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Controlling Loudspeaker Coverage

Understanding the physics behind sound radiation is the key to putting sound where you want it - and keeping it away from where you don't.

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Volumes have been written about the acoustical and psycho-acoustical factors that affect sound quality in large spaces — especially intelligibility (and by “large spaces” I mean any space requiring sound reinforcement). However, when we consider the challenges associated with deploying loudspeakers in these spaces, it nearly always comes down to a very simple objective: to cover the entire audience with sound, while keeping sound away from everywhere else.

This simple objective is the reason directionality is by far the most studied and important characteristic of commercial loudspeakers. There is a tremendous amount of data available to document the performance of various loudspeakers; yet there is very little explaining why they perform the way they do. By exploring the technical side of sound radiation, this article offers a more intuitive look at loudspeaker directionality. But first, you must understand the concept of a wavefront.

The physics of sound radiation

To comprehend the differences in coverage between various types of loudspeakers, it's helpful to understand the physics that make sound waves directional to begin with. Let's start with a definition of a “wave.” The physicist's overly exact definition of a wave is a disturbance that propagates through a medium. In the case of a sound wave, the medium is, of course, the air around us. The disturbance is any mechanism that adds to or subtracts air from the medium, or which causes a volume of air to move.

If there were such a physical device as a point source, it would alternately inject and remove air from a point in space (imagine air flowing in and out the end of a straw). A disturbance would emanate from the source like a three-dimensional version of the ripples that occur in a pond after a trout surfaces. This is spherical radiation, the only completely non-directional sound — which is to say that it propagates equally in all directions.

A vibrating wall would create a different sort of disturbance. Imagine a rigid wall moving back and forth and the wave that would emanate from it. A flat wavefront would propagate away from the wall and eventually arrive at the opposite wall. Every part of the wave would strike the opposite wall at the same time. This is planar radiation, the only completely unidirectional sound — which is to say it propagates in only one direction.

The essential difference in these two cases is the size of the source. A source with no size is non-directional; while a source that is large relative to the wavelengths it produces can be highly directional. Because the wavelengths of audible sounds range from millimeters to tens of meters, loudspeakers always fall somewhere in between these two cases. At very low frequencies, loudspeakers are very much like point sources. At very high frequencies, loudspeakers are capable of being highly directional. The directionality of a loudspeaker in between these two extremes is determined by the size of the wavefront it produces, which is of course closely related to the size of the loudspeaker itself.

At high frequencies, a loudspeaker doesn't necessarily, or even normally, become unidirectional, however. The radiation pattern a loudspeaker produces at high frequencies is determined by the shape of the wavefront the loudspeaker produces. A flat wavefront produces a highly directional beam. An arc-shaped wavefront produces a beam with the same opening angle as the included angle of the arc. Conveniently, this wavefront shape is both common and extremely useful.

Nearly everything you need to know about the radiation pattern of a loudspeaker is determined by the size and shape of the wavefront it produces. This also means that the design of loudspeakers can be approached by designing systems that produce particular wavefront shapes. If the designs are successful in producing the desired wavefronts, these wavefronts will be successful in producing the desired directional responses.

Armed with the basic knowledge that wavefront size and shape beget directionality, let's look at a variety of loudspeaker types and the wavefronts they produce.

Types of directional loudspeakers

Small, multi-way speakers. Most speakers designed for home entertainment, as well as small commercial installation speakers are considered acoustically small, which is to say the individual sources are smaller than the wavelengths they produce. The wavefront produced by an 8-inch woofer makes up a section of a sphere that is not quite 8 inches in diameter, with its center at the apex of the cone. Its included angle is typically in the neighborhood of 120 degrees. A wavefront with these dimensions is omnidirectional at very low frequencies, and narrows to a 120-degree beam between 1 kHz and 2 kHz.

A 3/4-inch dome tweeter is, of course, only one tenth as large as an 8-inch woofer. So, it will be omnidirectional over most of the audible range, only narrowing to 120 degrees between 10 kHz and 20 kHz.

Though small speakers like these may differ in many of the dozens of other attributes that define loudspeaker performance, they can't differ significantly in directionality because they simply aren't big enough.

Horns/waveguides. The original purpose of loudspeaker horns was to increase the efficiency at which electrical signals could be converted to sound. In the early 20th century, 15-watt power amplifiers were considered large, and efficiency was a central concern. The fact that horns were inconsistently directional was an inherent drawback. But it wasn't until inexpensive, high-powered, solid-state amplifiers became available that horn designers were willing to sacrifice some amount of efficiency to create horns with more consistent radiation patterns. Ironically, the constant directivity horns that resulted gave up next to nothing in efficiency, despite the fact that they deviated significantly from the ideal loading profiles that had been identified more than 50 years earlier.

This new emphasis on wavefront shaping, rather than power transfer, led to the common use of the term “waveguide,” rather than “horn,” to describe some of these devices. In reality, all horns shape wavefronts, and all waveguides provide some degree of horn loading. So, the choice of terminology is largely arbitrary. I prefer to use the term “waveguide” for horns that have a useful directional behavior but don't load particularly well.

The parameters of a horn's directional control can be defined separately for the horizontal and vertical planes. The width of the mouth and shape of the wavefront it produces in the horizontal plane determine the horizontal polar response of the horn. Likewise, the vertical size and wavefront shape determine the vertical polar response. The beamwidth and low-frequency limit of control are each directly related to the size of the mouth. Narrower beams require larger mouths to maintain control to a given frequency. This relationship can be stated in a simple equation:

Control frequency (Hz)= 1,000,000 / Mouth dimension (inches) x beamwidth (deg)

For example, a 30-inch-wide horn with a 90-degree beamwidth can control down to 370 Hz. A 45-degree horn with the same 30-inch mouth dimension will only control down to 740 Hz.

Where the equation refers to beamwidth, it's specifically referring to the angle between the -6 dB points. However, not all beams are created equal. A larger horn will produce a polar plot with more sharply defined corners and considerably more attenuation outside the nominal beam. In difficult acoustical situations — where it's desirable to limit the out-of-pattern energy as much as possible — there's no substitute for horn size. The bigger the horn, the more the output is confined to the nominal pattern.

Subtle details in the shape of the horn can also have an effect on the sharpness of the polar plots. A horn with a more prominent secondary flare and a very rounded blend between sections will tend to display polar plots with more rounded “shoulders” and a usable out-of-pattern frequency response. This would typically be desirable when a speaker is intended to be used independently of other speakers. In tightly packed arrays, speakers with hard shoulders tend to work best.

Arrays. Whereas a horn (or waveguide) creates a wavefront by constraining the propagation of the sound, arrays of loudspeakers create wavefronts in a fragmented fashion. The desired wavefront is divided into a number of small pieces — then a loudspeaker is placed at the location of each small piece. If the pieces are very small, or if the loudspeakers' wavefronts have the same shape as the ideal fractional wavefront, the result will be exactly the same as if the wavefront had been produced by a single source.

Of course, real loudspeakers are large compared to at least the highest frequencies, and their wavefronts never have exactly the correct shape. Because arrays are usually far from perfect in the technical sense, effective arraying is somewhat of an art form. Most experienced practitioners know what deviations from ideal will produce acceptable results and what will be perceived poorly.

Traditionally, the most common objective of arrays has been a horizontal arc. A specific coverage angle can be approximated by arranging a number of practice, the loudspeakers are usually relatively large and rarely exhibit wavefronts with the correct included angle. However, the results can still be very usable. In the few cases where the wavefronts are nearly correct, the results can be excellent.

More recently, the arraying problem has been applied in the vertical direction. Nearly every manufacturer of professional loudspeakers now offers one or more so-called “line array” modules, which are designed to provide a relatively flat vertical wavefront from an individual loudspeaker with which to construct much larger curved wavefronts by using multiple modules. The wavefronts that can be developed with these modules aren't limited to simple arcs. In fact, the most common configuration is a curve that's relatively flat at the top of the array and more tightly curved at the bottom. The upper part of the array addresses more distant listeners, and the beam it produces is correspondingly louder. This can partially, or in some cases, completely, compensate for the longer distance to the listeners.

A form of array that deserves special treatment is the true “line array,” as shown in the photo. A tall array of sources arranged in a straight vertical line looks very much like our prototypical planar source in the vertical plane, but in the horizontal plane it looks like a point source. The result is a radiation pattern that's unidirectional, vertically, and omnidirectional horizontally — a form referred to as “cylindrical radiation.”

In the most common application of a true line array, a relatively short array is aimed at the farthest listener, and the naturally attenuating underside of the radiation pattern covers most of the listeners. While this technique has been used historically to provide intelligible speech in many difficult environments, the evenness of the response outside the main beam of a line array falls short of the quality standard required for most of today's sound reinforcement applications, especially where music reproduction is involved. A true line array can, however, provide an interesting solution when it's possible to deploy an array that's taller than the audience. In that case, all of the listeners fall within the main beam of the array, and the relatively slow decay of SPL that occurs in a cylindrical wave may provide acceptably even SPL distribution.

Beam steered arrays. The technique commonly referred to as “beam steering” (a name that's more appropriate in the fields of radar and sonar) has been well known by acousticians for decades, but it has rarely been employed in audio until the last few years. The advent of inexpensive digital signal processing equipment and the power of the PC have suddenly made beam-steered systems not only practical, but also inexpensive to implement.

Now that you understand a bit of the connection between wavefront and directionality, the way these devices work should hopefully be much less mysterious. To create a particular radiation pattern, we must simply choose signal processing settings that create the wavefront shape known to produce that pattern.

The most powerful and basic technique for varying the radiation pattern is to apply a different delay to each transducer's signal. To steer the beam downward, the device at the top of the array is given the smallest delay possible, and each successive device is given a bit more delay than the device above it. Then the wavefront emanating from this array issues from the top element first; and each element in succession then follows with its contribution. The resulting wavefront tilts slightly downward, so the sound propagates slightly downward, rather than straight out. To create a diverging beam, the elements at the center of the array are assigned the shortest delays, with the longest delays going to the top and bottom elements. The following illustration shows how the sequenced wavefronts from a number of different sources can combine to produce a tilted or curved wavefront.

While delay alone is capable of producing useful beam shapes, techniques such as gain shading, EQ shading, and other more sophisticated signal processing techniques can improve those shapes, and of course, produce more sophisticated directional effects as well.

Wrap-up at a glance

We've covered a wide variety of loudspeaker types and behaviors. But hopefully, focusing on the wavefront sizes and shapes they each produce has created an intuitive connection to the way they perform. In fact, with some practice and experience, this technique can enable a practitioner to accurately judge the directional characteristics of an unfamiliar loudspeaker or array just by looking at it. Try it, and amaze your friends!

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