The Acoustical Design of Home Theaters

by

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This overview is intended to set a context within which readers can apply the more detailed technical information in the accompanying paper: "Loudspeakers and Rooms - Working Together". At some point, I plan to improve the relationship between the contents of the two documents, but for now there will be some redundancy, and stylistic differences. Some people come to this topic thinking that, as is some other things, that there must be a simple way to do acoustical design, a kind of cookbook, that anybody can understand. I wish that were so, because it would simplify all of our lives. As it is, achieving truly good sound in rooms requires knowledge of how sound behaves in rooms, and some effort – or more than a little bit of luck.

Multichannel audio has become a reality in home theaters, and it is rapidly becoming a presence in music and games. Much of the technology in audio, that we know today, has evolved during the nearly fifty years we have spent with two-channel stereo. For example, designs for loudspeakers and rooms have been developed that specifically serve that medium. With only two channels, many listeners found benefits in spraying the sound around the room, using multidirectional loudspeakers, and in tailoring the reflected sound field with strategically placed absorbing, reflecting and diffusing surfaces. Stereo remains an area ripe for experimentation, mainly because only two loudspeakers restrict what is possible in creating realistic senses of direction and space. Stereo needs help, and in experimenting with various enhancements, we often create something that is different from what was intended, although it may be thoroughly engaging and entertaining.

Multichannel audio changes the rules significantly. There are now multiple real sound sources surrounding the listeners. The front channel loudspeakers include a center, thus theoretically eliminating the need for a "stereo seat" - multichannel audio should not be an antisocial listening experience; it is intended to be shared. As things stand, I am sad to report that several of the new multichannel music recordings avoid using the center channel, and the phantom center image forces listeners back to the stereo seat. I hope that this remnant of the stereo era will pass as recording engineers learn how to use the center channel tastefully, perhaps with some new production tools. Of course, customers must also make a commitment, and use center channel loudspeakers that are up to the task of doing most of the important work in a multichannel system.

The surround side/rear loudspeakers have been matters for experimentation, especially for the reproduction of movie sound tracks, but the appearance of multichannel music changes the focus somewhat. In the days of Dolby Surround/ProLogic, film sound was well served by multidirectional (including dipole) surround loudspeakers. However, listeners are finding that the digital discrete 5.1-channel systems seem to work well with five identical loudspeakers, and this certainly is the early trend in multichannel music. The key factor here is that the perceptions of direction, space, depth and so on, are really very much in the hands of the artists and recording engineers. At the reproduction end of the chain, the multichannel audio system should be a faithful delivery system for their creations. There is less need for the customer to be creative, in order to hear good and exciting sounds.

With this little perspective behind us, let us dispense with a popular question: "aren't some loudspeakers better for movies, and some better for music?" This is really the wrong question. The real question of the day is: "aren't some loudspeakers better for stereo, and some better for multichannel audio?" There are good loudspeakers, and not-so-good loudspeakers of all design configurations. However, it is reasonable to assert that multidirectional designs, intended to enhance the spatial illusions in two-channel stereo, may not be ideal for the main loudspeakers in a delivery system in which the spatial illusions are supposed to be under the control of the artists and engineers. As for the loudspeakers designed for multichannel applications, it would be a terrible embarrassment to any competent loudspeaker designer if his products were not equally good sounding in multichannel performances of James Taylor or Fleetwood Mac in concert, Strauss waltzes, the 1812 overture, Armageddon and Terminator II. The only additional consideration in movies, is the need for higher sound levels, especially of deep bass, if one's taste runs to blockbuster adventure films with their spectacularly over-the-top pyrotechnics.

Getting good sound in a room. How is it done?

The science of room acoustics has mainly developed in the context of live performers in concert and recital halls. Relatively little scientific effort has been put into understanding sound in small rooms, especially as it relates to sound reproduction. The irony is that far more music is listened to at home, than in concert halls. Still, there has been significant progress, and we are beginning to understand some of the things we can do to ensure decent sound quality in the semi-infinite range of room sizes, shapes, arrangements, and furnishing variations that exist. It sounds as though it might be difficult. Well, it is not nearly as complicated as "rocket science", but neither is it a totally straightforward "cookbook" exercise. You will have to do some work, and think a bit.

Step One: Start with a good room

That is, of course, if there is a choice. Most often we must work within an existing space, or one that has been designed with things other than acoustics in mind. There are notions that some room dimensional ratios – length to width to height – offer special advantages. Personally, I have not found this to be so, and I think I know why. It is because the theories and calculations leading to these preferred ratios assume several things that are not true to our realities.

- First, it is assumed that the rooms are perfectly rectangular, with perfectly reflecting, perfectly smooth, flat walls. This rarely happens, and if it did, we would probably want to do something to change it. Such rooms are unpleasant listening spaces.
- Second, it is assumed that all calculable room resonances are equally important. They are not. In terms of their impact on audible characteristics, it is abundantly evident that, in most rooms, the axial modes have the strongest "voices", with tangential and oblique following behind. I have encountered a few rooms, with relatively massive, stiff walls, where one or two low-order tangential modes are audible problems, but that is all.
- Third, it is assumed that all of the calculated room resonances are equally energized by the sound sources, and are equally audible to listeners. This could only be true if we only had one sound source, on the floor in a corner, and if we positioned our head at another three-surface intersection. Such a notion is preposterous! In reality, there may be two or more sources of low-frequency sound. Two physically separated woofers, even if they both are in corners, do not energize all of the room modes equally, or at all. If they are not in corners, the modal excitation can be very selective indeed. Likewise, listeners do not stick their heads in corners. Out in the middle of a room, the coupling to room modes is extremely selective, and that is one of the biggest problems we have to deal with.

So, why did this whole business of special room ratios get started? Actually, it began decades ago, very scientifically, with serious minds trying to optimize the performance of acoustical reverberation chambers, where it was intended to conduct precise measurements of sound power. From there it got picked up and elaborated unrealistically to include rooms, like ours for sound reproduction, where those ideas simply do not apply.

Now, this does not mean that room ratios are irrelevant. It is a good idea to avoid a perfect cube, rectangles with simple (whole number) dimensional ratios, and long corridors. Beyond that I believe that, if you know what you are doing, it is possible to create excellent sound in rooms that are in gross violation of the "rules", and just as it is possible for truly mediocre sound to exist in supposedly "good" rooms.

In truth, the most problematic rooms that I have encountered, were ones that came too close to the first of the "ideals" listed above. The room boundaries were very hard, very dense, and very flat. The result was that all of the room modes were extremely powerful, high-Q, and very "resonant". Consequently, the resonant peaks were very high, the cancellation dips very deep, and the "booms" went on forever.

In order to be good, a room must have some low-frequency sound absorption, and if this is not to be found in the room boundaries themselves, then it must be added. A few inches of resistive absorbing material, such as fiberglass or acoustic foam, has no effect at low bass frequencies. Low-frequency absorption is most effectively done with panel, or membrane, absorbers. When large surfaces, including the room boundaries, floor, walls and ceiling, move in response to powerful bass sounds, they are behaving as membranes and they are absorbing sound energy. This absorbed sound energy cannot contribute to room resonances, and as a consequence, the resonances are weakened. This is a good thing. One can buy or build membrane absorbers, although getting them to be effective at very low frequencies can be a challenge. Many of the devices in the marketplace are not very effective below about 100 Hz, just where things get interesting. Be sure to check that the absorption coefficient is high in the frequency range where your problems are. If possible, one can anticipate the problem and build the interior structure of the room so that the room boundaries are somewhat flexible. It turns out that one layer of gypsum board on single wooden studs is not a bad compromise – and it is inexpensive. A layer of acoustic board under the gypsum board can add mechanical damping, without adding much mass or stiffness. Some people have promoted varying the stud spacing to "detune" the mechanical wall resonances. By doing this, you can certainly anticipate the wrath of your builder, for making his job much more difficult. Much the same result can be achieved by occasionally doubling the studs, and by ensuring that the wall surfaces are not perfect flat slabs – a good thing from the point of view of diffusion.

This done, another very important benefit will have been realized, and that is to improve the uniformity of the bass sound over a large listening area. By reducing the "Q" of the room resonances, the pressure peaks are lowered, and the pressure nulls are not as deep, making good bass possible at more than a few locations. Multichannel audio is to be shared.

Step Two: Start with good loudspeakers – ones that are "room friendly".

What we hear in a room is controlled by different factors at different frequencies. At low frequencies it is the room that dominates, but at middle and high frequencies, it is the loudspeaker itself – its frequency response and directivity – that dominate sound quality. Little-to-nothing can be done, with an equalizer in a room, to fix a loudspeaker that is fundamentally poorly designed. Here the solution is to start with a loudspeaker that is designed to be "room friendly". It may come as a surprise to you, but not all are.

An example of this that many of you may remember is the fashion, a few years ago, of building rooms that were acoustically live at the listener end, and acoustically dead at the loudspeaker end. The inspiration for this appears to have been the need to improve the sound of a, then popular, studio monitor loudspeaker that misbehaved dreadfully in its off-axis response. The only way to deliver good sound quality was to absorb the sounds that would normally have reflected off the floor, walls and ceiling. This is the definition of a loudspeaker that is hostile to ordinary rooms, and that required a major overhaul of the listening space to make it acceptable. This ludicrous exercise managed to survive for some time, even in the normally-rational world of professional audio. It is totally ridiculous for home audio. Not surprisingly, when subjectively evaluated as a "hi-fi" loudspeaker, in a normally reflective room, this loudspeaker was enthusiastically disliked.

The real solution, for professionals as well as consumers, is loudspeakers that deliver similarly good timbral accuracy in the direct, early reflected and reverberant sound fields. This can be described as a loudspeaker with a flattish, smooth, axial frequency response, with constant directivity (which together result in flattish, smooth, sound power). Then it becomes an option, whether the room is acoustically damped, or not. If reflected sounds are absorbed, the listener is placed in a predominantly direct sound field, making the experience more intimate, and the imaging tighter and more precise. If the reflections are allowed to add their complexity, the overall illusion is altogether more spacious and open, to many listeners, more realistic. In part, this is a matter of taste. In either case, a room-friendly loudspeaker will yield timbral accuracy. So, at middle and high frequencies, the proper solution to getting good sound quality, is to choose good loudspeakers to begin with.

Step Three: Improving Bass Performance – working with standing waves

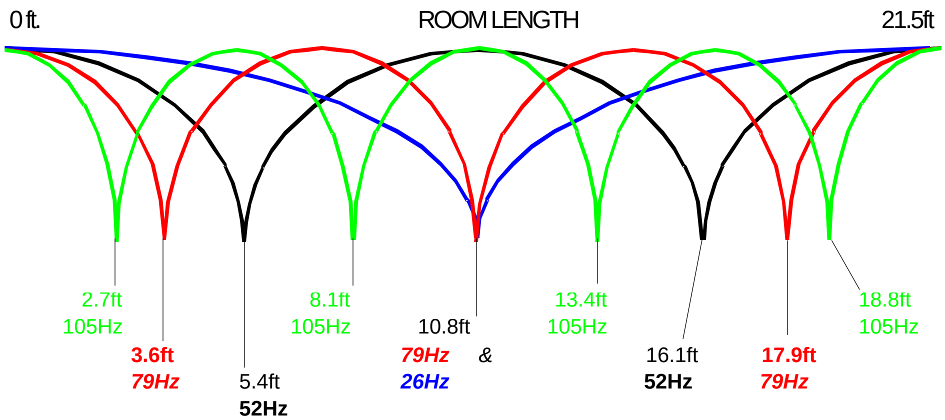
At low frequencies, the situation is very different, and the room, and the arrangement of sources and listeners within it, dominates the quality of bass. Of course, the woofer must be capable of the necessary quantity of sound, with low distortion, over the necessary frequency range. Taking control of this means that it is necessary to get a bit technical, in order to understand how the subwoofers couple their energy into the room resonances, and what listeners hear. There are several forms of computer aids that make life easier, and there are some simple manual methods that can take us most of the way.

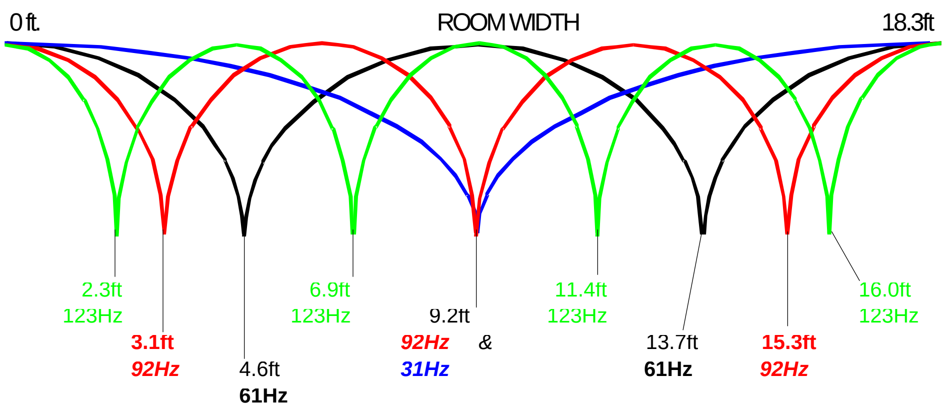
Measurements of what is happening in the room are absolutely necessary if you are to be successful. However, they must be of the right kind – more detailed than is available from the normal 1/3-octave real-time analyzers. Use a high-resolution measurement system, such as MLSSA, SMAART, TEF, or even old fashioned swept or stepped tones, set up to give at least 1/10-octave resolution (2Hz resolution at 20 Hz). Measure what is reaching the listening positions when all subwoofers are simultaneously active.

If the room is a simple rectangle in shape, the resonant modes are easy to calculate, at least the axial modes, which are usually the biggest problems. Calculating the frequencies at which the resonances occur is just a start; it is then necessary to determine where in the patterns of pressure peaks and nulls (the standing waves) it is best to locate the subwoofers, and where to position the listeners. It will be found that maximizing the pleasure and minimizing the pain involves some tradeoffs. Figure 1 shows a printout of a useful program that illustrates the sound pressure distribution along each room axis, allowing you to choose the listener locations to avoid the worst peaks and dips. Subwoofers need to be in high-pressure regions, preferably against the wall, or better still in a corner in order to excite the room modes. The PC program that does this is available, at no charge, from the author: ftoole@harman.com.

If measurements indicate that there is too much energy at a resonant frequency, try to move the listener towards a null in that particular standing wave pattern; too little, means moving out of a null, towards a peak. By these trial and error methods it is often possible to alleviate many of the problems, smoothing and flattening the frequency response.

Standing Waves							
Enter dimensions, in feet			1st	2nd	3rd	4th	
	Height:	8.00ft	*70Hz*	141Hz	*211Hz*	281Hz	
	Width:	18.30ft	*31Hz*	61Hz	*92Hz*	123Hz	
	Length:	21.50ft	*26Hz*	52Hz	*79Hz*	105Hz	
Room volume =			3148CU ft				





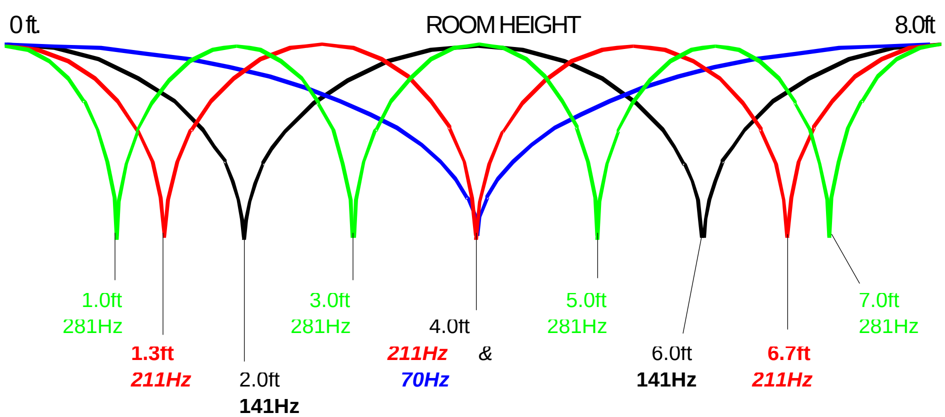


Figure 1 The output of a program that calculates the axial modes of a room, and plots the pressure as a function of distance along each of the principal axes.

If the room is not rectangular in shape, or if there are large openings in one or more of the walls, predictive calculations will not work well, or at all. In this case, one must revert to measurements, and trial and error repositioning of subwoofers and listeners. This is not a good situation to be in. Non-rectangular rooms do not eliminate room resonances, they just make it impossible to calculate them simply.

With the best rooms, and intentions, perfection may be elusive. Given the practical constraints of real environments, and the limits on listener positions, viewing distances and angles, acoustical manipulations may not be enough to eliminate all room resonance problems. In fact, in my experience, it is rarely enough.

Step Four: Improving Bass Performance – equalization does work!

It is in these situations, when you have exhausted the acoustical possibilities, that equalization of the right kind can be very helpful. However, it must be done intelligently, since there are some things that equalization can correct very well, and other things that it is a mistake to try to fix.

Not everybody agrees with equalization, accusing it of introducing "phase shift", and other nasties. Well, there is no doubt that equalization has acquired a bad reputation over the years, but from the perspective of what we know now, it has been absolutely deserved. There are four principal reasons:

1. The popular measuring instruments, 1/3-octave real-time analyzers, do not have enough resolution to describe the problems accurately.
2. The popular equalizers, 1/3-octave "graphic" equalizers, do not have enough resolution to address the problem resonances specifically, without doing a lot of "collateral" damage.
3. Attempting to fill deep frequency response dips caused by acoustic cancellations or nulls is an absolutely futile effort, because no matter how much sound energy one pumps into a room the cancellation persists. All that happens is that amplifiers clip, and woofers distort, or worse, destruct. The only solution to this kind of problem is to relocate the loudspeaker or the listener, whichever is sitting in the null.
4. Equalization is attempted at too high a frequency. Low-frequency room resonances behave like minimum-phase phenomena, and addressing them specifically with parametric filters is a true solution. Above a few hundred Hz, the situation is very different, because we are using steady-state measurements to examine a complicated combination of direct and reflected sounds – time domain phenomena. The measurements may show "comb filtering" that is alarming to the eyes, but the ears hear only the natural sounds of a room – not necessarily a problem at all. If the reflections are perceived to be too energetic, the solution is not equalization, but rather the addition of some strategically placed sound absorbing or diffusing devices. As stated earlier, if there are obvious sound quality problems at middle and high frequencies, the only true solution is a properly designed, room friendly, loudspeaker.

Intelligent Equalization

So, how do we do "intelligent" equalization? The first step, is to work with high resolution measurements that can show you what is really going on, the 1/3-octave real-time analyzers simply do not cut it. The ability to average measurements made at several locations within the listening area is a big help, because it will tend to attenuate the interference dips that equalization cannot fix, and help bring into focus the room resonances, that equalization very effectively addresses. Then the task is to decide what to change with equalization. A safe place to start is to use the equalizer to pull down peaks, and to avoid trying to fill holes. A broad, gentle, depression might be filled, but do it in stages, listening to see if something positive is actually happening. It is wise not to add more than a few (say 3 to 6) dB of boost. If you do add boost, remember that each 3 dB doubles the power requirement from the amplifiers, and the loudspeakers. Everything will be working much harder. Preferably, try to find acoustical ways to fill holes, and use the equalizer to smooth out the peaks. If there is a persistent notch, try to identify which mode is involved, and whether the loudspeaker or the listener is in or close to a null. Move the suspected element a foot or so away and see if there is improvement. The room mode analysis program is a big help in this – assuming you have a rectangular room. If all attempts fail, be content that at least the resonant peaks are gone, and that narrow dips are much more difficult to hear.

Here is an example, taken from the hands-on workshop held after this course at the 1998 CEDIA convention. The room we were given to work with was clearly going to be a problem (which we liked), because it had rigid masonry walls (good strong, high-Q resonances), and dimensions that were in simple ratios to each other (8 x 12 x 24 feet). With a TV at the end wall, a good viewing distance of 12 feet put the prime listening location close to the mid-point of the room. This puts the listener near a null for the first-order length mode (1130 / 2 x 24 = 23.5 Hz). It is difficult to get very concerned about this, because there is almost no useful information at this low a frequency, but we might try to ensure that the listener's ears are just ahead of or just behind the half-way point of the room. However, at the second-order modal frequency, 47 Hz, there is an abundance of audio information, and here the listener is sitting in a broad pressure peak.

Figure 2 shows what we measured for the subwoofer, by itself and, as predicted, there was a prominent peak right around 47 Hz. When we listened, the bass was flabby and boomy, with a "one-note" quality. Even movie explosions sounded fake. To address this problem we dialed in a single parametric filter, set to 47 Hz, with the appropriate bandwidth, or Q, and simply turned the resonance down. Room resonances at low frequencies behave as "minimum phase" phenomena, and so, if the amplitude vs. frequency characteristic is corrected, so also will the phase vs. frequency characteristic. If both amplitude and phase responses are fixed, then it must be true that the transient response must be fixed – i.e. the ringing, or overhang, must be eliminated. Figure 3 shows that this is so. Equalization of the right kind can work. Notice that we completely ignored the acoustical cancellation dip at about 73 Hz.

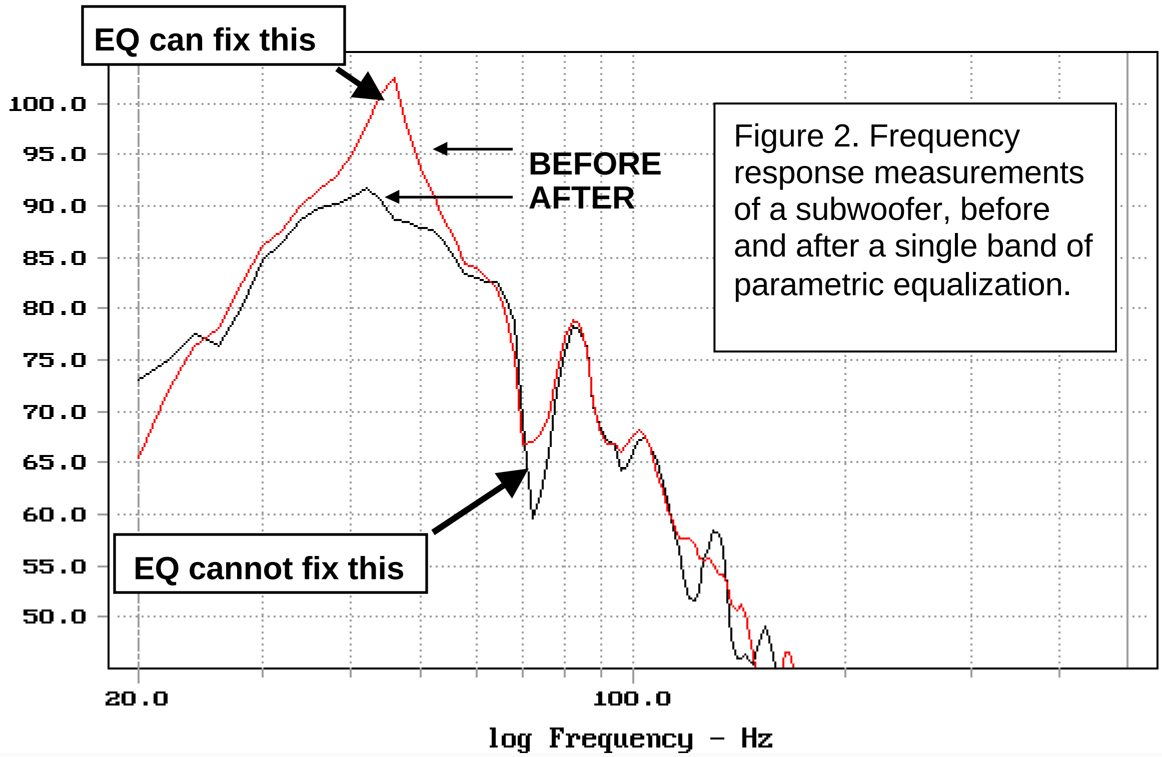


Figure 2. Frequency response measurements of a subwoofer, before and after a single band of parametric equalization.

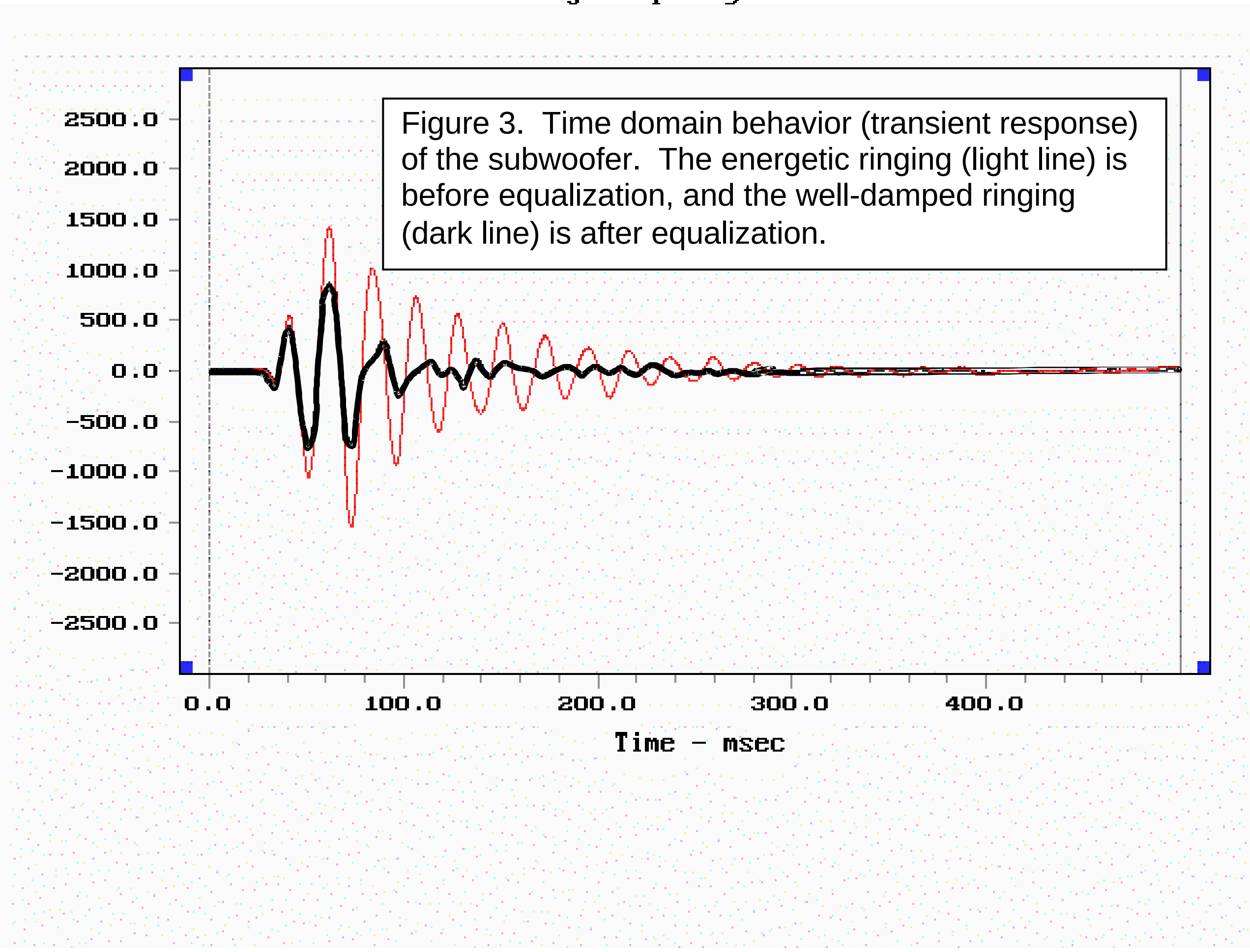


Figure 3. Time domain behavior (transient response) of the subwoofer. The energetic ringing (light line) is before equalization, and the well-damped ringing (dark line) is after equalization.

So, what would have happened in this case if we had used the traditional methods based on 1/3 – octave measurements and equalization?

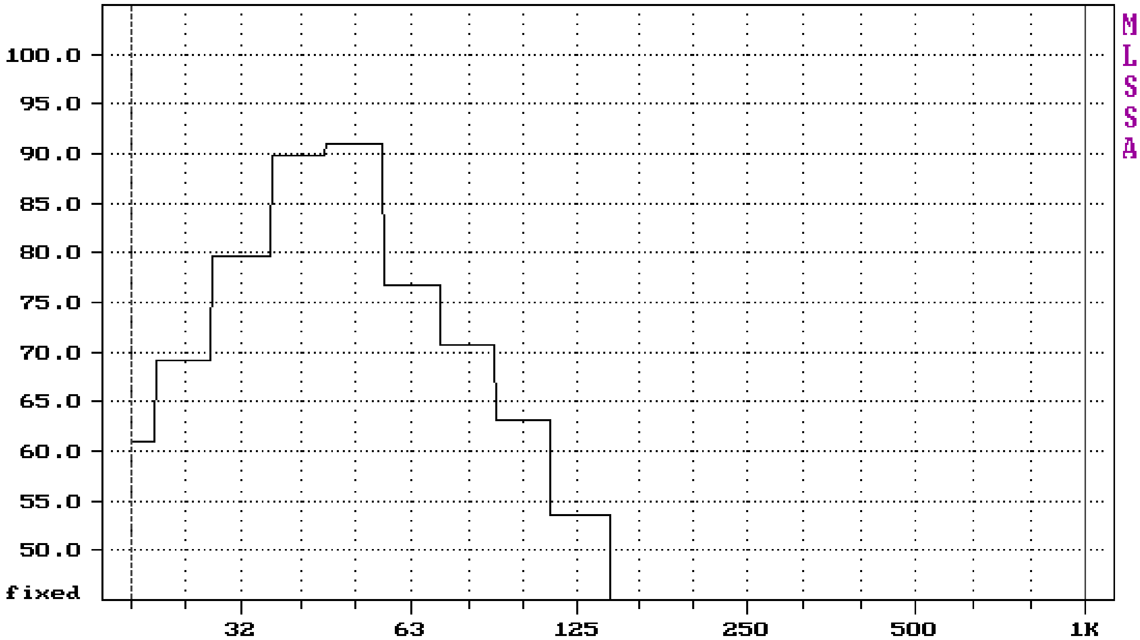


Figure 4. A 1/3-octave version of the unequalized high-resolution frequency response curve in Figure 2. Note the absence of any hint of a high-Q resonance at 47 Hz, and the lack of any evidence of an interference dip at 73 Hz. It doesn't look all that bad, really.

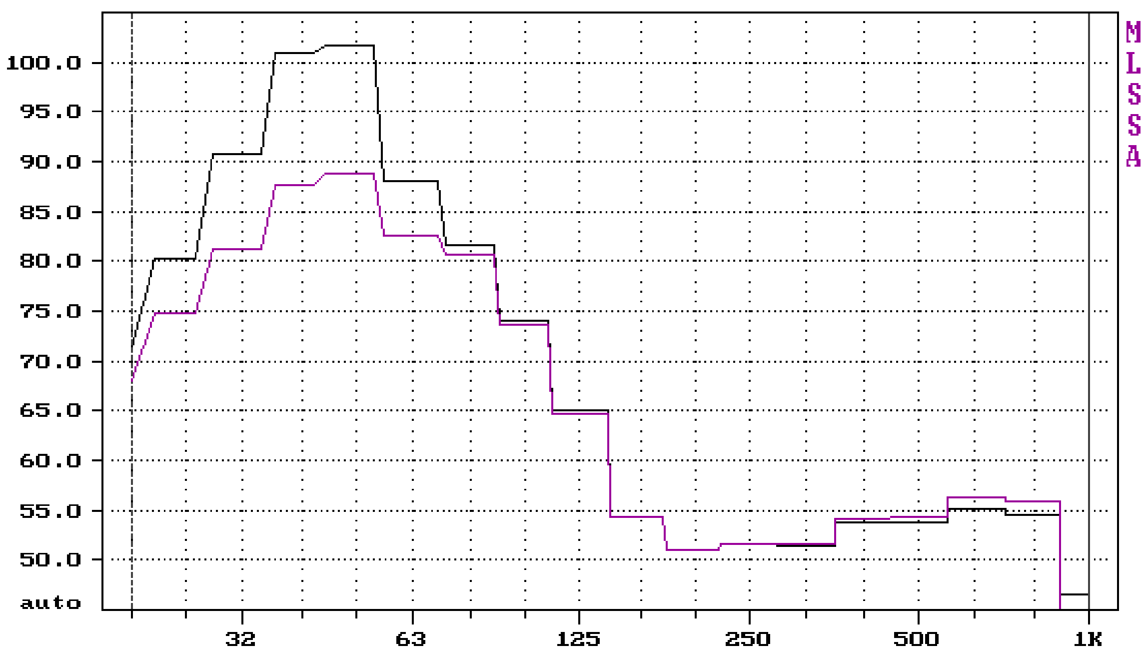


Figure 5. We think we can improve the shape a bit, so we dial in some attenuation at the two highest peaks, using a 1/3-octave graphic equalizer (lower curve).

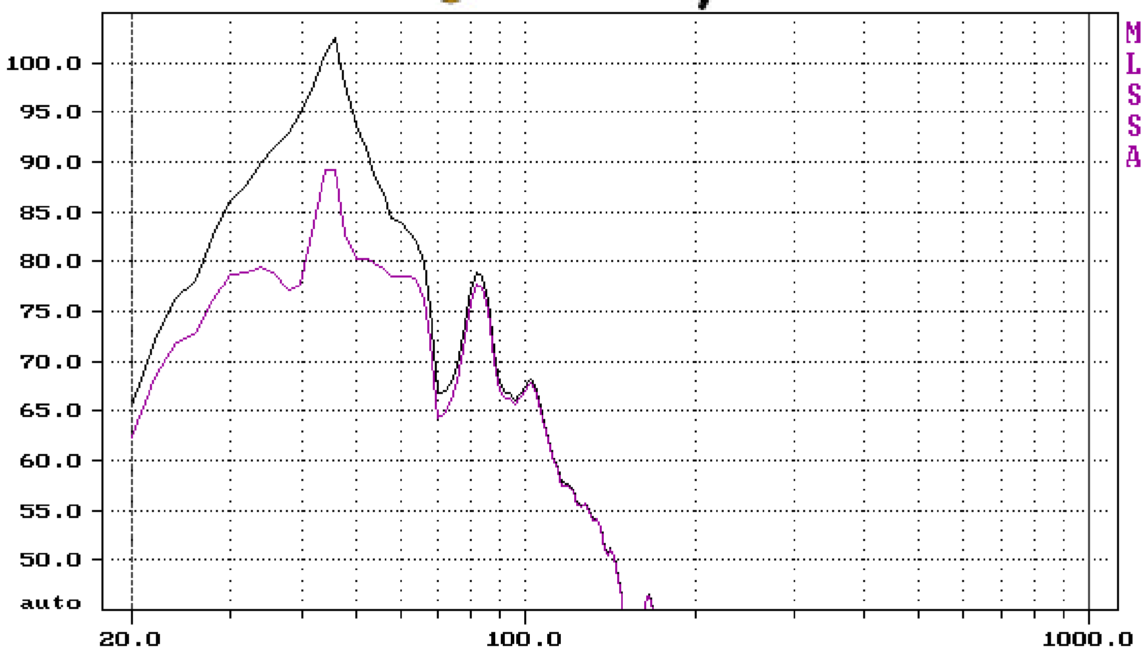


Figure 6. These are the high-resolution frequency response measurements of the subwoofer before (top curve) and after (bottom curve) equalization with the 1/3-octave graphic equalizer.

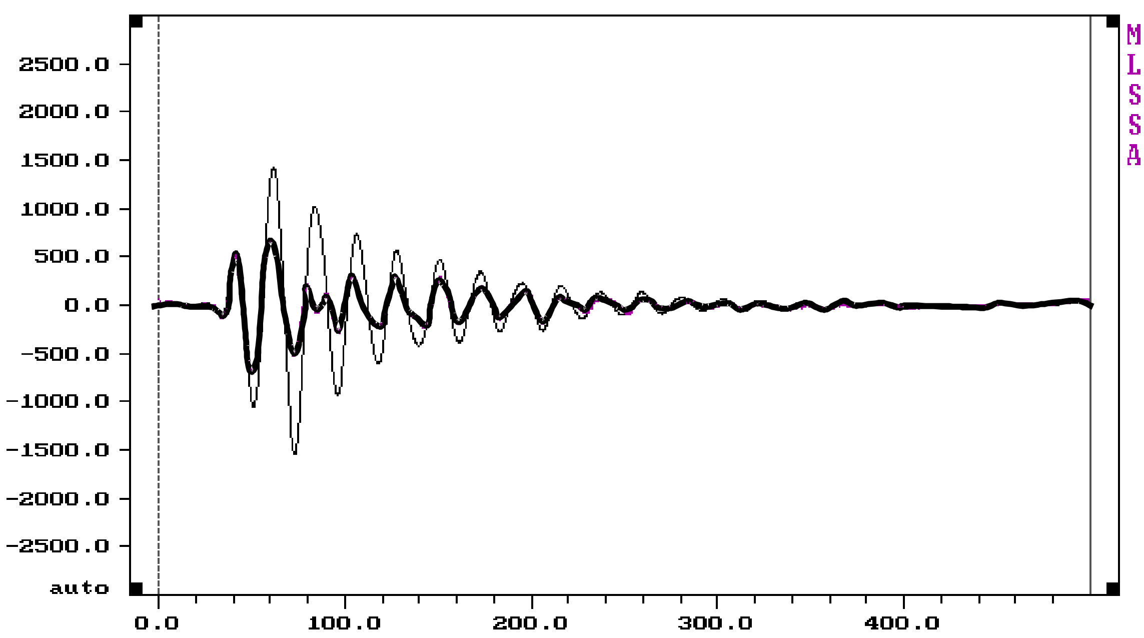


Figure 7. Time-domain behavior of the system before (light line) and after (dark line) equalization with a 1/3-octave equalizer.

The evidence of this series of measurements is quite clear. The 1/3-octeve measurements lulled us into a sense of security by presenting data that did not look all that bad. Certainly there was no evidence of the sharp peak and dip that was obvious in the high-resolution measurement. If we thought we could tweak the performance a little by using a 1/3-octave graphic equalizer, we did not succeed. It can be seen that, just as the 1/3-octave measurement failed to show any evidence of the high-Q resonance at 47 Hz, the 1/3-octave equalization failed to get rid of it. The annoying ringing, or bass "boom" was almost as strong after, as before, the equalization. It is no wonder that equalization has acquired its bad reputation. We threw away some good bass energy, and left the annoying boom.

To be fair, it is possible for a resonance to have a frequency that coincides with the center frequency of one of the 1/3-octave filters, and for that resonance to have a Q that can be addressed by a 1/3-octave filter at the same frequency. In that case, the resonance would have been attenuated, just as in the first example. However, a fortunate instance of that kind is not enough to justify using a system of such extremely limited usefulness.

So, now you are a room acoustics expert

Perhaps that is an exaggeration. However, there is no doubt that the majority of people in the audio business do not know most of the facts and techniques you have just read about. They rely on the roll of the dice, or purely subjective trial and error, to get good sound. Often they do not succeed. This is not an acceptable way to run a business, much less an entire industry.

Given that the room is the final audio component, and it is the one over which the audio manufacturers normally have no control, any improvement is a tremendous asset to both loudspeaker manufacturers, and customers. Those people who know how to elicit good sound from loudspeakers in a room – every time – have an enormous advantage. They are the ones who can truly serve their customers, by delivering something tangible: great sound.

No, these few pages have not made anybody an expert, but they do contain the essential information and methods that, with study and practice, can make a person into one. It is an important start.

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