer to each listening location are available, and any of the following apply: • Subwoofer locations flexible • Individual subwoofer level can be adjusted • Individual subwoofer delay can be adjusted • Individual subwoofer filtering available	**Advanced Optimization** Expected result: Good to excellent	

Table A-1 – Optimization *procedure selection criteria*

Positional Optimization

Positional optimization refers to a method of choosing optimal locations for subwoofers and seats in rectangular rooms without regard to exact room dimensions. This works best with two or more subwoofers when the seating area is located in the center of the room (preferred) or between the center and rear of the room, and with the subwoofers located near or in the walls.

Systematic research suggests that in such cases (rectangular room, seats generally in the center of the room), symmetric subwoofer layouts with two or four subwoofers are preferable. Furthermore, configurations where the subwoofers are located at wall midpoints tend to work best.

Keep in mind that these configurations are not guaranteed to work better in every case, but they produce more seat-to-seat consistency on average. Figure 1 below shows the preferred layouts. Configuration 1 of the layouts is a special case, requiring subwoofers to be located away from the walls, possibly in or on the ceiling. Though likely not practical, it is mentioned because it provides almost perfectly flat and consistent bass throughout most of the room.

Note that a rectangular room is here assumed to have reasonably similar wall construction for all four walls. For example, a room with brick construction on one wall and single layer sheetrock on the other walls may not behave as a rectangular room or may behave as a rectangular room with dimensions moderately different than its actual physical dimensions.

An additional caveat is that positional optimization results for a room with seats on risers may be somewhat unpredictable, since this case has not yet been systematically investigated.

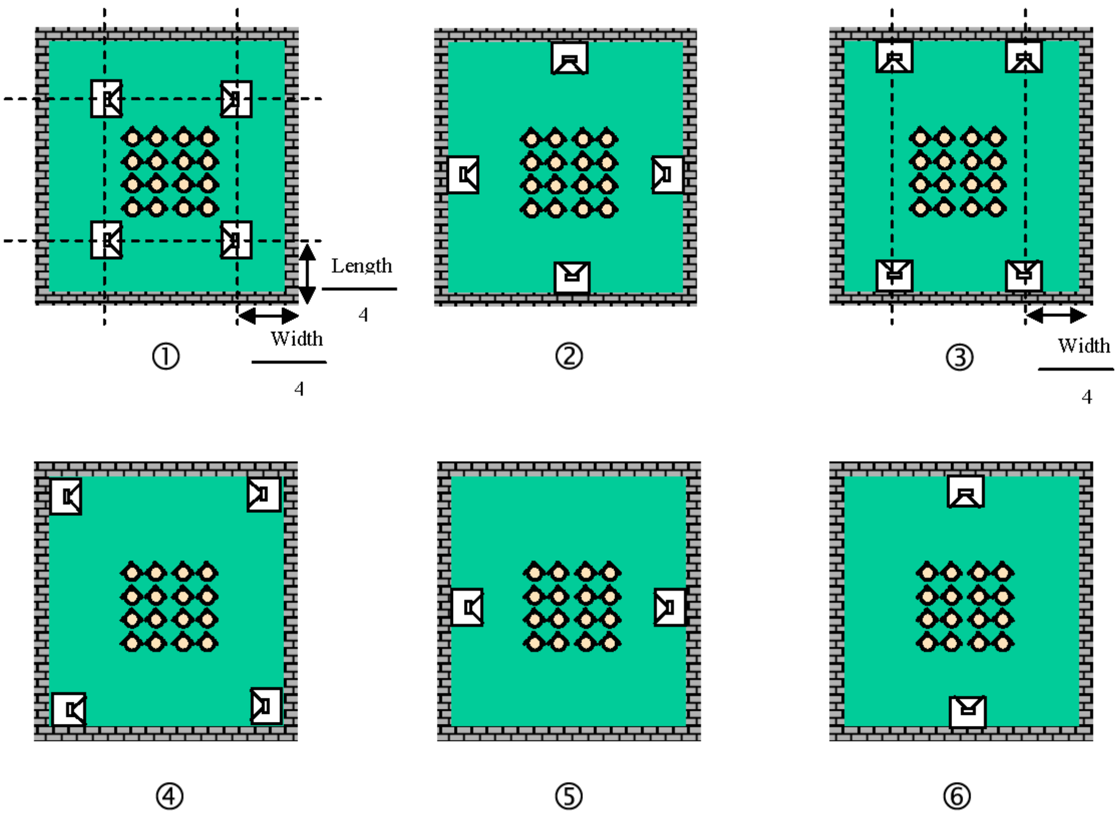


Figure A-1 –
Subwoofer configurations in a rectangular room

Figure A-1 depicts the six best subwoofer configurations for a rectangular room where exact dimensions are not known.

Configuration 1 produces the lowest seat-to-seat variance in the seating area. The other configurations are ranked from good (6) to best (1). Configuration 4 tends to produce slightly higher low frequency output levels than the others (1–3 dB typical).

Assuming that one of the positionally optimized subwoofer layouts shown in Figure 1 is used, a further optimization of the seating configuration can be made by avoiding placement of seats at or very close to the null points of the 2nd order axial length and width room modes. Listeners at these locations will not hear certain bass frequencies. (See Figure A-2 below.)

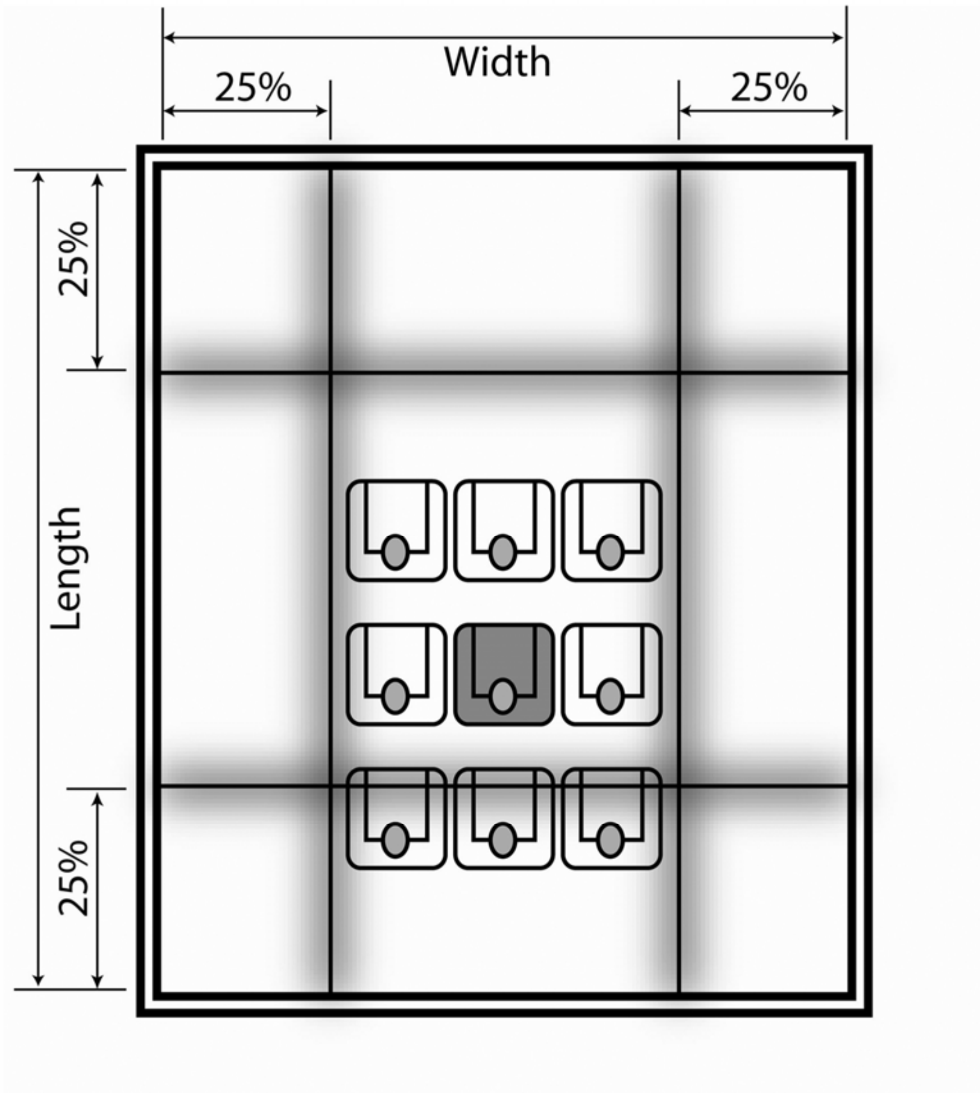


Figure A-2 – *This floor plan shows locations of the pairs of nulls for the 2nd order axial (width and length) room modes. The shaded areas indicate that the designer should locate chairs such that listener's ears are more than 18" away from the nulls. Unshaded areas show acceptable locations for seats.*

It should be mentioned that effective subwoofer optimization generally requires the use of bass management. To the extent that the signals in the different subwoofers are different, optimization is virtually impossible. Currently published research seems to indicate that spatial effects below

80 Hz due to bass management of 2-channel real world audio content in real rooms are subtle at best, and non-existent for the bulk of popular music which employs predominantly mono bass. See "Subjective Comparison of Single Channel versus Two Channel Subwoofer Reproduction," [2] T. Welti, *Journal of Audio Engineering Society*, October 2004, for a review. On the other hand, not using bass management can result in seat-to-seat variation of 40 dB or more at some frequencies or similar variations at one seat from different subwoofers. Therefore, there is little justification for the argument that optimization methods which rely on bass management are inherently objectionable.

The general assumption so far has been that the subwoofers are located at reasonably similar distances from the listener. If a subwoofer is located very near a listener, there may be a moderate localization pull towards that subwoofer under certain conditions (listening to subwoofers only, distortion products or port noise from the subwoofer, etc.). In any case, when the seating area is a substantial fraction of the room, this may be an issue regardless of the how many subs there are and whether they are bass-managed.

Positional/Dimensional Optimization

This method includes room dimensions as part of the optimization. More details can be found in "Optimizing Multiple Subwoofers"[3]. The idea of optimizing room dimensions has been around for a long time; however, it is much more effective when used in combination with positional optimization. In fact, with positional optimization, rooms where one dimension is an even multiple of the other (often maligned in the past) can be successfully optimized. This method works best for rectangular rooms with seating in the center of the room or between the center and rear.

Figures A-3 and A-4 below show the average seat-to-seat variation in frequency response (from 20-80 Hz) that results in rectangular rooms of various dimensions for several subwoofer configurations. This performance metric is called Mean Spatial Variance (MSV). A low value of MSV is desired, meaning that the frequency responses at the different seats are more similar.

The seat-to-seat variation is calculated on a theoretical basis, but is a reasonable indicator of what you can expect in real rooms. If the room dimensions and seating area location (middle of room or between middle and rear of room) are known, the best subwoofer configuration can be determined from Figures A-2 and A-3. A lower MSV value means more consistency in bass response from seat to seat. These are the lighter colored areas in the plots. Conversely, if the subwoofer configuration is fixed and is one of those shown, the optimal range of room dimensions can be determined. Note that these figures assume an 8- to 10-foot (2-3m) ceiling.

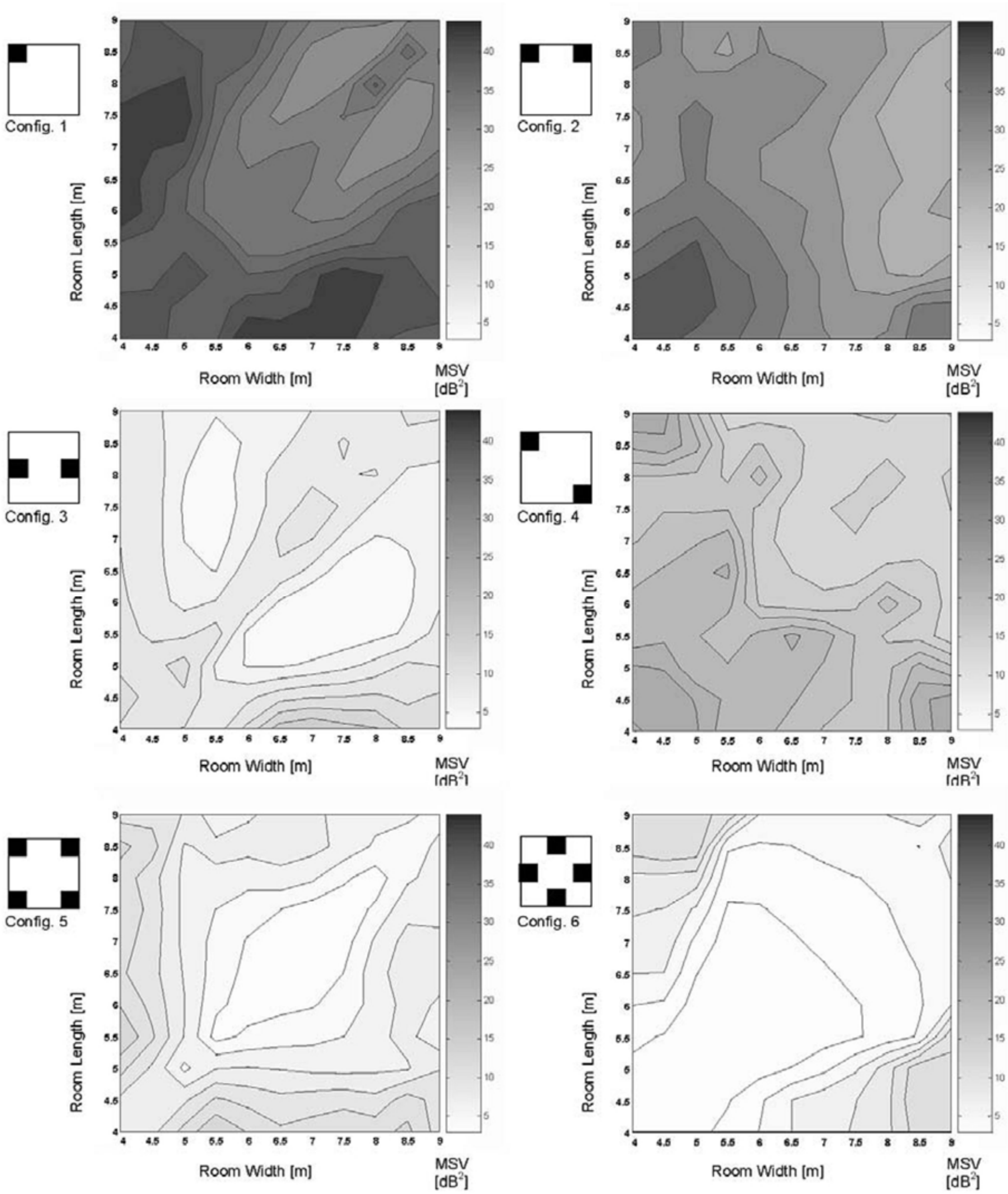
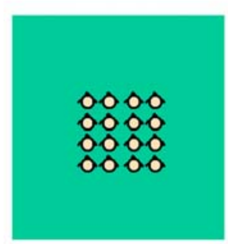


Figure A-3 – *Predicted Mean Spatial Variance (MSV) for low frequencies (20-80 Hz) as a function of room dimensions, for six different subwoofer configurations – seating area centered in room. Lighter areas in the plots correspond to lower MSV, which means less seat-to-seat level variation (good).*



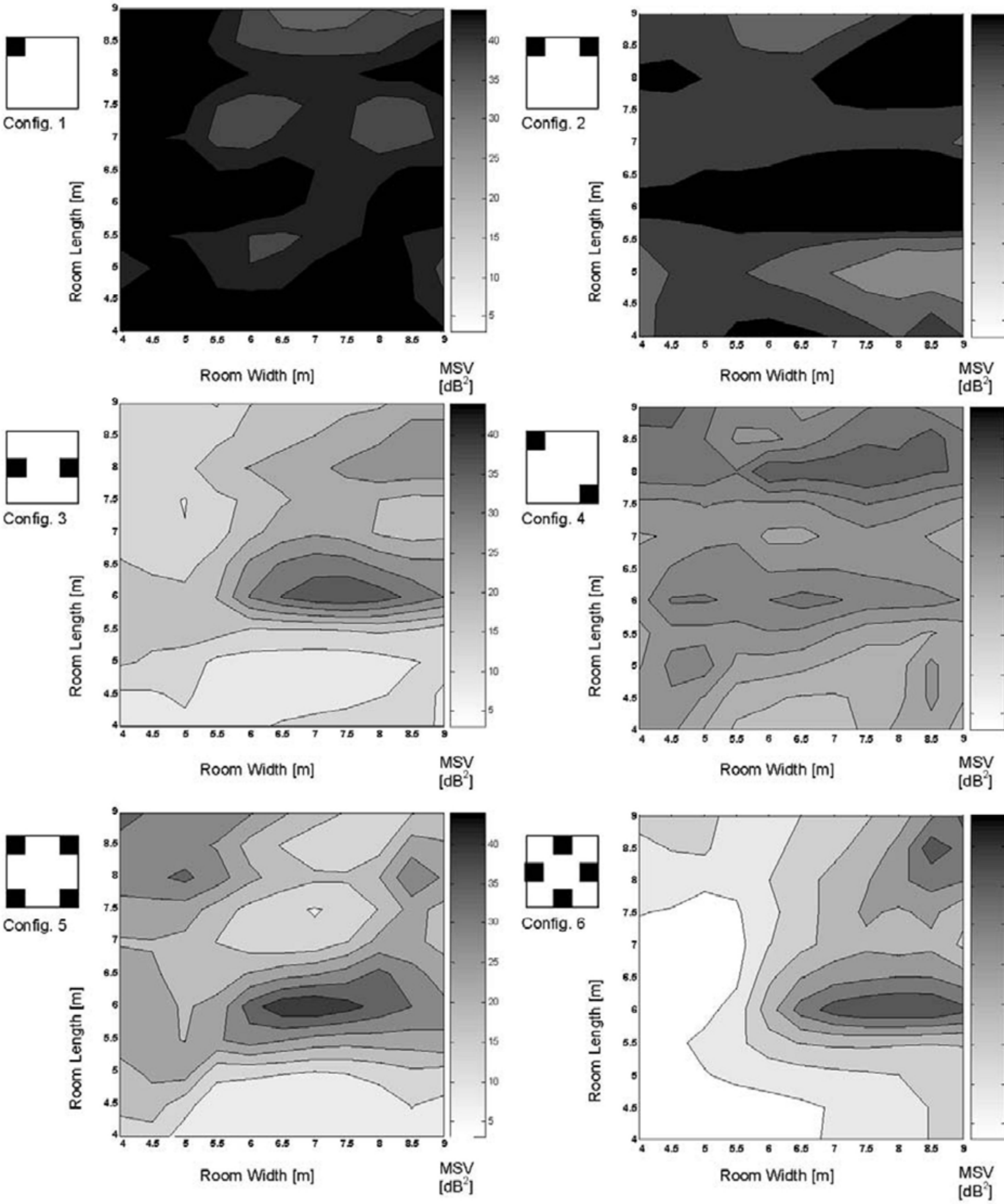
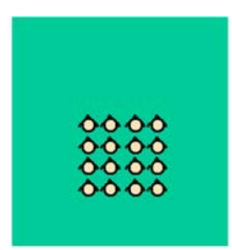


Figure A-4 – *Predicted Mean Spatial Variance (MSV) for low frequencies (20- 80 Hz) as a function of room dimensions, for six different subwoofer configurations – seating area moved back in room. Lighter areas in the plots correspond to lower MSV, which means less seat-to-seat level variation (good).*



Advanced Optimization

More advanced methods for optimization of subwoofers have been developed. These methods generally require subwoofer-to-listening-location impulse response measurements and some type of signal processing for each independent subwoofer.

Welti and Devantier[3] show how a computer algorithm can be used to predict and evaluate thousands or even millions of possible settings of the signal processing equipment and/or potential subwoofer locations in the room, based solely on in-room measurements. These settings may be as simple as level or delay settings on each subwoofer. The best solution can then be implemented.

Other methods, such as those used by Kirkeby and Nelson[4] and Miyoshi and Kaneda[5], use more analytical approaches, e.g., solving simultaneous linear equations to remedy the problem, which results in a single best solution, generally implemented using sophisticated digital filters.

An important advantage of all of these methods is that they are not limited to rectangular rooms with typical seating configurations. They will work in virtually any room, and they work well. A disadvantage is that they require measurement data from a built room. Using this approach with a computer-modeled room does not work well in most cases.

Commercial products that use these more advanced approaches are just now becoming available. An alternate method, described in Celestinos and Nielsen[6], is simpler to implement but is not very flexible with respect to locating the subwoofers. (It uses one particular configuration of four subwoofers.) This method also only works in rectangular rooms.

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APPENDIX 2: Calculating Reverberation Time Using the Classic Sabine Equation

The Sabine Equation is an alternative method for calculating reverberation time (RT). This too is an approximation, but a better one, since it allows us to combine the contributions of many different materials having different acoustical performances. Again, it is assumed that the absorbing materials are reasonably evenly distributed on the room surfaces. The Sabine formula for calculating RT is:

$$RT = .049\ V/A$$

where *V* is the total volume in cubic feet and *A* is the total absorption in the room in sabins. "A" is calculated by adding up all of the areas (carpet, drapes, walls, etc.) of the boundaries that are covered by materials that absorb sound, multiplied by their individual absorption coefficients:

$$A = (S1\alpha1 + S2\alpha2 + S3\alpha3\ .\ .\ .\ )$$

Where *S* is the area in square feet, and α is the absorption coefficient for the material covering that area. Absorption coefficient is a measure of the percentage of sound that is absorbed when sound reflects from the material. It is frequency dependent, so we look for materials that have relatively constant absorption over large frequency ranges, ideally, at all frequencies above about 300 Hz. For purposes of this calculation, we use the absorption coefficient at 500 Hz. The product of *S* and α is a number with the unit sabins. The absorption of some items, such as people or chairs, is sometimes quoted directly in sabins.

The metric equivalent of the Sabine Equation is:

$$RT = 0.161V/A$$

where the volume is in cubic meters, areas are in square meters and *A* is in metric sabins.

Example

Let us confirm that the recommendation 1, above, is correct. A room 24×20×9 ft. (7.5×6×2.75m) has wall-to-wall carpet on the floor. Its absorption coefficient at 500 Hz is 0.6 so the absorption in sabins is the floor area (480 sq. ft. or $45m^2$) multiplied by 0.6, which gives us 288 sabins. In addition to this we will place areas of 3- or 4-inch (75-100mm) thick fiberglass or mineral wool at several locations around the walls, for a total of 25% of the wall area (88×9=792 sq. ft. × 0.25=198 sq. ft. or $18.5m^2$). This material has an absorption coefficient of approximately 1.0 at 500 Hz, giving us 198 sabins. The total amount of absorption therefore is 288+198=486 sabins. The room volume is 24×20×9=4320 cu. ft. ($123.75m^3$) Plugging these numbers into the simple equation gives us the predicted RT: 0.049×4320 / 486 = 0.44 second. In reality, there will be other absorbing devices (chairs and people) and scattering from surface irregularities and furnishings, so the final estimate will be slightly lower. We are comfortably inside the desired range of RT.

APPENDIX 3:
Wall and Ceiling Construction

Home theater installation technicians can use multiple wall and ceiling construction applications to achieve sound isolation. Each method has its own inherent advantages and disadvantages. Key considerations, however, are that such constructions incorporate high mass, mechanical decoupling from the building's structure, and absorption.

Framing techniques

- **Room-within-a-room method**

  In the framing process, the most effective method is the room-within-a-room method. This method however may not be acceptable due to the amount of floor space consumed, local fire-code objections and loss of floor to ceiling clearance. A true room-within-a-room style of construction dictates an isolated floor, isolated base/top plates, and an isolated ceiling framing. Prior to proceeding on such a path, one is advised to seek professional input from either an architect or structural engineer.

- **Stagger-stud method**

  The least effective is the stagger-stud method of framing. While this method does provide mechanical isolation, neither the base nor top plates are isolated. More of an issue is implementing stagger joist to provide ceiling isolation. Usually stagger joist construction is not viable with existing mechanical and plumbing systems running through the joist space areas.

- **Isolation clips**

  The third method utilizes isolation clips installed onto the framing members (wall and ceiling), a metal "HAT" or furring channel installed into the clips, and then the drywall is installed to the HAT channel. The isolation clips consist of a rubber, or flexible material, which isolates, or damps, the wall/ceiling from the structure. This method is can be very effective and is not cost or space prohibitive. Traditional "Z" channel or resilient channel is not an effective solution for music or cinema sound reproduction spaces.

All joist and framing cavities should have fiberglass batts, blown-in wet cellulose, or similar insulation material in the cavities. Closed cell foam insulation products are counterproductive. If open cell foam is to be used, the foam should not contact both sides of a wall or ceiling. This would re-couple the walls.

Drywall isolation techniques

Drywall is installed directly onto the framing for double wall or stagger-stud construction or into the "HAT" channel when isolation clips are utilized. Two layers of drywall are highly recommended and provide a doubling of mass. Such high mass walls will reduce the resonance frequency of the wall assembly.

When multiple layers of drywall are used, each layer should be completely installed before any subsequent layer. In other words, ceiling then walls followed by ceiling and walls again. This results in a lap joint in the corners rather than a butt style joint which, if not well sealed, will provide a flanking path and defeat your sound isolation efforts. Layers of drywall should have a viscoelastic coating applied between each layer of drywall. Such coatings have been shown to be very effective in damping (absorbing) low frequency energy.

Drywall products are available which have been manufactured with a constrained layer damping material laminated into the drywall at the time of manufacture. Special caution should be taken when electing to utilize such manufactured products. First, two layers of the material may be required to achieve a wall with a mass equal to two layers of ½” or 5/8” drywall. Second, using such single layer products will require careful attention to sealing any gaps or flanking paths where the sheets of material butt together.

For less critical applications, or where the existing space is already dry walled, a second layer of drywall can be installed over the existing walls and ceiling using a viscoelastic material applied between the old and new drywall. Do not be tempted to install resilient channel or isolation clips over an existing wall surface and then install the new drywall. This form of construction will create a triple leaf and will result in more transmission of sound through the barrier rather than less.

In order to effectively seal the room, it is suggested the installation of drywall occur before the installation of any architectural acoustical treatment elements such as columns, soffits, stages, or raised seating platforms. Columns can be used to house speakers, electrical outlets, and lighting control dimmers without the adverse effects associated with putting holes in the sound isolation barrier around the room. Installing wall to wall seating and stage platforms inside the barrier will also allow these items to be used as bass traps.

Floor Isolation Techniques

Floors should be decoupled from the structure of the building. Failing to do so will create a significant and undesirable flanking path. Again, in a double wall construction method, floor faming can be isolated by use of commercially available isolation pucks, “U” anchors, floor suspension devices and similar materials. Such methods will generally consume more height than is desirable in most residential situations. Concrete is an excellent transmitter of kinetic sound energy and any temptation to avoid isolating concrete slab floors should be dismissed.

An effective method of floor isolation (without large structural impacts on upper floor rooms) is to install a high mass 5/16- to ½-in. (7.5-12.5mm) rubber mat over the existing subfloor or slab. This mat should be installed after the drywall is installed; any gap between the bottom of the drywall and the subfloor should be thoroughly caulked. The mat should be installed ¼” (5mm) short of the drywall and not contact the drywall at any point. Oriented strand board (OSB) or plywood is then installed over the mat, again not contacting the drywall, using an approved mastic. Seating platforms and stages are then installed over the new subfloor.

Consumer Technology Association Document Improvement Proposal

If in the review or use of this document a potential change is made evident for safety, health or technical reasons, please email your reason/rationale for the recommended change to standards@CTA.tech.

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