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Loudspeaker Response in Real Rooms

Why do rooms with very similar measured acoustic responses often sound so different?

Words: Barry Ferrell, Senior Vice President/Cinema, QSC, LLC

1 Sounds arrive at different times, from different directions

The first thing to consider is how we measure sound. In cinema, we typically use a real time analyser (RTA). Most technicians have adopted the four-microphone multiplexer technique — standard practice for several decades. The RTA creates a spatially averaged measurement of more than one microphone location in the room. But what are we actually measuring with the RTA? All of the content arriving at that microphone, from all directions, with no regard to time of arrival. It's not really measuring direct sound from the speaker. It is simply measuring all of the energy arriving at that microphone, at that time. You may get some of the direct sound, but you also get many different time arrivals bouncing off of walls, floor, ceiling, furnishing and other surfaces, each with its own absorptive, diffusive, and reflective characteristics.

Many researchers, notably Dr Floyd Toole and Dr Sean Olive formerly of the National Research Council of Canada, have done a great job relating objective measurements to subjective sound quality, helping us understand how to measure a speaker and how to make it "sound good". But what do we hear with the human ear? Unlike an ordinary microphone, our ears can distinguish direction and time of arrival. When we sit listening in the theatre, we can focus on and localise where that sound is coming from. We know it's coming from that loudspeaker from the screen. There are reflections and reverberation and echoes you hear in the room, but the ear does a good job of ignoring a lot of that. But if we expect to measure the system with a device that doesn't care about direction or time of arrival and get consistent results from room to room — it's just not going to happen.

If the frequency (or the spectral) content) of those reflections varies significantly from that of the direct sound, and we then measure and tune and adjust the system with an RTA, inevitably what we hear and what we measure will differ. We need a speaker that's going to provide smooth, even coverage, not only on-axis, but also as we move off-axis from the loudspeaker.

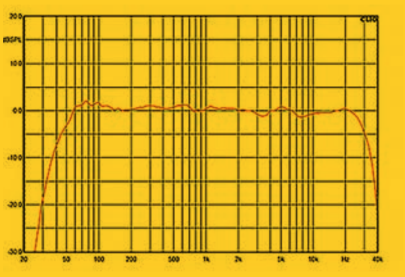
What affects sound quality? First is the subjective hearing ability of the listener. There's a lot of speaker-related factors. Does it have a 'flat' frequency response? If it's a 2-way (or 3-way/4-way speaker, are the different sections "time aligned" so their energy reaches the listener at approximately the same time? Are the levels matched at the crossover points? What about distortion — how well does the signal going into the speaker match the one coming out? Does it have a uniform coverage angle, or "directivity", with frequency?

There are room-related issues, too. We all know how to build good rooms — and it doesn't have to cost a lot of money. We need adequate room absorption and good proportions, like avoiding square rooms where length and width are equal. When you build a room with equal proportions, there will be room modes (resonances) occuring at the same frequency. They will sum together and create cancellations. So the RTA shows peaks and dips (which have nothing to do with loudspeakers themselves) in the frequency response.

Another issue is speaker placement and aiming. Loudspeakers must be able to create the sense that the sound and image appear to originate from the image on the screen; this is known as "localisation". And, they must be aimed so that the loudspeakers project their acoustical energy to where the listeners are — not at ceilings or walls.

We also need to address diffraction and reflection from room surfaces. At a minimum, you must treat side walls nearest the screen; that's where some of the most damaging reflections (to dialogue intelligibility) come from.

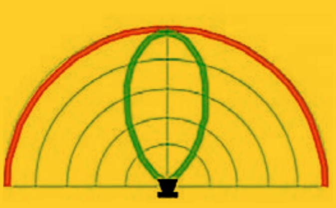
2 Direct, on-axis flat frequency response of a loudspeaker



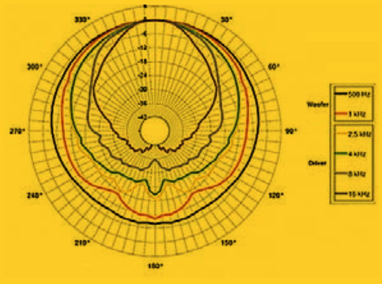
When evaluating speakers, some rely on published data and specs. Often, they look for a "flat" frequency response chart. While it's necessary for a speaker to have flat on-axis frequency response, it's certainly not sufficient for good response in the actual room. We need to know more about that particular speaker — more than is often revealed in the specifications. We need to know how the coverage angle varies with frequency. If a speaker is covering a wide angle, it's putting a lot of energy into the room. If it's covering a very narrow angle, it's putting a very small amount of energy into the room. So even if it's "flat" on-axis, the RTA will show peaks and dips based on changes in coverage angle of the loudspeaker throughout the frequency response. Most cinema technicians react to these peaks and dips by making (often drastic) equalisation adjustments. What does that do? That distorts the previously "flat" direct sound arriving from the speaker, and makes the problem — and sound — worse. What does a speaker actually do? With a direct radiating loudspeaker (like a woofer) with no waveguide or horn in front, the coverage angle naturally narrows as it goes up in frequency, because the wavelength of the sound is getting shorter, and the speaker is able to control more precisely that sound and make it go in a much narrower direction.

3 Polar representation of loudspeaker dispersion at high and low frequencies

If we looked at a representation of the coverage pattern of that loudspeaker (below), we would see that — at high frequencies (represented by the green line) — it would be very narrow. The sound would appear to drop off very quickly as you get off-axis. Low frequencies (represented by the red line) would be very wide. At low frequencies, a loudspeaker is almost omnidirectional. If we want "constant directivity", the only way to get close to that is really by adding a horn or a waveguide.

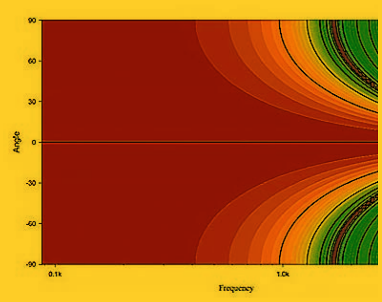


4 Example of a loudspeaker polar plot



This is all well and good, but what do you do with the information? How do you learn about a particular speaker you may be investigating? Many audio companies publish "polar plots". Each line represents the coverage of that speaker at a different frequency range. At higher frequencies, you may see controlled coverage; at low frequencies it inevitably becomes virtually omni-directional — there is almost as much sound pressure level at the back of the loudspeaker as there is from the front. There's not that much we can do with this data. It tells us intuitively what a speaker is doing, but there are other ways we can look at that.

5 Spectrograph representing SPL



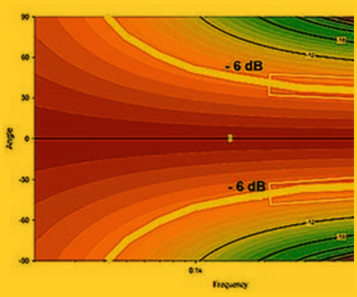
A spectrograph uses the different colours to represent different SPL levels, showing frequency along the bottom of this chart on the X-axis, and coverage angle along the side or the Y-axis. Along the centre line is directly on-axis of the direct sound of the loudspeaker, and as you go above or below, you're seeing coverage increasingly off-axis.

Figure 5 above is the theoretical spectrograph of a "piston"-type driver, which moves air by the mechanical motion of a piston (a voice coil in a magnetic field) attached to a cone or diaphragm. At the low frequencies, this very broad high SPL red level (indicated by the red region) is the loudest SPL, indicating the essentially omnidirectional characteristic at low frequencies.

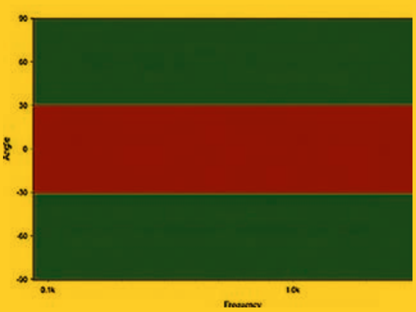
All conventional loudspeakers behave this way; the difference among loudspeaker types is how quickly (at which frequency) it begins to narrow. A larger diameter loudspeaker will narrow at a lower frequency, and a smaller loudspeaker will narrow at a higher frequency. At the highest frequencies to the right, radiation (or coverage) gets very narrow, which is also called "beaming".

7 Spectrograph of a real loudspeaker

In the graph of a real two-way loudspeaker (Fig. 7 below), mid to high frequencies are very close to parallel. This is how a "well-behaved" loudspeaker would look like in the real world. Remember, the extent to which you can maintain that coverage in the low frequencies is dependent upon the physical size of the speaker.



6 Spectrograph of an ideal loudspeaker

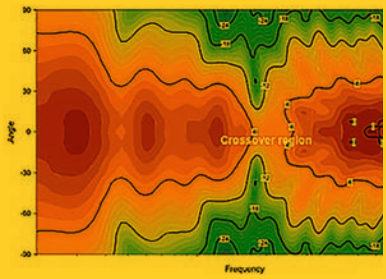


If we could make a perfect loudspeaker, what would this spectrograph look like? The ideal would be a loudspeaker that had exactly the same coverage angle at every frequency, represented by Fig. 6. It's the same loudness at every frequency until you reach the limits of the coverage (60 degrees in this case) and then there's no sound. As you might expect, this doesn't exist in the real world. It's just not possible, according to the laws of physics. What we can do is build a loudspeaker that has pretty good coverage in the mid to high frequencies with uniform transition to the wider coverage of the woofers.

8 Spectrograph of a poorly-controlled loudspeaker

With this as the "ideal", let's consider the other extreme: a poorly controlled two-way loudspeaker. Figure 8 shows a real loudspeaker that has a poorly designed crossover; it doesn't have a good match between the woofer and the high-frequency tweeter. You can see there is a tremendous gap where coverage narrows. What's happened is the woofer is being asked to reproduce frequencies higher than its natural ability to control the pattern, so the coverage gets very narrow. Above the crossover frequency, the horn is too small to maintain the pattern control at the transition frequency, and then the coverage angle gets very wide again in the higher frequencies. This causes a significant loss of energy in the mid-range, which will appear as a dip on the RTA. Many technicians will attempt to address this with an equalisation boost which results in a big peak in the direct field of the loudspeaker. Remember, this is a speaker that measured flat on-axis, but it's not really going to sound very good everywhere in the room.

In order to quantify all of this, it's helpful to use a measure called the Directivity Index (DI). The best way to conceptualise DI is to imagine a point source, which is a theoretical sound source that's a "point" in space radiating energy equally in all directions. If we use a waveguide (horn) or an array of identical loudspeakers to narrow that coverage



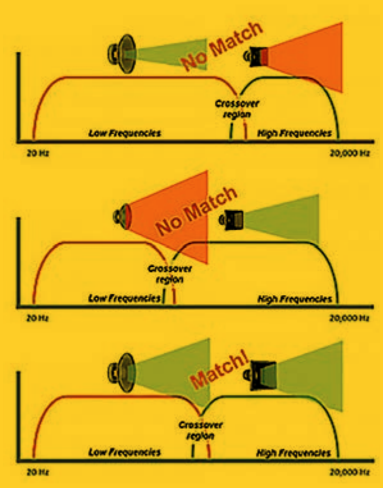
angle, then we can increase the amount of energy delivered to a much smaller part of the room. That increases the sound level in that area by a certain number of decibels at a given distance, and that amount is the Directivity Index. It's how much louder the speaker is for that same amount of acoustic energy compared to an omnidirectional point source. It turns out that the directivity index of a typical horn-loaded loudspeaker is between 8 to 10dB. A 10dB increase is perceived as twice as loud, so we can use a horn to make a quantity of acoustic energy produce 10x more acoustic power, which sounds twice as loud — just by confining that energy to a smaller section of the room.

"The bottom line? In-situ equalisation of poorly designed loudspeakers will never result in good sound"

"Constant directivity" means that we're going to cover as wide an area as possible for as much of the frequency range as possible. In practice, the goal is to try to cover as much of the audience with the same frequency response at all listening positions. But it's only really practical at mid to high frequencies. For example, a 30-inch wide horn from a cinema screen channel loudspeaker is good down to about 500 to 600 Hz. A large high-powered immersive surround speaker with a 15-inch horn will maintain coverage down to about 1 kHz; a smaller 12-inch horn will maintain wide coverage down to about 1.5 kHz. But a tiny little 8-inch speaker and a corresponding horn of that same size will probably only maintain pattern control down to about 2.5kHz or 3kHz.

9 Matching coverage pattern in the crossover region is critical

With directivity, size matters. A designer's job is to ensure they select the right audio components to cover the widest possible frequency range, and to do this with good directivity match at the crossover points — this means horns about the same size as the woofer. Large compression drivers run down to a lower crossover frequency, depending on size (and coverage pattern) of the woofer. If the design results in peaks and dips in the DI, you'll see peaks and dips on the RTA — that cannot be corrected with equalisation. It won't sound right.



10 Ideal target directivity index for a screen channel loudspeaker in full space (4pi)

The ideal target DI for a screen channel speaker shows constant directivity down to about 500Hz, then gradually (naturally) widens at the lowest frequencies (Fig. 10 below). A directivity index of 0dB is omnidirectional. Why is DI so important? When a loudspeaker produces wide coverage, it puts more energy into the room, when it's narrow it puts less energy into the room. Peaks and dips in the directivity index are actually reflected in what you measure. An inverted graph of the DI would show a good approximation of how that speaker would measure in a real room at low to mid frequencies. At the highest frequencies, we run into atmospheric absorption and other factors. Unavoidably, a speaker with an erratic DI or poor on-axis response is going to sound bad compared to a well-behaved one. Flat on-axis response is not by itself an indication of a well-behaved speaker. Finally, that erratic DI or poor coverage angle can't be fixed by DSP or equalisation. It's an inherent part of the acoustic design. This does not mean it is impossible to design a speaker that performs well in real rooms. If you were to overlay an actual measurement of a high-quality screen channel loudspeaker onto Fig.10, they'd line up fairly well. Many manufacturers make well-behaved screen channel loudspeakers for a reasonable price — it requires attention to detail. In the real world, this speaker will require little equalisation, because when we put it behind a typical perforated screen, that flat on-axis frequency response is going to translate fairly naturally to the target X-curve. Good on-axis frequency response is necessary but not sufficient for good sound. Speakers with constant directivity at high frequencies and smooth transitions from LF to HF horns will be easier to equalise, resulting in better sound. A few visible clues that might indicate potentially good directivity is when the HF horn is nearly as large as the woofer, and a large HF driver allows the crossover point to be low in frequency, preventing beaming of the woofers at the crossover.

The bottom line? In-situ equalisation of a poorly designed speaker will never result in good sound, no matter how perfect the RTA. And your ears will know it. **CT**