Psychoacoustics and Loudspeaker Design

by Angsuman Roy

What is Psychoacoustics?

- **Psychology:** The scientific study of the human mind and its functions, esp. those affecting behavior in a given context.

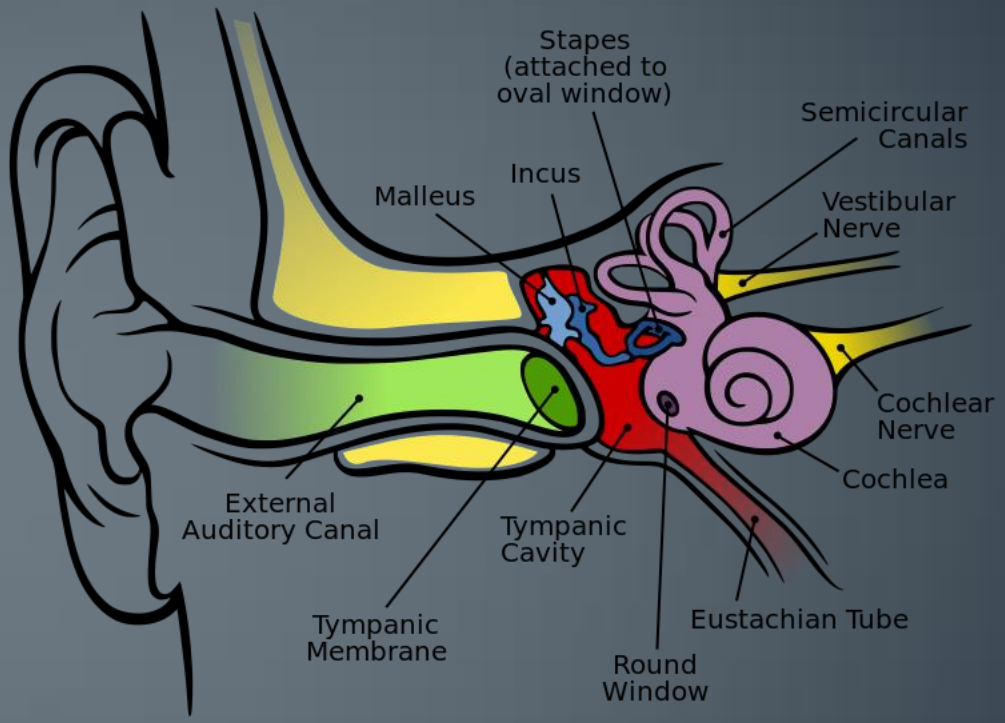
- **Acoustics:** The branch of physics concerned with the properties of sound.

- **Psychoacoustics:** The branch of psychology concerned with the perception of sound and its physiological effects.

Psychoacoustics and Speakers

- Psychoacoustics required for designing good speakers.
- Without psychoacoustics, speaker design is a shot in the dark.
- Human ear can rarely be trusted.

Basic Anatomy of the Human Ear

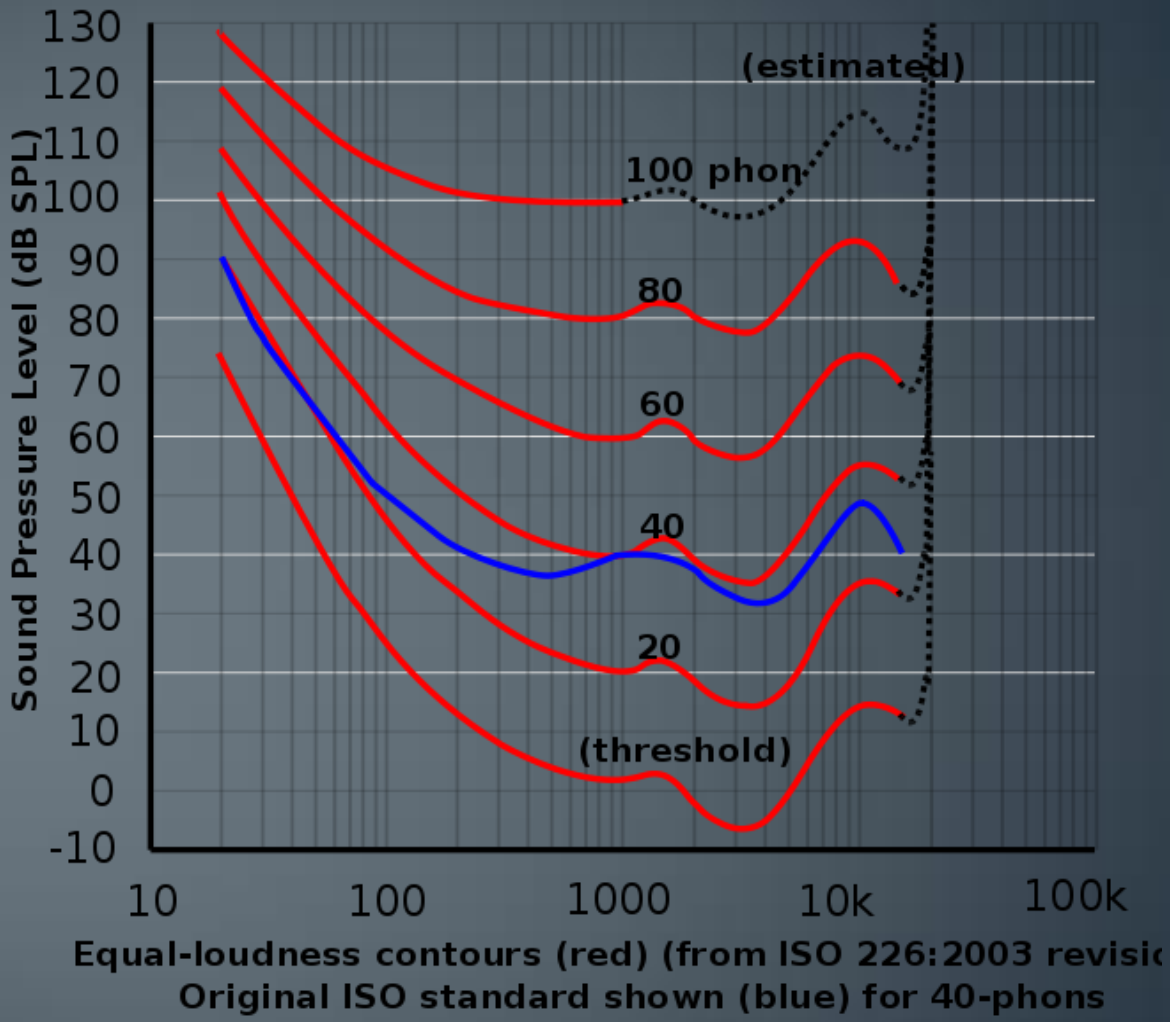


A very advanced electromechanical device!

Performance of Human Hearing

Characteristic	Performance
Directional Accuracy	Within 1 degree Azimuthal
Frequency Response	20Hz-20Khz
Dynamic Range	135dB or 10*log(32 trillion)!
Frequency Discrimination	0.35% relative to a set tone [2]
Amplitude Discrimination	0.25dB level change [1]

Equal-Loudness Contours



Curves showing amplitude vs. frequency for equal perception level.

Humans: Highly Suggestible and Can't be Trusted

- The ear and brain are closely linked.
  - Hearing is widely believed to be the last sense to go before death
- Often we think we hear things that we really didn't.
- Everyone hears a little differently due to head shape, body composition, ear structure, past hearing loss etc.
- Everything must be measured by objective equipment .

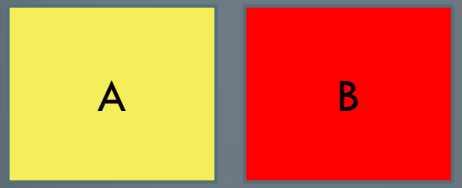
- Never believe something sounds better because someone tells you so. Never trust someone else's opinion.

Proof Humans Can't be Trusted

- In 1929 record bandwidth was improved to 100Hz-5KHz from 400Hz-1.5Khz…people hated the new sound.
- In 2009 experiments showed that young people prefer the lower sound quality of MP3 to higher quality CD.
- Conclusion: People like what they are used to.

Subjective Perception Tests

- Double-blind A-B-X testing.
- Goal is to see if listener can identify a source correctly without knowing which is which.



Possible Source

Unknown Source
Presented to Listener

Listener must guess the source correctly a statistically significant number of times.

Quantifying Loudspeaker Performance

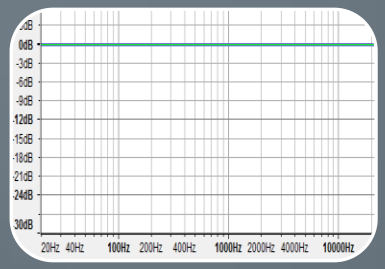
- Frequency Response (linear distortion)
  - On-Axis
  - Off-Axis
- Distortion (non-linear distortion)
  - Harmonic
  - Intermodulation
- Impulse/Step Response (less important)

Frequency Response

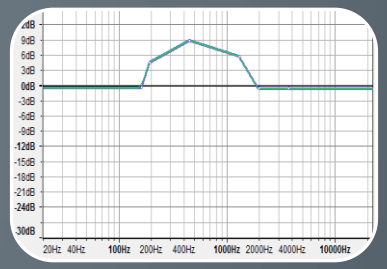
- A plot of amplitude over a frequency range.
  - Usually 20Hz to 20Khz for audio applications.
- Linear Distortion
  - Uneven frequency response.
  - Often specified as a tolerance such as 35Hz-20Khz +/- 3dB

Subjective Audio Perception Due to Frequency Response

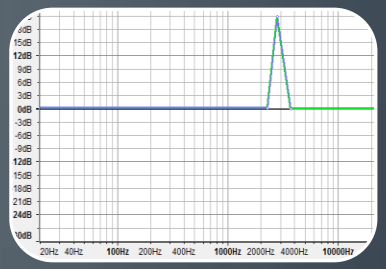
- Let's listen to the following sound clips…
- Music
- Pink Noise
- Single Tone
- …processed with different frequency responses.*



Flat



Broad Hump



Sharp Peak

*Since our speakers and room are far from perfect we can't draw any absolute conclusions

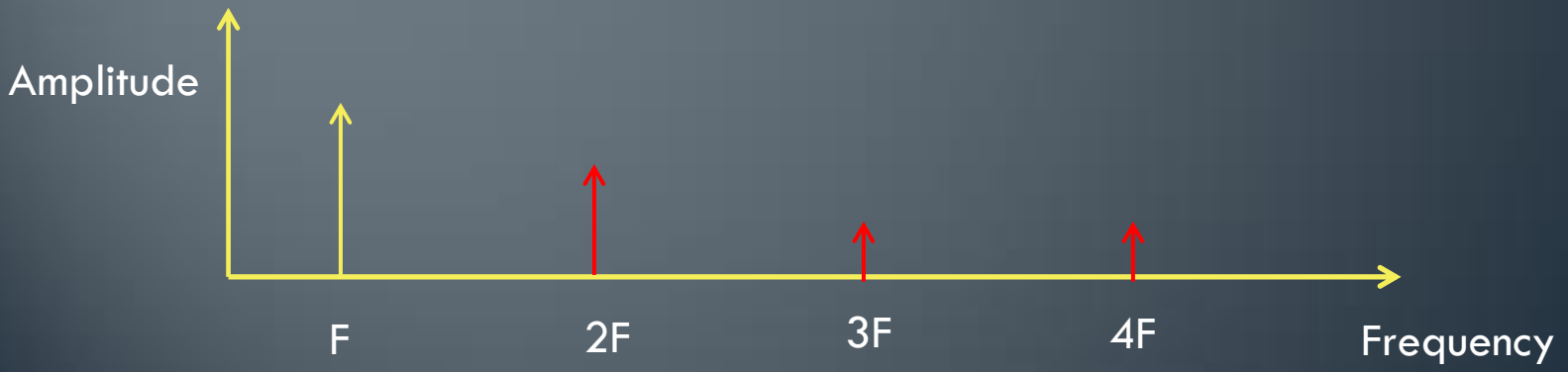
Non-Linear Distortion

- Harmonic Distortion
  - Addition of frequency components not in the original signal spaced at integer multiples of the fundamental frequency.
- Intermodulation Distortion
  - Sum and difference frequencies resulting from a multi-tone input.
- Measuring Distortion
  - Measured in percentage compared to the fundamental or in decibels beneath the fundamental e.g. 0.1%, -60dB.

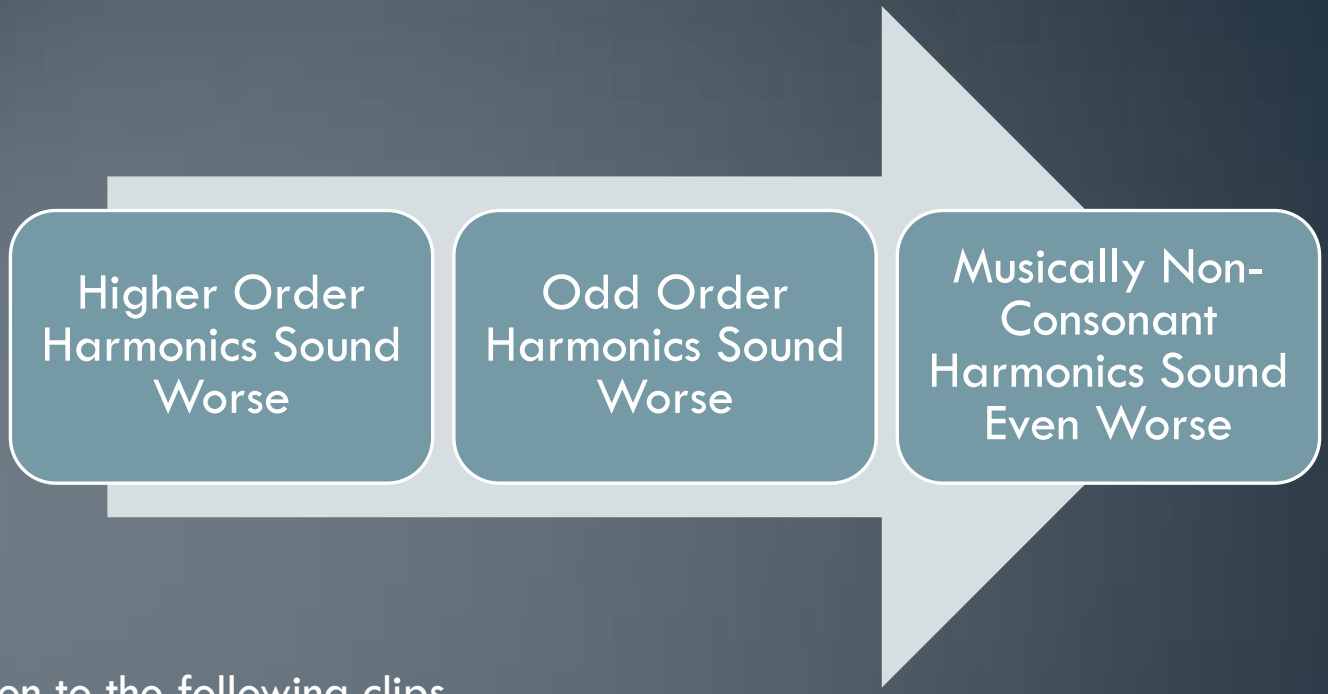
Harmonic Distortion

- Harmonic Distortion
  - Addition of frequency components not in the original signal spaced at integer multiples of the fundamental frequency.

- Total Harmonic Distortion
  - The ratio of the RMS sum of all the harmonics to the fundamental.
  - THD=[Sqrt(AF2^2+AF3^2+AF4^2…AFn^2)/AF1]
  - Generally stops at the 5^{th} or 10^{th} harmonic.



Subjective Distortion Perception



Let's listen to the following clips…

Cello

Human Voice

…with the following harmonics added

20% Second

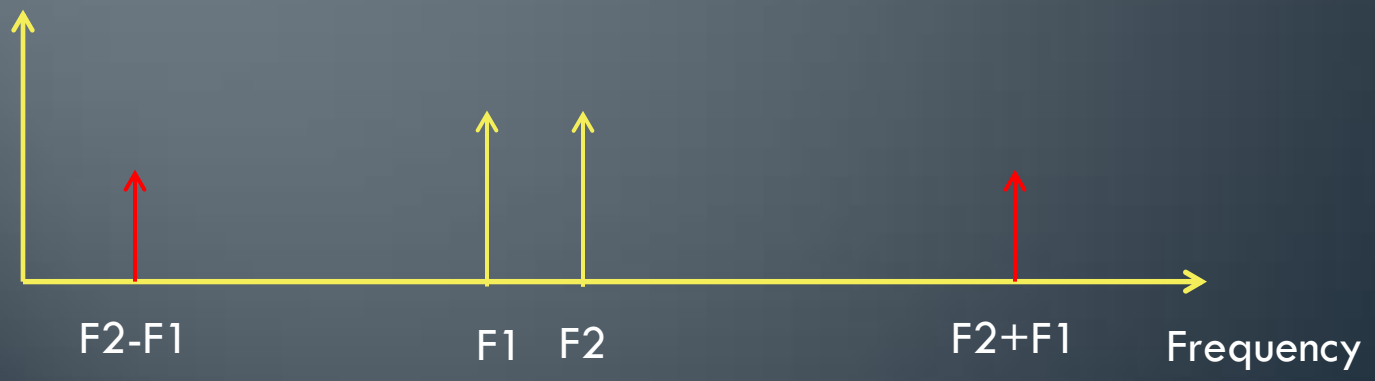
10% Third

10% Seventh

5% Tenth

Intermodulation Distortion

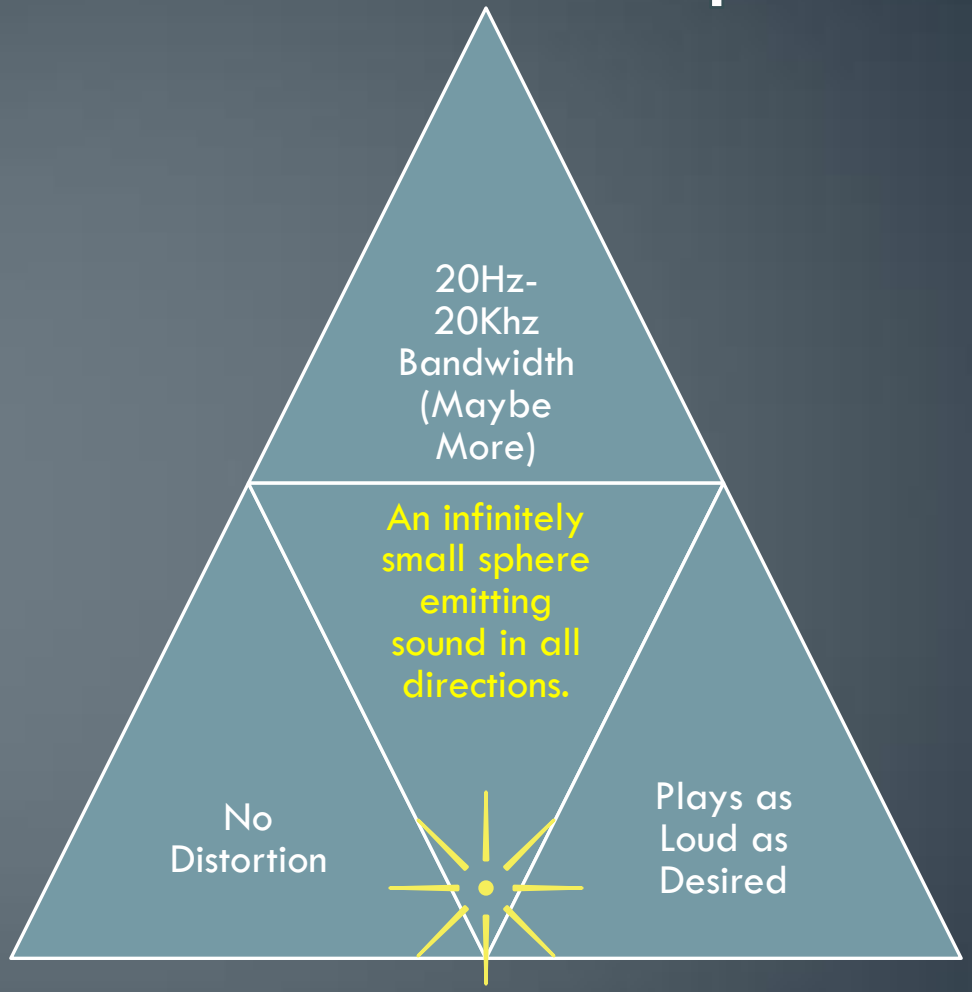
- Intermodulation Distortion
  - Sum and difference frequencies resulting from an input of two or more tones.
  - Effect is more pronounced the closer the tones are together.
- A common test is to use a 19Khz and 20Khz tone and see if 1Khz can be heard.
- IMD sounds really bad.



Distortion Audibility

- Studies show minimum levels of THD perception to be between 0.2%-1%.
- Harmonics beyond the 4^{th} can be perceived at levels below 0.05%!
- It is very important to limit high order distortion.

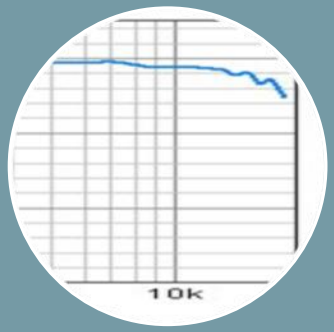
The Perfect Loudspeaker



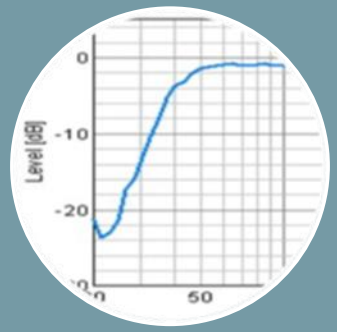
*The perfect speaker is also infinitely expensive.

*The perfect speaker also needs the perfect room.

Loudspeaker On Axis Frequency Response

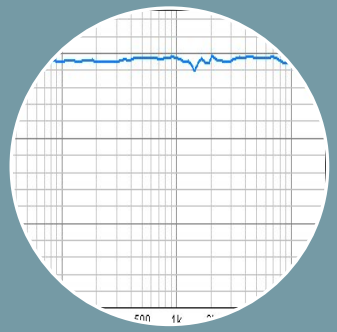


Upper -3dB point should extend to 20Khz or beyond.



Lower -3dB point limited by budget and space.

50Hz-80Hz is a good target to aim for.

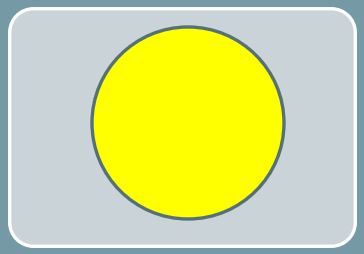


Within the specified bandwidth variations should not exceed +/- 3dB.

Loudspeaker Off-Axis Frequency Response

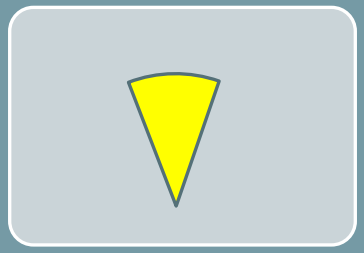
- As one moves away from the front of the speaker the frequency response changes.
- Usually high frequencies diminish.

Lots of Thoughts on This



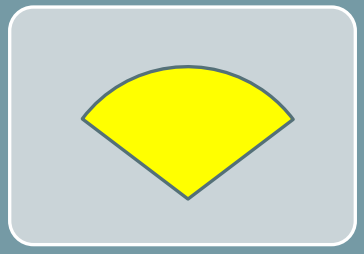
Omnidirectional

- Frequency response is consistent for 360 degrees.
- Can be harsh sounding in certain rooms.



Controlled Directivity

- High frequencies limited to a well defined window.
- Commonly used in PA systems.



Somewhere in Between

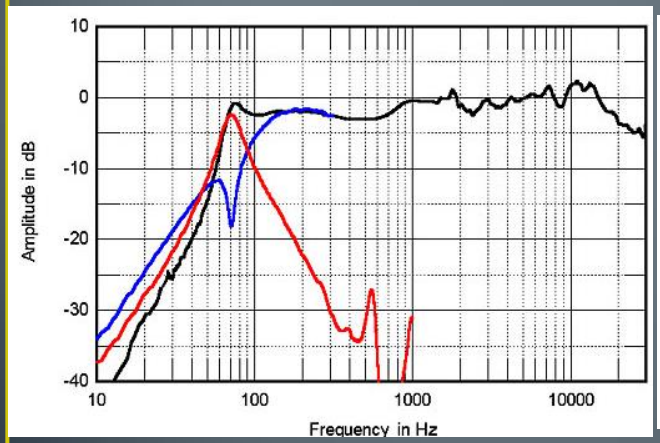
- Fairly consistent frequency response for +/-45 degrees.
- Works best in typical rooms and is subjectively preferred.

What Should We Shoot For?

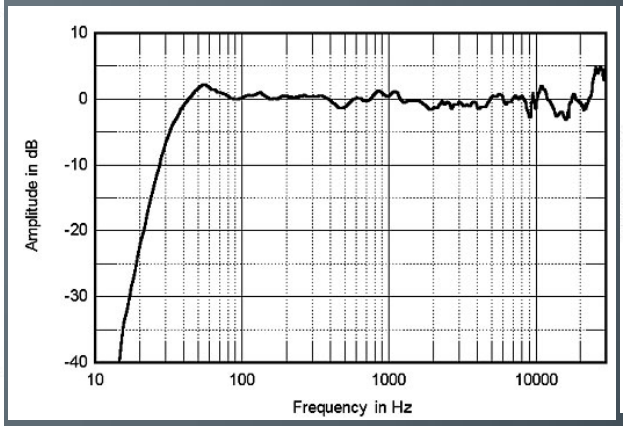
- According to the Canadians (the foremost leaders in speaker research):
  - Frequency response variations should be kept to a minimum.
  - THD should be below 1% and significant high order distortion avoided.
  - Directivity should be wide and constant but limited to the front of the speaker.
  - Averaging the frequency responses between 0 and 45 degrees give us a good indication of the tonal perception of the speaker.

Cost?

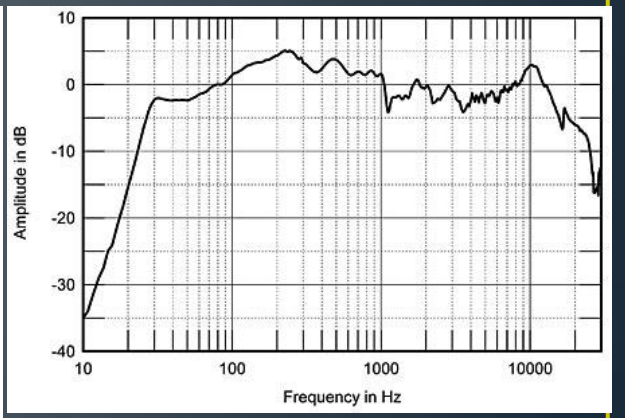
- A good speaker does not have to be expensive.



$160/Pair



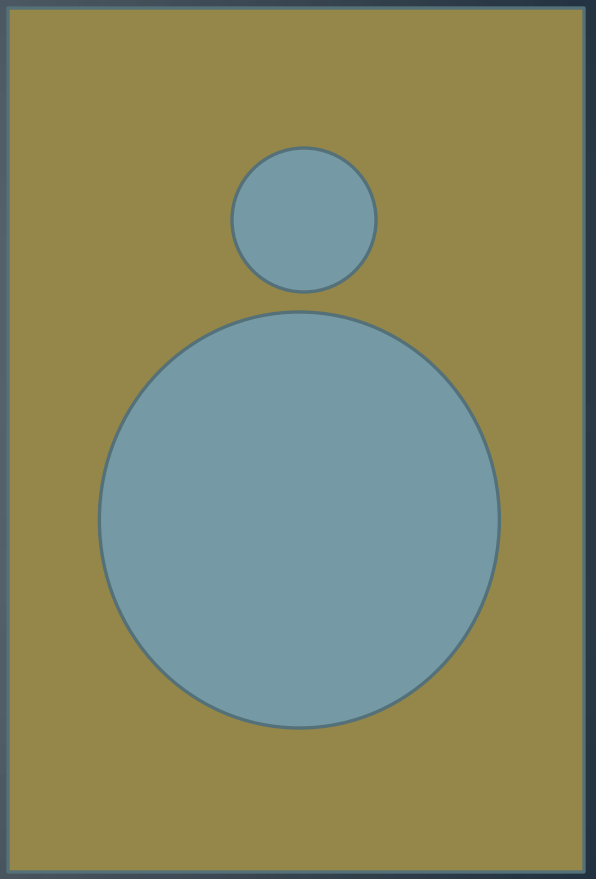
$30,000/Pair



$13,000/Pair

Images from Stereophile

What Are We Going to Build?



Price<$100/Pair

References

- 1. F.E. Toole and S. Olive, "The Modification of Timbre by Resonances: Perception and Measurements", JAES vol 36, # 3, March 1988, pp 122-142
- 2. http://www.cochlea.eu/en/sound/psychoacoustics/pitch

Resources

- http://www.troelsgravesen.dk
- http://www.zaphaudio.com
- http://www.diyaudio.com
- http://www.rjbaudio.com
- http://www.speakerdesign.net