# Headphones

## Electroacoustic Design and Verification

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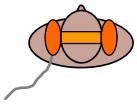
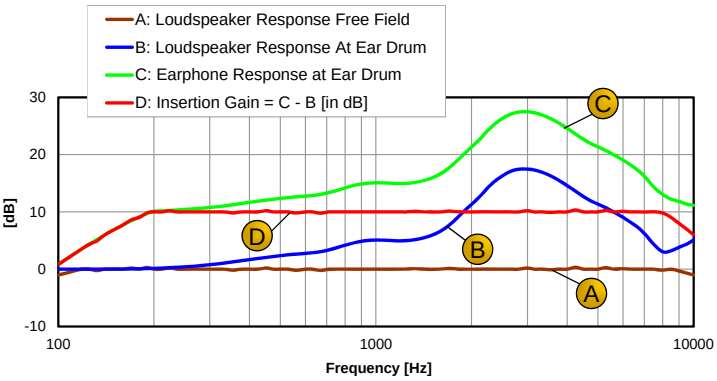
## Overview

- The Insertion Gain Concept
- Orthotelephonic, Free & Diffuse Field Responses
- Acoustic Impedance
- Couplers, Ear Simulators & Manikins
- Electroacoustic Measurements as per
  IEC 60268-7 & ANSI/ASA S3.7-2016
  - Electrical Impedance
  - Frequency Response
    - Free- and Diffuse Field Corrected Response
    - L-R Tracking
  - Non-Linear Distortion
    - Harmonic, Difference Frequency, Intermodulation
  - Crosstalk
  - Noise Isolation
    - Noise-canceling Headphones
  - Maximum Voltage & Maximum Output

# The Insertion Gain Concept

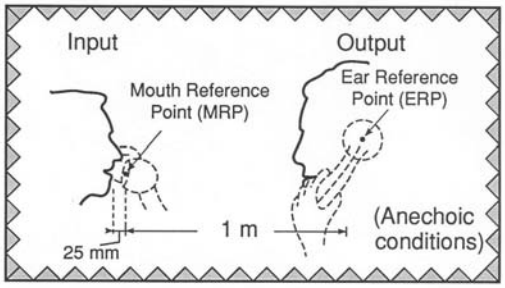




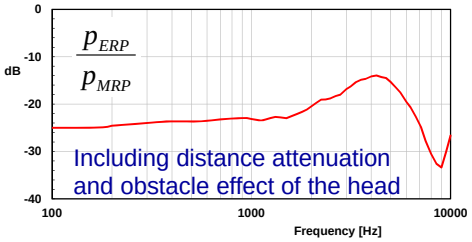

***The target is a "flat" Insertion Gain!***



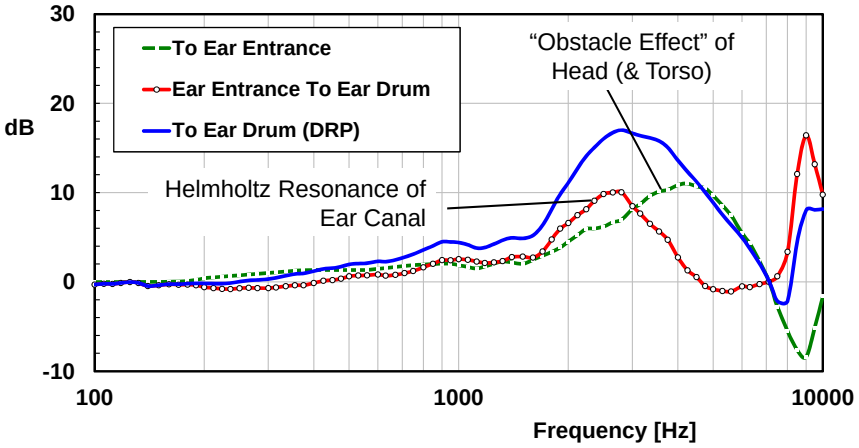
# Orthotelephonic Reference




Acoustic transfer function intended to represent a typical conversation

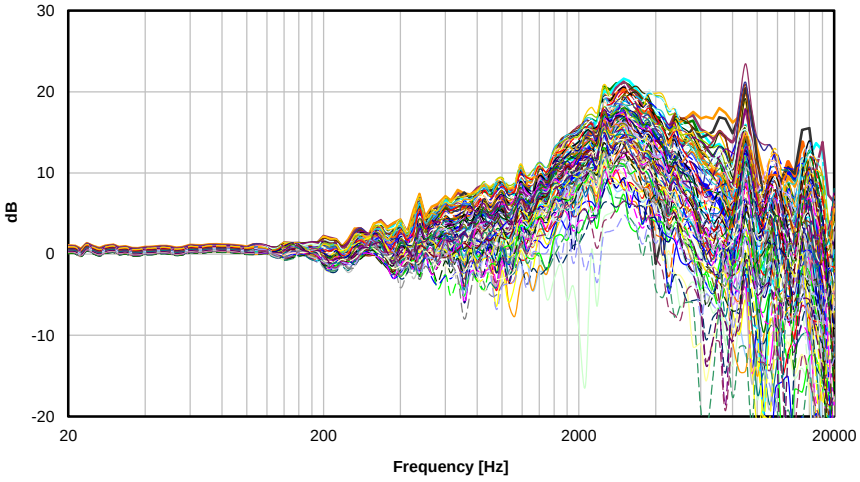


# Components of the Orthotelephonic Response



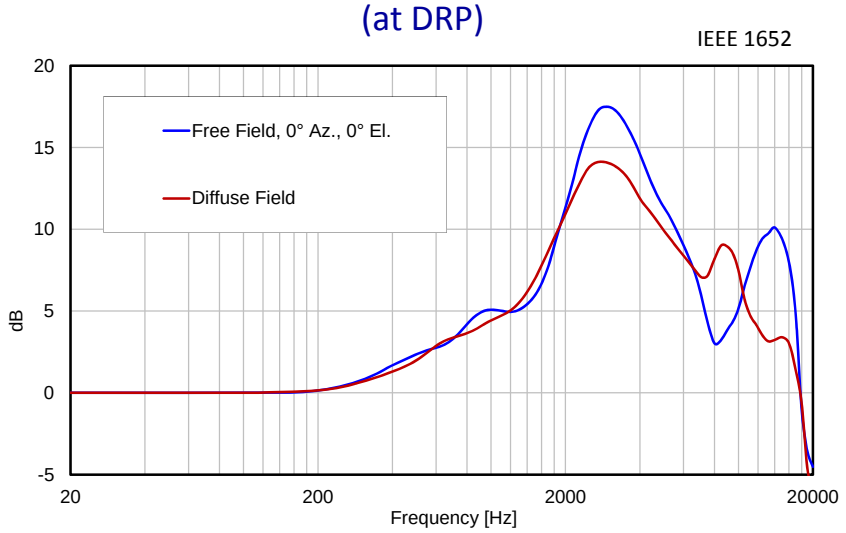



# Head Related Transfer Functions



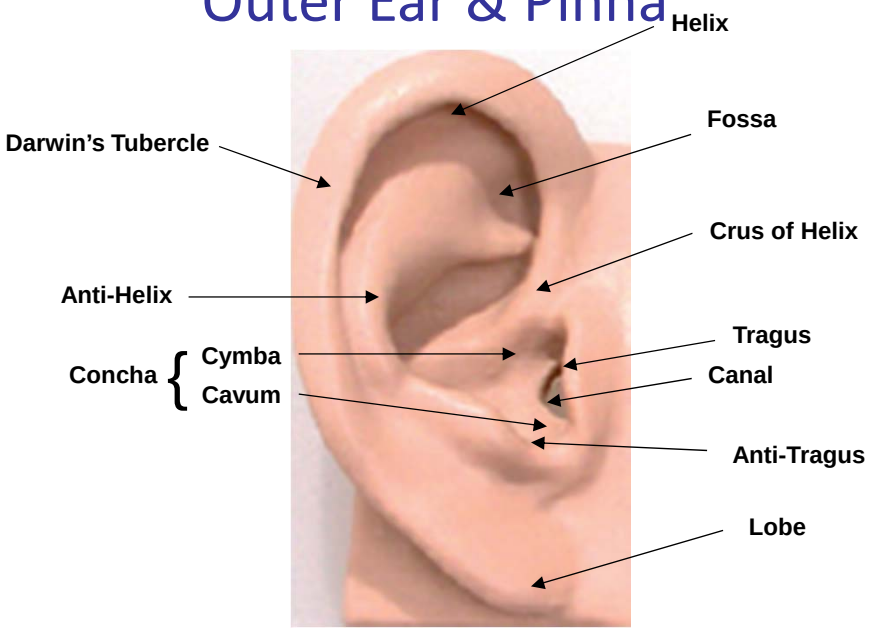
# Free & Diffuse Field Responses

(at DRP)



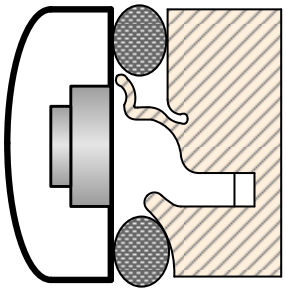



# Outer Ear & Pinna

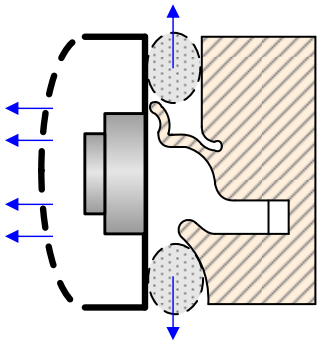


# Acoustical Impedance of Headphones

High Acoustic Impedance
(Sealed)

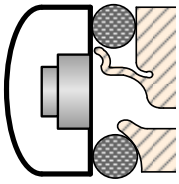


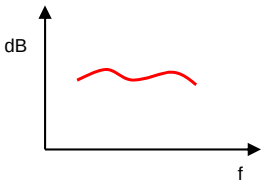
Low Acoustic Impedance
(Open)

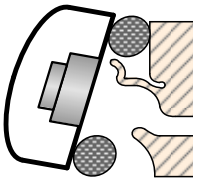


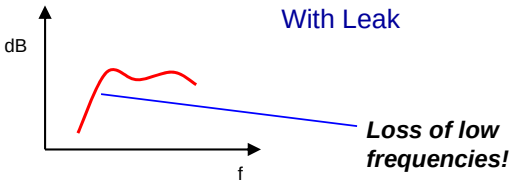


# The Effect of Leakage on Response





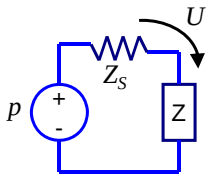






…assuming a high acoustic impedance source

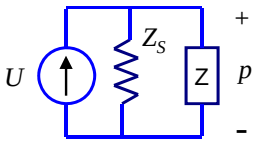
# Acoustic Impedance

*Thévenin Equivalent*




*Low $Z_S$ Pressure Source*

*Norton Equivalent*

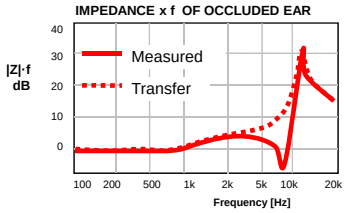


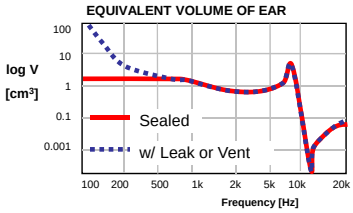

*High $Z_S$ Volume Velocity Source*

*Ohm's Law*

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

[ N·s/m$^5$ (mks acoustic ohms)]

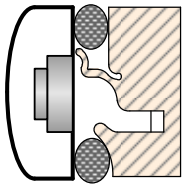
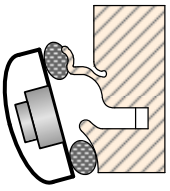
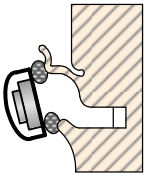
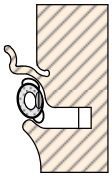
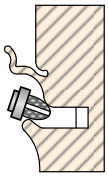



$$\therefore\ Z_A \cdot f \propto 1 / V_{Equivalent}$$



# 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**

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


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

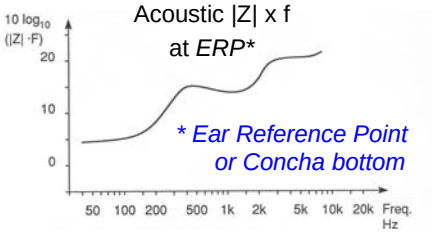
Braun Coupler
*ca. 1953*
*(DIN standard ca.1968)*
**Telephone Handset Testing (Legacy)**



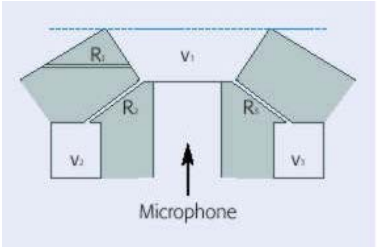
# Artificial Ear

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

Acoustic |Z| x f at *ERP**



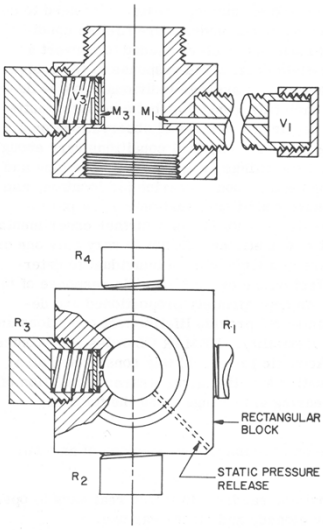

** Ear Reference Point or Concha bottom*




- Audiometer Calibration
- Telephone Handset Testing (Legacy)

# Zwislocki Coupler

*(Legacy)*

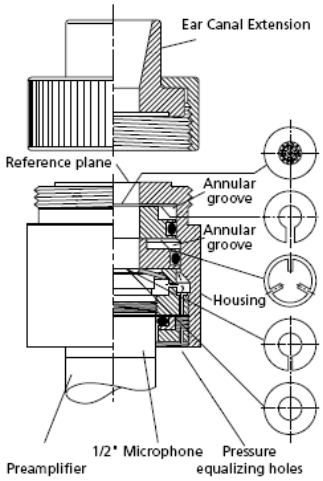





# IEC 60318-4 Ear Simulator

*(formerly IEC 711)*

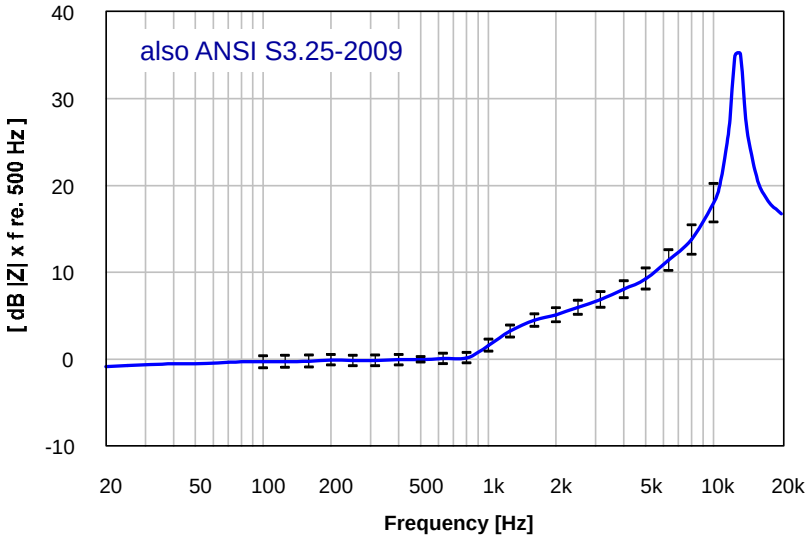
also ANSI S3.25-2009




***Measurement Microphone Diaphragm is at DRP!***

# IEC 60318-4 (formerly 711) Ear Simulator

## Acoustic Transfer Impedance






# Ear & Cheek Simulator

- Uses IEC 60318-4 (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

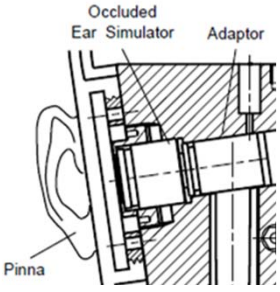
# QC Test Fixture

- Can be configured with IEC 60318-4 Ear Simulators
- Crosstalk, Isolation & Insertion Response Test results may differ from manikin tests
- Positioning may be more consistent but less realistic than manikin
- Optimized for QC/QA



# Brüel & Kjær Head And Torso Simulator

- IEC 60318-4 (formerly 711) Ear Simulators
- Anatomical Pinnæ
- Fulfills *IEC 60318-7, ANSI S3.36,* and *ITU-T Rec. P.58*
- Mouth Simulator for headset testing



# g.r.a.s. KEMAR Manikin

- IEC 60318-4 (formerly 711) Ear Simulators
- Anatomical Pinnæ
- Fulfills *IEC 60318-7 and ANSI S3.36*
- Optional mouth simulator for headset testing

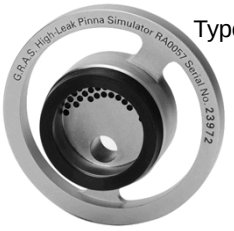


# Pinna Simulators

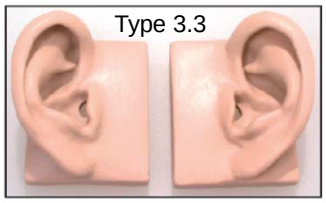
## ITU-T Rec. P. 57 Type 3 (all fitted to IEC 711 Ear)

*ca. 1996*

Type 3.2



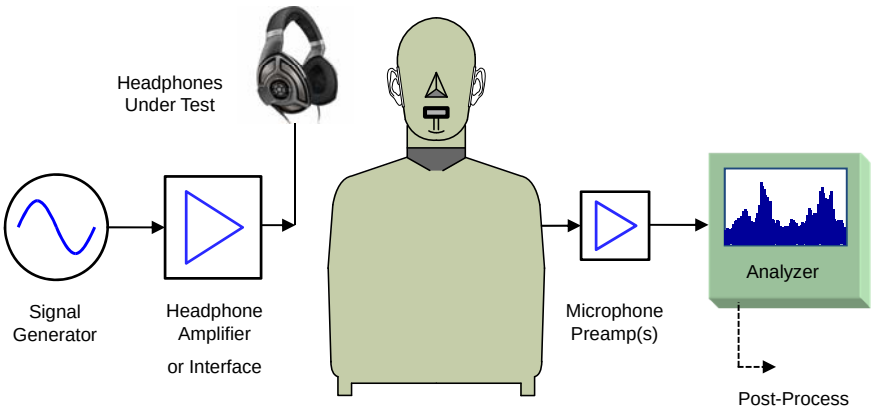

Type 3.3



Type 3.4

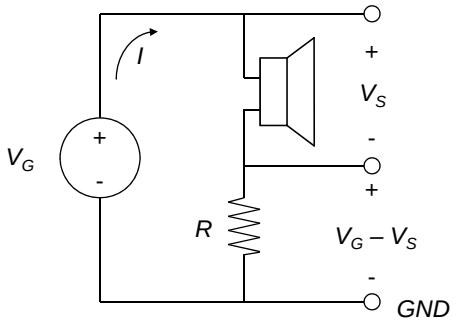
| | |
|---|---|
| Type 1 (IEC 60318-1/2) (Legacy) | Sealed High-Z Telephones Audiometer Calibration |
| Type 2 (IEC 60318-4) Occluded Ear (no pinna) | Insert Earphones |
| Type 3.2 High Leak / Low Leak | Hard Earcap Telephones |
| Type 3.3 Soft Anatomical (HATS) | All Types. Most Realistic. |
| Type 3.4 Simplified Soft Anatomical | Handset Telephones Binaural Recording |

# Basic Test System






# Electrical Impedance




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

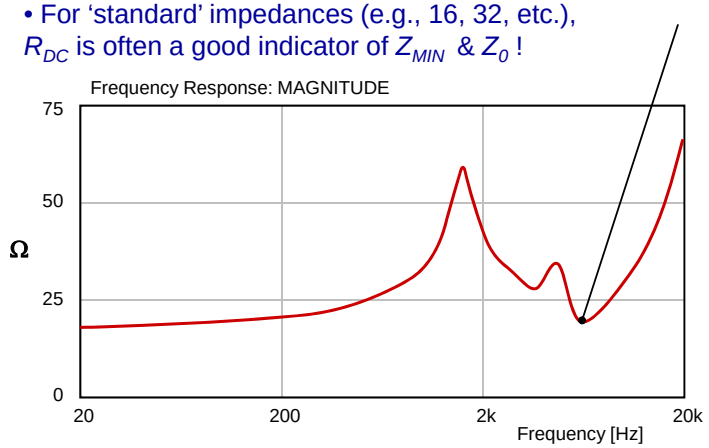
$$Z(f) = \frac{V_S(f)\,R}{V_G(f) - V_S(f)}$$

# Electrical Impedance

- Low Voltage (LINEAR!)
- R40 40th decade (1/12 octave) stepped sine
- Can also measure phase, if desired
- Measured with headphones on manikin!
- For 'standard' impedances (e.g., 16, 32, etc.), $R_{DC}$ is often a good indicator of $Z_{MIN}$ & $Z_0$ !

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

$Z_0 \geq 1.25\ Z_{MIN}$






# Source Output Impedance

- IEC 60268-7 Specification:
  $Z_{OUT}$ = 120 Ω
- Actual headphone amplifiers vary from
  < 1Ω to > 100 Ω

∴ Recommend measuring at both 120 Ω *AND* 1 Ω

# Test Conditions - 1

- **Characteristic Voltage:** The sinusoidal voltage at 500 Hz (or IEC 60268-1 simulated program signal*), 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).
  - ***NOTE: Some devices for portable music players may not be capable of producing 94 dBSPL!***
- **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 for IEC 60268-7. Required for EN 50332.*



# Test Conditions - 2

- **Working Sound Pressure Level:** SPL resulting from a sinusoidal voltage (single figure at 500 Hz or simulated program signal) through the rated source impedance (120 ohms), across the input connector of the headphone, ***at a level such that would cause 1 mW to be dissipated in a pure resistance equal to the rated impedance of the headphone***.

Voltages for 1 mW for Nominal Impedance, $Z_0$ :

| | | |
|---|---|---|
| 16 Ω : 126 mV | 60 Ω : 245 mV | 250 Ω : 500 mV |
| 20 Ω : 141 mV | 80 Ω : 283 mV | 300 Ω : 548 mV |
| 25 Ω : 158 mV | 100 Ω : 316 mV | 400 Ω : 632 mV |
| 32 Ω : 179 mV | 120 Ω : 346 mV | 500 Ω : 707 mV |
| 40 Ω : 200 mV | 160 Ω : 400 mV | 600 Ω : 775 mV |
| 50 Ω : 224 mV | 200 Ω : 447 mV | |

*Ohm's Law*

$$V = IR, P = VI$$

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

$$V^2 = PZ_0$$

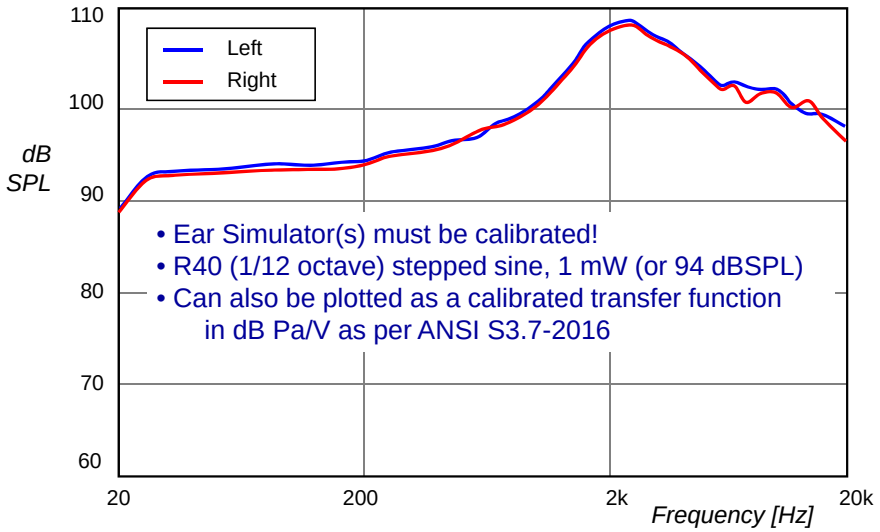
$$V = \sqrt{PZ_0} = \sqrt{0.001 \cdot Z_0}$$

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

- **Maximum Sound Pressure Level:** SPL produced in the ear simulator when the headphone is supplied with a sinusoidal voltage of the Rated Maximum Voltage at 500 Hz (see also EN 50332).

# Frequency Response

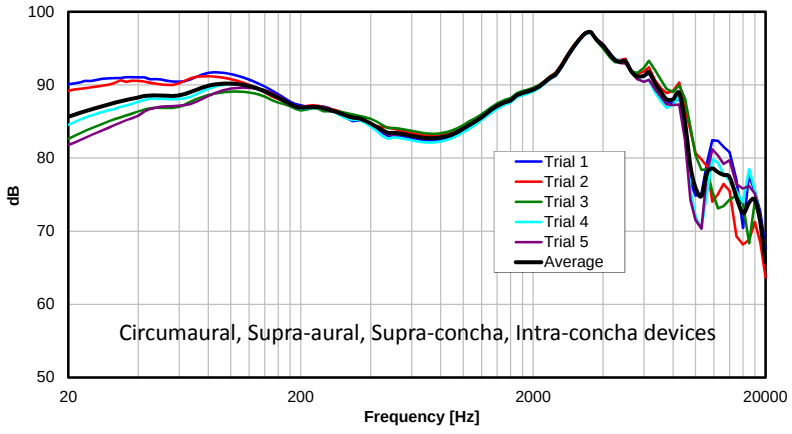
1 mW Input




- Ear Simulator(s) must be calibrated!
- R40 (1/12 octave) stepped sine, 1 mW (or 94 dBSPL)
- Can also be plotted as a calibrated transfer function in dB Pa/V as per ANSI S3.7-2016

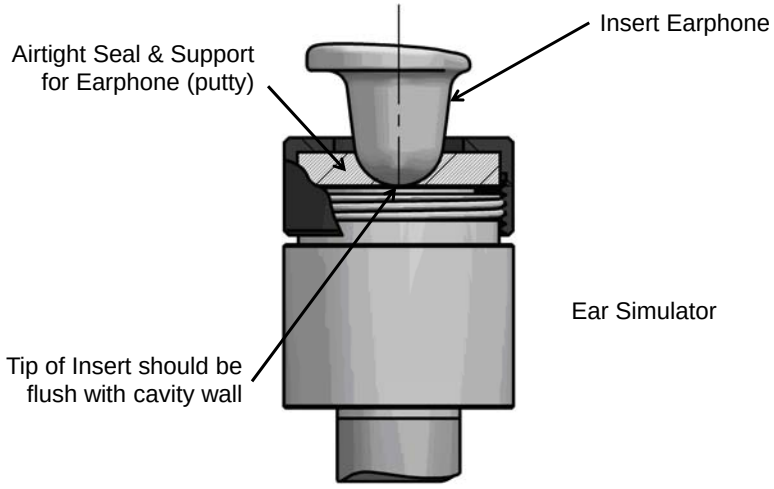


# Positioning Errors & Test Repeatability




- Test/Re-Test: dB Average of 5 re-positions:
  - *Complete removal and re-installation!*
  - *Reject re-positions > ± 2 dB (500Hz – 5 kHz)*
  - Check low frequency response for leakage
  - Report Average & Max $\sigma$

# Coupling Sealed Insert Earphones

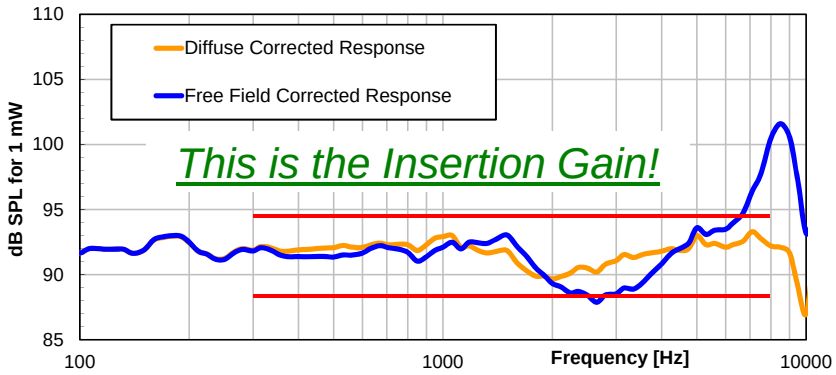





# Diffuse & Free Field Corrected Response

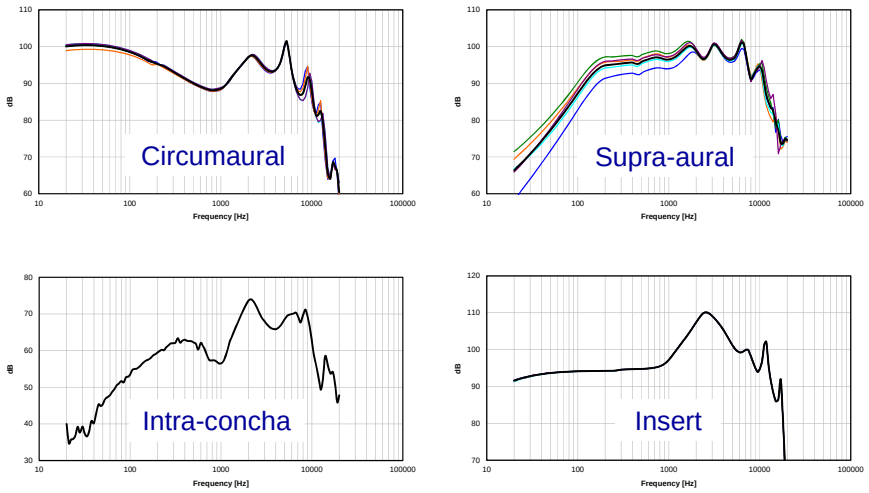
*DIFFUSE:* $H_{DFC}(f) = H(f) - H_{Diffuse}(f)$ *[in dB]*

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




- *Maps to perceived response*
- *Simplifies visualization and tolerance application*
- *Important range: 300 Hz – 8 kHz*

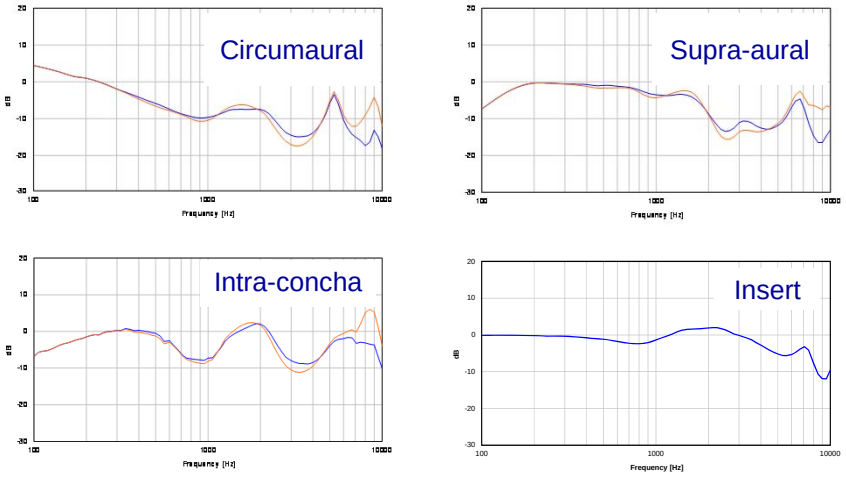
# Measured Responses at DRP






# Resulting Insertion Gain

Diffuse Field Corrected Response
Free Field Corrected Response

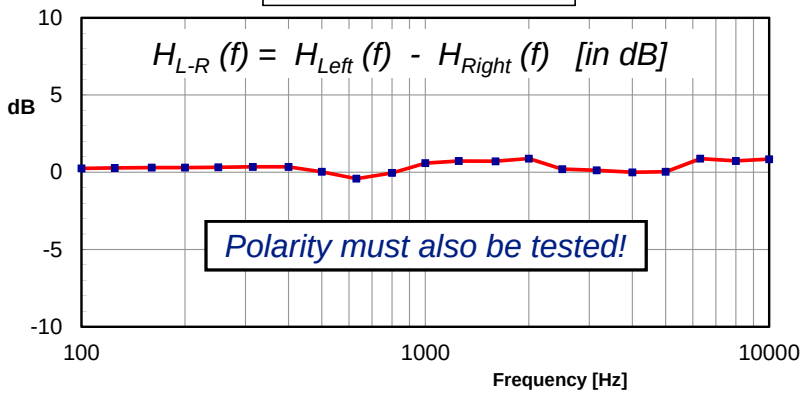


# Left-Right Tracking

*L & R Responses are 1/3 octave power averaged in each band:*

*In each 1/3 octave band:*

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

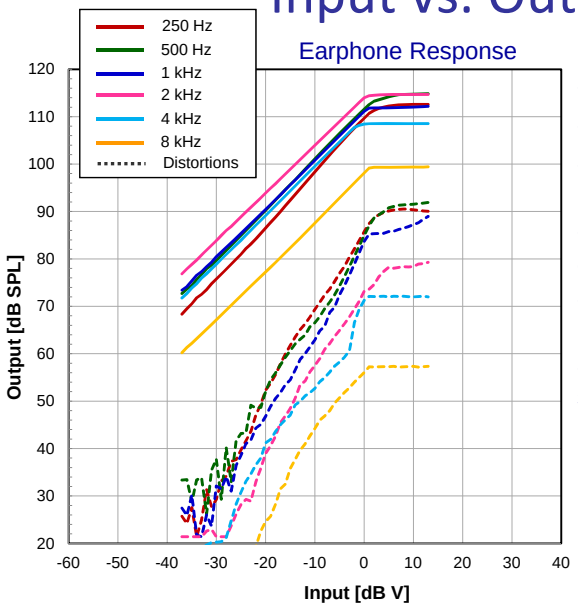





# Polarity Test Methods

- Low Frequency Phase comparison
  - $\phi(f)$ asymptotes toward 0° or 180°
- $H_L(f) + H_R(f)$ complex summation
  - Magnitude: +6 dB or noise floor
  - Change in shape of Lissajous figure
- Time Domain Pulse
  - Positive or negative going waveform

# Input vs. Output

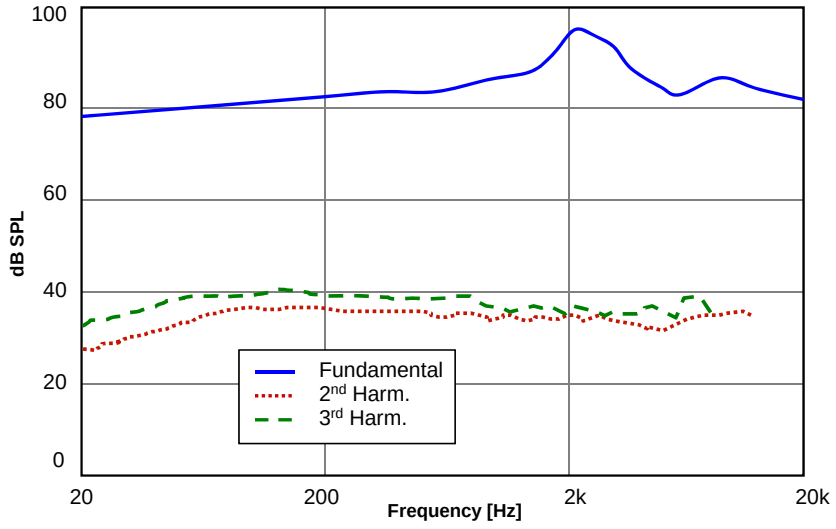



- Traditional measure of linearity
- Step size: 1 dB
- Tested at multiple frequencies, but limited frequency information
- Linear is at 45° for correct aspect ratio
- Upper "knee" point shows linearity limit
- Total Distortion is the power sum of the 2nd & 3rd Harmonics

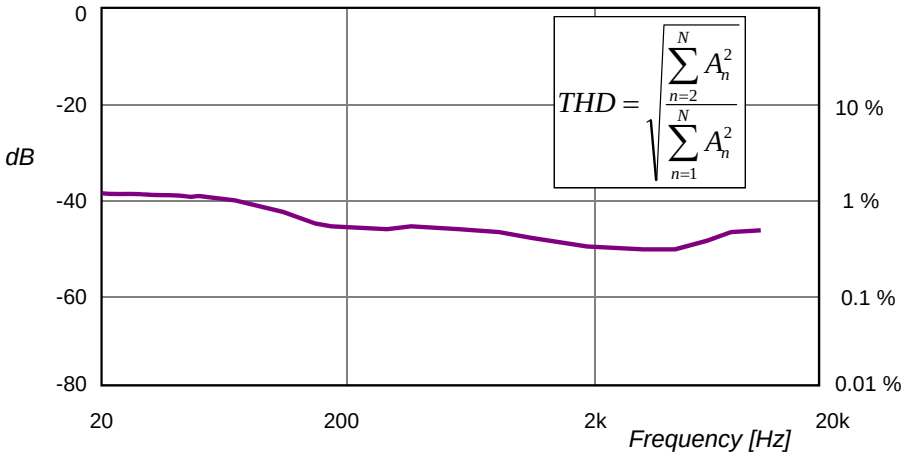


# Harmonic Distortion

## at Rated Voltage

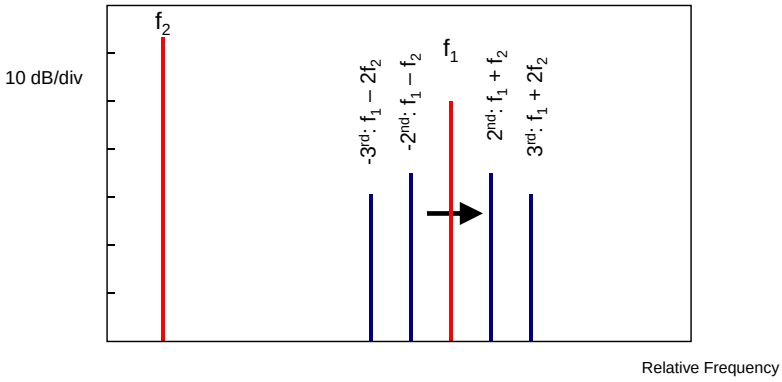


# THD vs. Frequency



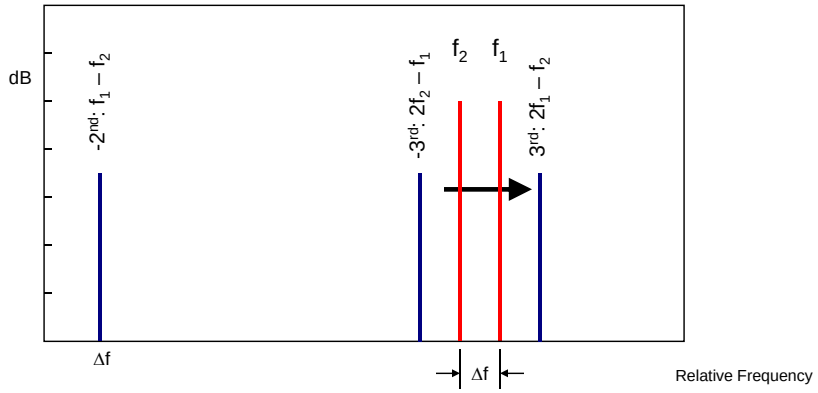



# Intermodulation Distortion




- $f_2$ 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 $f_1$ as a group

# Difference Frequency Distortion

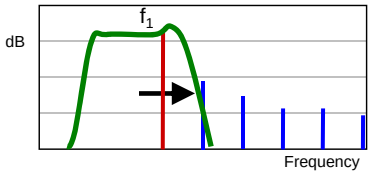



- $f_1$ & $f_2$ each at -6 dB re: Rated Voltage, stepped or swept.
- $\Delta f = f_1 - f_2 = 80$ Hz
- $\Delta f$ is the frequency interval between distortion products
- Odd-order products follow as a group with $f_1$ & $f_2$ . Even order products fixed.

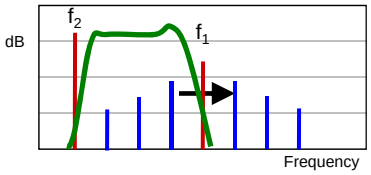


# Distortion Measurements in Band Limited Systems

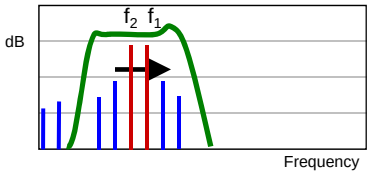
**Harmonic Distortion**
- Most Harmonics above passband
- Does not excite higher order non-linearities



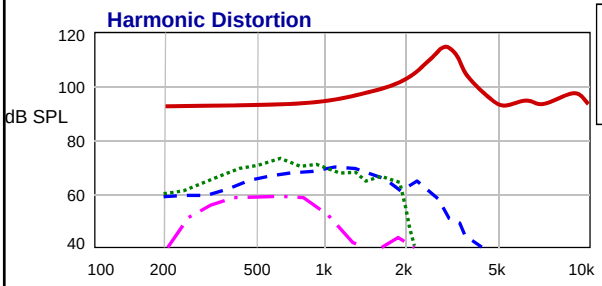

**Intermodulation Dist.**
- $f_2$ below passband *OR* IM products outside passband




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

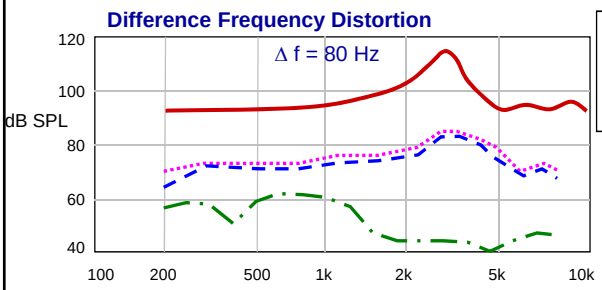


# Diff. Freq. vs. Harmonic Distortion




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

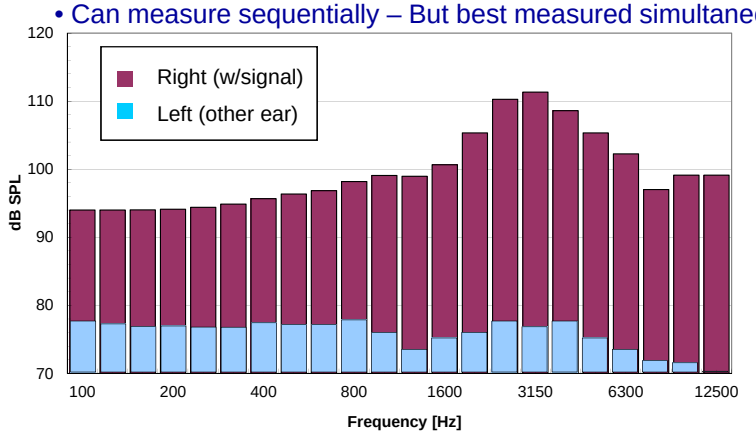


# Crosstalk

*In each 1/3 octave band:*

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

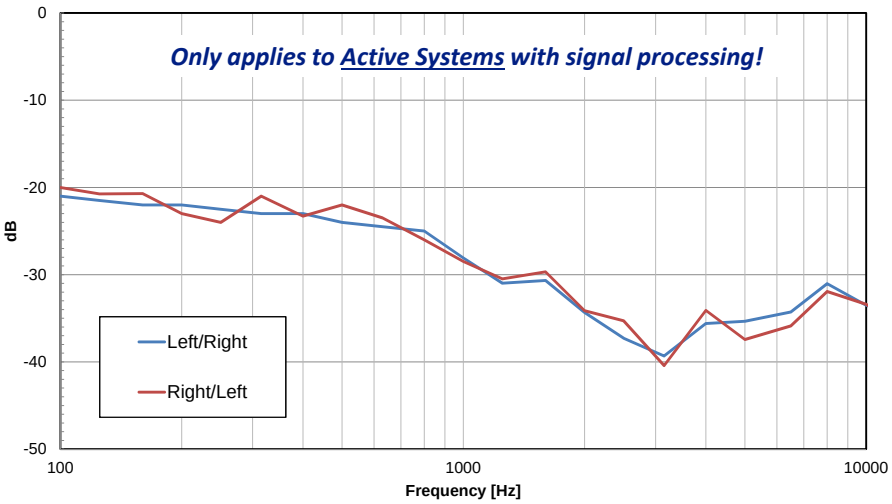
- Requires 2 Ear Simulators
- Measurement S/N is poor:
  - Use 94 dB SPL sinusoidal test signal
  - Convert to 1/3 octave as power summation*
  - Check background noise level ( ≤ -10 dB in each band!)
- Can measure sequentially – But best measured simultaneously



# Crosstalk

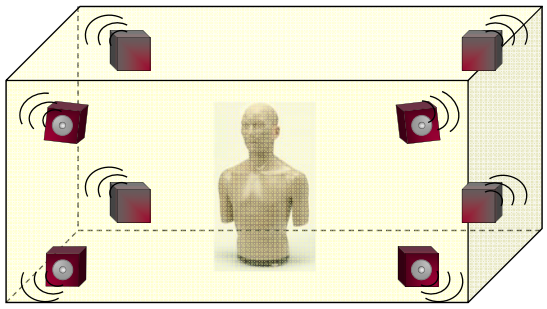
$C_{L\text{-}R}(f) = G_{L/R}(f) - G_{R/R}(f)$ [in dB] *for signal applied to RIGHT Ear*

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





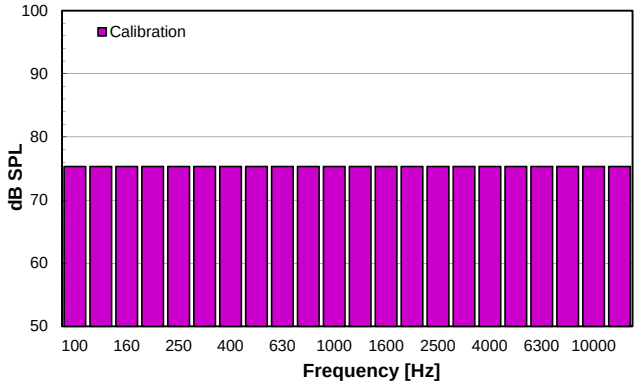

# Noise Isolation



## Diffuse Noise Field

- Reverberant Room and/or Uncorrelated Sources
- 90 dB SPL at Test Point

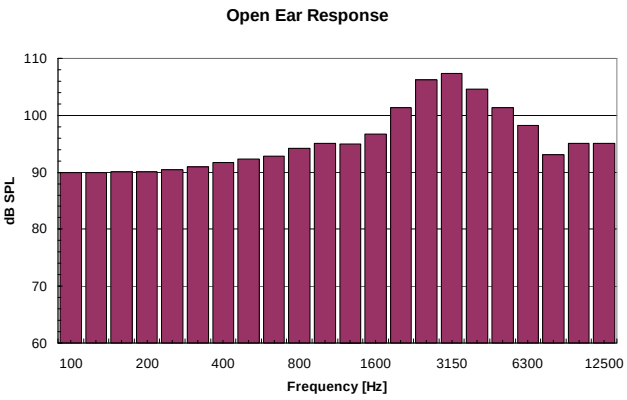
# Noise Isolation - 1




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

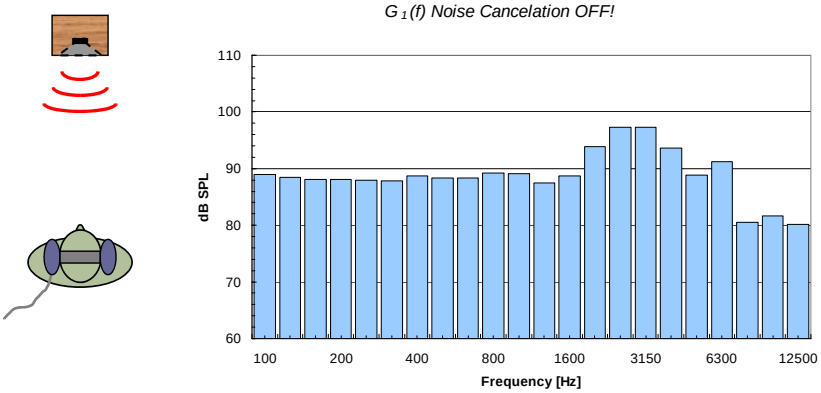


# Noise Isolation - 2




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

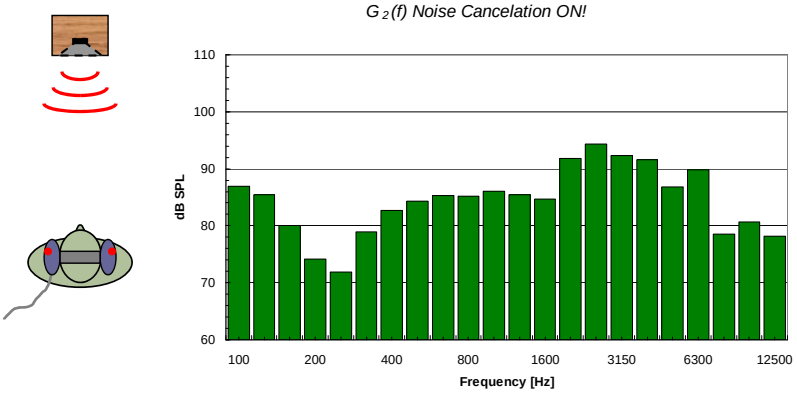
# Noise Isolation - 3




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



# Noise Isolation - 4



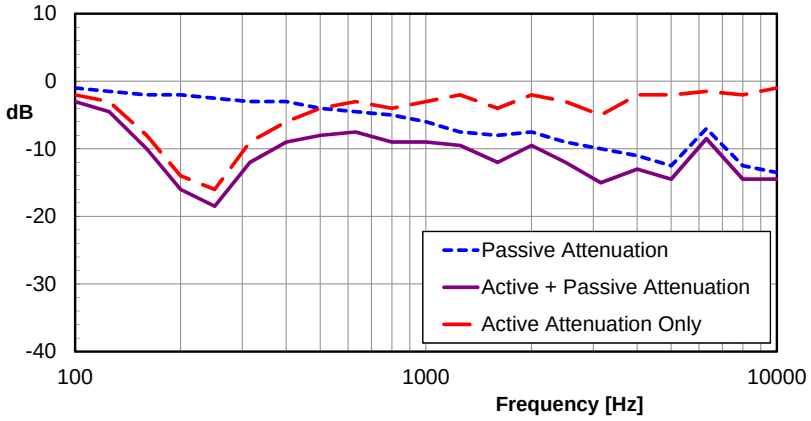

90 dBSPL Pink Noise w/ Real-time Filter Analysis *OR* FFT + 1/3 Octave Synthesis

# Noise Isolation

$L_{Passive}\ (f) = G_{NR\text{-}OFF}\ (f) - G_{Open\ Ear}\ (f)$ *[in dB]*

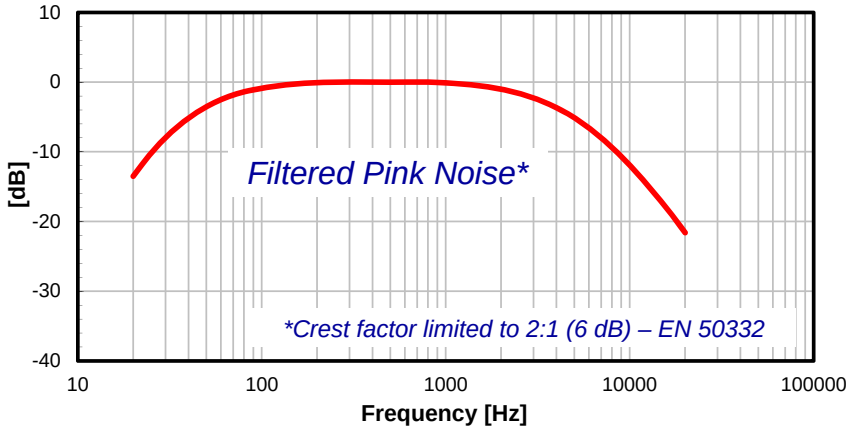
$L_{Active\ +\ Passive}\ (f) = G_{NR\text{-}ON}\ (f) - G_{Open\ Ear}\ (f)$ *[in dB]*

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

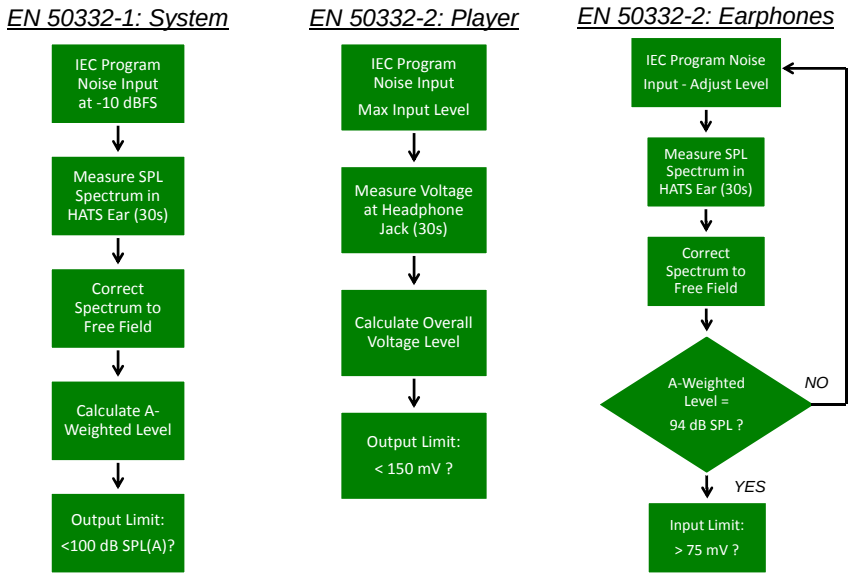





# IEC 60268-1 Simulated Program Spectrum



# EN 50332 Maximum Output






# Maximum Voltage

- Maximum RMS voltage of the IEC 60268-1 program noise signal, limited 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 rest/storage
- **Rated Maximum Permanent Noise Source Voltage:**
  - Signal applied continuously for 100 hours!
  - *No change in specs after 24 hours of rest/storage

***NOTE: THIS IS A DESTRUCTIVE TEST!***

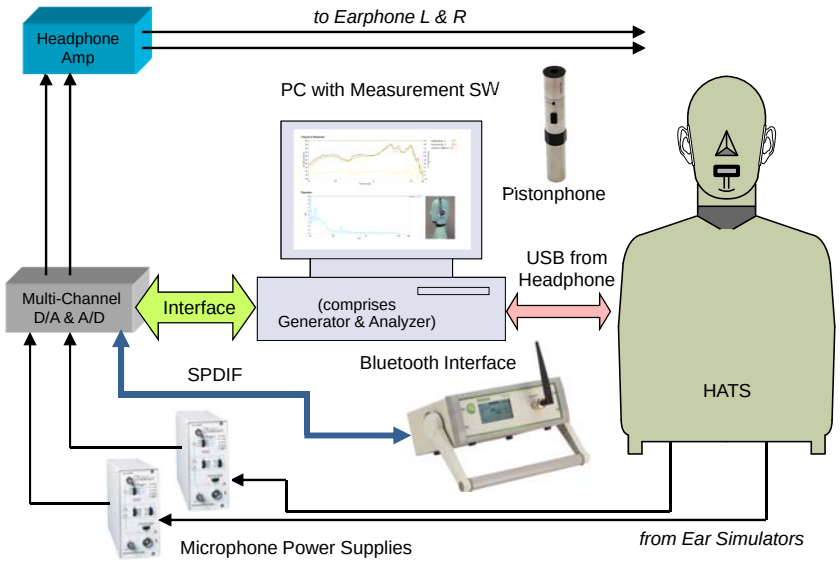
# A Minimum Test Suite

- L & R Frequency Response[1]
  - Show Mean and all re-position trials
- Left-Right Tracking
- L & R Harmonic Distortion[2]
- Free and Diffuse Field corrected responses

[1]Test level, and nominal electrical impedance (if applicable) should also be reported
[2]Assumes 2-tone distortion test capability is not available.



# Headphone Test System



# Conclusion (1)

- Insertion Gain
  - A *FLAT INSERTION GAIN* is the target!
  - *This is 'corrected' from the measured response at DRP.*
- 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
  - Present data using the IEC 60263 preferred aspect ratio:
    - 10, 25, or 50 dB = 1 decade



# Conclusion (2)

*Vis-à-vis* IEC 60268-7 {Ed. 3.0} 2010-1:

- 120Ω amplifier $Z_{OUT}$ not representative in many cases
- Average of 5 trials can mitigate positioning errors
- Free & Diffuse Field responses provide useful estimates (bounds) of perceived response, i.e., the *insertion gain*
- Left-Right Tracking in 1/3 octaves correlates to loudness match. Polarity is also important!
- I/O response reveals range of linearity vs. input level
- 2-Tone distortion tests are a realistic indicator of non-linearity in band-limited systems
- **ANSI/ASA S3.7-2016** incorporates most of these refinements

# References


- C. J. Struck, *"Refinements in the Electroacoustic Testing of Headphones"*, proceedings of the Audio Engineering Society International Conference on Headphone Technology – Aalborg, Denmark (2016 August 24–26).
- IEC 60268-7 – Sound System Equipment. Part 7: Headphones
- ANSI/ASA S3.7-2016 – Earphone Measurement and Calibration
- IEC 60268-1 – Sound System Equipment. Part 1: General
- ANSI/ASA S3.25-2009 – Occluded Ear Simulator
- IEC 60318-4 – Occluded Ear Simulator (*formerly IEC 711*).
- IEC 60118-7 Electroacoustics – Simulators of human head and ear – Part 7: Head and torso simulator for the measurement of hearing aids
- IEEE Standard 1652-2016 "IEEE Standard for Translating Head and Torso Simulator Measurements from Eardrum to Other Acoustic Reference Points"
- ISO 4869-3: 2007 – Acoustics – Hearing protectors -- Part 3: Measurement of insertion loss of ear-muff type protectors using an acoustic test fixture
- European Standard EN50332-1 (2000), "Sound system equipment: Headphones and earphones associated with portable audio equipment. Maximum sound pressure level measurement methodology and limit considerations. Part 1: General method for "one package equipment"
- European Standard EN50332-2 (2003), "Sound system equipment: Headphones and earphones associated with portable audio equipment. Maximum sound pressure level measurement methodology and limit considerations. Part 2: Matching of sets with headphones if either or both are offered separately".
- BS EN 62368-1:2014 Audio/video, information and communication technology equipment. Safety requirements
- J. Borwick, Loudspeaker and Headphone Handbook 3rd Ed. 2001
- Møller, H. *et al*, "Design Criteria for Headphones" J. Audio Eng. Soc., Vol. 43, No. 4 – April 1995.
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