FOR YOUR INFORMATION

THE LIMITATIONS OF WIDE DISPERSION

White Paper

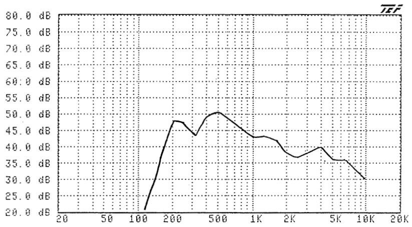


Fig. 1
Female Speech Spectrum

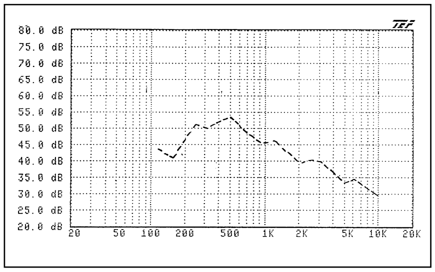


Fig. 2
Male Speech Spectrum

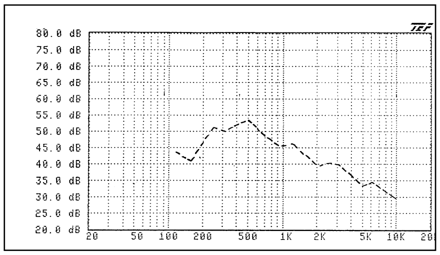


Fig. 2A
Male/Female Speech Pattern

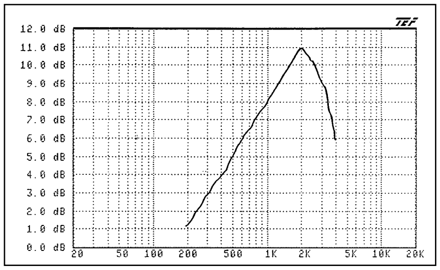


Fig. 3
Relative Contribution to Intelligibility

Distributed sound systems are the most common approach to providing sound for background music and paging systems. Because distributed systems are so common, it is important to have a clear understanding of the basic laws of audio which apply.

Intelligibility

Consider some practical basics of understanding speech, or intelligibility as it is known in the audio industry.

In **Fig. 1** and **Fig. 2** show the average distribution of frequencies in female and male speech. Individual voices will each be slightly different. Indeed, the relative levels of various frequencies is one of the clues used to distinguish one voice from another. Other clues include accent, inflection, and vocabulary. By examining these two curves it can be seen that a loudspeaker needs to cover the frequencies from about 200 Hz to about 5000 Hz to reproduce the human voice with a fair degree of accuracy. Greater bandwidth might be needed for a deep male voice. The loudspeaker must not only reproduce the frequency range, but it must do so without obvious emphasis on any part of the frequency range. In other words, it should not reshape the curve of the voice. In audio terms, a flat frequency response is required.

No loudspeaker has a perfectly flat frequency response. Some very expensive ones come fairly close with response that may be on the order of +/- 2 dB. Commercial audio speakers must be reasonable in cost and a response variation of +/- 5 dB is a realistic window to require. Speaker specifications which do not list the + and - limits of the frequency response are meaningless because they do not define the accuracy of the speaker over the width of the frequency band.

Refer again to **Fig. 1** and **Fig. 2**. Note that in both the male and female speaking voice there is a great deal of energy in the 400 Hz and 500 Hz third octave bands. That energy must be present in the reproduced sound for the speech to sound natural. Speech must also be understood; it must be intelligible. Speech understanding or intelligibility depends on consonants.

In **Fig. 3** it can be seen that a different part of the frequency spectrum is responsible for intelligibility. The most critical region is the octave band centered on 2000 Hertz (1414 Hz to 2825 Hz or wavelengths of 10 - 5"). This is because so much of the energy of consonants falls into this region. The difference between rake, take, make, sake, fake, bake, and lake is only one consonant and that consonant must be clear for the listener to make sense out of what he hears. “The fig bat jumped out of the lace in the dark as the fun tent down in the nest,” does not make a lot of sense. Just by clearly hearing the correct consonants the sentence becomes, “The big bass jumped out of the lake in the park as the sun went down in the west.” So it can be seen that it is especially critical that the 2000 Hz octave band can be heard at all locations.

For sound systems involving music one must consider a wider range of frequencies. It is fairly obvious that music usually includes frequencies that extend far below the speaking voice. Now it becomes important to use speakers that were designed to work well in whatever enclosure or lack of enclosure is involved in the project. There are speakers available that were designed to perform well in an infinite baffle, speakers designed for sealed enclosures, and speakers designed for ported enclosures. In fact, several manufacturers offer pre-engineered sealed and ported ceiling speaker systems.

At the other end of the frequency spectrum, music makes greater demands on high frequency performance. For music to sound clear, to sparkle and shine, to sizzle, the upper octaves must be reproduced in their natural proportions to the midrange frequencies. In a music system, depending on the demands of the job, you will need to consider the performance in the 4 kHz and the 8 kHz octave bands. Today, many systems will require true high fidelity.

DISPERSION

Does a sound system cover the area evenly? The directionality of a loudspeaker and its position will determine the evenness of coverage.

There are various ways of describing the directionality of a loudspeaker. Terms such as "Q", directivity index, and dispersion are often used. For distributed systems, the most common specification used to calculate the area of coverage is dispersion. Dispersion is usually defined as the total angle over which the output level is no lower than -6 dB compared to the on-axis level - at some given frequency. If, for example, we said that the dispersion angle is 120 degrees at 1000 Hz it would mean that on a polar plot the curve would be 6 dB lower in level at 60 degrees on each side of the on-axis sound pressure level. **Fig. 4** gives an example of this situation.

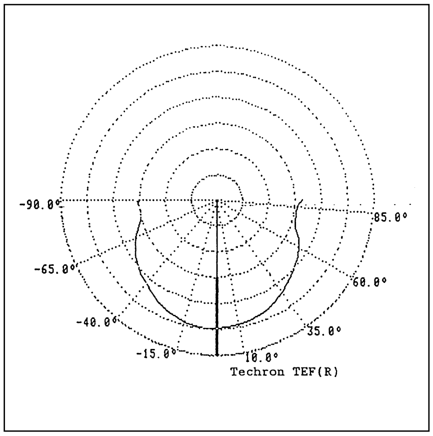
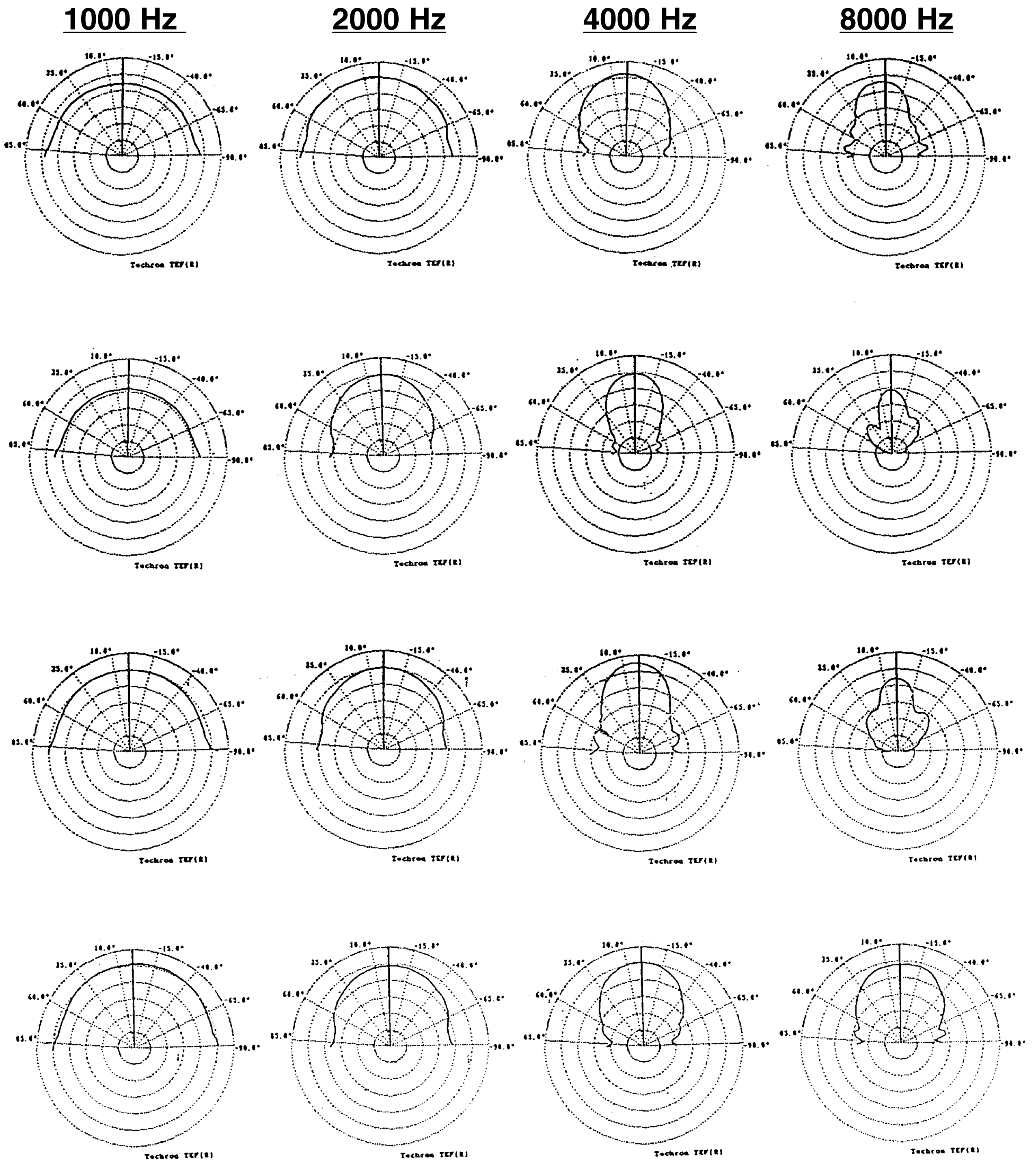


Fig. 4
Polar Plot

Dispersion angle can be specified as so many degrees or it may be shown in graphic form as a polar plot. It is very important to know both the angle and the frequency when considering dispersion. Cone speakers are an attempt to make a vibrating piston. Most come fairly close to being a practical piston. The laws of physics dictate two things: (1) a piston will produce very wide dispersion at low frequencies and increasingly narrower coverage as frequency is increased, and (2) the smaller in diameter the piston, the higher in frequency the narrowing of coverage begins. Conversely, a large speaker begins to "beam" at lower frequencies than a small speaker. It also follows from the laws of physics that all eight inch speakers have similar dispersion patterns as do all four inch speakers or all twelve inch speakers, so far as they are able to approach pure piston movement.

In **Fig. 5** the polar plots of four different speakers at four octave bands are arranged for easy comparison. The vertical columns are, from left to right, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz octave bands. The rows are, from top to bottom, a 5 inch speaker, an 8 inch speaker, a 6.5 inch speaker, and a 6.5 inch coax speaker. Note that in the 1000 Hz octave band all four speakers have a basically hemispherical polar response. At the 2000 Hz octave band the 8 inch speaker has a noticeably narrowed response. In this critical region the 6.5 inch speakers have not narrowed their pattern nearly as much as the 8 inch. In the next two higher octaves, 4000 Hz and 8000 Hz, the pattern of the top three speakers continues to narrow but the 6.5 inch coax pattern stabilizes at a fairly broad pattern. In this region of frequencies, the coaxial tweeter has taken over and with its smaller diameter it has a broad dispersion. While somewhat helpful in voice only systems, this wide dispersion of upper frequencies is most important in music systems.



6" Coaxial Speaker

Fig. 5 Polar Plot

Since it is important that a paging message be understood at all locations in the area covered by the sound system, and since the 2000 Hz octave band is critical for intelligibility, we come to the conclusion that the dispersion angle for the 2000 Hz octave band is a very important specification to know if we want to engineer a system where speech can be understood at all points in the system's coverage. Traditionally, the dispersion angle of a speaker has been given as the angle at which the level is reduced by six dB (as compared to the on-axis level) at a frequency of 2000 Hz (or preferably, for the octave band centered on 2000 Hz).

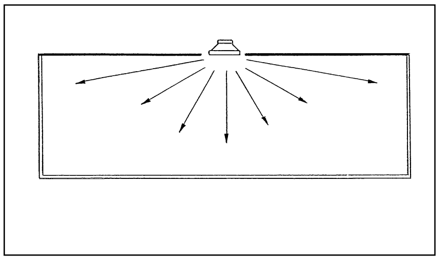


Fig. 6
160 Degree Dispersion

A 12 inch "full range" speaker - as was typically used some years ago in distributed ceiling systems - had a dispersion angle of about 60 degrees. An 8 inch speaker has a nominal dispersion angle of 100 degrees. A 6.5 inch speaker has a dispersion angle of about 130 degrees. A 5 inch speaker will typically have a dispersion of 160 degrees in the 2000 Hz octave band. This would seem to imply that if the ceiling is fairly high only one speaker would be needed to cover the whole room (see **Fig. 6**).

Unfortunately, this is not the case because of the inverse square law. An extremely wide dispersion speaker will not effectively cover a large room, even if the coverage angles extend all the way to the walls.

The inverse square law simply states that each time the distance from the sound source is doubled, the level decreases by 6 dB. Stated mathematically,

$$\text{change} = 10 \log \ [1/2]^2 \ = 10 \log 1/4 \ = -6 \text{ dB}$$

In **Fig. 7A**, the relative distance to a ceiling speaker is illustrated. For a dispersion angle of 90 deg., the level at 45 deg. off-axis is going to be 3 dB lower than on-axis due to distance differences alone.

For a speaker with 120 deg. dispersion, the level at 60 deg. off-axis will be 6.0 dB lower than directly under the speaker due to the inverse square law.

At 130 deg. dispersion the loss is an additional 1.5 dB. The distance losses at 140 deg. dispersion is 3.3 dB greater than it is for 120 deg. dispersion.

Watch what is happening here. As dispersion angles get larger, the level loss due to distance increases dramatically.

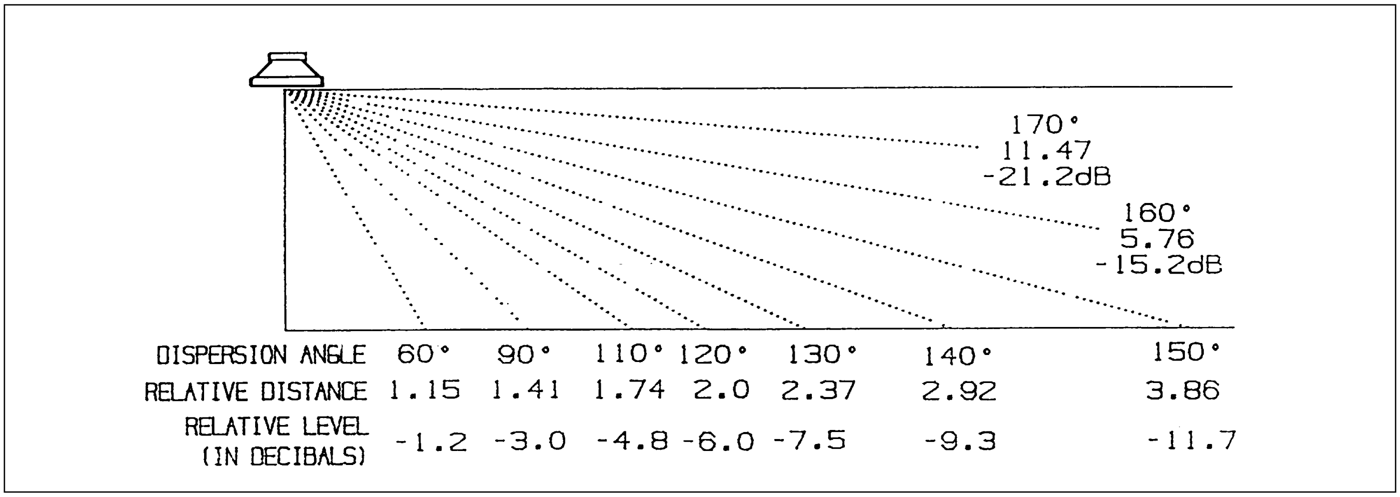


Fig. 7A Inverse Square Law - Level Change with Angle of Dispersion

Now examine **Fig. 7A** and note that for dispersion angles of 60 and 90 degrees the increase in distance from the speaker does not make a big difference in level. But as the dispersion angle increases, the drop in level due to distance becomes more and more important.

A 150 deg. dispersion angle speaker sounds like it would be very beneficial. At first glance, it would seem that it would take far fewer speakers to a job with a speaker like that. But the inverse square law and losses due to distance must be considered.

The project will determine how much sound pressure level variation can be tolerated. Nonetheless, if there is a difference of 12 dB from the level on-axis and the level somewhere else in the facility, the designer will either get complaints about the level being too low, or will find some poor person who has been pounded into the floor by the speaker directly above him!

So far, we have three important points:
1. The 2000 Hz octave band must be present because it is important for speech to be understood.
2. At any given frequency or band of frequencies, the radiated level decreases as the angle away from on-axis is increased.
3. As the angle from on-axis is increased, the sound pressure level at ear height will decrease due to increased distance.

In addition to the inverse square law losses, one must not overlook what a polar plot indicates and what a dispersion angle really is. All of those losses in **Fig. 7B** were for distance alone. If a speaker has a dispersion angle of 120 degrees that means that its response is down 6 dB at 60 degrees off-axis and that must be added to the distance loss for a total of -12 dB!

Look at **Fig. 8**. Here is a typical 8" speaker. The line labeled “Polar Loss” lists the relative level at various angles on the polar plot. The next line lists the distance losses at those same angles. The bottom line shows the total losses - and they are pretty impressive.

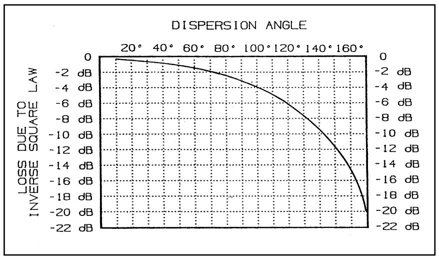
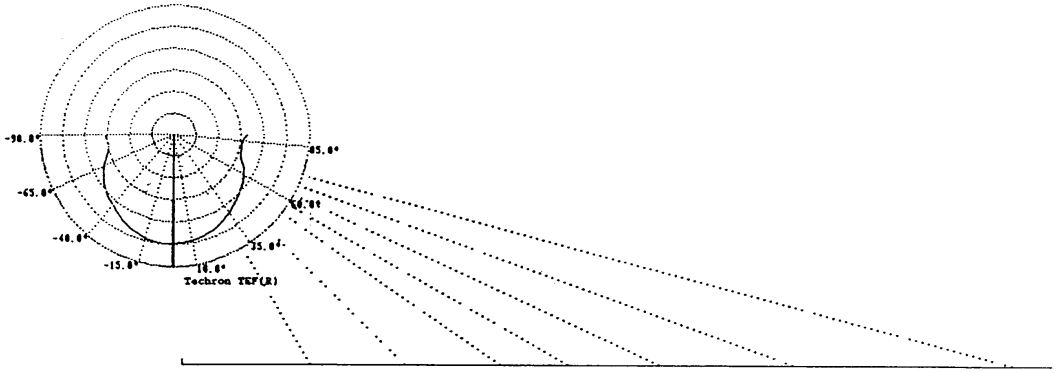


Fig. 7B
Polar Plot of Dispersion Angle



DISPERSION ANGLE	60°	90°	110°	120°	130°	140°	150°
POLAR LOSS, dB	-2.7	-5.3	-7.0	-8.1	-9.1	-10.5	-11.4
DISTANCE LOSS, dB	-1.2	-3.0	-4.8	-6.0	-7.5	-9.3	-11.7
TOTAL LOSS, dB	-3.9	-8.3	-9.9	-11.8	-14.1	-16.6	-23.7

Fig.8 Total Loss for Typical Eight Inch Speaker

MULTIPLE SOURCES

Multiple speakers in a room add together to increase the level. It must be remembered that speakers in a distributed system are precisely that - distributed - and that at any given point two or more speakers will be covering that point to a greater or lesser extent. If two speakers cover a point equally, the resulting sound pressure level is +3 dB more than the level of a single speaker at that point. If three speakers are at equal levels at a point the resulting sound pressure level is +4.8 dB more than a single speaker.

# of equal levels	2	3	4	5	6
net increase, dB (over single source)	+3.0	+4.8	+6.0	+7.0	+7.8

Unfortunately, the additive effect of multiple speakers will not compensate for distance losses due to the inverse square law. Suppose speakers are arranged so that six of them are all equidistant from some point and that they have 150 degree dispersion. Polar losses are -6 dB by definition, distance losses are -11.7 dB, and multiple source gain is +7.8 dB for a net difference from on-axis of -9.9 dB.

A more common layout would be the minimum overlap arrangement where there would be three speakers interacting equally. Suppose a more common dispersion angle of 130 deg. Polar loss is -6 dB, distance loss is -7.5 dB, and multiple source gain is +4.8 dB for a net loss of -8.7 dB.

Even if there are 15 speakers in a room and they are all adding to the sound pressure level, the problem is not improved. Instead, it is slightly worse. The closest two or three speakers will add together in level and they will contribute to the understanding of a page. But, all of the rest of the speakers will be quite low in level and their signals will arrive long after the nearest speakers. The net effect is much like the multiple reflections that make up reverberation and the result is a decrease in intelligibility rather than a positive effect.

Increasing dispersion is beneficial. But it is not a cure-all and it is less helpful than we might wish it were. When is increasing dispersion no longer a factor? The answer is, of course, when inverse square law losses alone would cause too great a variation in level to be acceptable. Beware of the 180 degree speaker. It will not allow the separation of ceiling speakers to be as great as one might think at first.

The simple rule to remember is: subtract the polar losses,subtract the distance losses, and add the multiple speaker gains.

MATCHING SPEAKER PERFORMANCE TO AMBIENT NEEDS

First, and foremost, one must keep in mind that no single model of speaker - with or without an enclosure - will work for every distributed sound system. The sound system designer must determine the level of quality needed by a project. More quality than is required will at the least be wasted, and in the worst case may cause loss of the project in a competitive bid situation.

By the same token, a system of lower than needed quality will make the customer unhappy, will degrade your reputation, and may cost you a lot of time and money if you have to go back and rework the system.

Here are some rules of thumb:

1. If the project is an occasional use paging system only, then small speakers widely spaced will fill the need. If building codes require an enclosure, the bass response that is lost will not be a problem.

2. If a large lecture hall with a low ceiling is the project, you will want very even cover age so that all can hear without anyone being directly under a speaker being uncomfortable.

3. If the ambient noise level is high or if the paging system must always be heard and understood, then closer spacing is needed to prevent large dips in the sound level.

4. If you want voices to sound more pleasant and natural, such as in a retail store environment, you will want to pay attention to the speaker/enclosure interaction. The octave from 100 to 200 Hz can provide chest tones that will make male voices sound rich and natural instead of nasal, pinched, and harsh. Even female voices will sound more pleasant and full bodied.

If music is going to be part of the system, the type of music, the fidelity desired, and the sound pressure level all need to be considered.

5. For background music designed to soothe the listener, the quality only needs to be a step above voice paging needs.

6. In a more foreground situation where the music is meant to be consciously heard,you must pay attention to bass response, to even distribution through close spacing, and to upper octave polar response so that the “sparkle” of the high end is well distributed.

7. If the project calls for rock and roll, country/western, gospel, or classical music at fairly loud levels, you cannot afford to overlook any of the points we’ve considered.

The Audio System Designer, by Peter Mapp, published by Klark Teknik

Sound System Engineering, by Don & Carolyn Davis, published by Howard Sams & Co.

Ceiling.3, (software for ceiling layouts) by Joe Etrick