Electroacoustic Measurements of Headphones

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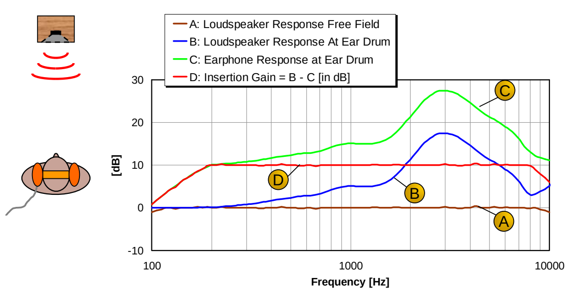
Overview

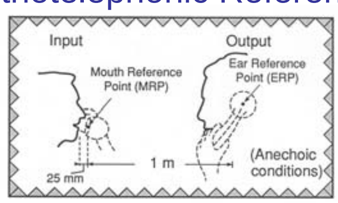
- The Insertion Gain Concept
- Orthotelephonic & Diffuse Field Responses
- Acoustic Impedance
- Couplers, Ear Simulators & Manikins
- Electroacoustic Measurements
  - – Electrical Impedance
  - – Frequency Response
    - Manikin Response
    - Corrected Response
    - L-R Tracking
    - Crosstalk
  - – Non-Linear Distortion
  - – Noise Isolation
    - Noise-canceling Headphones

The Insertion Gain Concept

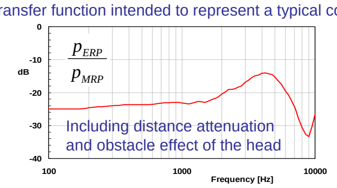


The target is a "flat" Insertion Gain!

Orthotelephonic Reference

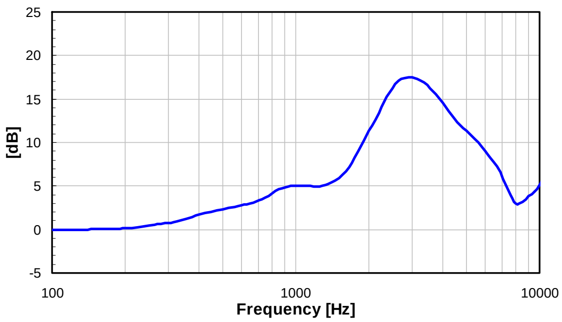


Acoustic transfer function intended to represent a typical conversation

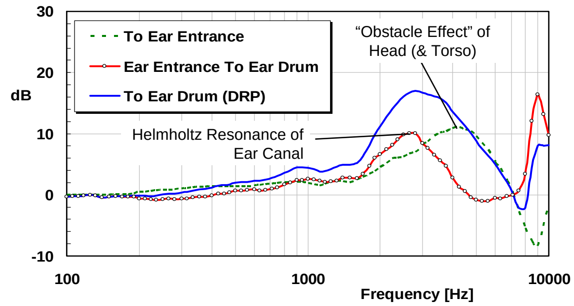


Free Field to Drum Reference Point (DRP)

On-Axis: 0° Azimuth, 0° Elevation

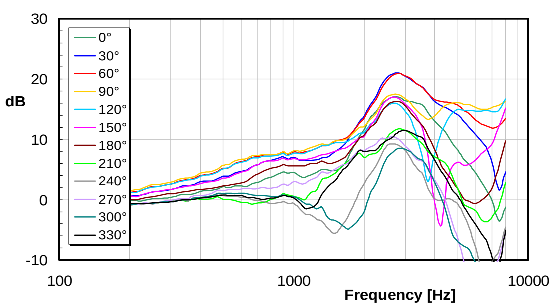


Components of the Orthotelephonic Response

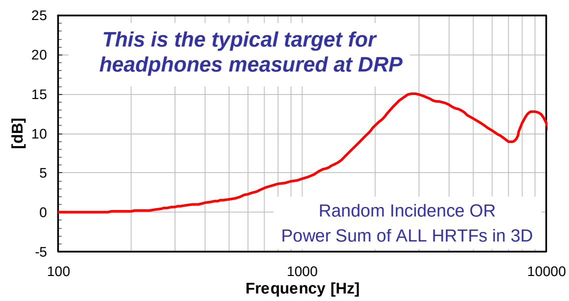


Head Related Transfer Functions

vs. Azimuth Angle, 0° Elevation

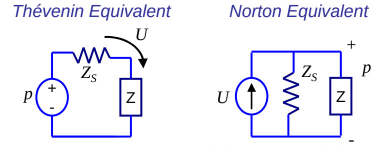


Diffuse Field to DRP Response



Acoustic Impedance

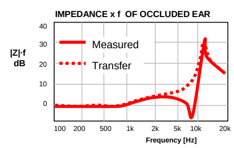
Thévenin Equivalent *Norton Equivalent* *Ohm's Law*

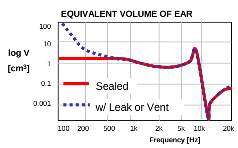


$$Z_A = \frac{p}{U}$$

[N·s/m^5 (mks acoustic ohms)]

Low Z_S Pressure Source *High Z_S Volume Velocity Source*



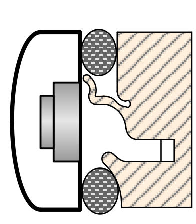


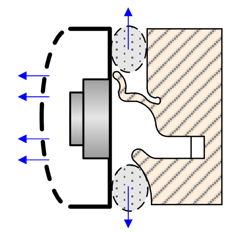
$$\therefore\ Z_A \cdot f \ \propto\ 1 / V_{Equivalent}$$

Acoustical Impedance of Headphones

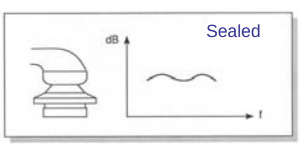
High Acoustic Impedance (Sealed)

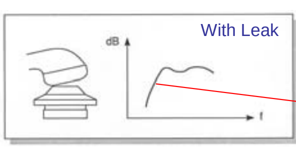
Low Acoustic Impedance (Open)





The Effect of Leakage on Response

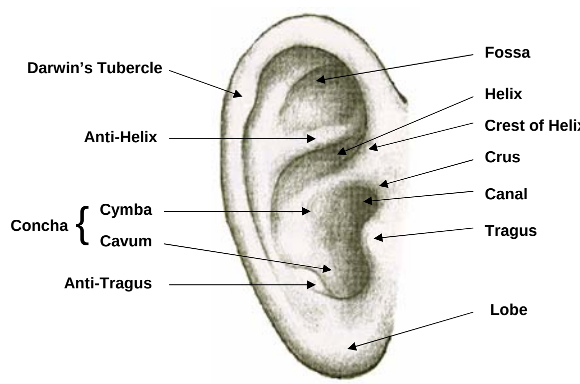




Loss of low frequencies!

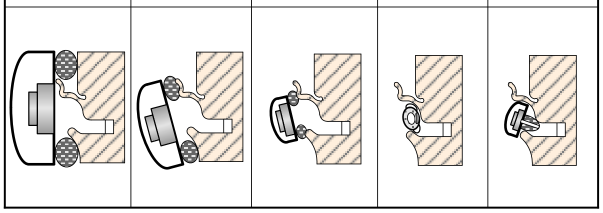
…assuming a high acoustic impedance source

Outer Ear & Pinna



Earphone Types

Circumaural	Supra-aural	Supra-concha	Intra-concha	Insert



Acoustic Couplers

- Couples measurement microphone to earphone receiver
- Approximates (simplified) acoustic load of ear

A Brief History of some Legacy Couplers:

2cc Coupler
1945 (standardized 1961)
Hearing Aid & Insert Earphone QC/QA

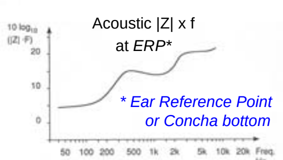
NBS 9A (6cc) Coupler
ca. 1950
(standardized ca. 1961)
Audiometer Calibration

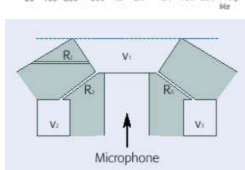
Braun Coupler
ca. 1953
(DIN standard ca.1968)
Telephone Handset Testing (Legacy)

NOTE:
No "reference point", *per se*

Artificial Ear

IEC 60318 (ITU-T Type 1)
ca. 1962-68 (standardized 1973)

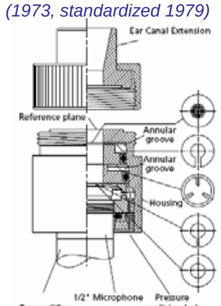




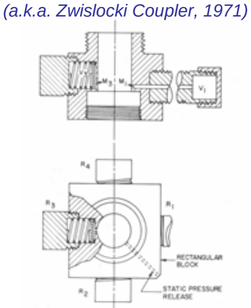
- Audiometer Calibration
- Telephone Handset Testing (Legacy)

Ear Simulators

IEC 60711 Ear Simulator (1973, standardized 1979)



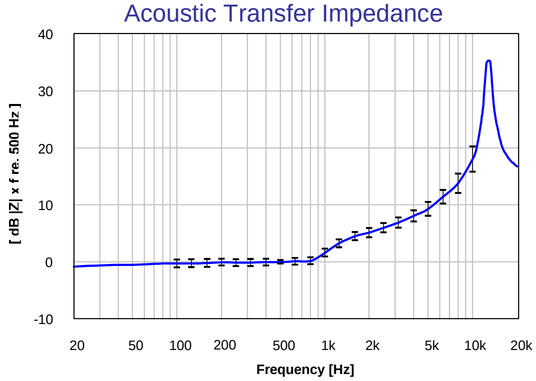
ANSI S3.25-1989 Ear Simulator (a.k.a. Zwislocki Coupler, 1971)



Measurement Microphone Diaphragm is at DRP!

IEC 60711 Ear Simulator

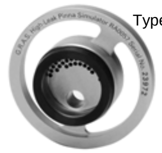
Acoustic Transfer Impedance



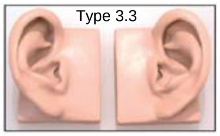
Pinna Simulators

ITU-T Rec. P. 57 Type 3 (all fitted to IEC 711 Ear)

ca. 1996



Type 3.2



Type 3.3

Type 3.4

Type 1 (IEC 60318-1/2) (Legacy)	Sealed High Z Telephones Audiometer Calibration
Type 2 (IEC 60711) Occluded Ear	Insert Earphones
Type 3.2 High Leak / Low Leak	Hard Earcap Telephones
Type 3.3 Soft Anatomical (HATS)	All Types. Most Realistic.
Type 3.4 Simplified Soft Anatomical	Handset Telephones Binaural Recording

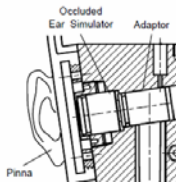
Ear & Cheek Simulator

- Uses IEC 711 Ear
- No Crosstalk or Insertion Response Testing
- Cannot utilize actual headband force
- Retaining force arm may occlude some open-back designs
- Serial Testing of L & R
  - Requires pinna substitution

Test Fixtures

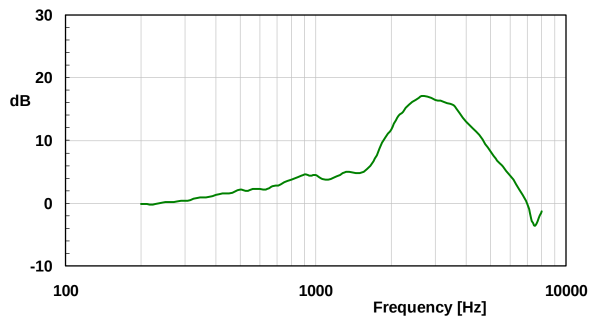
- Can be configured with IEC 711 Ear(s)
- Crosstalk & Insertion Response Test results may differ from manikin tests
- Positioning may be more consistent but less realistic than manikin, i.e., good for QC/QA

Head And Torso Simulator



- IEC 60711 Ear Simulators
- Anatomical Pinnæ (soft or hard)
- Simplified Geometry
- Fulfills IEC 60959 and **ITU-T Rec. P.58** *(and ANSI S3.36)*

HATS Free Field Response

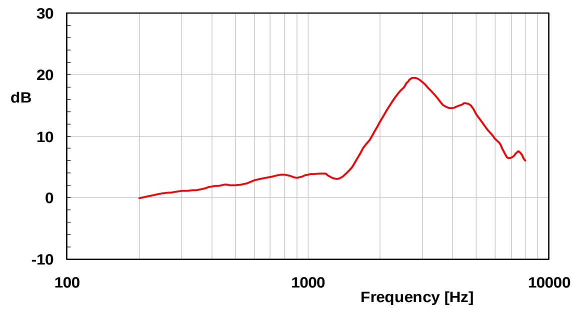


KEMAR

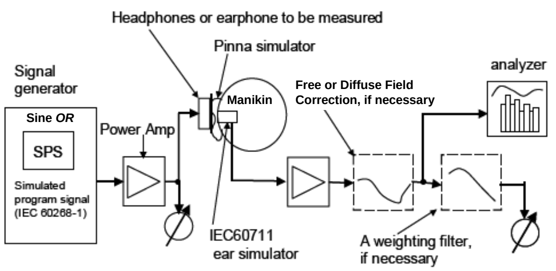
- Zwislocki *OR* IEC 60711 Ear Simulators
- Anatomical Pinnæ (soft or hard)
- Anthropomorphic Geometry
- Fulfills **ANSI S3.36** *(and IEC 60959 and ITU-T Rec. P.58*

KEMAR Free Field Response

with Zwislocki Coupler

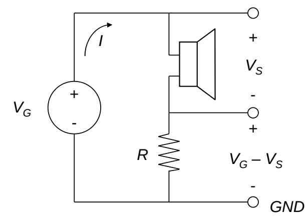


Test System



(adapted from IEC 60268-7)

Electrical Impedance



For R << 0.1 |Z_{MIN}(f)| (typically *0.1 Ω):*

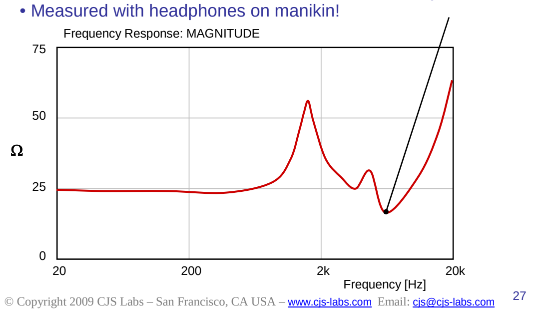
$$Z(f) = \frac{V_S(f)\,R}{V_G(f) - V_S(f)}$$

Electrical Impedance

- Low Voltage (LINEAR!)
- R40 40th decade (1/12 octave) stepped sine
- Can also measure phase, if desired
- Measured with headphones on manikin!

$Z_{MIN} \geq 0.8\, Z_0$!

$Z_0 \geq 1.25\, Z_{MIN}$



Test Conditions - 1

- **Characteristic Voltage:** The sinusoidal (or IEC 60268-1 simulated program signal*) voltage at 500 Hz, applied through the rated source impedance (120 ohms), to obtain a sound pressure level of 94 dB SPL in the ear simulator (with or without A-Weighting).
- **Rated Source Voltage**: Maximum specified RMS voltage which should be applied to the headphone through the rated source impedance, during the reproduction of normal program signals. NOTE: For headphones complying with IEC 61938, Rated Source Voltage = 5 V. Preferably, should not exceed the Characteristic Voltage by more than 15 dB.

**only applicable to systems with integral signal processing*

Test Conditions - 2

- **Working Sound Pressure Level:** SPL resulting from a sinusoidal voltage at 500 Hz (or simulated program signal) through the rated sourc[e impedance (120 ohms)] across the input connector of t[...] ***such that would cause 1 mW [...] pure resistance equal to the [...] headphone***. This is the SPL S[...] SPL) for 1 mW input.
- **Maximum Sound Pressure L[...]** ear simulator when the headp[...] sinusoidal voltage of the Rate[...] Hz.

Ohm's Law

$$V = IR, P = VI$$

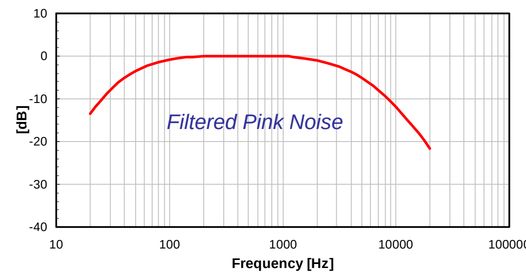
$$P = \frac{V^2}{R} = \frac{V^2}{Z_0}$$

$$V^2 = PZ_0$$

$$V = \sqrt{PZ_0} = \sqrt{0.001 \cdot Z_0}$$

$$V = 0.0316\sqrt{Z_0}$$

IEC 60268-1 Simulated Program Spectrum



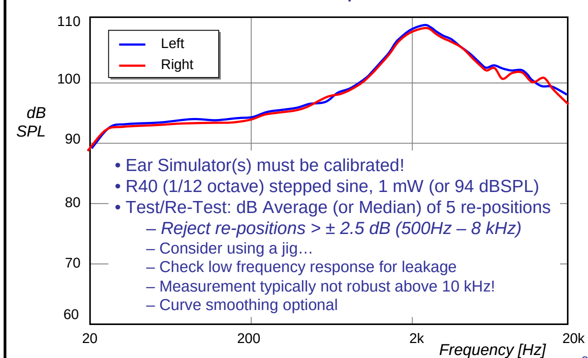
Maximum Voltage

- Maximum *[RMS ?]* voltage of the IEC 60268-1 program noise signal, clipped to a crest factor between 1.8 and 2.2, through the rated source impedance, which the headphone can tolerate without permanent damage*
- **Rated Long-Term Maximum Voltage:**
  - Signal applied for 10 periods of 60s *ON*, 120s *OFF*
  - *No change in specs after 4 hours of storage
- **Rated Maximum Permanent Noise Source Voltage:**
  - Signal applied continuously for 100 hours!
  - *No change in specs after 24 hours of storage

NOTE: THIS IS A DESTRUCTIVE TEST!

Frequency Response

1 mW Input

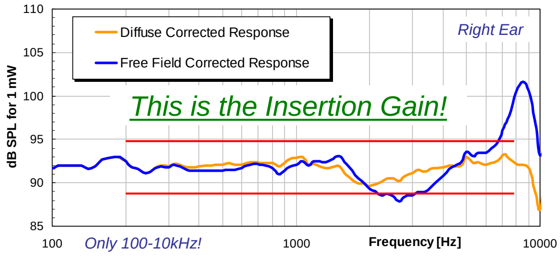


- Ear Simulator(s) must be calibrated!
- R40 (1/12 octave) stepped sine, 1 mW (or 94 dBSPL)
- Test/Re-Test: dB Average (or Median) of 5 re-positions
  - *Reject re-positions > ± 2.5 dB (500Hz – 8 kHz)*
  - Consider using a jig…
  - Check low frequency response for leakage
  - Measurement typically not robust above 10 kHz!
  - Curve smoothing optional

Diffuse and Free Field Corrected Response

$H_{DFC}(f) = H(f) - H_{Diffuse}(f)$ *[in dB]*

$H_{FFC}(f) = H(f) - H_{FF\,0°,0°}(f)$ *[in dB]*



Only 100-10kHz!
OK to apply smoothing
Simplifies visualization and tolerance application

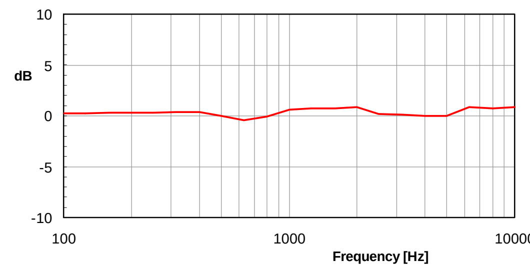
Left-Right Tracking

In each 1/3 octave band:

$$L(f) = 10\log_{10} \frac{1}{N} \sum_{i=1}^{N} 10^{L_i/10}$$

$H_{L\text{-}R}(f) = H_{Left}(f) - H_{Right}(f)$ *[in dB]*

Responses 1/3 octave power averaged

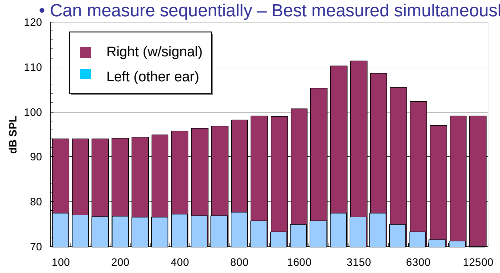


Crosstalk

In each 1/3 octave band:

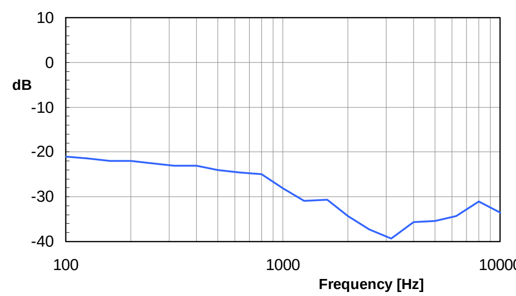
$$L(f) = 10\log_{10} \sum_{i=1}^{N} 10^{L_i/10}$$

- Requires 2 Ear Simulators
- Measurement S/N is poor:
  - Use 94 dB SPL sinusoidal test signal
  - Convert to 1/3 octave as power summation*
  - Check background noise level (≤ -10 dB in each band!)
- Can measure sequentially – Best measured simultaneously



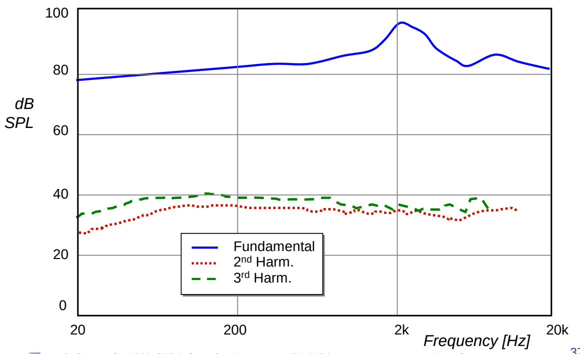
Crosstalk

$C_{L\text{-}R}(f) = G_{L/R}(f) - G_{R/R}(f)$ *[in dB]* *for signal applied to RIGHT Ear*

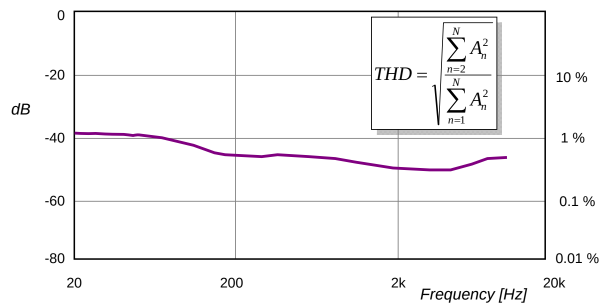


Harmonic Distortion

at Rated Voltage

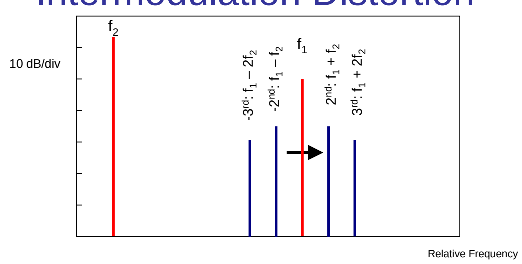


THD vs. Frequency



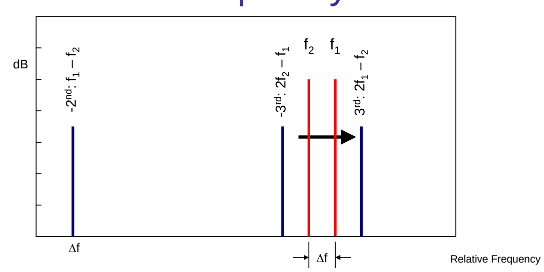
$$THD = \sqrt{\frac{\sum_{n=2}^{N} A_n^2}{\sum_{n=1}^{N} A_n^2}}$$

Intermodulation Distortion



- f_2 low frequency fixed tone at -1.9 dB re: Rated Voltage at 70 Hz
- f_1 tone at -14 dB (4:1) at 600 Hz *OR stepped or swept*
- f_2 is the frequency interval between distortion products
- IM products follow f_2 as a group

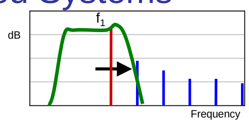
Difference Frequency Distortion



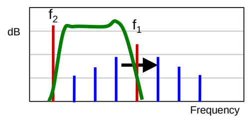
- f_1 & f_2 each at -6 dB re: Rated Voltage, stepped or swept.
- $\Delta f = f_1 - f_2 = 80$ Hz
- Δf is the frequency interval between distortion products
- Odd-order products follow as a group with f_1 & f_2. Even order products fixed.

Distortion Measurements in Band Limited Systems

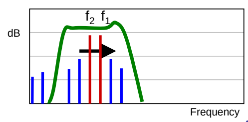
Harmonic Distortion
- Most Harmonics above passband



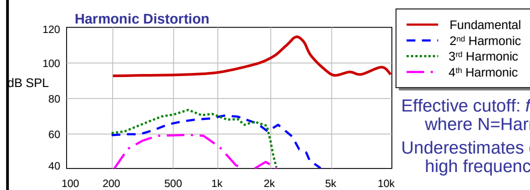
Intermodulation Dist.
- f_2 below passband *OR* IM products outside passband



Difference Frequency Dist.
- Odd-order products within passband
- Even-order products may be inside or outside passband

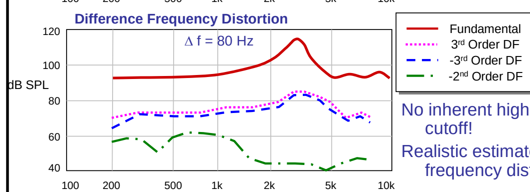


DF vs. Harmonic Distortion



Effective cutoff: f_{MAX} / N where N=Harmonic order

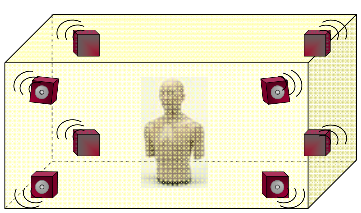
Underestimates distortion at high frequencies



No inherent high frequency cutoff!

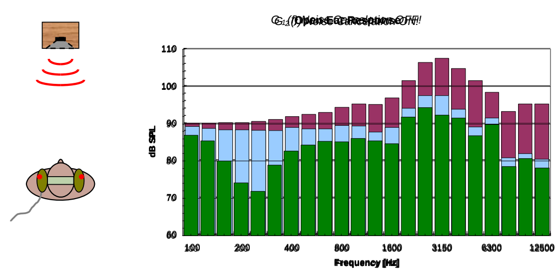
Realistic estimate of high frequency distortion

Noise Isolation



Simulated Diffuse Noise Field
- 8 Uncorrelated Sources:
  - Independent noise generators *OR*
  - Noise signals recorded independently *OR*
  - Generator with multi-tap delay line

Noise Isolation

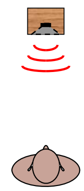


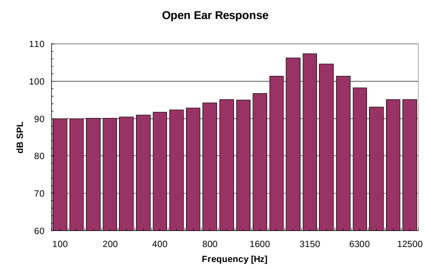
90 dBSPL Pink Noise w/ Real-time Filter Analysis *OR* FFT + 1/3 Octave Synthesis

Noise Isolation - 1

90 dBSPL Pink Noise w/ Real-time Filter Analysis *OR* FFT + 1/3 Octave Synthesis

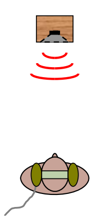
Noise Isolation - 2

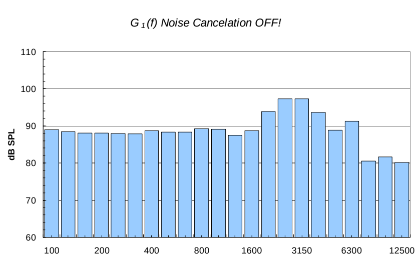




90 dBSPL Pink Noise w/ Real-time Filter Analysis *OR* FFT + 1/3 Octave Synthesis

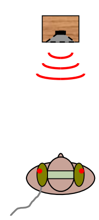
Noise Isolation - 3

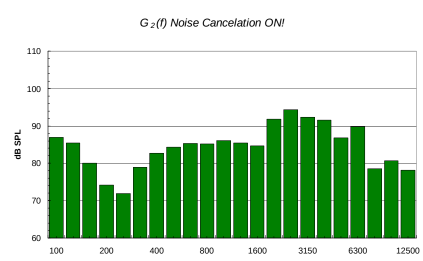




90 dBSPL Pink Noise w/ Real-time Filter Analysis *OR* FFT + 1/3 Octave Synthesis

Noise Isolation - 4





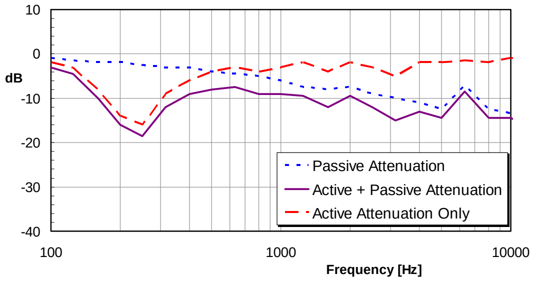
90 dBSPL Pink Noise w/ Real-time Filter Analysis *OR* FFT + 1/3 Octave Synthesis

Noise Isolation

$L_{Passive}(f) = G_1(f) - G_{Open\ Ear}(f)$ [in dB]

$L_{Active + Passive}(f) = G_2(f) - G_{Open\ Ear}(f)$ [in dB]

$L_{Active}(f) = L_{Active + Passive}(f) - L_{Passive}(f)$ [in dB]



Conclusion

- Insertion Gain – *This is the TARGET!*
  - Orthotelephonic & Diffuse Field Responses
- Acoustic Impedance
  - *Low Acoustic Z = Open*
  - *High Acoustic Z = Sealed*
- Test System and Tests
  - Requires a manikin equipped with calibrated ear simulator(s)
  - Sine AND Noise stimuli may be required
  - FFT Data requires 1/3 octave synthesis (power averaging)
  - Most post processing is simple dB subtraction (Excel?)
  - All results shown as *GAIN!*
  - Present data using the ANSI/IEC preferred aspect ratio:
    - 10, 25, or 50 dB = 1 decade
  - Curve smoothing is OK for corrected responses!

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