"Loudspeaker Response in Real Rooms"

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It's a question that has been vexing cinema technicians for decades: why do rooms with very similar measured acoustic responses often sound so different?

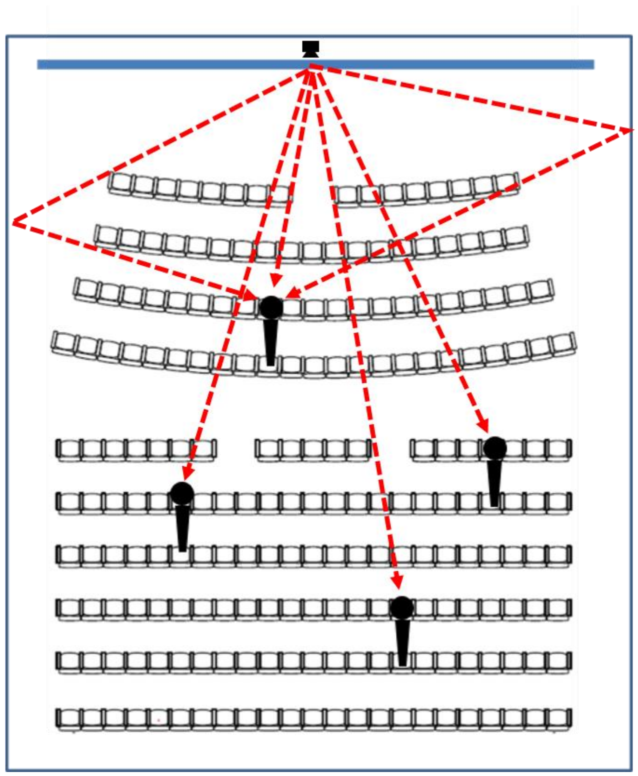

Fig. 1. Sounds arrives at each microphone at different times, from different directions.

The first thing to consider is how we are making the measurement. In cinema, the most common way is using a real time analyzer (RTA). Most cinema technicians have adopted the four microphone multiplexer technique, which has been the standard practice for several decades. This technique creates a spatially averaged measurement of more than one microphone location in the room. But what are we actually measuring with the RTA? We're measuring all of the content that is arriving at that microphone, from all directions, with no regard to time of arrival. So it's not measuring only the direct sound from the loudspeaker. It is simply measuring ALL of the energy that's arriving at that microphone, at that time. You may get some of the direct sound, but you will also get many different time arrivals that come bouncing off of the walls, floor, ceiling, furnishings, and other surfaces, each with their own absorptive, diffusive, and reflective characteristics.

Many researchers over the years, notably the esteemed Dr. Floyd Toole and Dr. Sean Olive, formerly of the National Research Council of Canada, have done a great job of relating objective measurements to subjective sound quality, helping us to understand how to measure a loudspeaker and how to make it “sound good”. But what do we hear with the human ear? Unlike an ordinary microphone, our ears are actually capable of distinguishing direction and time of arrival. So when we're sitting there listening in the theatre, we can actually focus on and localize to where that sound is coming from, and we know that it's coming from that loudspeaker from behind the screen. Yes, there are reflections and reverberation and echoes that you hear within the room, but the human ear does a really 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 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 are going to be very different. So we need a loudspeaker that's going to provide smooth even coverage, not only on-axis, but also as we move off-axis from the loudspeaker.

So what affects sound quality? First of all, there is the subjective hearing ability of the listener. But there's a lot of loudspeaker related factors too. Does it have a “flat” frequency response? If it’s a 2-way (or 3-way or 4-way) loudspeaker, are the different sections properly “time aligned” so that energy from each 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 loudspeaker match the signal coming out of the loudspeaker? And of course, the big question - does it have uniform coverage angle, or “directivity”, with frequency?

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

Another issue is loudspeaker placement and aiming. Loudspeakers must be able to create the sense that the sound and image appear to be originating from the image on the screen; this is known as “localization”. And, they must be aimed properly so that the loudspeakers project their acoustical energy to the where the listeners are – not at the ceiling or walls.

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

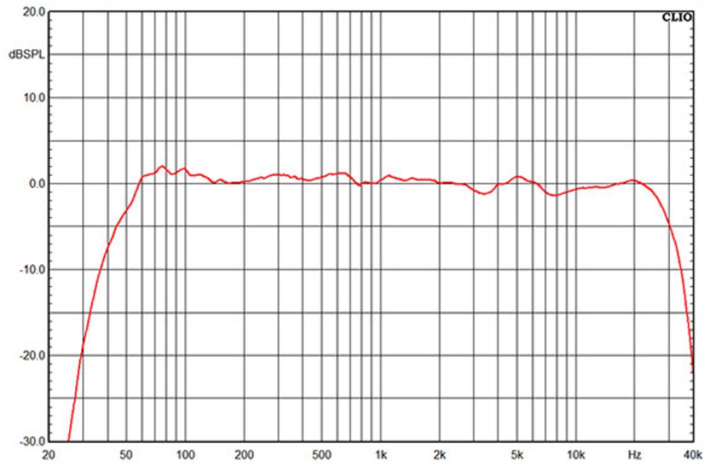

Fig. 2. Direct, on-axis flat frequency response of a loudspeaker.

When evaluating loudspeakers, some people rely on published data and specifications. Often, they look for a nice "flat" frequency response chart. While it's necessary for a loudspeaker to have flat on-axis frequency response, it's certainly not sufficient for good response in the actual room. We really need to know more about that particular loudspeaker – more than is typically revealed in published specifications. We need to know how the coverage angle varies with frequency. If a loudspeaker is covering a very 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 the changes in coverage angle of the loudspeaker throughout the frequency response. Most cinema technicians react to these peaks and dips by making (often drastic) equalization adjustments. What does that do? That distorts the previously "flat" direct sound arriving from the loudspeaker, and makes the problem – and the sound – worse.

What does loudspeaker coverage really look like? With a direct radiating loudspeaker (like a woofer) with no waveguide or horn in front of it, the coverage angle naturally narrows as the sound goes up in frequency. Because the wavelength of the sound is getting shorter, and the loudspeaker is able to more precisely control that sound and make it go in a much narrower direction.

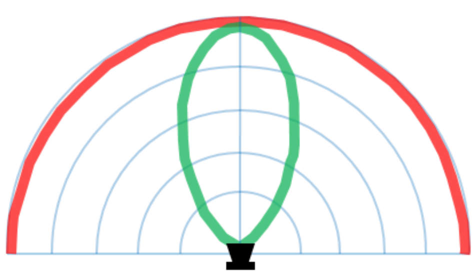

Fig. 3. Polar representation of loudspeaker dispersion at high and low frequencies.

If we looked at a graphical representation of the coverage pattern of that loudspeaker, 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 by adding a horn or a waveguide.

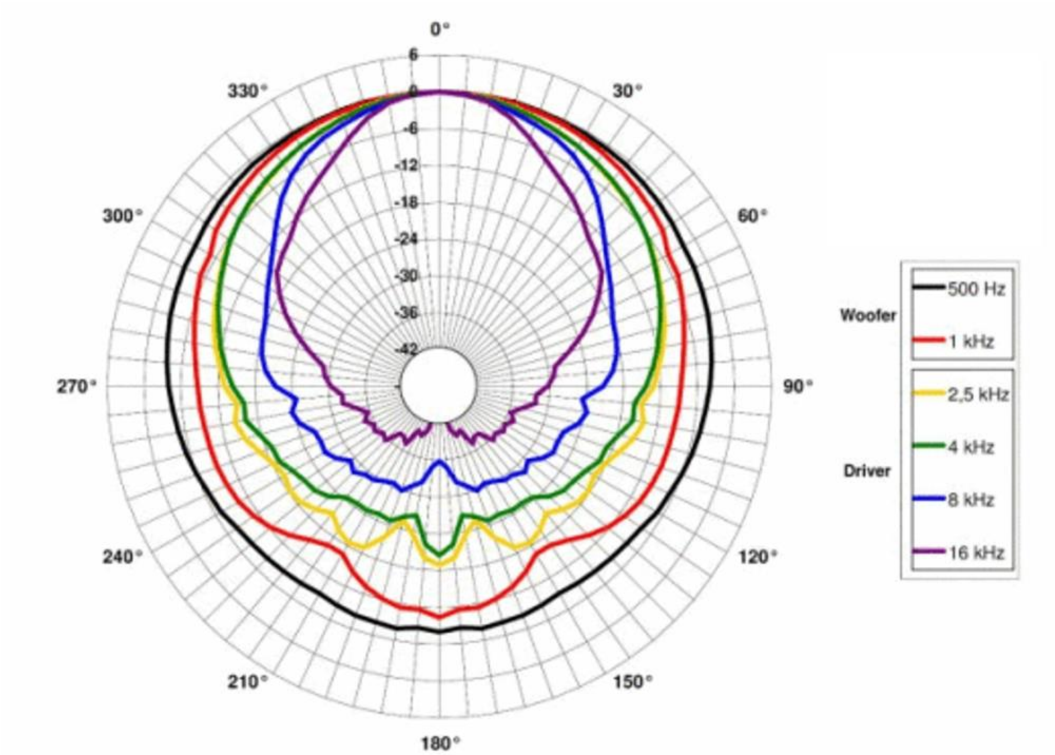

Fig. 4. Example of a loudspeaker polar plot.

So this is all well and good, but what do you do with it? How do you learn about a particular loudspeaker that you may be investigating? Many loudspeaker companies publish what are called “polar plots”. Basically, each of the lines represents the coverage of that loudspeaker at different frequency ranges. At higher frequencies, you may see controlled coverage. But at low frequencies it inevitably becomes omnidirectional – there is almost as much sound pressure level at the back of the loudspeaker as there is from the front. But there's not that much that we can do with this data. It tells us intuitively what the loudspeaker is doing, but there's other ways that we can look at that.

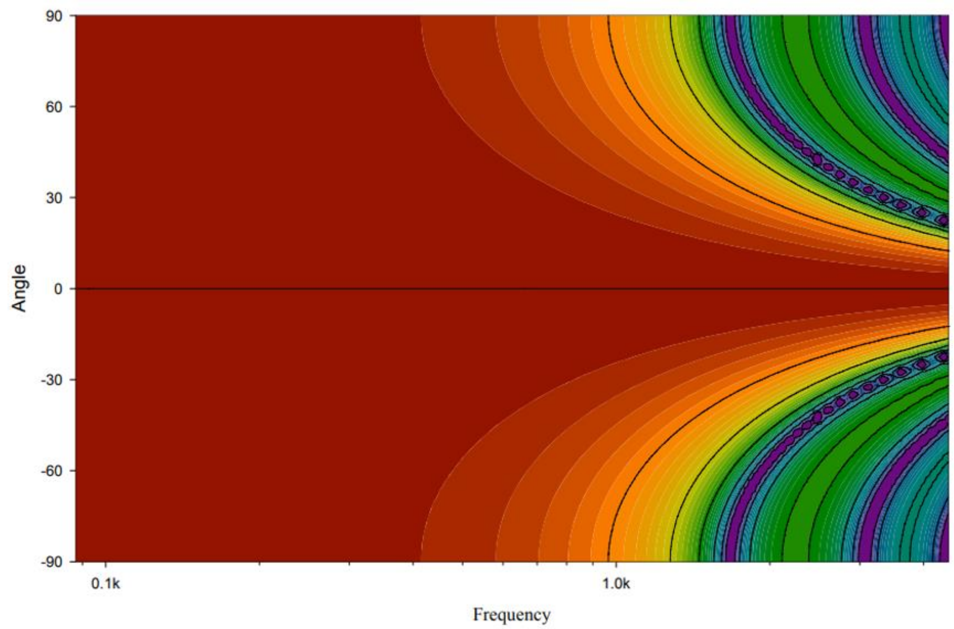

Fig. 5. Spectrograph.

A spectrograph uses the different colors to represent different SPL levels, showing frequency along the bottom of this chart on the X-axis, and coverage angle along the side or Y-axis. Along the center 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 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 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".

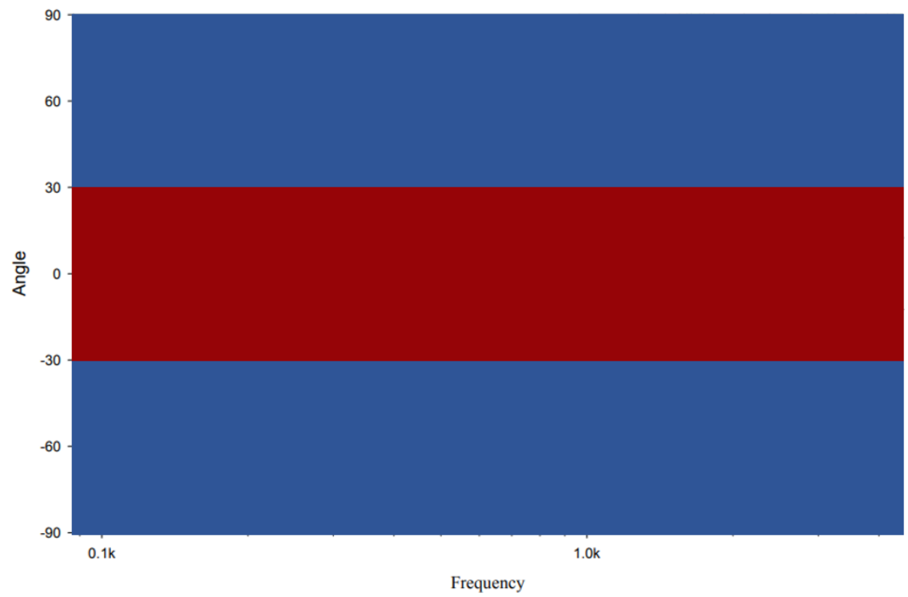

Fig. 6. Spectrograph of an ideal loudspeaker.

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.

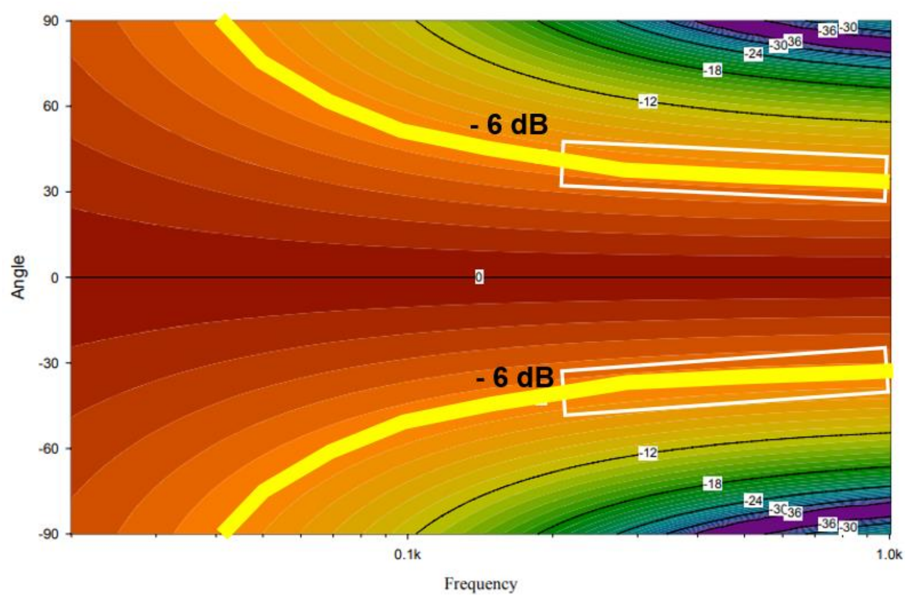

Fig. 7. Spectrograph of a real loudspeaker.

In this graph of a real two-way loudspeaker (Fig. 7), the mid to high frequencies are very close to parallel. This is what 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 loudspeaker.

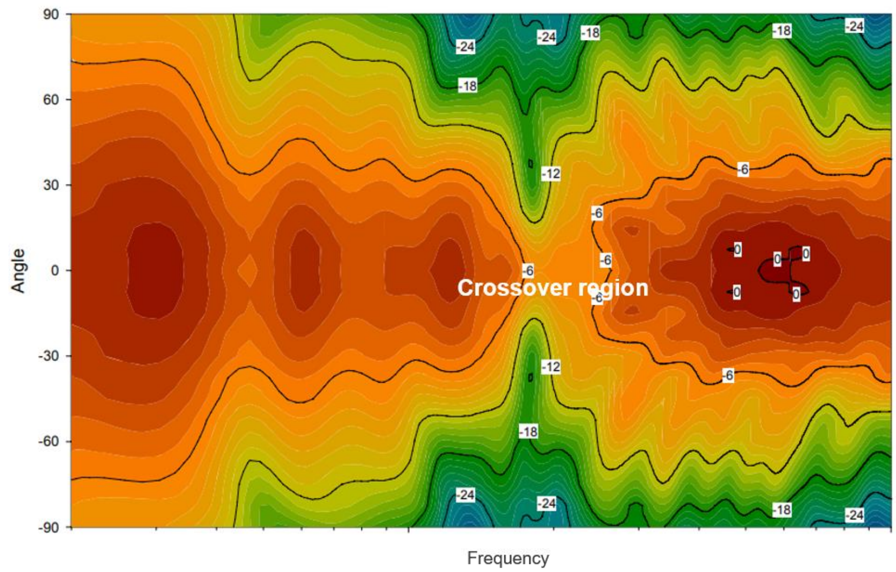

Fig. 8. Spectrograph of a poorly-controlled loudspeaker.

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 very poor performance in the crossover region; it doesn't have a good match between the directivity of the woofer and the high frequency tweeter. You can see that there is a gap where the coverage narrows. What's happened is the woofer is being asked to reproduce frequencies higher than its natural ability, so the coverage gets very narrow. Above the crossover frequency, the tweeter is too small to maintain the pattern control at the transition frequency, so the coverage angle gets wider above the crossover. You can see that 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 equalization boost which results in a big peak in the direct field of the loudspeaker. Remember, this is a loudspeaker 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 conceptualize 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 loudspeaker 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 10 dB. A ten dB increase is perceived as twice as loud, so we can use a horn to make a quantity of acoustic energy produce 10 times more acoustic power, which then sounds twice as loud - just by confining that energy to a smaller section of the room.

“Constant directivity” means that we're going to cover as defined 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 2.5 kHz or 3 kHz.

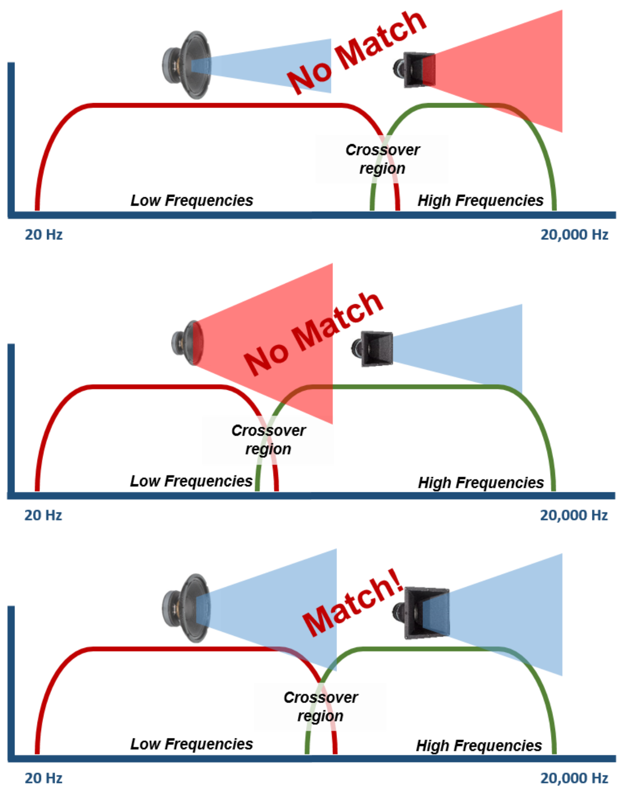

Fig. 9. Matching coverage pattern in the crossover region is critical to good loudspeaker performance.

When it comes to maintaining directivity, size does matter. The loudspeaker designer's job is to make sure that they select the right components to adequately cover the widest possible frequency range, and to do this with good directivity match at the crossover points. This is only accomplished using horns that are just about the same size as the woofer. We also need large compression drivers that can run down to a lower crossover frequency, depending on the size (and therefore coverage pattern) of the woofer. If the design results in peaks and dips in the directivity index, we're going to see peaks and dips on the RTA, and that cannot be corrected with equalization. We might be able to make it look nice on the RTA screen, but it's not going to sound right.

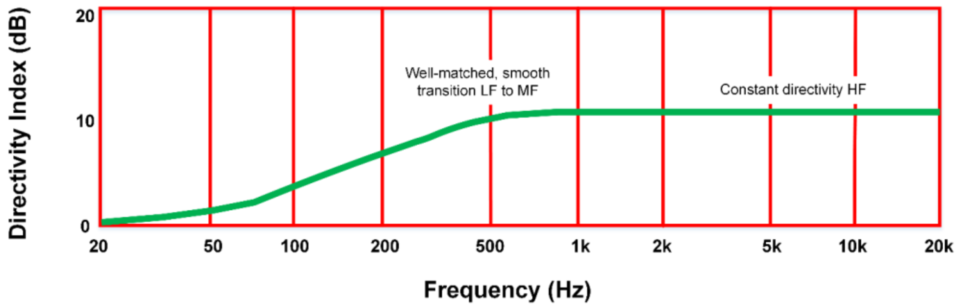

Fig. 10. Ideal target directivity index for a screen channel loudspeaker in full space (4pi), Dr. Floyd Toole presentation, 2012 AES Convention/San Francisco, "Home Theaters to Cinemas: Sound Reproduction in Small and Large Rooms".

If we were to look at what an ideal target directivity index for a screen channel loudspeaker would look like, we would see constant directivity going down to about 500 Hz, and then gradually (naturally) widening as you get down to the lowest frequencies (Fig. 10). A directivity index of 0 dB is omnidirectional.

Why is the directivity index so important? When a loudspeaker produces wide coverage, it puts more energy into the room, and when it's narrow, it puts less energy into the room. So if we have peaks and dips in the directivity index, they are actually reflected in what you measure in the room. If you were to produce a graph of the directivity index and invert it, it would show a pretty good approximation of how that loudspeaker would measure in a real room at low to mid frequencies. At the very highest frequencies, we also run into atmospheric absorption and other factors. Unavoidably, a loudspeaker with an erratic directivity index or poor on-axis response is going to sound bad compared to a well-behaved loudspeaker. Flat on-axis response is not *by itself* an indication of a well-behaved loudspeaker. And finally, that erratic directivity index or poor coverage angle can't be fixed by any DSP or equalization. It's an inherent, inevitable part of the acoustic design of the loudspeaker.

This does not mean it is impossible to design a loudspeaker that performs well in a real room. If you were to overlay an actual measurement of a high quality screen channel loudspeaker onto Figure 10, they would most likely line up fairly well. A number of loudspeaker manufacturers make really well-behaved screen channel loudspeakers, and it is achievable for a reasonable price. It simply requires proper attention to the details from the loudspeaker manufacturer. In the real world, this loudspeaker will require very little equalization, 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. Loudspeakers with constant directivity at high frequencies and smooth transitions from the LF to the HF horns will be easier to equalize and will result in better sound in real rooms. A few visible clues that might indicate potentially good directivity is when the HF horn is nearly as large as the woofer, and there's a large HF driver that allows the crossover point to be low enough in frequency to prevent beaming of the woofers at the crossover. But the bottom line is that the in-situ equalization of a poorly designed loudspeaker will never result in good sound, no matter how perfect the RTA looks - and your ears will know it.

(Images used in Figs. 5,6,7,8 are from "Directivity in Loudspeaker Systems", a whitepaper by Dr. Earl Geddes, January, 2010. Used with permission from the author.)