The Science of Audio - a series of lectures by Floyd E. Toole, Ph.D. Vice President Acoustical Engineering
Harman International Industries, Inc.
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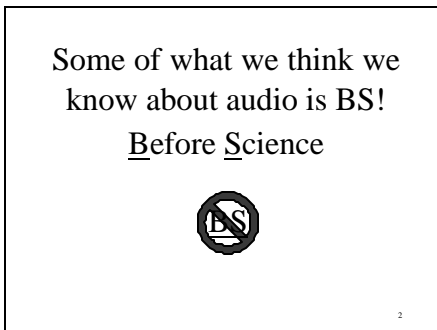
Loudspeakers and Rooms for Multichannel Audio Reproduction

by
Floyd E. Toole
Vice President Acoustical Engineering
Harman International

Part 2 – Making a good loudspeaker - Imaging, space and great sound in rooms.

Loudspeakers can be designed to be "room friendly" so that they can sound good in a variety of different rooms. Controlling reflections can optimize imaging and spatial effects.

Some of what we think we know about audio is BS!
Before Science

Music and Movies are Art

Audio is a Science

Science in the Service of Art is our Business!!

Audio is an industry that is unfortunately burdened with a lot of ideas and beliefs that are not based on physical facts. Our business is complicated enough without adding the confusion of half-truths and folklore. An understanding of at least the fundamentals of room acoustics, and how loudspeakers and rooms interact with each other, takes us a long way towards our goal of truly excellent sound. This benefits everyone, the customer, the installer/consultant/retailer, and the manufacturers of the equipment.
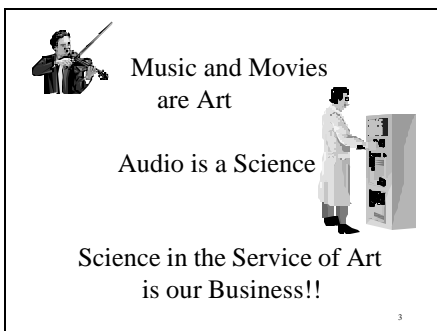
The fact is that audio is a technology with a firm scientific grounding under most of it. It is not an art, and audio products do not possess artistic characteristics, except in the visual sense. The better we understand and use the real science to achieve excellent performance from our products, the more often the true audio artistry, the sound of music and movies, will be heard by us and by our customers.

The existence of custom audio installers and consultants is something relatively new to our industry. For the first time in the history of audio, there are professionals whose job it is to help the customer, in his or her own home, to achieve the best possible sound.

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The Goal: To deliver high quality sound to our customers' ears.

The Problem:
ROOMS, the final audio component.

They affect sound quality and imaging
They dominate bass quality
They do this during the making of the recordings, and during their playback at home.
They are all different.

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The traditional problem in audio has been that the room, the final audio component, is not within our control. Customer satisfaction, assuming that it is based on good sound, has been, therefore, a matter of chance.

This can change. With the selection of the appropriate loudspeakers, the application of some fundamental room acoustical knowledge and, if necessary, the right kind of equalization, we can greatly increase the odds in the favor of the customer and thereby ourselves.

Loudspeakers should sound good . . .

. . . and that is part of the problem.

How do we judge what is "good"?

5

No matter what measurements tell us, a loudspeaker isn't good until it sounds good. Complications in determining what is "good" include variations in rooms and recordings. The latter is something often ignored as we go about our daily businesses.
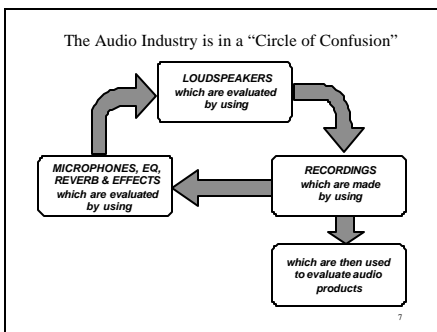
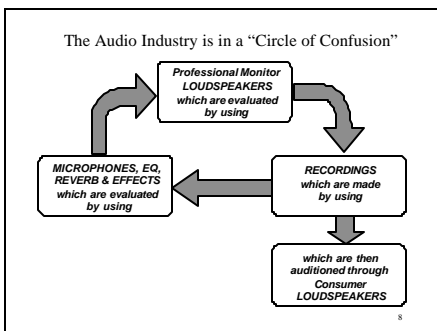We listen, of course .

But when we do . . .

6

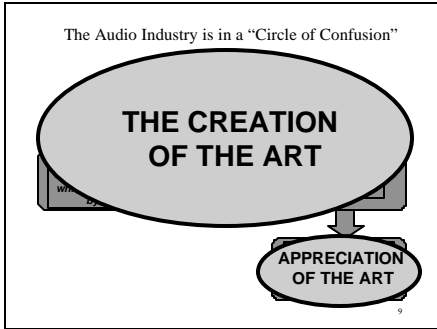When we listen we are instantly trapped in the "audio circle of confusion".
 Loudspeakers are evaluated by listening to recordings.
Recordings are made using microphones that are selected and positioned, equalized and processed in a variety of ways using the masses of equipment in a recording studio.
All of this is done while listening through loudspeakers in a room – a recording control room or movie dubbing stage.
The quality of the sound in a recording is very much dependent on the quality of sound from the monitor loudspeakers in that particular room.

The Audio Industry is in a "Circle of Confusion"

LOUDSPEAKERS which are evaluated by using

RECORDINGS which are made by using

MICROPHONES, EQ, REVERB & EFFECTS which are evaluated by using

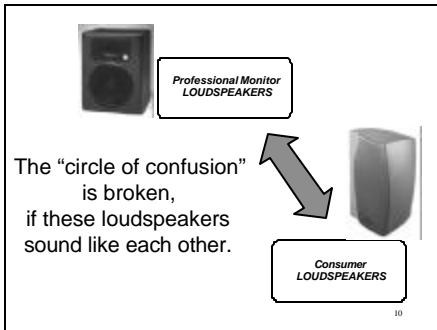which are then used to evaluate audio products

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The recording industry has NO critical standards relating to loudspeakers for monitoring and for the rooms in which they are used. Consequently, recordings are extremely variable in quality, even in the gross characteristics of bass and treble balance. Yet, we try to evaluate audio products using such recordings. It is like making a technical measurement with an undefined test signal. The result is that mistakes are made. We cannot tell whether a good sound is the result of a truly good loudspeaker/room combination, or whether it is a case of compensating errors: a recording with, for example, too much bass being combined with a playback system that is deficient in bass.

The Audio Industry is in a "Circle of Confusion"

Professional Monitor LOUDSPEAKERS which are evaluated by using

RECORDINGS which are made by using

MICROPHONES, EQ, REVERB & EFFECTS which are evaluated by using

which are then auditioned through Consumer LOUDSPEAKERS

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Some control rooms sound superb, while others are back in the dark ages of loud "mid-fi". Some even go out of their way to use bad monitor loudspeakers that they think represent what people are listening to in their homes and cars. It is obvious to anyone who listens carefully that all loudspeakers are getting better, and that the good ones are sounding more and more alike, and much more like the "real thing". However, bad loudspeakers can be bad in an infinite number of ways. No two are alike, and they can be dramatically different. How, then, is it possible for one "bad" monitor loudspeaker to represent the huge variety of sounds from clock radios, boom boxes, mini-systems, headphones and entry level car audio? It isn't!!

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The Audio Industry is in a "Circle of Confusion"

THE CREATION OF THE ART

*WITH...
DA...*

APPRECIATION OF THE ART

9

All of us need to exercise whatever influence we have to elevate the quality of sound everywhere. Then, and only then, will we have some assurance, when we listen at home or in our cars, that we are hearing what was intended by the artists. The enemy in this effort is ignorance and apathy. Most customers are intimidated by these kinds of decisions, and some truly say they don't care. Yet, I have never in my life demonstrated a truly good sound system to anyone who was not impressed, if not absolutely "blown away".

Professional Monitor LOUDSPEAKERS

The "circle of confusion" is broken, if these loudspeakers sound like each other.

Consumer LOUDSPEAKERS

10

Ironically, the problem exists at both the professional and consumer levels. Both need to be aware of the genuine advances in acoustic science and technology.

PRESERVATION OF THE ART

...KERS

11
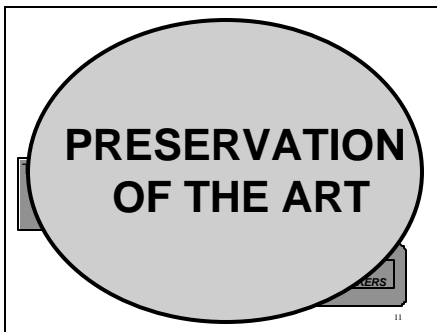
Only then can we say that we are working within an industry that aims to preserve the audio artistry.

This is a problem to which there is not a single, or a simple, solution.

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If we cannot totally rely on our ears, what else is there?

Science Involves Measurements, and We Need to Do Two Kinds:

OBJECTIVE

1. Frequency Response - on and off axis, spatial averages including sound power.
2. Phase Response
3. Non-Linear Distortion - THD, IMD, noise
4. Power Compression

SUBJECTIVE

1. Sound Quality - timbre, bandwidth
2. Directional and spatial effects in stereo and multichannel systems
3. Distortions and noises
4. Dynamic Capabilities

13

The scientific method requires data. Data of all kinds, and the more the better. In this case, we must use technical measurements, because they are the essential tools of the engineers designing the products. It is necessary to measure everything that we think might be relevant to how something sounds. This is more than is commonly thought. However, we also need subjective data, relating to listeners' opinions of the many perceptual dimensions of sound quality as well as spatial and directional attributes.

Scientific Design Requires:

(a) carefully controlled listening tests: subjective measurements
          combined with
(b) accurate and comprehensive technical measurements
          combined with
(c) knowledge of the psychoacoustic relationships between perceptions and measurements .

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If listeners like or dislike something, it is important to try to identify what, technically, was responsible. By taking the listening reports back to the lab, it is possible to learn the relationships between what we measure, and what we hear. This is the science of psychoacoustics, and the better we understand it, the better we will be at delivering good sound to our customers' ears.
Technical measurements must be accurate, or else they lie to us. Getting accurate acoustical measurements without good facilities is very difficult to impossible. Much of the data floating around the loudspeaker industry is not accurate.

What are Subjective Measurements?

They are LISTENING TESTS in which the OPINIONS OF LISTENERS relate to the SOUNDS OF THE LOUDSPEAKERS rather than:

How they look
How much they cost
What reviewers think of them
What listeners think of the manufacturer
How loud they are
How the room is physically arranged
Etc. . . .

These are NUISANCE VARIABLES -they MUST be controlled

15

Most listening tests are valid only at a specific time and place, for the specific recordings that were listened to, and for the people offering their opinions. This can be acceptable if it is you choosing your own system in your own home. It is not acceptable for a loudspeaker manufacturer, who is trying to design products that can sound good to many listeners, in many rooms, with many recordings. Consequently, we get scientific about it, and start to remove some of the variables that have nothing to do with the sound from the loudspeaker, letting the listeners focus as much of their attention as possible on the sound, and the sound alone. Purveyors of 'magic' in the audio industry find these double-blind tests very threatening.
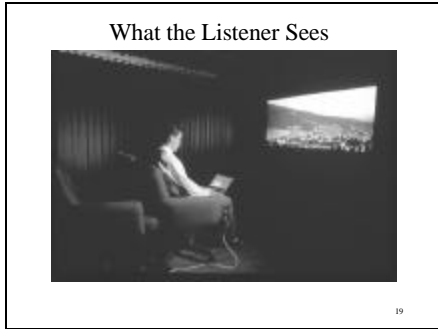
Mono, Stereo and Multichannel Tests

16

One of the most problematic nuisance variables is the position of the loudspeaker and the position of the listener in the room. To control this variable at Harman, we have created a room with a "shuffler" that physically moves speakers around, bringing them always to the same locations when they are being auditioned. It is pneumatically driven, quiet, and computer controlled so that the positions are precise. It takes about three seconds to switch the positions of the active and inactive loudspeakers.


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A pair of speakers ready for listening.

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And, about three seconds later, a second pair can be heard.

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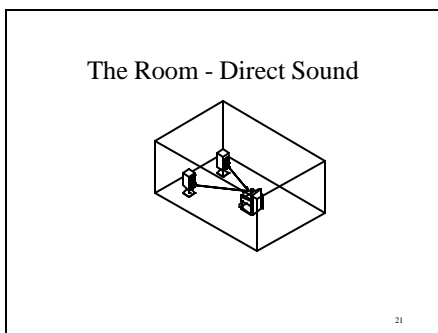
What the Listener Sees

The listener (and we prefer to use one listener at a time) sees none of this, of course. Here we show a video display on a large perforated screen. For the evaluation of most products this is not used.

The tests are controlled by the listener, who takes as long as is needed in order to form a satisfactory judgment. A computer randomizes the choice of music, and the coded identity of the test loudspeakers for each musical selection, so that the opinions must relate as much as possible to the sound itself.

Listeners are selected for normal hearing and aptitude, and then are trained to be really fussy. They yield remarkably consistent opinions.

In the Real World

The room is the final audio component,
and it is not under control!
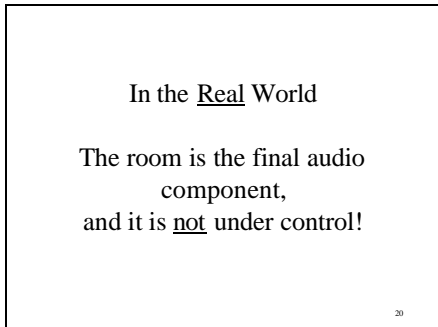
"Where the rubber hits the road", in the customer's home, we have no such conveniences, so we must develop products and techniques that allow good sound to prevail even when the local acoustical conditions are less than ideal.

This is where knowledgeable custom installers, consultants and audio specialists come to the rescue.
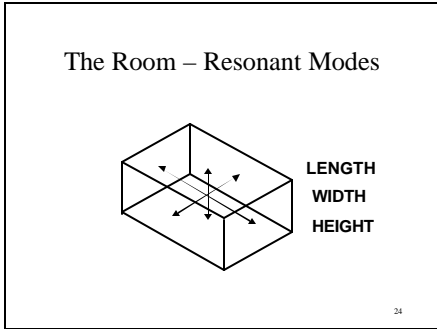
The Room - Direct Sound

The first sound to arrive at a listener's ears is the "direct" sound. If the loudspeakers have been angled to face the listener, this will be the on-axis sound, often the best possible sound from the loudspeaker.
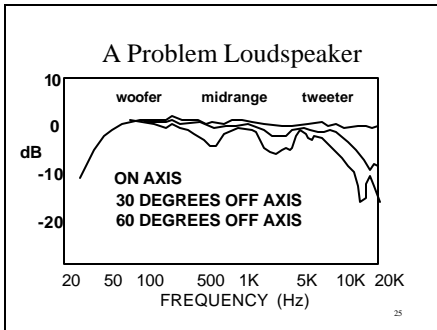
The Room - Early Reflections
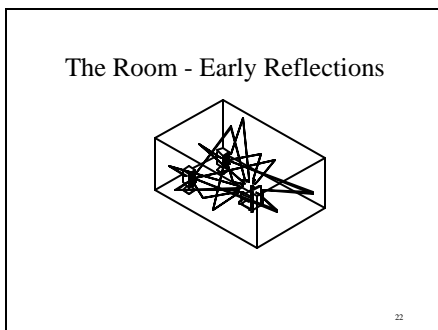
However, following only a few milliseconds behind, and only slightly less loud, will be the early reflections: sounds that have been reflected from only one surface in the room.
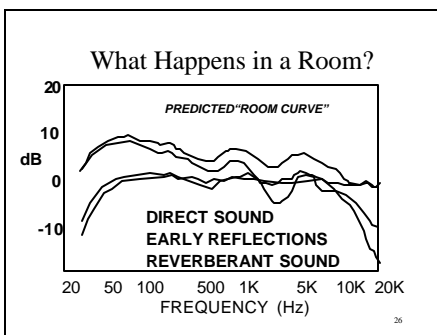
The Room - Reverberation
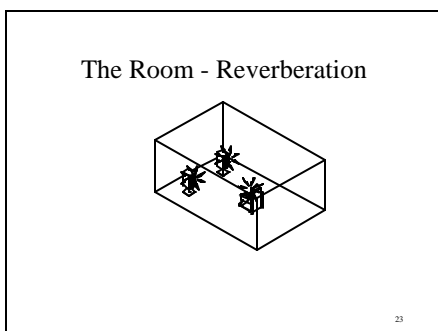
Still later, come the multitudes of reflections that have been reflected more than once, perhaps many times. These are individually much lower in amplitude, but collectively loud enough to be a powerful factor in our impressions of sound quality, space and imaging. In small rooms, typically furnished, this sound field, although often called 'reverberation' is not the directionally diffuse and temporally complex reverberation that we hear in a concert hall, or many other large, acoustically 'live' spaces. Some would argue that it deserves a different name.

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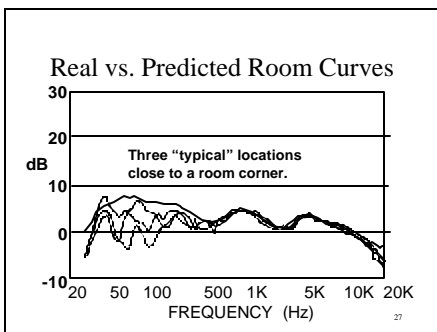
The Room – Resonant Modes

LENGTH
WIDTH
HEIGHT

24

Rooms also have resonances that emphasize certain frequencies, attenuate others, depending on the dimensions and shape of the room. And, they do so in a manner that depends on where the loudspeakers and listeners are located within the room. These effects are strongest at low frequencies.

A Problem Loudspeaker

woofer   midrange   tweeter

ON AXIS
30 DEGREES OFF AXIS
60 DEGREES OFF AXIS

dB

FREQUENCY (Hz)

25

Using a loudspeaker that we know, in retrospect, had a design flaw, let us see what happens in a room. This loudspeaker was designed using the philosophy that the direct sound, the on-axis sound, is the most important. The top curve is the on-axis measurement, and it is very smooth and flat, a credit to the design team.
The second and third curves, moving downward, are the 30- and 60-degree off-axis measurements, showing that these sounds are not nearly so neutral; the output varies with frequency. What happens to this in a room?

What Happens in a Room?

PREDICTED"ROOM CURVE"

dB

DIRECT SOUND
EARLY REFLECTIONS
REVERBERANT SOUND

FREQUENCY (Hz)

26

The data in this slide are derived from many measurements made in a large anechoic chamber. This is a room having no "echoes", used for acoustical measurements. All surfaces are covered with highly effective acoustical absorbing material that is, in this case, about four-feet thick. The color coding of the curves is not visible here, so it is not possible to see which curve is which. However, one might recognize the flat on-axis curve representing the direct sound, and see also that none of the other curves is remotely smooth or flat. This tells us that all of the sounds arriving at the ears do not convey the same message about the sound quality, or timbre. The top curve is a calculated prediction of what a measured "room curve" might be.

Real vs. Predicted Room Curves

dB

Three "typical" locations
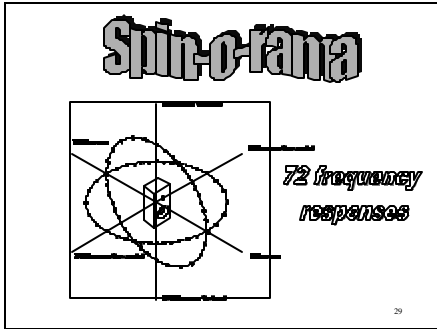close to a room corner.

FREQUENCY (Hz)

27

The loudspeaker was then placed in a typical left or right channel location in a real room. It was measured at the listening position, then moved to two other locations within a radius of two feet, and measured at each location. The fourth curve, the top one, is the calculated room curve from the previous slide. Obviously, little is changing at frequencies above about 300-400 Hz, and the prediction is right on target. However, below these frequencies, there are considerable location-dependent changes, and the prediction fails completely. The reason? Room resonances and boundary effects that are specific to that particular room. These can only, with precision, be evaluated by measurements in the room itself.

There is a region where the room dominates, and one where the loudspeaker dominates.

dB

ROOM   SPEAKER

FREQUENCY (Hz)

28
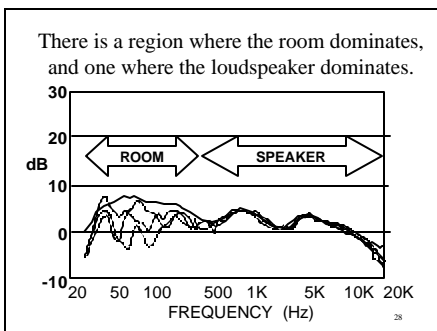
However, it is also clear that through the middle and high frequencies the anechoic measurements made in the laboratory have done an excellent job of predicting what happened in the room. However, doing so required many, many measurements at positions all around the loudspeaker.

If we are to try to anticipate how a loudspeaker will sound in a room, it is necessary to measure everything, and not just a few curves around the on-axis measurement.

31 January, 2002

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At Harman, the engineers have dubbed our basic measurement of frequency response, the Spin-o-rama, since it involves spinning the loudspeaker on two axes, and accumulating a total of 72 measurements.
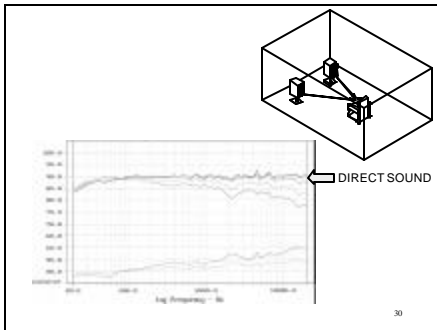

The collection of raw data is computer processed to generate a set of curves showing estimates of the distinctive regimes of sound arriving at a listener's ears in a typical room. To do this, a large survey of real rooms was undertaken, and a statistical analysis of angles and distances led to the algorithm that generated these curves. All measurements have a frequency resolution of 1/20 octave, from 20 Hz to 20 kHz.

The top curve is the on-axis curve, representing the direct sound for a person in the "sweet spot".
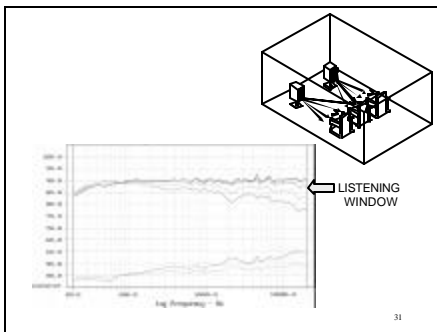

The second curve is a spatial average over +/- 30° horizontal, and +/- 10° vertical, representing the direct sound for listeners seated in a row of chairs or a large sofa, and possibly standing and sitting.
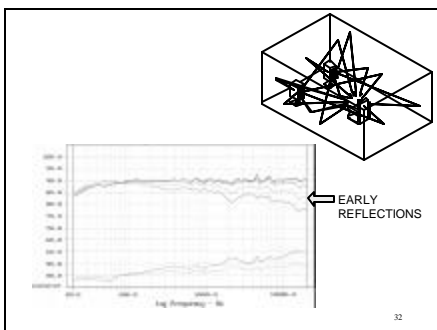

The third curve is the energy sum of the set of early reflections. Ideally, these should look a lot like the on-axis curve, so that it conveys the same timbral information.
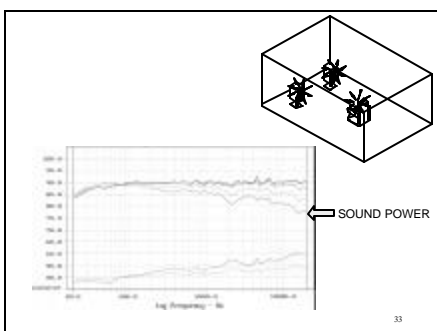

The fourth curve is a calculation of the total sound power radiated by the loudspeaker in all directions (this is NOT a simple average or sum of all 72 measurements). Again, this curve should be smooth and flattish.

31 January, 2002

DIRECTIVITY INDEX

34
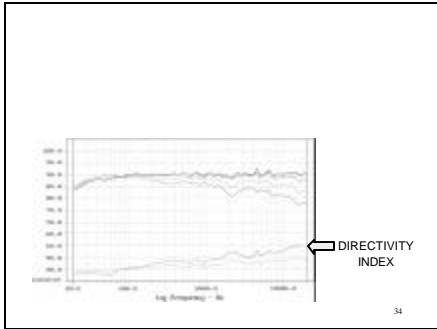
The uppermost of the bottom pair of curves is the Directivity Index, or DI. This is an indication of the angular uniformity with which the loudspeaker radiates its energy into a room as a function of frequency. It is a measure of the uniformity of its dispersion as a function of frequency.
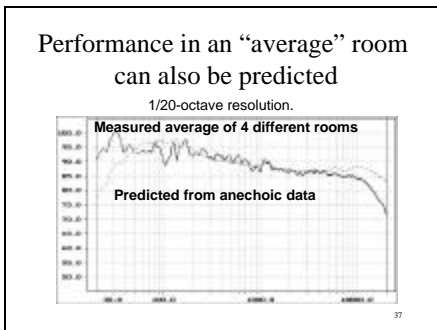

EARLY REFLECTIONS DIRECTIVITY INDEX

35
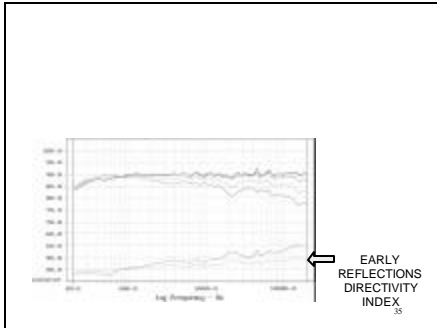
The bottom curve is an invented DI, this time just for the early reflections.

The Complete Set –
A Picture of Performance
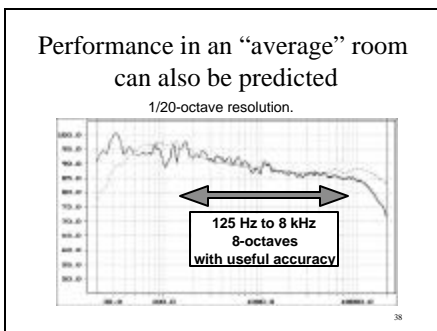

10 dB
5 dB **DI**
0 dB

36
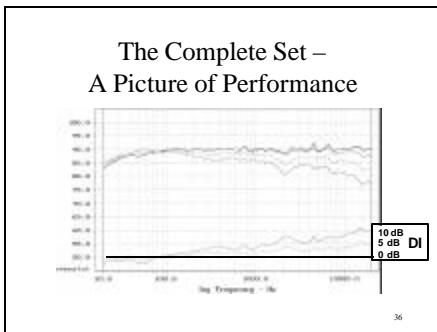
Here we see the complete set as they are presented for visual inspection. The whole idea of this is to present to the eyes, a set of data that can be interpreted in a way that allows one to anticipate how a loudspeaker might sound in a room.

The curves shown here describe a truly excellent loudspeaker, not perfect but, currently, a good example of the state of our art. Note the smoothness of all of the curves, and the basic similarities in all of the curves, from the single on-axis measurement, through to the estimate of the total sound radiated in all directions, the sound power.

Performance in an "average" room
can also be predicted

1/20-octave resolution.

Measured average of 4 different rooms

Predicted from anechoic data

37

In the same way that the earlier example was calculated, we can generate a curve that tries to anticipate a room curve. Here we have not included all of the possible refinements, but it suffices to get us within a couple of dB over most of the frequency range.

Performance in an "average" room
can also be predicted

1/20-octave resolution.

125 Hz to 8 kHz
8-octaves
with useful accuracy

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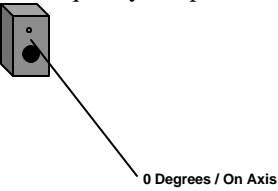
Now, how do we interpret the measurements?

- Frequency response curves are not flat and smooth. Does this matter? How much does it matter? What is the ideal shape?
- Can we hear phase shift?
- What about time-domain behavior: transient response, "speed", etc.?

39

O.K. So we get some curves. The real problem is that they ARE curves, and not straight lines. What is the ideal shape? How much deviation from the ideal is audible? Is there more to this than just frequency response?

For Example: What is in a Frequency Response?

0 Degrees / On Axis

40

Let's start with the most basic of all measurements, the frequency response. In the case of a loudspeaker we would begin with a look at what happens on the major axis.

Incidentally, such a measurement should be made at a distance of 2 m (6 feet) or more. The industry standard specifies loudspeaker sensitivity at one meter, however, the standard also requires the measurement to be made in the "far field" of the source, and if necessary, for the measurement to be calculated back to 1 meter. Many people mistakenly do not do this, and also make frequency response measurements at 1m. For loudspeaker systems of typical size, these measurements can exhibit large errors.

What is in a Frequency Response?

Spectral Balance and Bandwidth

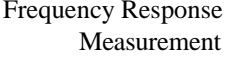*Resonances*

Acoustical Interference

41

Of the features that our eyes can extract from a curve like this, it is obvious that spectral balance and bandwidth are important. Try playing with the bass and treble controls, and you will find that small changes are audible.

Resonances are REALLY important because our perceptual system (the ears and brain) is highly sensitized to them. The reason: resonances are the "building blocks" of all of the sounds that we are really interested in listening to – voices and musical instruments. Resonances can cause peaks and dips in a frequency response curve. However, so can acoustical interference, a phenomenon that turns out to be much less audible under normal listening circumstances.

The components must be separated

Spectral Balance and Bandwidth
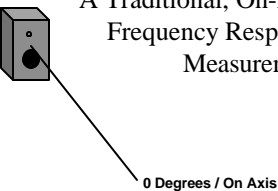
Resonances

Acoustical Interference

42

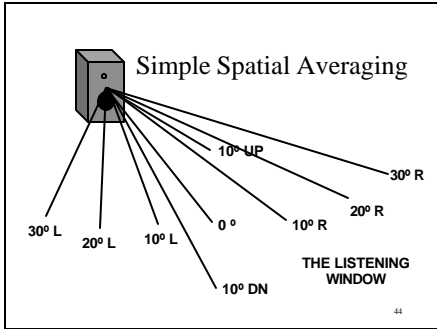So, we need a measurement system that allows us to separate, visually, those features in a curve that are caused by each of these phenomena. Only then can we be truly analytical, and make good judgments about how good or bad the device is.

## A Traditional, On-Axis Frequency Response Measurement

0 Degrees / On Axis

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Once upon a time, it was thought that a single curve told us useful information.

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Simple Spatial Averaging

10º UP
30º R
20º R
10º R
0 º
30º L
20º L
10º L

THE LISTENING
WINDOW

10º DN

44

Then we learned that spatial averaging allows us to separate those peaks and dips caused by resonances from those caused by acoustical interference. The explanation is really simple: those features associated with resonances tend not to change when the microphone location is changed, while those associated with interference do.

A lot of Spatial Data

45
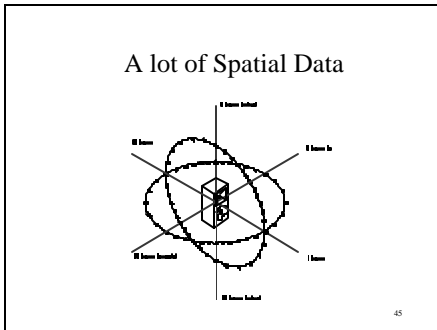
When we average a lot of measurements made at a lot of different locations, and certain visual shapes do not disappear, we can be quite confident in concluding that those are resonances, and not the result of acoustical interference.

Spatial Averaging in Rooms

• Helps to reveal the presence of resonances, which can be equalized.
• Attenuates the effects of acoustical interference, which cannot be equalized.
• Helps to eliminate visual evidence of dips in the frequency response, and thereby the temptation to try to fill them with equalization – which does not work!
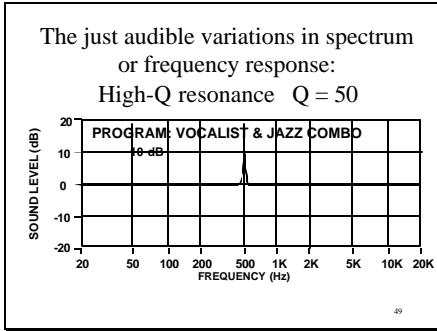
46

In rooms, there is an abundance of acoustical interference, caused by multitudes of reflections. Therefore, spatial averaging, i.e. combinations of measurements made at several locations, can help to isolate resonances. This is important because it turns out that we can equalize resonances (about which, more later), and we cannot equalize the effects of acoustical interference.

Resonances are major problems!

• In loudspeaker drivers
  – cone flexure modes
  – suspension and frame modes
• In enclosures
  – mechanical resonances in panels and surfaces
  – acoustical resonances in cavities
• In rooms

47

So, we expend a great deal of effort eliminating resonances from loudspeaker systems, and when they are installed in rooms, we need to spend some time and effort to identify and eliminate serious resonance problems.

Resonances of Different "Q"

10 dB

Q = 1
Q = 50
Q = 10

100 200 500 1K 2K 5K 10K
FREQUENCY (Hz)

48
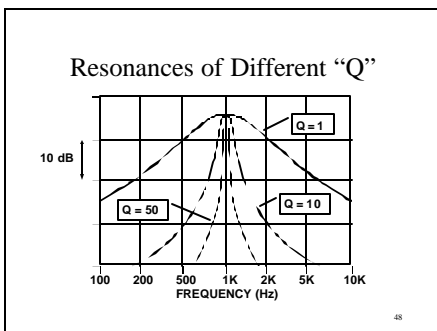
Resonances are differentiated by their "Q", or quality factor. A high-Q resonance is one that is very frequency specific and that rings a long time. An example of a high-Q resonance is an empty wine glass, held by the stem, and tapped with a finger nail. It emits a clear tone that rings. If one places a finger on the side of the glass and taps it again, the ringing is shorter. The finger has taken some energy out of the resonant system, and the 'quality' is reduced. If the entire glass is grasped by a hand, and the tap is repeated, there is almost no ringing at all. A tone is still recognizable, but it is a low 'quality', or low-Q, resonance. High-Q resonances have sharp peaks, and low-Q resonances are broader when they are seen in frequency responses.

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The just audible variations in spectrum or frequency response:

High-Q resonance   Q = 50

PROGRAM: VOCALIST & JAZZ COMBO

10 dB

49

Sean Olive and I, when we were at the National Research Council, in Canada, published a paper in which we showed the shapes of deviations in frequency responses that corresponded to the just audible thresholds for resonances of different Q, at different frequencies, for different kinds of music or sounds. The effect of frequency was secondary, so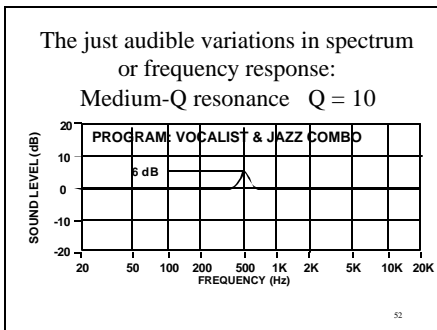 here I show only what happens at 500 Hz. The results at different frequencies are similar. It shows that, for multimiked pan-potted, low reverb, pop or jazz, the threshold of audibility corresponds to a 10 dB spike in a frequency response curve. It looks bad, but it is just barely audible!

The just audible variations in spectrum or frequency response:

High-Q resonance   Q = 50

PROGRAM: SYMPHONY ORCHESTRA

6 dB

50
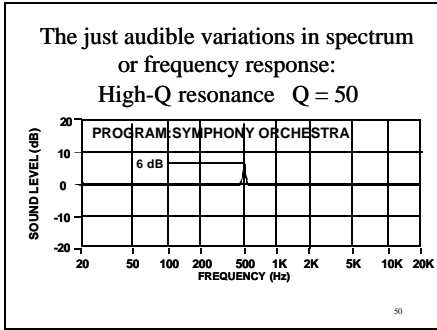
With a big band or symphony orchestra (complex orchestration) in a reverberant hall, the threshold is lower (we are more sensitive).

The just audible variations in spectrum or frequency response:

High-Q resonance   Q = 50

PROGRAM: PINK NOISE

3 dB

51
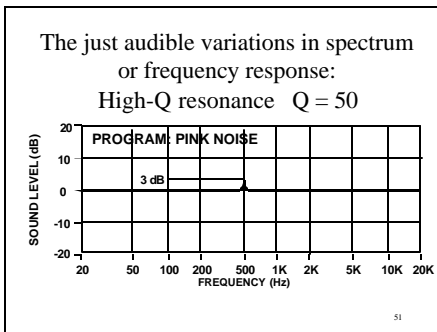
Of all the signals we tested, pink noise was the most revealing of resonances. It produced the lowest thresholds. Such low-amplitude, narrow, spikes are difficult to measure with precision at all frequencies.

The just audible variations in spectrum or frequency response:

Medium-Q resonance   Q = 10

PROGRAM: VOCALIST & JAZZ COMBO

6 dB

52

When the Q is reduced, the pattern of audibility is much the same, but the thresholds are lower.

The just audible variations in spectrum or frequency response:

Medium-Q resonance   Q = 10

PROGRAM: SYMPHONY ORCHESTRA

4 dB

53

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The just audible variations in spectrum
or frequency response:
Medium-Q resonance   Q = 10

PROGRAM: PINK NOISE

1.5 dB

54

The just audible variations in spectrum
or frequency response:
Low-Q resonance   Q = 1

PROGRAM: VOCALIST & JAZZ COMBO

2.5 dB

55

When we get to really low-Q resonances, the ones that ring very little, it turns out that we can hear them at very low measured amplitudes. What, then, of the arguments that the ringing of high-Q resonances "smears" sounds, making them less articulate? These are arguments that are most likely based on visual interpretations of measured data, not on actual subjective tests of the audibility of the effects. They sound as though they should be true but, except at very low frequencies, they are fanciful. Good engineering should attempt to eliminate resonances of all kinds, but it is important to understand what is and is not audible.

The just audible variations in spectrum
or frequency response:
Low-Q resonance   Q = 1

PROGRAM: SYMPHONY ORCHESTRA

1.5 dB

56

The just audible variations in spectrum
or frequency response:
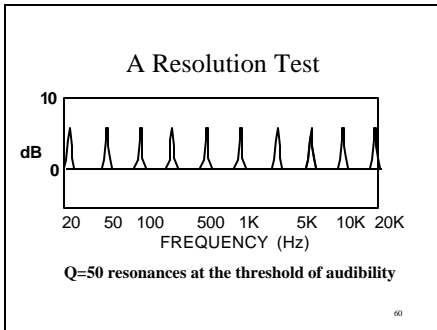Low-Q resonance   Q = 1

PROGRAM: PINK NOISE

0.3 dB

57

This "curve" looks almost like a straight line. Our eyes are telling us that it is almost perfect, yet our ears are telling us that there might still be something audibly wrong.

So, in this case, what our eyes tell us does not intuitively correspond with what we hear. This is why it is so important to do the science, and to establish what the real psychoacoustic relations are. Our instincts can be wrong.

The just audible variations in spectrum
or frequency response:
These are all EQUALLY audible!

PROGRAM: SYMPHONY ORCHESTRA

58

Is there an explanation? It is probably because music and speech are ever-changing. Also, voices and many musical instruments are played with vibrato – a modulated pitch. High-Q resonances take time to build up, as well as to decay. We tend to talk about the ringing, overhang or decay of resonances after the signal has stopped, ignoring the front-end effect. High-Q resonances are narrow, very frequency-specific, and musical sounds must be sustained long enough to energize them. Few are. Low-Q resonances are wide enough that they respond to everything, and they take almost no time to reach full amplitude.
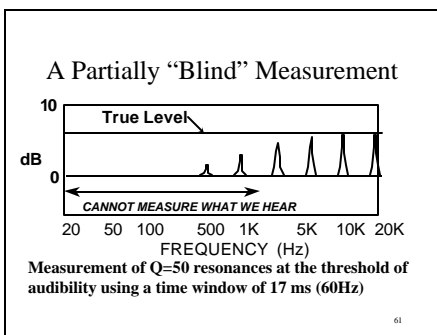
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Measurements must have enough resolution to show what we can hear

59

In order to make any sense at all of a frequency response curve, or a set of curves, they must be capable of revealing to our eyes everything that is audible.
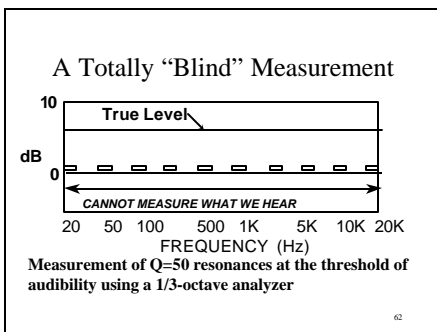
The belief, still widespread in this industry, that we cannot measure what we can hear, has its origins in situations where the measured data were erroneous or incomplete. Such situations are common in the loudspeaker business.

A Resolution Test

10

dB

0

20   50   100   500   1K   5K   10K 20K
FREQUENCY (Hz)

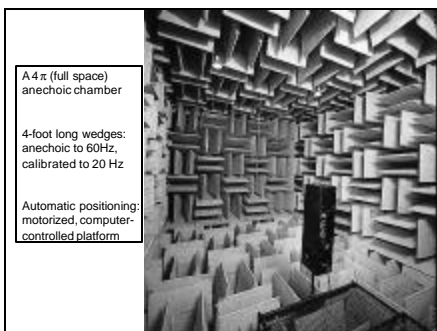**Q=50 resonances at the threshold of audibility**

60

Let's create a test. Suppose we had an imaginary system in which there were high-Q resonances uniformly distributed from low to high frequencies. A competent measurement system would reveal them to our eyes as they truly are.

A Partially "Blind" Measurement

10

True Level

dB

0

CANNOT MEASURE WHAT WE HEAR

20   50   100   500   1K   5K   10K 20K
FREQUENCY (Hz)

Measurement of Q=50 resonances at the threshold of audibility using a time window of 17 ms (60Hz)

61

However, not all measurement systems are equal. Many very commonly used ones "gild the lily", making the curves smoother than they really are. All systems that use time windowing, or the equivalent (MLSSA, TEF, and any FFT-based system) can do this IF the measurement window is not sufficiently long. Here I show what happens with a quite long window (17ms), more than is used by many manufacturers and reviewers. It is clear that the measurement does not reveal the existence of the high-Q resonances in the middle and low frequency regions. It does not show things that we know we can hear.

A Totally "Blind" Measurement

10

True Level

dB

0

CANNOT MEASURE WHAT WE HEAR

20   50   100   500   1K   5K   10K 20K
FREQUENCY (Hz)

Measurement of Q=50 resonances at the threshold of audibility using a 1/3-octave analyzer

62

The popular one-third-octave measurements, very common in room measurements, simply fail. These give only a very "broad-brush" view of what is happening, and are of very limited use. One needs an analyzer capable of at least 1/10 octave resolution in order to reveal what we need to see.

A 4π (full space) anechoic chamber

4-foot long wedges: anechoic to 60Hz, calibrated to 20 Hz

Automatic positioning: motorized, computer-controlled platform

For loudspeaker measurements, very long measurement windows are necessary, and these can be accomplished only in anechoic spaces. Outdoors, away from all reflecting surfaces, is free, but impractical. Anechoic chambers, such as the one shown here, are very practical, but also very expensive. However, this is the price of entry if you are seriously in the business. The length of the wedges determines how low in frequency one can measure accurately. These 4-foot wedges create a reflection-free environment down to about 60 Hz. We have calibrated it down to 20 Hz for specific measurement locations within it. With a large enough measurement time window, ANY measurement system should yield accurate data.

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AND the most commonly used
specification for frequency
response is useless . . .

. . unless it is accompanied by
a graph!!!

64

---

20 Hz to 20 kHz +/- 3 dB
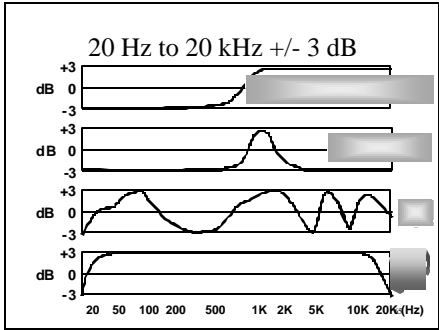
Every audio device has a specification for frequency response. A tolerance of +/- 3 dB is sufficient to describe a range from junk to jewels. By itself, it is meaningless window-dressing. A curve, and the ability to interpret it, are necessary. If the tolerance is small enough, then it does have meaning, of course.
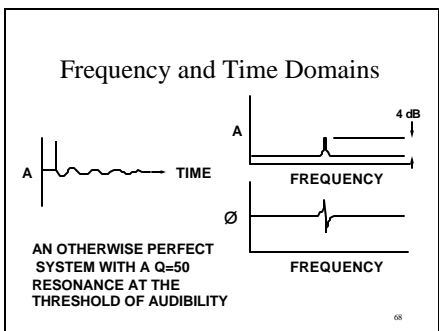

Frequency and Time Domains

• Related by Fourier Transformation
• Behavior in one domain is paralleled by corresponding behavior in the other

66

So far, we have talked about frequency response as though it were the only important factor. What about the all-important transient response, speed, punch, drive, and all of those descriptors of what happens in the time domain?

Well, it turns out that the two domains are related to one another, by the Fourier transformation.

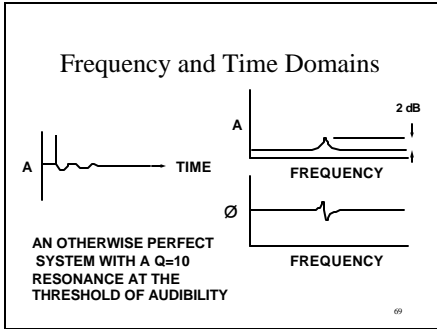Frequency and Time Domains

A PERFECT SYSTEM

67
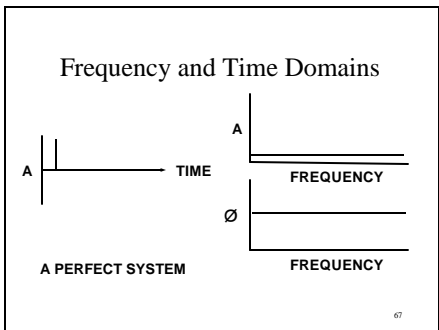
A perfect linear system would be described either by a clean uncluttered transient, or by a pair of flat straight lines portraying a constant amplitude vs. frequency characteristic (we call this the frequency response, although it is really the amplitude response), and a constant phase vs. frequency response. The flat amplitude response tells us that the signal level at all frequencies is constant. The flat phase response tells us that everything is happening at precisely the right instant in time. The combination of flat amplitude and phase responses correspond to a perfect impulse, or transient, response.
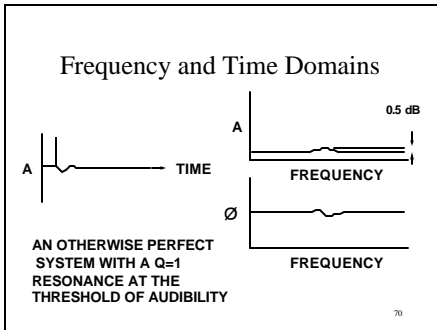

Frequency and Time Domains

AN OTHERWISE PERFECT
SYSTEM WITH A Q=50
RESONANCE AT THE
THRESHOLD OF AUDIBILITY

68

Here we have disrupted the perfect system with a single high-Q resonance. The narrow "footprint" in the amplitude response, as seen earlier, is repeated in the phase response. In the time domain, the corresponding effect is extended ringing (the empty wine glass).
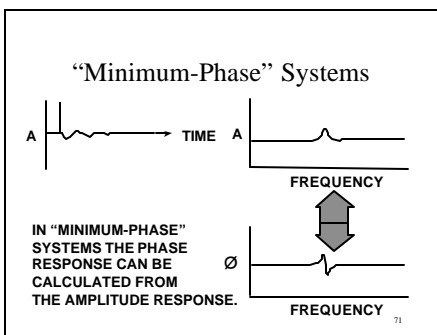
If we measured the amplitude and phase responses, a computer could perform a Fourier transform and give us the transient response. If we measured the transient response the computer could calculate the amplitude and phase responses. So the information on the left side of the slide is the same as that on the right side, only displayed in a different form.
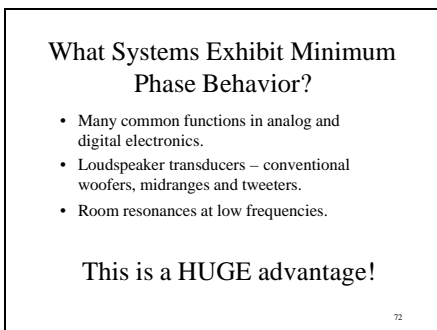
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Frequency and Time Domains

2 dB

A

A   TIME

FREQUENCY

Ø

FREQUENCY

**AN OTHERWISE PERFECT
SYSTEM WITH A Q=10
RESONANCE AT THE
THRESHOLD OF AUDIBILITY**

69

Here is a medium-Q resonance. The frequency-domain 'footprint' is larger, and the time-domain 'footprint' is smaller.

Frequency and Time Domains

0.5 dB

A

A   TIME

FREQUENCY

Ø

FREQUENCY

**AN OTHERWISE PERFECT
SYSTEM WITH A Q=1
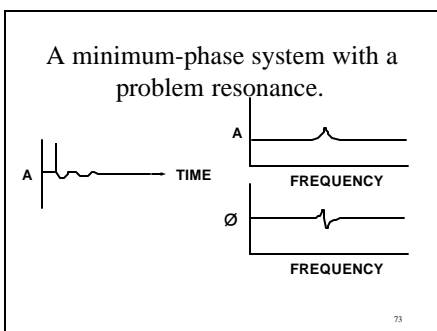RESONANCE AT THE
THRESHOLD OF AUDIBILITY**

70

And a low-Q resonance. Note the convenient relationship: as the footprint in the frequency domain gets larger, that in the time domain gets smaller.

"Minimum-Phase" Systems

A   TIME   A

FREQUENCY

**IN "MINIMUM-PHASE"
SYSTEMS THE PHASE
RESPONSE CAN BE
CALCULATED FROM
THE AMPLITUDE RESPONSE.**   Ø

FREQUENCY   71

There is a class of systems that behave as "minimum-phase" systems. In such systems, if one has measured only the amplitude response – our familiar "frequency response", it is possible to calculate the phase response from that data. Now, if we know both the amplitude and phase responses, we can calculate the time response. So, in a minimum phase system, a measurement of the frequency response, allows us to predict the time response. A bump in the frequency response means that the system <u>must</u> ring. A flat, smooth, frequency response means that there is no ringing. The previous data show that we are able to measure the visual evidence of audible resonances in frequency response curves. This is <u>really</u> important.

What Systems Exhibit Minimum
Phase Behavior?

- Many common functions in analog and digital electronics.
- Loudspeaker transducers – conventional woofers, midranges and tweeters.
- Room resonances at low frequencies.

This is a HUGE advantage!

72

Several very important devices are minimum phase systems, meaning that, for these devices, the frequency response curve is the single most important measure of audible performance in the linear domain. Of course we do measurements of non-linear effects as well, but in general these are much less troublesome.

A minimum-phase system with a
problem resonance.

A

A   TIME

FREQUENCY

Ø

FREQUENCY

73

If a minimum phase system has a resonance, and we wish to get rid of the audible effects, we can choose to do it electronically.

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Address the resonance with an equal and opposite parametric EQ filter

WHEN THE CORRECT AMPLITUDE RESPONSE IS "DIALED IN", THE PHASE RESPONSE IS AUTOMATICALLY CORRECTED.

74

Simply design a minimum-phase filter, in either analog or digital electronics, that exactly matches the shape of the bump in the frequency response, but is inverted. When the two are added, we get a straight line. The filter, because it is minimum phase, will have a phase shift that mirrors the phase shift in the resonance, so that a summation yields another straight line.

How often have you heard that equalizers are bad because they add phase shift? Here we show that it is a good thing – assuming that it has all been done properly, with the necessary precision.

And everything is fixed!

75

Two flat lines on the right, we know, correspond to a perfect impulse response on the left.

This is a very simple form of pre-distortion, a well known technique that, with the advent of digital processing, is likely to become more widespread. If we know what an electromechanical or acoustical system is doing wrong, there are some things that can be corrected by modifying, or pre-distorting, the signal so that what is eventually radiated as sound is correct.

Which is one reason why active/amplified loudspeakers are attractive.
A good loudspeaker without equalization can be an even better one with the right kind of equalization.

76

It is not magic, but it certainly seems like it. Good loudspeakers can be made better. Room resonances can be tamed (for specific listeners at least).
However, in order for it to work we need accurate, high resolution, frequency response data, and parametric filters.

Spatial Averaging ADDS Information

LISTENING WINDOW ± 30⁰ HOR. ± 10⁰ VERT.

ON AXIS

THESE ARE NOT RESONANCES

AND THEY SHOULD NOT BE EQUALIZED

SOUND POWER

77

Which brings us back to measurements and spatial averaging. Here we see a portion of a spin-o-rama for a loudspeaker showing some bumps in the on-axis curve. The bumps are attenuated, and even disappear, with spatial averaging. This tells us that the bumps are caused by acoustical interference (in this case diffraction from the cabinet edges). They are not resonances, and they should not be equalized.

In contrast – these are resonances, and they can be equalized

78

In this example, the series of bumps penetrate all of the curves, surviving even the 72-curve calculation of sound power. These truly are resonances, and they can be treated with individually designed parametric filters.

Spatial averaging ADDS information. Spectral averaging (smoothing) takes it away.

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Measurements make a nice story,
but
can people really <u>hear</u> the
differences?

Let's test them with four
"high-end" speakers.

79

If all of this really means anything, we should be able to prove it using our carefully conducted listening tests.

This one looks good: $10,000/pr

80
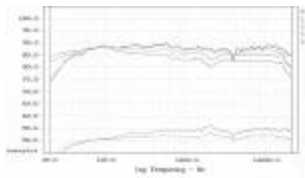
Four expensive and highly regarded loudspeakers are evaluated in the "shuffler" room, in a double-blind test. These are the measurements. The listeners, of course, do not get to see them until it is all over.

This one is well behaved. It has smooth, flattish curves, very wide, very uniform dispersion, and excellent low-frequency extension. The slight sag in the upper middle frequencies is something that is sometimes done to compensate for the numerous excessively bright recordings out there. The trade-off, others might sound a bit laid back.

This one too: $8000/pr

81
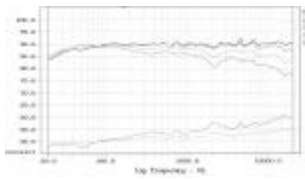
Here is a 'tell it the way it is' speaker. Unabashedly flat, very smooth, superb low bass extension, being only about 5 dB down at 20 Hz, with a directivity that smoothly and gradually rises with frequency. A small dip in sound power around 2 kHz might be barely audible, but likely only in quite 'live' rooms.
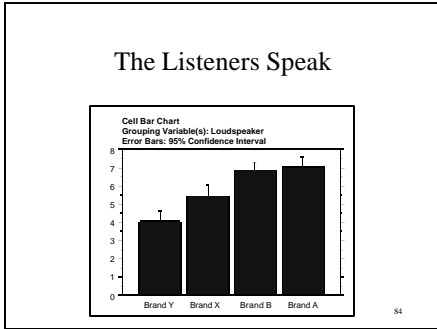
A bit wobbly: $8000/pr

82
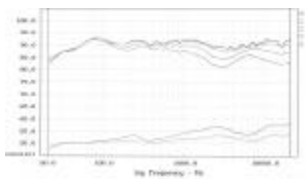
This one is likely to have a 'personality'. The undulations in the upper mids/lower treble are everywhere, including the directivity. It is possible to play detective, and guess that this is a three-way system, with the woofer crossing over to the midrange around 300 Hz, and the midrange crossing over to the tweeter around 3-4 kHz. How do we know? Look at the directivity curves. Very low frequencies are omnidirectional. The curve rises as the woofer becomes more directional until it crosses over to the smaller midrange when the directivity drops. It then rises again with frequency until it crosses over to the small tweeter, at which point the cycle begins again. The low bass is fair, but a small bump just below 100 Hz spoils it.

A Mountain Skyline: $5000/pr

83
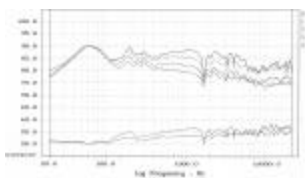
This speaker has a bunch of things going on. Clearly the designers didn't believe that flat was necessary, or they didn't know how to achieve it. Not only are the general trends not flat, but superimposed are peaks and dips suggesting resonances. The proof that they are resonances is in the fact that the patterns are repeated in all of the curves. The directivity is interesting, being zero up to 100 Hz (the woofer) and then abruptly rising to about 5 dB and hovering around that all the way to 20 kHz. Since 4.8 dB is the directivity of a dipole, we could suspect that this is a hybrid system with a panel loudspeaker operating above about 100 Hz. The woofer exhibits a significant bump and then rolls off below about 60 Hz. No subwoofing here.

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The Listeners Speak

Cell Bar Chart
Grouping Variable(s): Loudspeaker
Error Bars: 95% Confidence Interval

Brand Y   Brand X   Brand B   Brand A

After several rounds of listening to different kinds of music, several listeners yielded subjective preference ratings that were processed in a statistical analysis program. One of the results is a bar graph showing the average rating for the group of listeners, for each of the loudspeakers. The tiny lines on top of the bars show the 95% confidence intervals. If the differences in the ratings are greater than these lines, the differences are probably statistically significant, and not due to chance. The two top-rated speakers are not significantly different from each other, according to this rule. The other two are truly less good.

Brand Y   Brand X   Brand B   Brand A
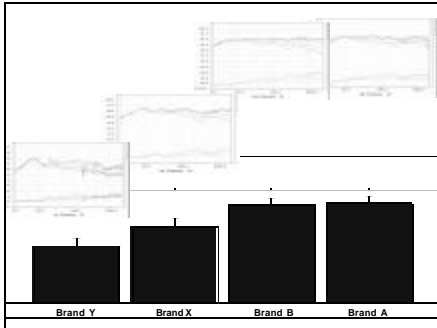
When we combine the subjective with the objective data, it is clear that the loudspeakers that yielded the best set of technical data, also were preferred by the listeners.

It works!

What do listeners say they like?

$2000/pr
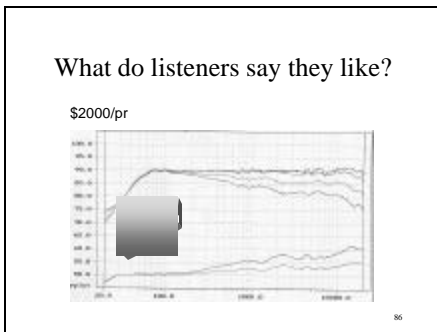
At Harman, we do hundreds of such listening evaluations, using competitors' products that we purchase on the open market. It is essential to know where our new products stand with respect to the competition.
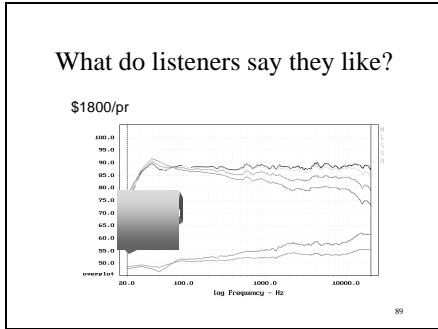
The results are monotonously the same. Loudspeakers that look good in the spin-o-rama measurements are the ones that are subjectively preferred.

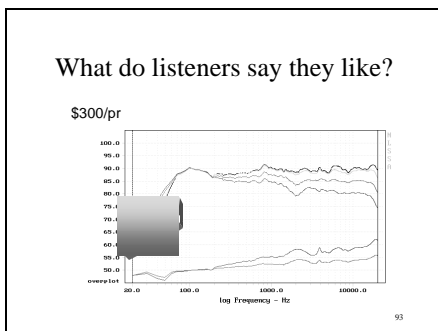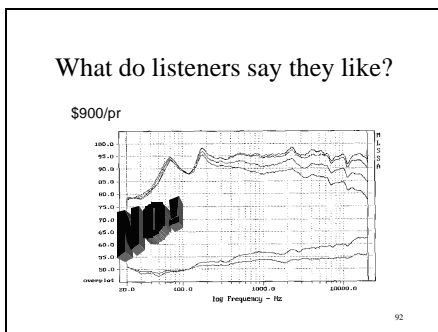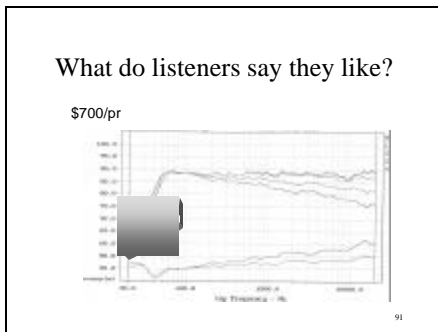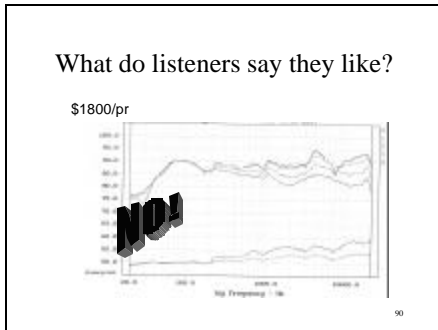What do listeners say they like?

$8000/pr

NO!
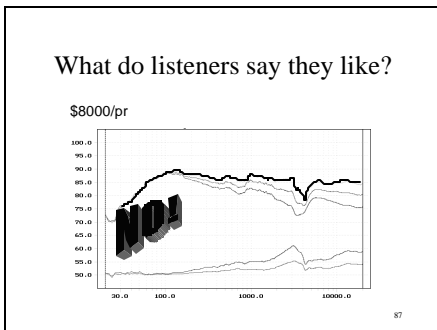
This is one of those pricey 'high end' bookshelf-sized speakers that some reviewers have raved about. The measurements suggest that it is a slightly dull sounding, moderately colored system with no real bass. The listeners agreed.

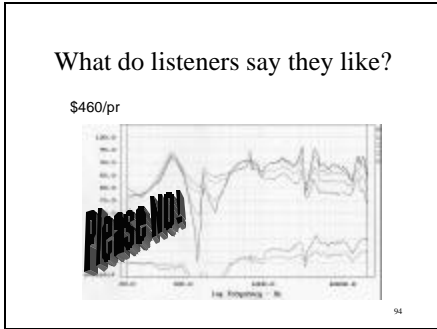What do listeners say they like?

$10,000/pr

NO!
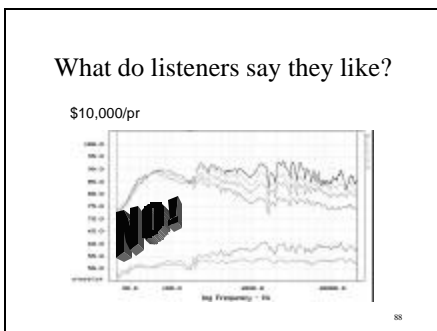
Note that price sometimes has nothing to do with sound quality. There may be material value to justify the high price, a sexy appearance, or just a lot of hype. This is the audio business, and reason and the laws of physics seem not to be universally applicable.

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What do listeners say they like?

$1800/pr

Truly excellent sound can be found at moderate prices.

What do listeners say they like?

$1800/pr

What do listeners say they like?

$700/pr

What do listeners say they like?

$900/pr

What do listeners say they like?

$300/pr

Even entry-level products can sound good. They will come in plain enclosures, and they may not play as loud as the bigger boys, but they are eminently capable of preserving most of the artistic integrity.

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What do listeners say they like?

$460/pr

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Here's one to avoid! It is amazing that anyone, especially a well-advertised brand as this one is, would actually let something like this out into the marketplace. For the same price, they could be selling good sound. Obviously they don't care. Instead they sell a slick package and a story.

Conclusion:

Listeners don't like resonances!!

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ALL of the most preferred loudspeakers are ones that exhibit the flattest, smoothest families of curves.
They exhibit the fewest, and the lowest level, resonances. They have the flattest, smoothest, widest bandwidth frequency responses when measured from <u>all</u> angles.
They have similar shapes in all of the curves – i.e. they have quite constant, or at least smoothly changing, directivity as a function of frequency.
Can we measure what we can hear? No, but we sure have made a good start.

Equivalent Measurements

SUBJECTIVE   **OBJECTIVE**

96
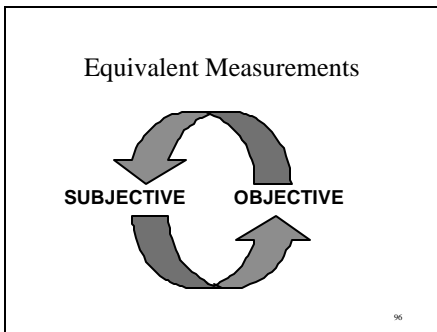
This is a powerful position to be in, when it is possible to demonstrate that the right set of accurate measurements has a consistent relationship with listener evaluations.
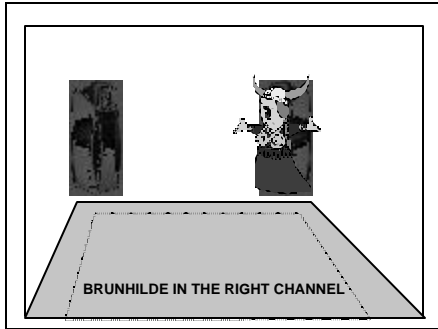
We do not claim to have mastered everything, at this stage. However, some things are understood. They even make logical sense.

So, let's assume that, to a first approximation, we understand how to design loudspeakers that have the potential of sounding good in a room.

The Rules for Good Sound in Rooms

At middle and high frequencies:
✓ Start with a loudspeaker that was designed to function well in a variety of different rooms.
➤ Use geometry, reflection, diffusion, and absorption to achieve good imaging and ambiance.
At low frequencies:
➤ Maximize the output from the subwoofer(s).
➤ Achieve a uniform performance over the listening area.
➤ Equalize to achieve good performance.

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The second rule for good sound requires that we look at some specifics of the room itself.

Reflections alter both
Sound Quality and Imaging

Reflected sounds can be controlled by:
(a) controlled-directivity loudspeakers,
(b) absorbing or diffusing objects on reflecting surfaces in the room,
(c) the shape of the room,
(d) some of each.

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**BRUNHILDE IN THE RIGHT CHANNEL**

Here is a cartoon description of what happens with reflected sounds in a room.

We start with only a floor, no walls. Brunhilde, of opera fame, is singing in the right speaker only.
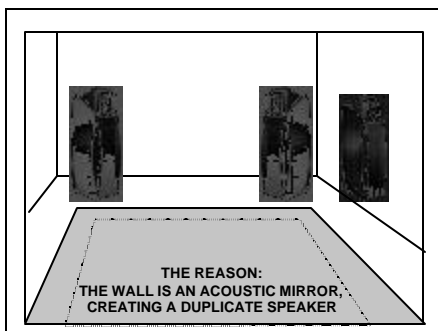

**ADD WALLS, THE RIGHT ONE FAR AWAY
& WE HEAR A ROOM AROUND THE IMAGE**
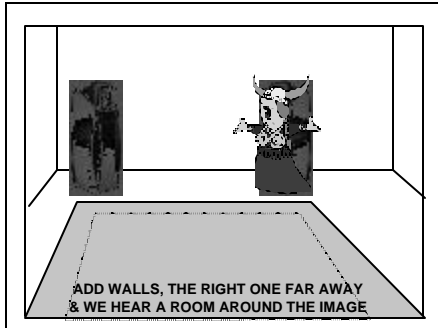
Adding walls, the one next to the right loudspeaker is some distance away, produces a nice warm "spatial" illusion. It sounds a little richer.

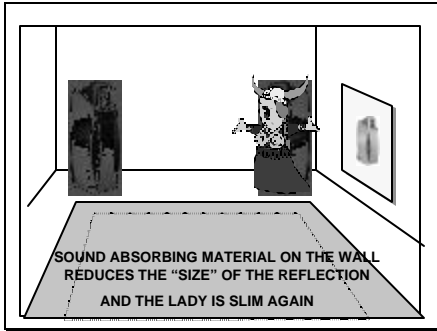**MOVE IT CLOSER AND THE FAT
LADY SINGS**
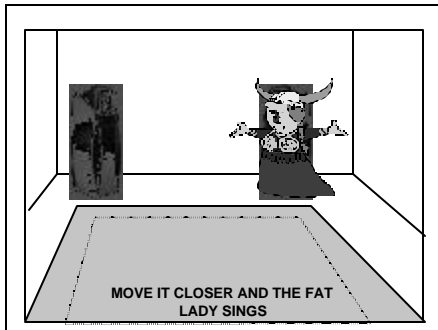
If the wall is moved a bit closer to the speaker, we note that the lady is a little bit "smeared", putting on some weight, and maybe leaning a bit to the right.

**STILL CLOSER AND THE REALLY
FAT LADY SINGS**
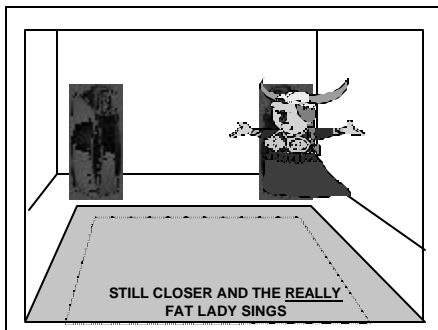
If the wall is too close, the truly fat lady is singing.

**THE REASON:
THE WALL IS AN ACOUSTIC MIRROR,
CREATING A DUPLICATE SPEAKER**

Why? Because the wall is an acoustic mirror, creating a second acoustical loudspeaker, just as it would create a second visual one if the wall were optically reflective. No wonder things got a bit fuzzy.

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**SOUND ABSORBING MATERIAL ON THE WALL
REDUCES THE "SIZE" OF THE REFLECTION
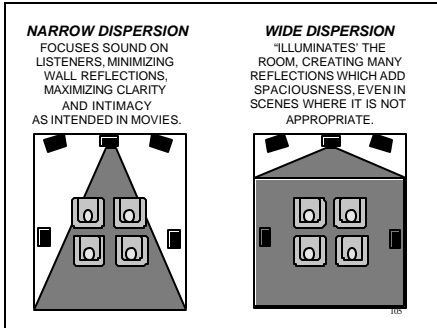
AND THE LADY IS SLIM AGAIN**

Placing some sound absorbing material on the wall, at the reflection point (have a helper hold a mirror against the wall and find the location where you can see the loudspeaker tweeter from the most important listening position). The reflected sound is attenuated, and the lady loses a bunch of weight.
What material? Acoustic foam or rigid fiberglass board, with or without acoustically transparent fabric covering.
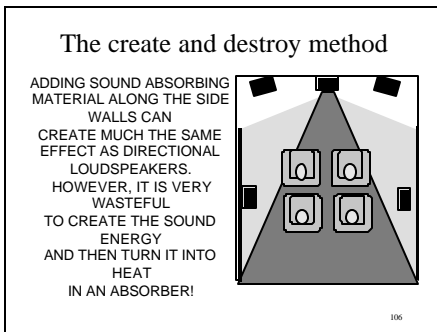How thick? Not less than one inch, preferably two to four inches.
How large? To be really effective, a patch at least 3 to 4 feet on a side is necessary. Tiny little "cushions" are more psychological than acoustical. Heavy, velour drapes, densely folded also work well.

NARROW DISPERSION
FOCUSES SOUND ON LISTENERS, MINIMIZING WALL REFLECTIONS, MAXIMIZING CLARITY AND INTIMACY AS INTENDED IN MOVIES.

WIDE DISPERSION
"ILLUMINATES' THE ROOM, CREATING MANY REFLECTIONS WHICH ADD SPACIOUSNESS, EVEN IN SCENES WHERE IT IS NOT APPROPRIATE.

Nowadays, we know enough about horn design to be able to make them sound really good, and take advantage of their directional control. The days of horns that are just loud and sound like megaphones are past – for good engineers at least.
If the room is acoustically live (the way many interior decorators like them), then the only option is to use horns, or waveguides, to control the radiation from the loudspeakers. This way the energy is focused on the listeners, and kept away from the reflecting surfaces, improving the intelligibility and directional effects.

The create and destroy method

ADDING SOUND ABSORBING MATERIAL ALONG THE SIDE WALLS CAN
CREATE MUCH THE SAME EFFECT AS DIRECTIONAL LOUDSPEAKERS.
HOWEVER, IT IS VERY WASTEFUL
TO CREATE THE SOUND ENERGY
AND THEN TURN IT INTO HEAT
IN AN ABSORBER!

Movies, especially, are designed for listeners in a strong direct sound field. Some people use wide-dispersion loudspeakers, and then cover the walls with sound absorbing material. This gets the job done, but in doing so it makes the entire system work harder, first to create the sound, and then turning it into heat in absorbers. The result, dynamic range is sacrificed. Not necessarily a good tradeoff.
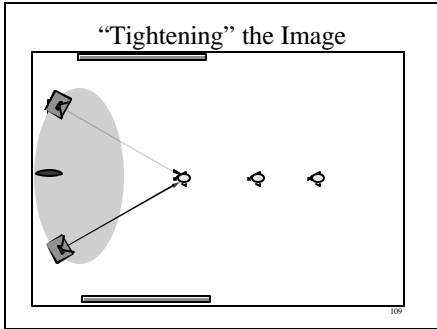Acoustically dead rooms are also not very pleasant places in which to spend time, conversing or anything else. Some custom home theaters are like this. It is not a recommended solution.

A Basic Imaging Test

THE SIGNAL: BROADBAND MONOPHONIC PINK NOISE
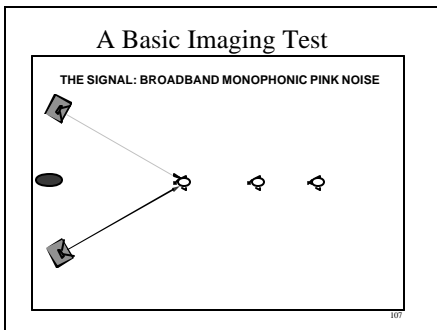
Whether it is a classic two-channel stereo system, or a multichannel system, one of my first tests is to play monophonic pink noise (available on numerous test CD's) through the front left and right speakers, sit in the "sweet spot" and listen. What should be heard is a compact image of noise, floating midway between the loudspeakers. As you move backwards in the room the image should stay. As you lean left or right, the image should move left or right. This is normal. It is a phantom stereo image.

"Normal" Stereo Imaging
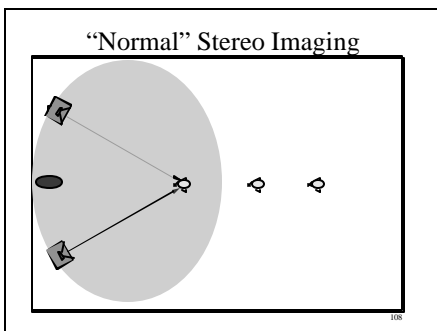
Now, put on some music. The featured artist in pop and jazz recordings should float in the middle location. The band should be across the front creating a solid sound stage (the success of this is greatly dependent on the recording, so be sure to try a few). In recordings with "ambiance", like most in the classical repertoire, you might sense an acoustical spaciousness around you. This is good.

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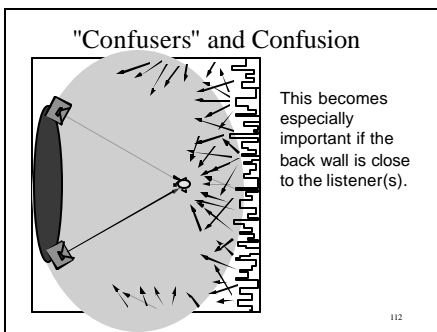

"Tightening" the Image

Some two-channel customers like to "get into the image". For them you can suggest some absorbing material, even heavy drapes will do, along the side walls. This attenuates the side wall reflections and the image "tightens" up nicely. Moving the curtains away, opens up the 'space' again.
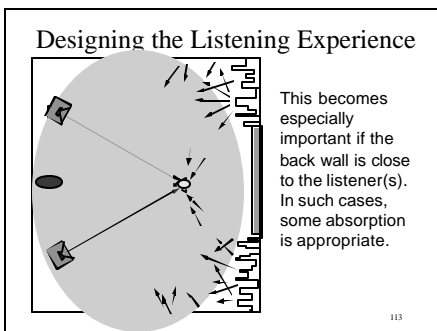

Opening it up with Reflections
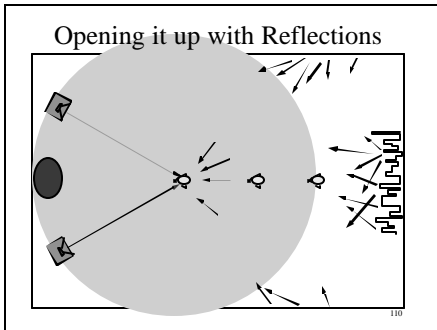
Other customers like to think that they are in the concert hall. For them room reflections are not necessarily a bad thing. In fact, you might consider adding a few more, using some of the commercial diffusing elements on the market. Just be careful not to overdo it. The test is that the center image stays intact even when you move to the rear listening locations.

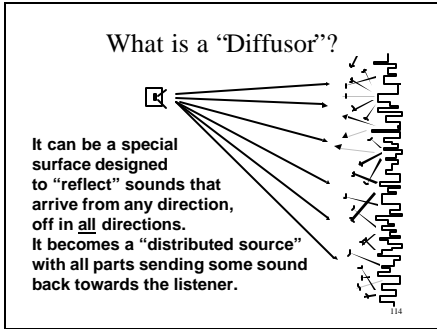"Confusers" and Confusion

Too much of anything can be bad
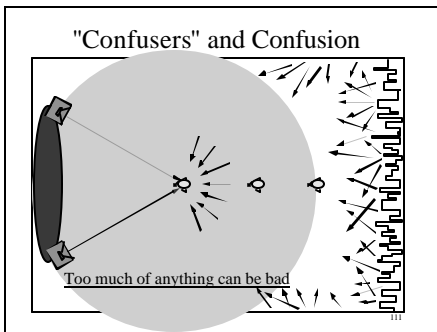
Even good things can be taken too far. I have been in recording control rooms where so much diffusion has been added that the center image is completely destroyed! The noise 'image' was the entire front wall. And recordings were being made in this situation! This design was fashionable – yes there are 'fashions' in acoustics too – a few years ago. Just as in many things, some fashions are just silly. This one was aided by the other fashion of that period: the live-end/dead-end room, another case of an idea taken to excess. It helped some bad studio monitor speakers sound better, but it is not something to be recommended, certainly not for recreational listening, and not for multichannel sound.

"Confusers" and Confusion

This becomes especially important if the back wall is close to the listener(s).

Many homes do not allow us the luxury of sitting away from the back wall. In those cases the last thing one would do is put diffusers directly behind the listeners' heads. Even a hard flat wall can disrupt the front soundstage. A simple demonstration can convince you, or your customer that something is wrong. While listening to the mono pink noise, just hold an upholstered cushion or pillow behind the head of a listener in the stereo seat. Usually the image tightens right up.

Designing the Listening Experience

This becomes especially important if the back wall is close to the listener(s). In such cases, some absorption is appropriate.

A patch of absorbing material is a much better solution. Use diffusers on the sides, if you like.

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What is a "Diffusor"?

It can be a special surface designed to "reflect" sounds that arrive from any direction, off in all directions.
It becomes a "distributed source" with all parts sending some sound back towards the listener.

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Commercial diffusers are highly specialized devices, designed to accept sounds arriving from any angle, and then to re-radiate them in all directions. Such diffusers, then, need to be considered as distributed sound sources.

115
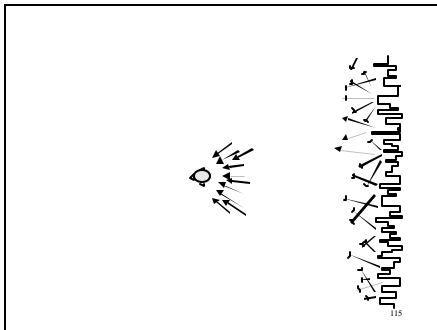
To a listener, these surfaces send a large number of individual reflections to the ears, from all parts of the device.

Or, it can be a shaped surface

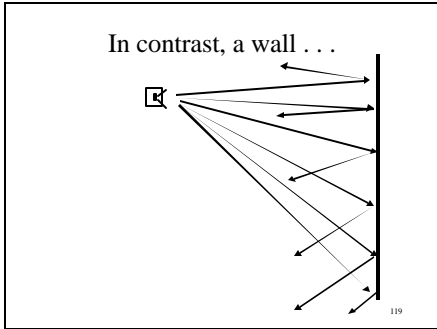Here, the conventional laws of reflection are obeyed

116
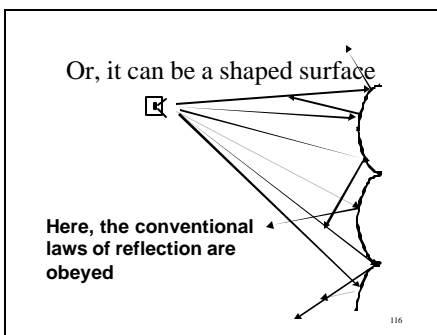
The classic "polycylindrical" diffuser, is nothing more than a curved surface intended to break up large flat surfaces. As diffusers they work very well indeed, and they are inexpensive. They can also be incorporated into interesting looking architectural features, possibly including lighting effects. If you want to get creative, there are many regular and irregular geometrical shapes that work well. A good dry-wall artisan will love you for giving him something interesting to do. Remember to bounce some of the sound vertically too. If the diffusion is to be effective over middle as well as high frequencies, some of the shapes must be a foot or more deep. The notion that textured paint does anything consequential is another fantasy.
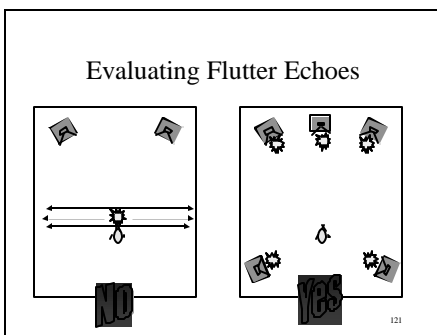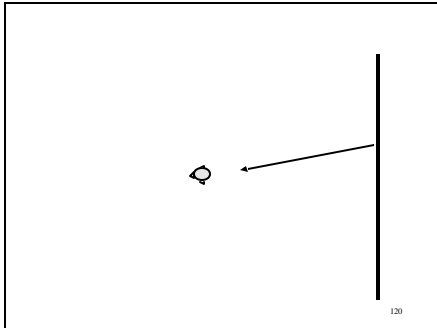
117
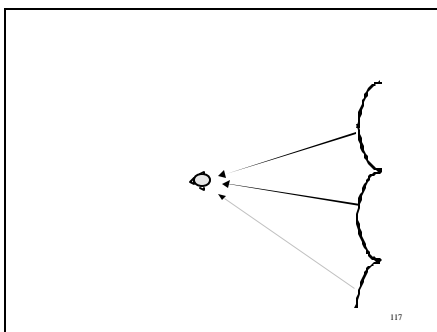
A listener receives only one reflection from each of the curved surfaces.

Or it can be furnishings: bookcases, cabinets, fireplaces, etc.

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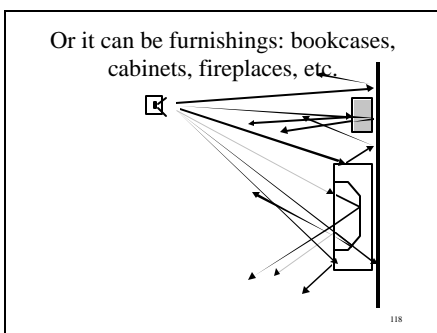
If the listening room is also a normal living space, it may not be necessary to use any special acoustical devices at all. With a little thought, bookcases, display cases, paintings, fireplaces, etc. can all do the job without making the room look at all "technical".
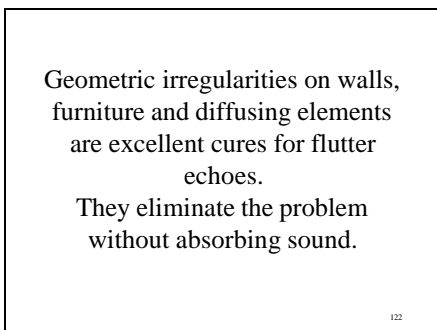
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In contrast, a wall . . .

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Flat empty walls not only look stark, but they sound that way too.

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Evaluating Flutter Echoes

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An acoustical consultant walks into a room, stands by the door, claps his hands, furrows his brow, and pronounces that this room has really bad flutter echoes and you need his (expensive) help to fix it. If this happens, say goodbye.

The only flutter echoes that are important to the quality of reproduced sounds in the room are those that are excited by the loudspeakers themselves. Have an assistant clap hands at the loudspeaker locations while you listen from the relevant locations in the room. If there is a problem then fix it. It matters not that flutters can be heard from the top of a step ladder.

Geometric irregularities on walls, furniture and diffusing elements are excellent cures for flutter echoes.
They eliminate the problem without absorbing sound.

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It is amazing how little it takes to cause an audible flutter, and it is amazing how little it takes to get rid of one. I have seen a picture, hung on a slight angle, do the job. Moving a bookcase, adding a wall bulge over a fireplace, a two-foot square patch of diffuser or absorber in a large wall, all have solved annoying problems without absorbing significant sound.

Coming up in Part 3

Perfecting the low frequencies. How many subwoofers? Where do I put them? Where do I sit? What about "bass traps"? How do I get rid of "room boom"?

Here we look at what it needed for truly excellent bass performance in rooms. An understanding of room modes, or resonances, is essential to achieving uniform bass over a listening area. The right kind of equalization can help to

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make that bass sound good, but it cannot do everything. Some traditional forms of equalization have a good chance of getting it wrong. Interestingly, two or more subwoofers, strategically located, can be very beneficial.