

We make loudspeakers. Why?

Well, we tried everything on the market, and about 12 years ago we decided to do it ourselves. Our loudspeakers are conceived, designed and executed to satisfy in ways which allow them to deliver a compelling musical experience.

How do we accomplish this?

We apply particular technological solutions not because we are enamored of them, but because we have found that by doing it the right way we can liberate the music from the technology. This begins by recognizing that human hearing judges things in ways which may not be susceptible to measurement (and conversely that there is a basic level of technical competence which is susceptible to measurement).

So we approach the task recognizing that from an electroacoustic design point of view there are some cardinal attributes of hearing which must be considered:

- Frequency range
- Dynamic range
- Temporal resolution
- Spatial discrimination

Frequency range

It has been long established that the frequency range of human hearing for stationary tones is about 16 Hz to 16 kHz. In musical terms this is about 10 octaves. The very young can sometimes hear beyond 16 kHz, and there are reports of audible sensation (as opposed to vibratory sensation) as low as 8 Hz. A useful indicator is that if you can hear the squeal of the horizontal flyback in an analog TV set, you can hear 15.75 kHz. If you are more than 30 years old and can't hear it, don't feel bad. Most other people can't either. Women tend to have more extended high frequency hearing than men.

There are also reports in the literature of measurable physiological responses to auditory stimuli up to about 30 kHz even though they are not necessarily accompanied by conscious perception. This may be important (or not).

One should not confuse frequency (which is objectively measurable) with pitch (which is a percept).

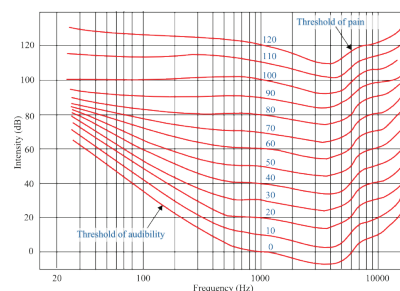
Dynamic range

The dynamic range of hearing is the range from the softest perceptible sound to the loudest tolerable sound. In the middle frequencies (around 1 kHz) it is about 120 dB. It must be remembered that the dB is a logarithmic measure of ratio. In terms of acoustic power, 120dB means that the loudest tolerable sound is about one trillion times (10^{12}) greater than the softest perceptible sound. A symphony orchestra has an actual dynamic range of about 70dB, or a power ratio of 10 million to one (10^7).

At low and (to a smaller extent) high frequencies, the dynamic range of hearing is much less. This is because the bottom end comes up. i.e., the minimum perceptible sound at 50 Hz will be much higher in level than at 1 kHz.

The most well known examination of this subject was conducted by Fletcher and Munson of Bell Laboratories in the early days of audio technology. They collected a statistically significant body of data by measuring thousands of people using pure tones. An important result of this work was the so-called "Fletcher-Munson" curves, more properly called the Contours of Equal Loudness. This work has been repeated with variations by other researchers in other countries with substantially similar results.

The contours of equal loudness are shown here:



The “crowding” of the curves at low frequencies means that care must be taken in sound reproduction to avoid deficient low frequencies. Small decreases in the intensity at low frequencies produce large decreases in perceived loudness.

Reproduction of the sound of a symphony orchestra at levels comparable to real life requires a sound pressure level (SPL) up to about 105 dB SPL at the listening position. Much popular music in certain genres requires higher SPLs. Instantaneous peak SPL may be up to 10dB greater than this.

As with frequency vs. pitch, the contours of equal loudness show that there is a variable relationship between intensity, which is objectively measurable and loudness, which is a percept.

Temporal resolution

This is a very inadequately considered aspect of human hearing. Much auditory research concerns itself with pure, continuous tones. This leads to the frequency range of hearing being described as extending to about 16-20 kHz as discussed above. Yet we are able to hear transient sounds whose time-domain representation indicates (via the Fourier transform) a frequency content which extends beyond “audibility”.

Very short transients, on the order of 10 microseconds (usec), are less audible than continuous tones of the same amplitude, but they are still audible. There is anecdotal evidence that editing a 44.1 ksp/s digital recording by randomly removing single samples causes some listeners to object to the result. A single sample represents a missing time of only 22.7 usec. There have been several studies directed to determining whether listeners can perceive differences (or improvements) from bandwidth extensions beyond 20 kHz in recording/reproducing systems. The general finding is ambiguous.

There is more to temporal response than bandwidth however. For sounds composed of many frequency components simultaneously (i.e. virtually all natural sounds), it is important to preserve the simultaneity of the various components. They must all emerge from the recording/reproducing system at the same relative times that they went in. Failure to do so is referred to as **group delay distortion**. The ear is fairly sensitive to group delay distortion but the exact thresholds at various frequencies have not been determined. There is a criterion established by Blauert & Laws, but this relates to the impairment of speech. The perceptual thresholds may be quite different for other types of signals.

The meta-linguistic descriptor of loudspeakers as being “fast” or “slow” appears to be related to group delay distortions (assuming adequate bandwidth is available).

Spatial discrimination

This is our ability to locate the origin of sounds. It is a very complicated mechanism which is becoming fairly well characterized if not yet well understood. In general, the differentiation of direction in azimuth (i.e. in the horizontal plane) is related to inter-aural time differences below about 700 Hz and to inter-aural intensity differences above about 2 kHz. The region in between seems to use both mechanisms. Differentiation in elevation is due to changes in the frequency response at the ear canal from constructive or destructive reflections from the outer ear structure, the pinna. Propagation of sounds around the head for azimuths other than zero degrees (straight ahead) is different for the two ears. These differences constitute the head related transfer functions (HRTF) which can be exploited in various audio processes to create virtual locations of sounds, but this technique only works reliably in conditions of very low reflection.

A great deal has been learned about spatial hearing by studying listener responses in anechoic conditions, i.e. an acoustically non-reflective environment. Yet we live all day, every day in environments which are acoustically uncontrolled and almost always fairly reflective. Our spatial discrimination operates quite well in these situations. Indeed, it is a requirement for survival. Presumably our ear-brain system understands how to factor the local environment so it does not interfere with understanding what we hear.

We will return to this subject later.

What are the implications of these matters for loudspeaker design?

What are Pipedreams’ solutions?

Frequency range

All Pipedreams™ systems are 3-way systems which operate over the range from slightly below 20 Hz to slightly above 20 kHz. We do not state the flatness of response because this is a very complicated topic and there is no single specification which is sufficient.

In general, the crossovers are optimized for flat power in consideration of the wide dispersion of the Pipedreams configuration.

Dynamic range

The essential sonic attributes of music are melody, harmony, rhythm, dynamic contrast and absolute loudness. Dynamic contrast and absolute loudness are tightly related. It is not enough to simply be able to make a loud noise with a loudspeaker system. The accurate rendering of dynamic contrast requires the accurate preservation of different levels of absolute SPL.

In most loudspeaker systems, especially ones which look big but are really just a mini-monitor co-packaged with a subwoofer, the problem is one of **compression**. This means that as the electrical input to the loudspeaker increases, there is a not-quite-corresponding increase in the sound output.

This occurs mainly for two reasons. First, the driving force in a speaker is never completely linear with displacement. As the cones are required to move farther to reproduce a louder sound two things happen: 1) the elastic elements of the suspension start to "tighten up" and 2) the driving force starts to diminish and may become asymmetrical. The result of these problems is an instantaneous error which simultaneously distorts the waveform and reduces the output. It is called **displacement compression**. Second, high input power to the driver(s) causes the voice coil(s) to get hot. Since the voice coils are made with either copper or aluminum wire, both of which have a high temperature coefficient of resistance, their resistance increases when they heat up. Almost without exception, power amplifiers are what are called constant-voltage sources. What this means is that for a given input voltage, the amplifier's output voltage will be a certain value irrespective of the resistance of the load placed on the output. As the resistance of the voice coil rises due to heating, the amplifier output voltage will be unaffected. Because power P is equal to voltage squared divided by resistance ($P=E^2/R$), as resistance rises the power actually absorbed by the voice coil falls. This is called **thermal compression**. It occurs at a slower rate than displacement compression and does not result in much waveform distortion, but rather in a slow decrease in the sensitivity of the loudspeaker. Thermal compression is a greater problem with loudspeakers of low sensitivity because they require more power in the first place.

Both of these compression mechanisms are damaging to the perception of dynamic range because they have no counterpart in natural sounds. Other types of distortion mimic natural acoustic phenomena. Harmonic and intermodulation distortions are not unlike natural modifications of sounds which can occur. Dynamic compression has no such counterpart. This is important because when our hearing is presented with types of distortion which do not occur in natural sounds, those distortions are likely to be more offensive or at least more noticeable.

There are a few ways to reduce or eliminate dynamic compression. Since it is due mainly to large diaphragm movement or high input power (or both), the obvious solution would be to improve the sensitivity and reduce the diaphragm motion. The historical solution to this is to use a **horn**. This is still often done on tweeters but is not very practical for woofers (or even midrange) because the required dimensions are very large. The most elementary horn is cupped hands or a megaphone. Technically, the horn improves the efficiency through improving the acoustic impedance match between the talker's mouth and the air. This is accompanied by **sharper directivity** which is intuitively easier to understand. As we will see in the discussion below concerning spatial reproduction, this increased directivity is not what we want. So even though the horn would address the dynamic range problem, it does it by introducing other difficulties which are not surmountable in practice.

Another way to approach the problem is to make the diaphragm larger. This reduces the excursion in proportion to the increase in area. This approach is found in big full-range electrostatic loudspeakers and in planar magnetic loudspeakers. Like the large mouth of a horn, this expansion of the area is accompanied by increased directivity. Also, and this is very important, both electrostatic and planar magnetic loudspeakers operate with stationary structures directly in front of (and behind) the diaphragm. All claims to the contrary notwithstanding, these structures are not acoustically transparent. In some cases they produce cavity resonances which are so severe they have to be trapped in the crossover network. Also, these types of large area loudspeakers are almost invariably **dipoles**, i.e. they radiate in opposite polarity from the back. Dipoles are hard to place because the placement which achieves passable bass response is almost never the same as the one which gives good image rendition.

There is a straightforward solution which simultaneously addresses diaphragm motion, directivity, sensitivity and power handling: Extend the radiator in one dimension only, i.e. a **line source**.

A true line source is not readily achieved. There are some attempts with "ribbon" loudspeakers and narrow planar magnetic transducers, but these are either fragile or plagued with the problem of fixed obstacles on either side of the diaphragm.

A sufficient approximation to a "true" line source is accomplished with a multitude of small, identical dynamic drivers which are small enough and closely spaced enough to coalesce into an apparently continuous line. Further, this allows us to take advantage of the fact that this is the most mature and highly developed loudspeaker transducer technology. There are no obstacles in between the diaphragm and the listener, and very high levels of driving force are possible.

The use of many drivers means no single driver ever receives very much power, so thermal compression is effectively eliminated.

The same is true of diaphragm motion, so displacement compression is similarly eliminated. Because the individual drivers are virtually always operating in the small-signal regime, all the non-linearity and distortion are held to very low levels.

We see from various manufacturers heroic design techniques applied to individual drivers. This is usually because such drivers are being asked to do too much. Our line array directly circumvents this problem avoiding the need for tortured driver design. An important result of this is the use of soft dome tweeters which, while not ideal at extremely high drive levels, are surpassingly transparent when not overdriven. In a Pipedreams array, they virtually cannot be overdriven.

The direct solution of the dynamic range problem confers **unique listening attributes** which must really be heard to be appreciated. First, and most unusual, the "surface loudness" is low. This is noticed as you approach the speaker and it doesn't get a lot louder. Rather, there is an impression of listening "through" the speaker. Conversely as you move away, the sound doesn't become "small". But the most rewarding attributes are the qualities of

- **effortlessness**
- **power** and
- **scale**

in the most dynamic kinds of music.

So, to refer back to the dynamic range of hearing discussed earlier, the Pipedreams loudspeaker systems properly applied are capable of reproducing, in a normal listening environment, the entire dynamic range of all music. Continuous SPL of over 110 dB is possible with low distortion, high reliability and reasonable amplifier power, even in very large domestic rooms.

The vertical line source, because it remains small in the horizontal dimension, retains wide dispersion in the horizontal plane. The long vertical dimension causes the dispersion in the vertical plane to be limited to the length (height) of the line. As long as the line is tall enough to encompass all listening heights this is not a limitation.

Temporal resolution

Temporal resolution in loudspeaker terms is the ability to render the fine structure of sounds. This is commonly called transient response. In the time domain, it is a measure of how quickly the loudspeaker can respond to changes in the input signal, not only with respect to the onset of a sound but also its cessation. In the frequency domain, it is a measure of bandwidth and group delay distortion as discussed earlier. The frequency and time domains are not exclusive to each other but are rather alternative views of the same thing. The Fourier transform allows the view in one domain to be converted to the other.

Accurate response to a rapidly changing signal requires the diaphragm to be accelerated (and decelerated) rapidly. Since acceleration = force/mass (Newton's Second Law), it follows that for a given moving-mass, acceleration will be proportional to available force. The mass is defined by the weight of the moving parts (voice coil, diaphragm, suspension) as well as the air load on the diaphragm. The force is provided by the motor (magnetic circuit and voice coil) due to current from the amplifier passing through it.

Using many drivers in an array does not alter the ratio of force to mass. Therefore, a line array does NOT present an opportunity to use low-performance drivers. What does happen is this: for a given acoustic output, the displacement per driver is reduced in proportion to the number of drivers (neglecting that there is also an improvement in radiation resistance). This reduces diaphragm velocity by the same amount. Since kinetic energy is proportional to the square of velocity, the kinetic energy which must be imparted to the diaphragm and then removed from it is tremendously reduced (by the square of the number of drivers). The ability of the drivers to respond to transient inputs is correspondingly improved.

Loudspeaker drivers are minimum phase devices. This means that the phase response is directly predictable from the amplitude response. If the amplitude response is smooth and flat, so will be the phase response which is equivalent to low group delay distortion as discussed earlier. It then remains to design the crossover so that the transitions from woofer to midrange and midrange to tweeter also exhibit low group delay variations.

The combination of drivers with good force/mass ratios, proper crossover design and large arrays leads to subjectively amazing qualities of

- **clarity** and
- **speed**

which are encountered to this degree in no other loudspeakers.

Spatial discrimination

In loudspeaker terms this is usually referred to as *imaging*. The general sense in which the word is used, suggests the ability to locate sounds, but there is more to it than that. Lateralization (i.e. across the soundstage) is just one dimension of imaging. Localization (i.e. depth) is another. Yet another is the sense of *space* surrounding the music and the related sense of *scale*.

Not all these aspects of musical presentation are equally well encoded in all recordings, so we must assume that discussion of these attributes presupposes a well made recording.

The attributes required for temporal resolution discussed above are also important keys to preservation of the spatial attributes. But now we come to one of the most important and difficult matters in loudspeaker system design: the interaction between the loudspeakers and the room.

Most loudspeakers are optimized for flat on-axis response along a particular line perpendicular to the front of the unit. In general, some attention is paid to the response up to 30° off-axis horizontally and maybe 10° vertically. Beyond that very little attention is paid. The assumption is that the far off-axis response doesn't matter. This is **incorrect** for at least two reasons: 1) the far off-axis sound is a strong contributor to the reflected soundfield in the room (correctly called reverberation only in very large rooms) and 2) the far off-axis frequency response of the loudspeaker is likely to be very irregular.

Our hearing faculty allows us to have excellent spatial discrimination even in the presence of reflections of the sound we are trying to discriminate. So presumably our ear-brain system is able to use the reflected information, or possibly disregard it. But if the reflections are initiated by a severely deformed version of the direct sound then our ability to factor out the reflections seems to become impaired. This is what happens when bad off-axis response excites reflections.

The usual proposal to remedy this situation is to eliminate the reflections. This is accomplished by deadening the room with absorbent material on all its surfaces. If the loudspeakers required this room treatment in the first place, then for the same reason they have poor off-axis response they will also have a narrow frontal coverage angle. So the result is a narrow listening area ("sweet spot") in an unpleasant room. This is such a solipsistic solution you might as well buy a good pair of headphones and listen all alone and forget about the room. This situation is the result of treating the symptom rather than the disease. The disease in this case is conceptually defective loudspeakers.

We believe that listening to music is a fundamentally social activity which is most pleasantly conducted in a nice room with comfortable furnishings and is a place where listening to recorded music or movies is only one of many appropriate uses. To this end we are careful to make all our loudspeaker designs interact with the room in a smooth and predictable way. The important results of this approach are:

- **Broad useful listening area** (big sweet spot)
- **Easy placement of the speakers**
- **Superior imaging**
- **Aesthetic preservation of the room**

An important consequence of this emphasis is that the acoustic *of the recording* is clearly intelligible because the local acoustic of the listening space is not suppressed but rather is correctly "illuminated".

Another aspect of the rendering of space is the sense of the size of the *space*. Where a very large space, as in a cathedral, is to be rendered there is a requirement to preserve the extreme low frequencies. The presence of stereophonic deep bass (no mono subwoofers allowed) contributes strongly to the sense of "vastness". All our subwoofer systems maintain uniform response to 20 Hz with significantly high output.

Scale is an important consideration as well. The Pipedreams are very tall loudspeakers, yet the sense of how big the performer is, is remarkably correct. The singer's mouth is not perceived to be six feet tall or wide. This seems to be a counterintuitive result, but on further consideration it is probably due to the smooth interaction between the speakers and the room. The ear-brain system is not being deceived by spectrally distorted reflections.

Summary & Conclusions

We have identified the principal attributes of human hearing to establish a context for the technical considerations in designing loudspeaker systems:

- Frequency range
- Dynamic range
- Temporal resolution
- Spatial resolution

We have presented our approach to addressing these requirements and why it is **superior** to other commonly applied approaches.

The validity of our position is established by the ability of our speaker systems to **connect the listener to the music**. In terms of line-array speakers our position is further validated by the now widespread **imitation** of our products. But remember, we were there **first**. We use the **best** components, we have the longest experience and we deliver the most convincing result. Also remember, **imitation is the sincerest form of flattery**.

Further reading

A short list of especially pertinent technical literature.

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