Headphones

Electroacoustic Design, Verification and Standards

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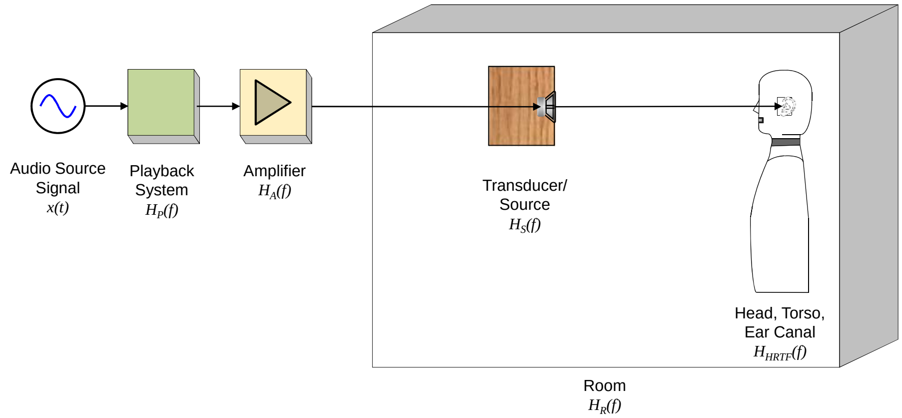
Overview

- 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

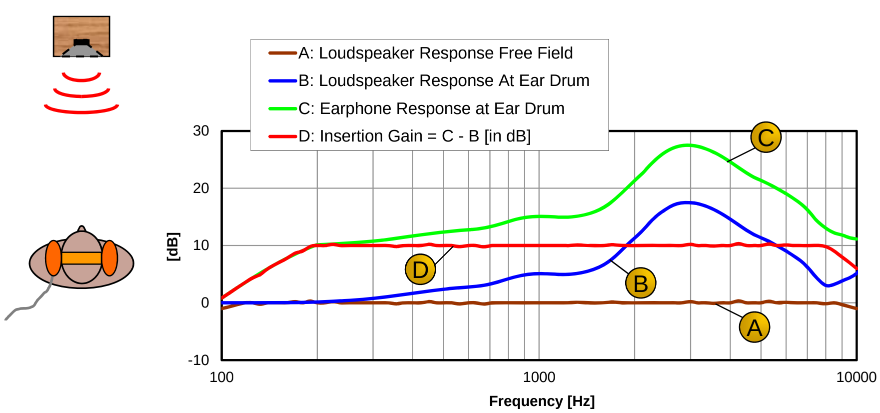
The Audio Signal Chain



Overall Frequency Response: $H_T(f) = \cancelto{1}{H_P(f)} \cdot \cancelto{1}{H_A(f)} \cdot \cancelto{1}{H_S(f)} \cdot \cancelto{1}{H_R(f)} \cdot H_{HRTF}(f)$

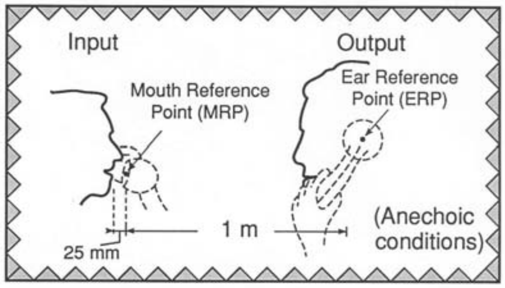
Signal at DRP: $x_{DRP}(t) = \; x(t) \circledast h_P(t) \circledast \cancelto{\delta(t)}{h_A(t)} \circledast \cancelto{\delta(t)}{h_S(t)} \circledast \cancelto{\delta(t)}{h_R(t)} \circledast h_{HRTF}(t)$

The Insertion Gain Concept

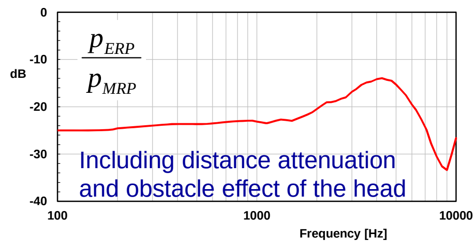


The target is a "flat" Insertion Gain!

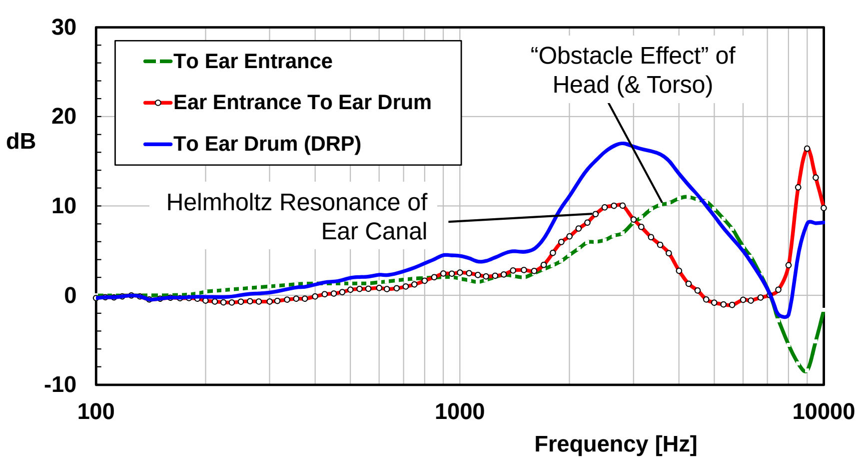
Orthotelephonic Reference



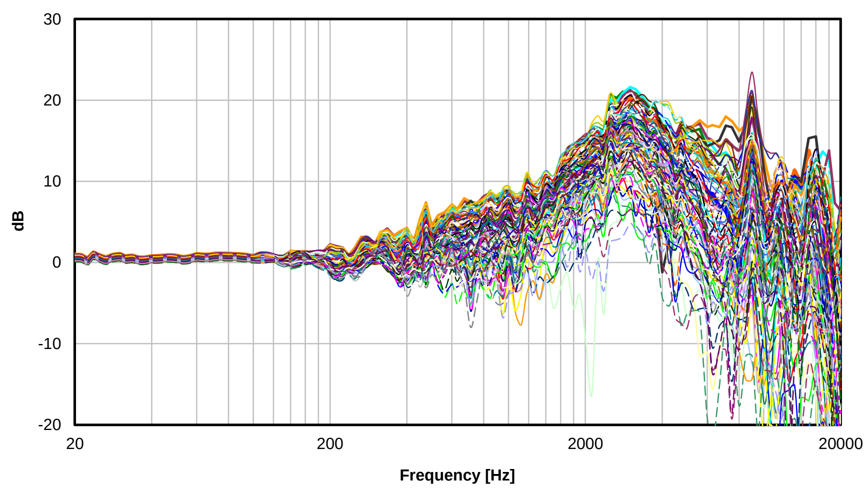
Acoustic transfer function intended to represent a typical conversation



Components of the Orthotelephonic Response



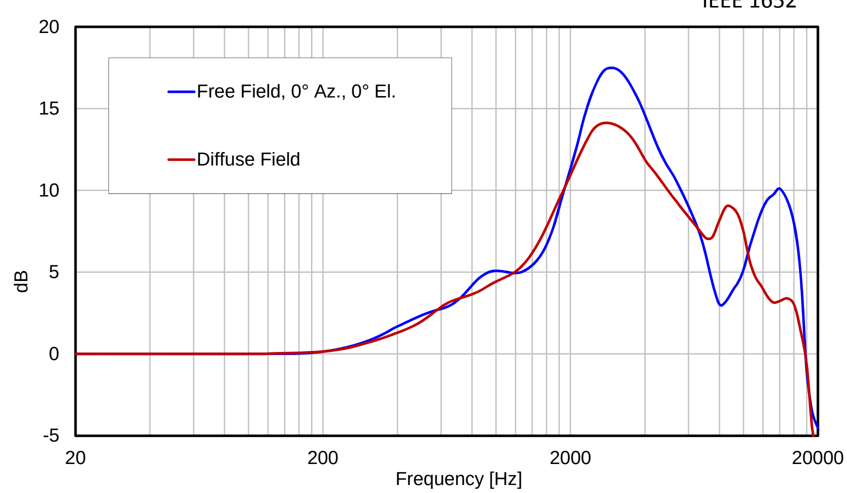
Head Related Transfer Functions



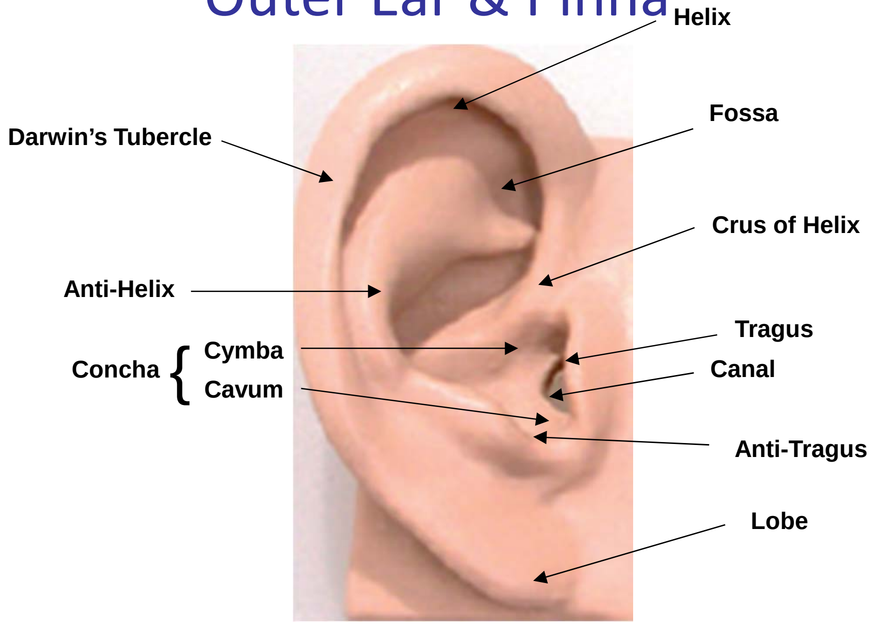
Free & Diffuse Field Responses

(at DRP)

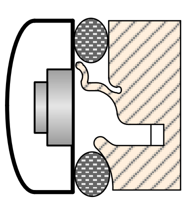
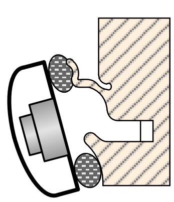
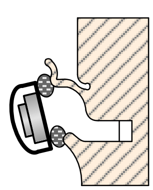
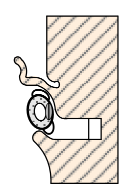
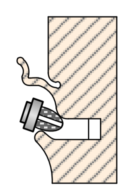
IEEE 1652



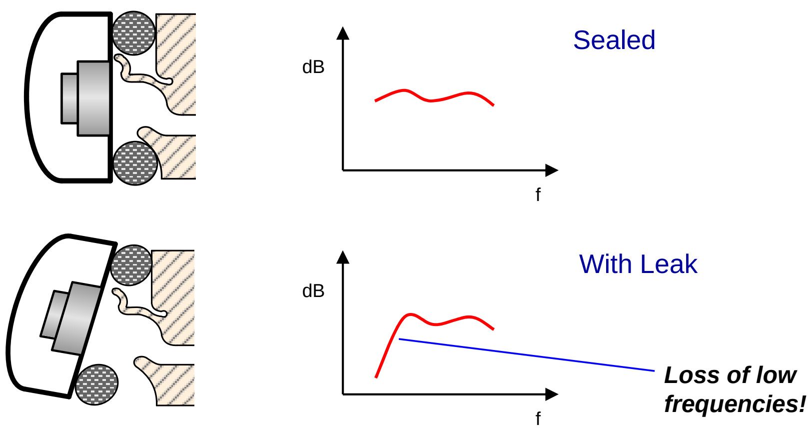
Outer Ear & Pinna



Earphone Types

Circumaural	Supra-aural	Supra-concha	Intra-concha	Insert
				

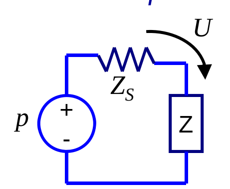
The Effect of Leakage on Response



…assuming a high acoustic impedance source

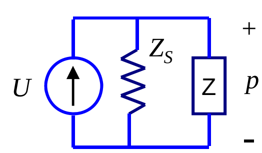
Acoustic Impedance

Thévenin Equivalent



Low Z_S Pressure Source

Norton Equivalent

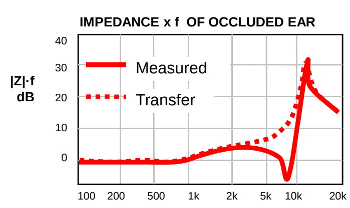


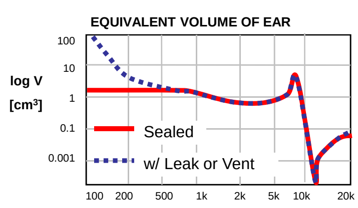
High Z_S Volume Velocity Source

Ohm's Law

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

[N·s/m⁵ (mks acoustic ohms)]

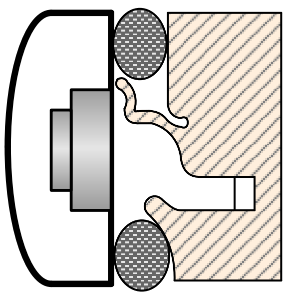




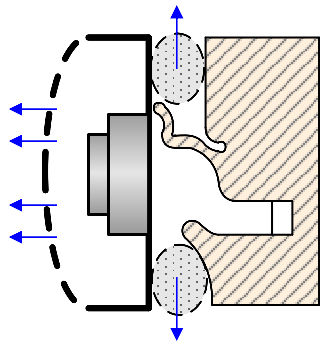
$$\therefore\ Z_A \cdot f \ \propto\ 1 / V_{Equivalent}$$

Acoustical Impedance of Headphones

High Acoustic Impedance
(Sealed)



Low Acoustic Impedance
(Open)



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

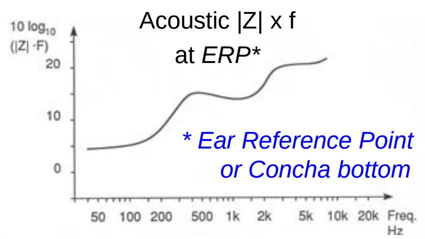
NOTE:
No "reference point", *per se*

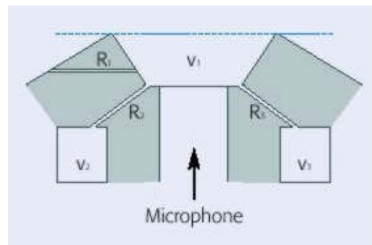
Braun Coupler
ca. 1953
(DIN standard ca.1968)
Telephone Handset Testing (Legacy)

Artificial Ear

IEC 60318-1 (ITU-T Type 1)

ca. 1962-68 (standardized 1973)



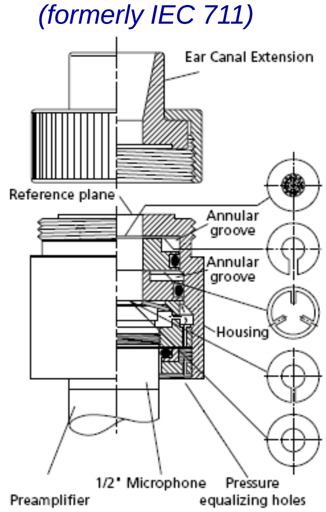


- Audiometer Calibration
- Telephone Handset Testing (Legacy)

IEC 60318-4 Ear Simulator

(formerly IEC 711)

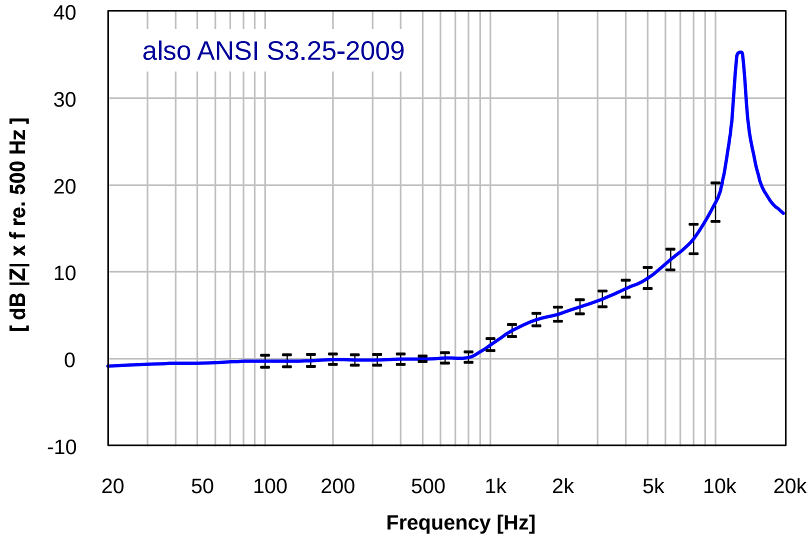
also ANSI S3.25-2009



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

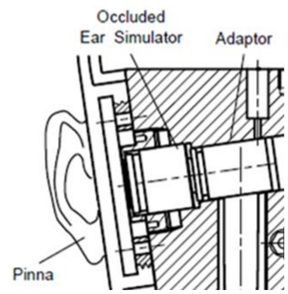
  requires pinna substitution

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

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



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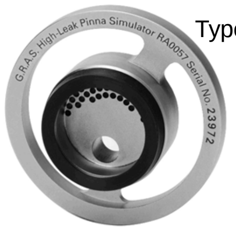
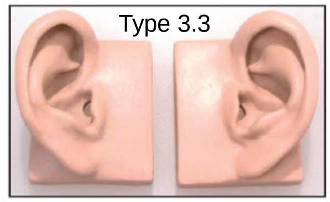
Pinna Simulators

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

ca. 1996



Type 3.2

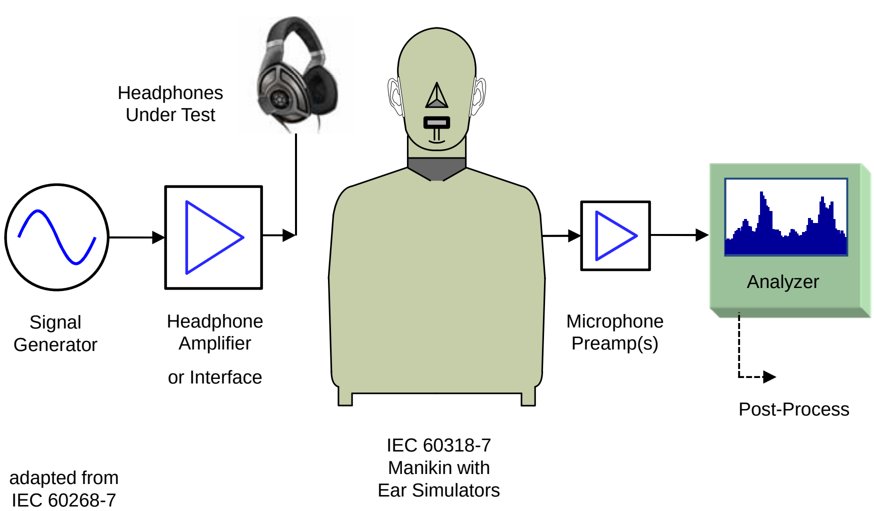


Type 3.3

Type 3.4

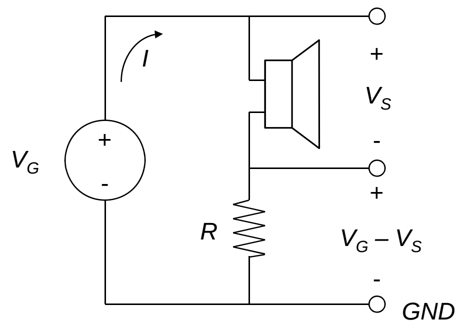
Type 1 (IEC 60318-1/2) (Legacy)	Sealed High Z Telephones Audiometer Calibration
Type 2 (IEC 60318-4) Occluded Ear (no pinna)	Insert Earphones
Type 3.2 High Leak / Low Leak	Hard Earcap Telephones
Type 3.3 Soft Anatomical (HATS)	All Types. Most Realistic.
Type 3.4 Simplified Soft Anatomical	Handset Telephones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

Basic Test System



adapted from
IEC 60268-7

Electrical Impedance



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

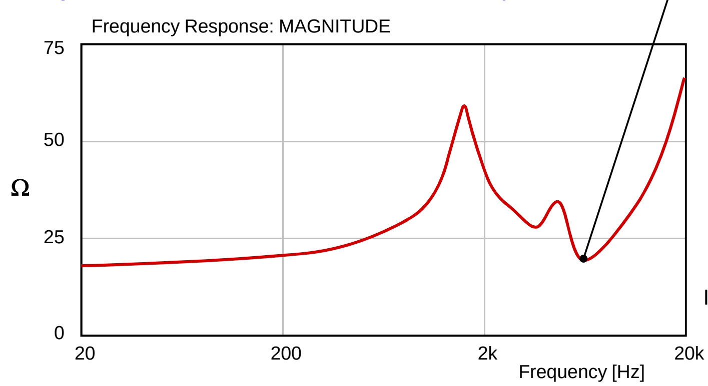
$$Z(f) = \frac{V_S(f)\,R}{V_G(f) - V_S(f)}$$

Electrical Impedance

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

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

$Z_0 \geq 1.25\ Z_{MIN}$



IEC 60268-7

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

- **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

- **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

$$V = IR, P = VI$$

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

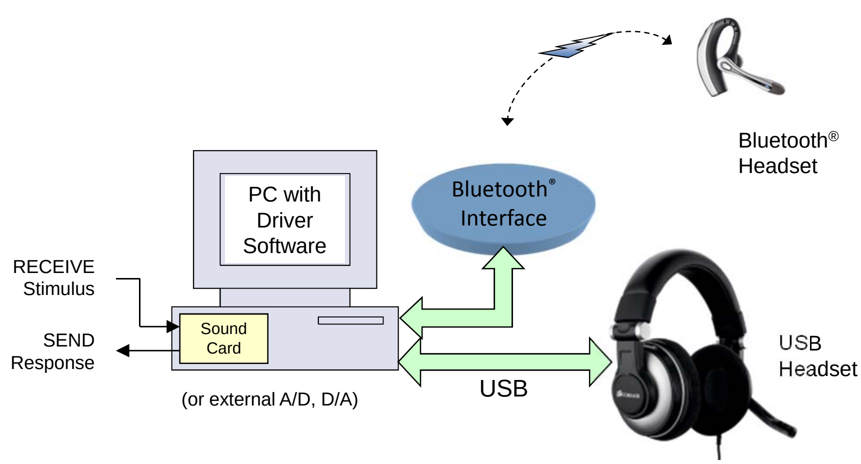
$$V^2 = PZ_0$$

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

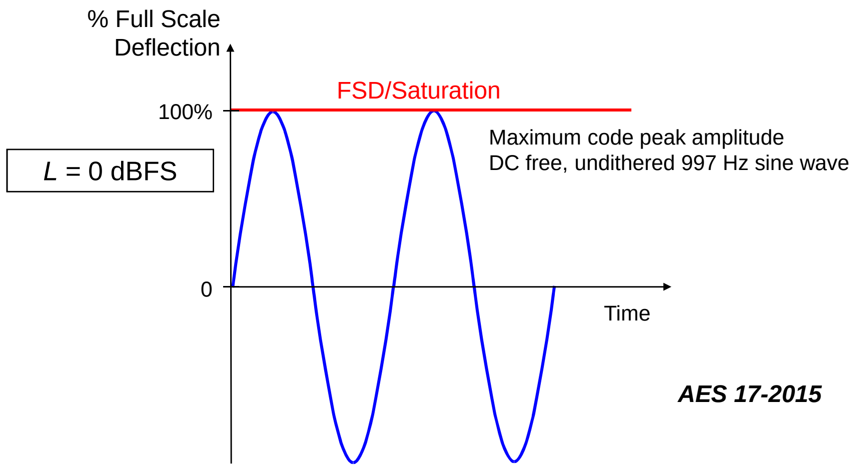
$$V = 0.0316\sqrt{Z_0}$$

- **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).

Interfacing to a Bluetooth® or USB Device



Digital Levels: 0 dBFS



NOTE 1: This is +3.01 dB re. the RMS level for a unity peak amplitude sine wave and is equivalent to a dB reference of 0.707.

NOTE 2: *L* = +3.01 dBFS for a square wave of the same peak amplitude.

Bluetooth®

- What is it?
  - A low power, low data rate digital wireless communication protocol
  - Device types include computer mice, keyboards, medical monitors, loudspeakers, headphones, headsets, etc.
  - Each device classification has its own “profile”
  - Communication is asynchronous – There is no master clock
    - May require additional processing (sample rate conversion, frequency alignment) before analysis
- Relevant Audio Profiles:
  - **A2DP**: Unidirectional Music Playback, 16-48 kHz Stereo
  - **HPF/HSP**: Bidirectional Voice Communication, 8-16 kHz Mono
- More info at: https://www.bluetooth.com/

Bluetooth® Pairing

1. Inquiry
   - Bluetooth® Device broadcasts an ID beacon, then waits for other devices to respond.
2. Discovery & Authentication
   - After discovery, devices exchange features they support and authenticate, generally by Simple Secure Pairing Protocol
3. Exchange of Link Keys
   - The link keys are encrypted tokens that ensure the Bluetooth® connection remains private

Pair By Name

After Inquiry, pair with the first device that matches the specified name

Pair By Address

Skips Discovery and proceeds immediately with Link Key exchange

Non-Concurrent Stimulus-Capture-Analysis

For Devices with:

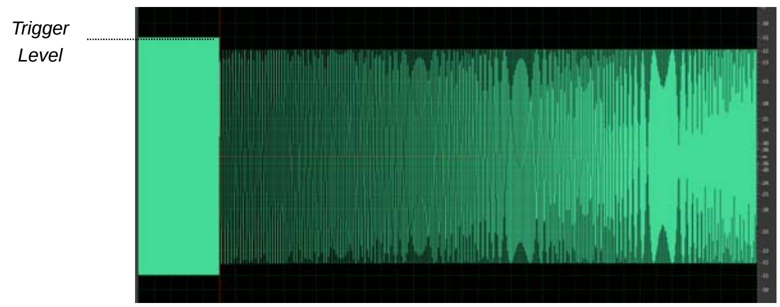
- Input and Output in different domains
  – E.g., Digital Input, Analogue Output
- Access to only Output (Playback) ***OR*** only Input (Recording)
- Different sample rates or asynchronous Input & Output
- Unstable delay and/or phase between Input and Output

The following additional steps may be required:

– Pre-Conditioning Tone & Triggered Analysis
– Sample Rate conversion
– Frequency re-alignment
– Time window or edit/trimming of captured waveform

Pre-Conditioning Tone

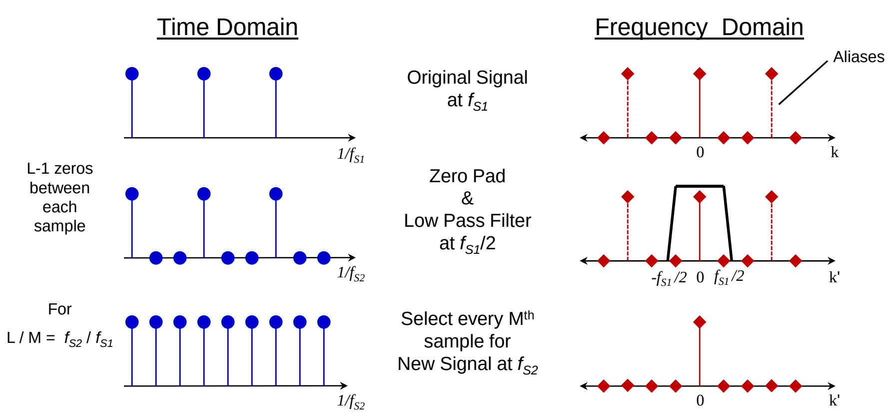
- Typically a short burst of a mid-band tone preceding the actual test stimulus, e.g., 1 kHz for 250 ms
- Used to:
  - Bias the DUT into a quasi stable state
  - Synch/align the DUT clock and sample rate to the analysis sample rate
  - Trigger the *start* of a data capture (but ignored in the analysis)



Sample Rate Conversion

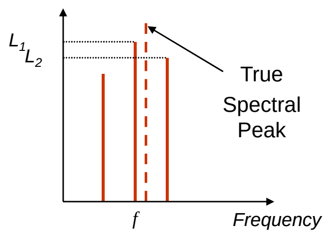
- Required for asynchronous I/O systems, even if the stated sample rate matches the analysis!

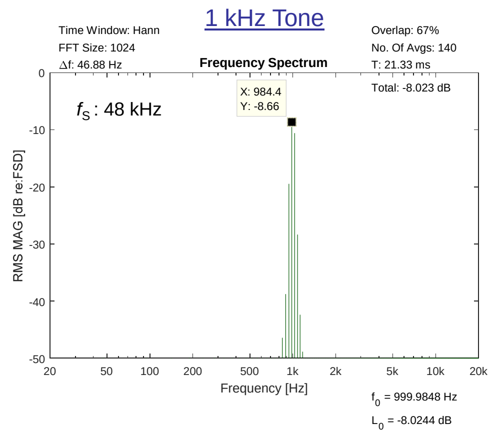
Conversion between two sample rates $f_{S1} < f_{S2}$:



Frequency Alignment

- Scale frequency response to the true frequency of the conditioning tone
- Requires frequency resolution beyond Δf of the FFT





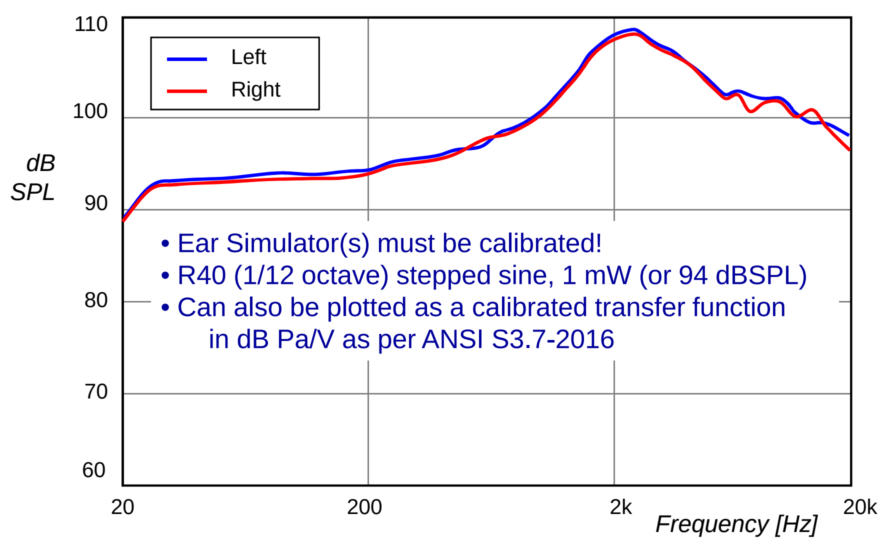
For pure tones & Hann Weighting:

$$f_{\mathrm{TRUE}} = f + f_C$$

where $$f_C = \frac{2 - 10^{(L_1 - L_2)/20}}{1 + 10^{(L_1 - L_2)/20}} \cdot \Delta f$$

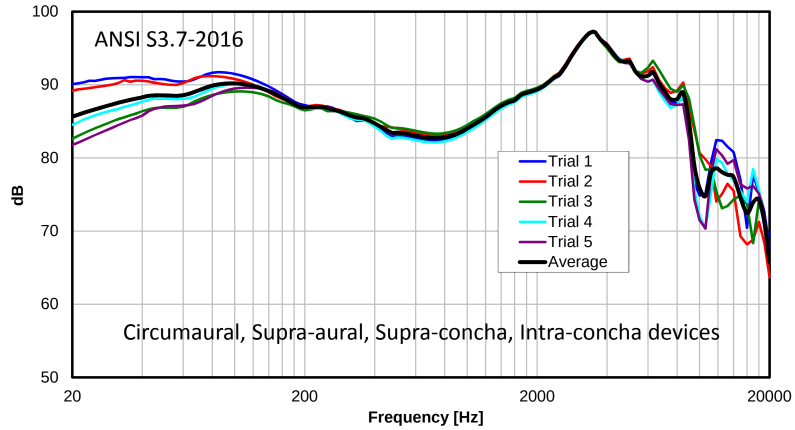
Frequency Response

1 mW Input



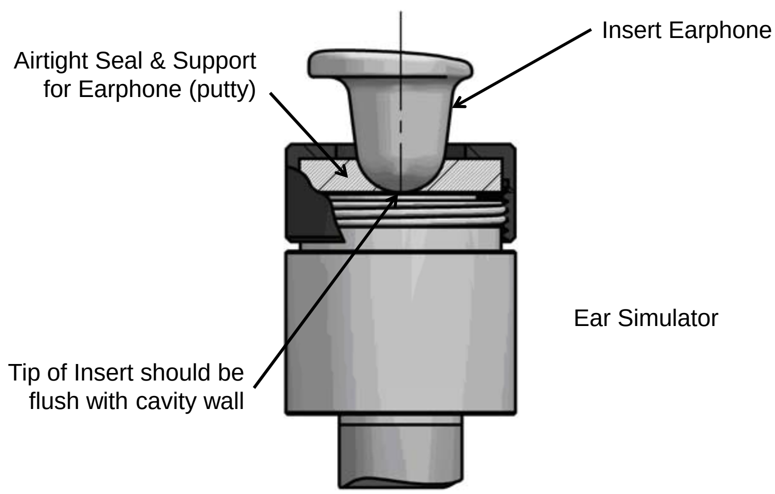
- Ear Simulator(s) must be calibrated!
- R40 (1/12 octave) stepped sine, 1 mW (or 94 dBSPL)
- Can also be plotted as a calibrated transfer function in dB Pa/V as per ANSI S3.7-2016

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 σ

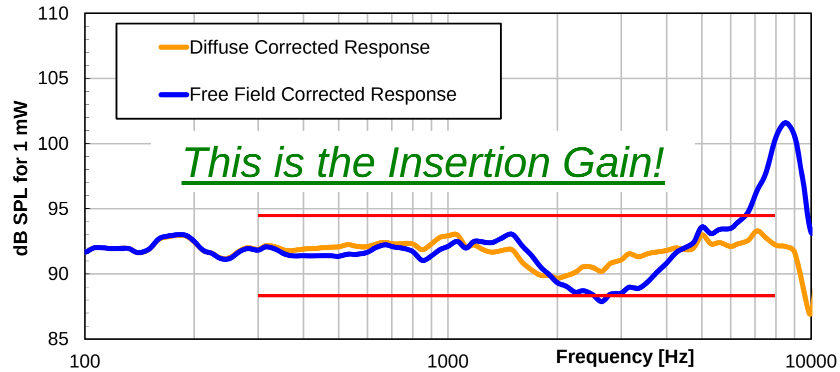
Coupling Sealed Insert Earphones



Diffuse & Free Field Corrected Response

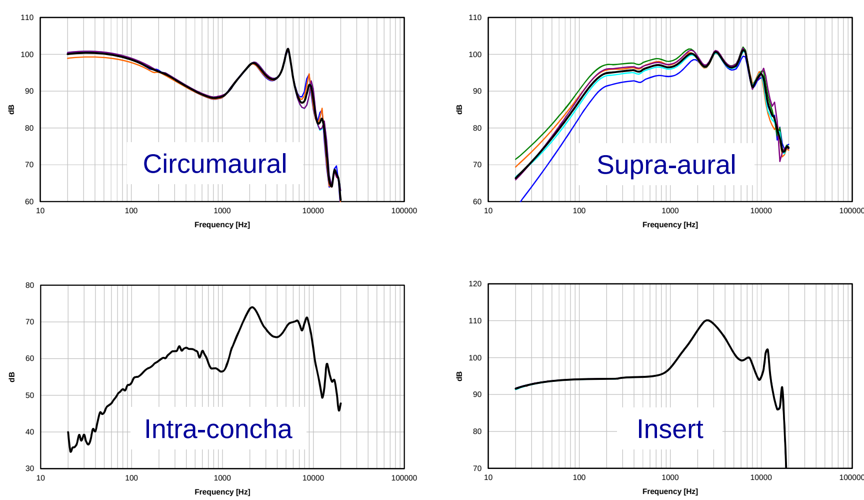
DIFFUSE: H_{DFC} (f) = H (f) – $H_{Diffuse}$ (f) [in dB]

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

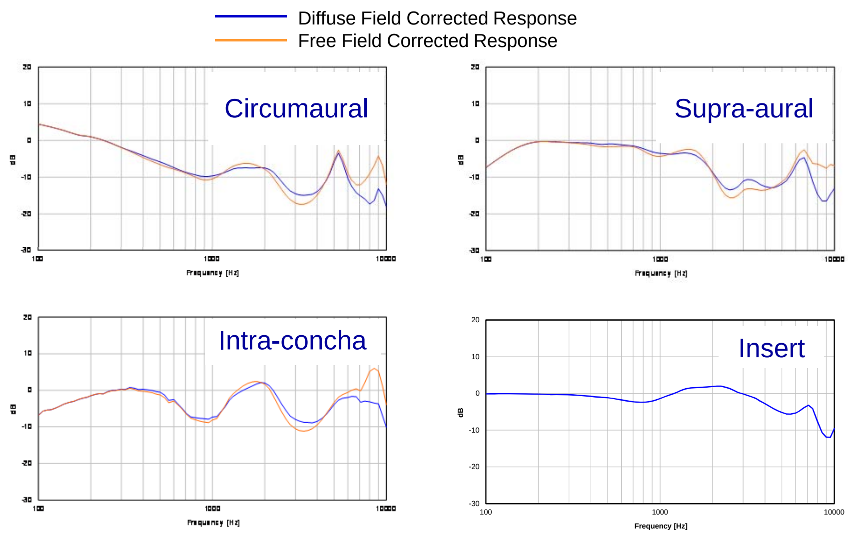


- *Maps to perceived response*
- *Simplifies visualization and tolerance application*
- *Important range: 300 Hz – 8 kHz*

Measured Responses at DRP



Resulting Insertion Gain



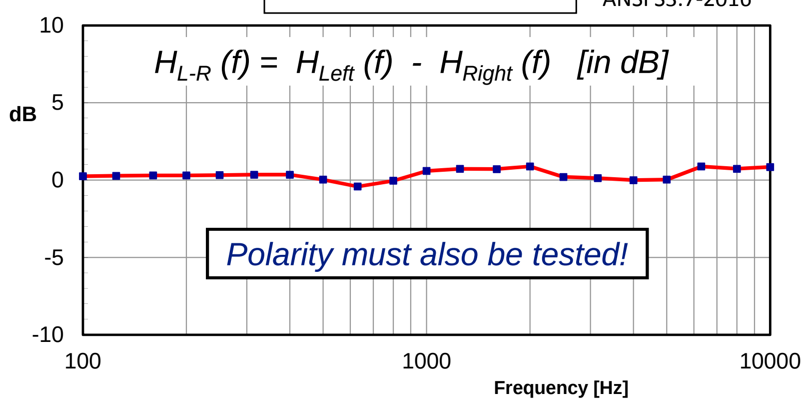
Left-Right Tracking

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

In each 1/3 octave band:

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

ANSI S3.7-2016

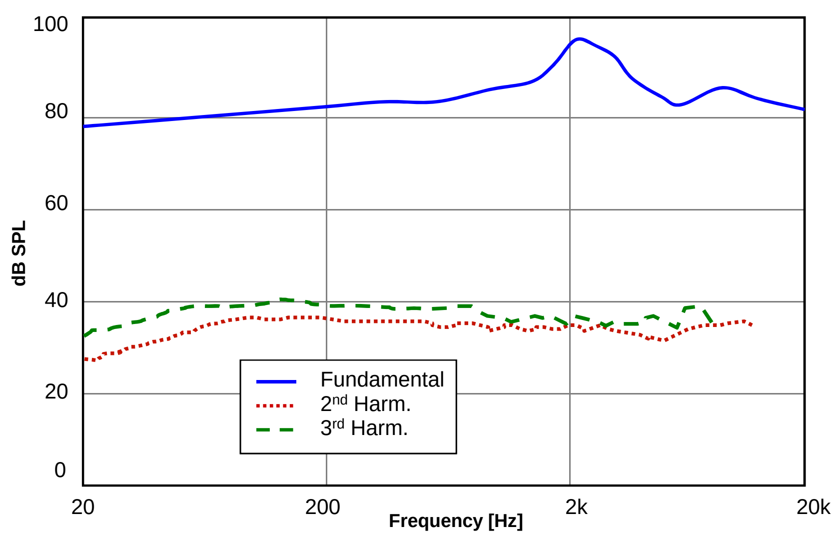


Polarity Test Methods

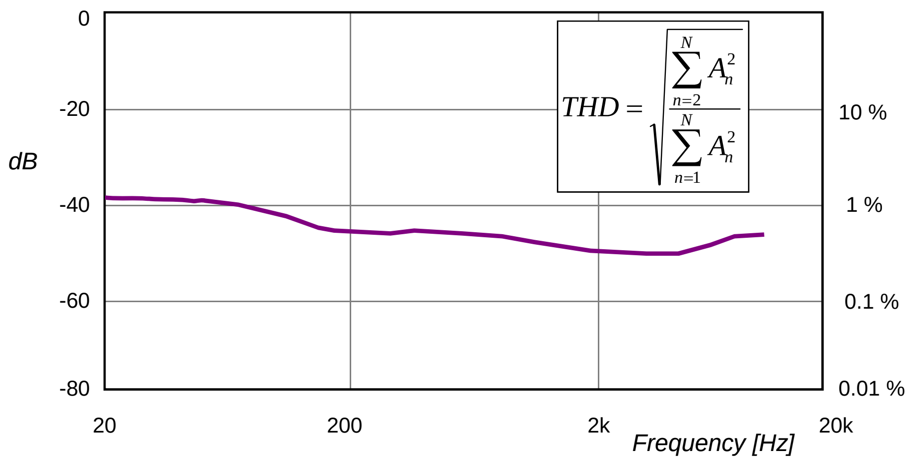
- Low Frequency Phase comparison
  - $\phi(f)$ asymptotes toward 0° or 180°
- $H_L(f) + H_R(f)$ complex summation
  - Magnitude: +6 dB or noise floor
  - Change in shape of Lissajous figure
- Time Domain Pulse
  - Positive or negative going waveform

Harmonic Distortion

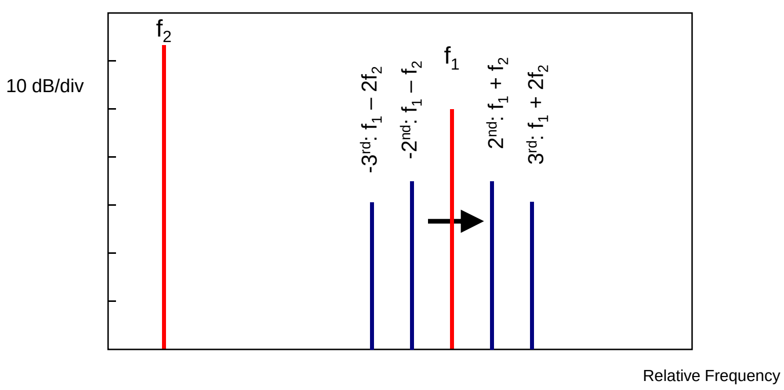
at Rated Voltage



THD vs. Frequency

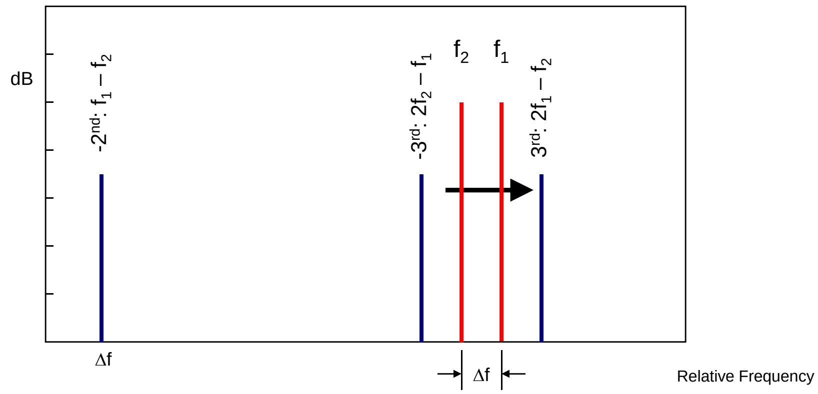


Intermodulation Distortion



- 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

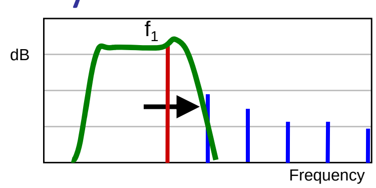


- f_1 & f_2 each at -6 dB re: Rated Voltage, stepped or swept.
- $\Delta f = f_1 - f_2 = 80$ Hz
- Δf is the frequency interval between distortion products
- Odd-order products follow as a group with f_1 & f_2 . Even order products fixed.

Distortion Measurements in Band Limited Systems

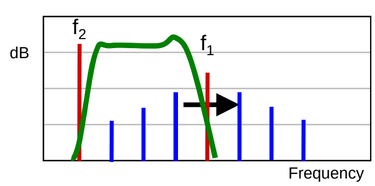
Harmonic Distortion

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



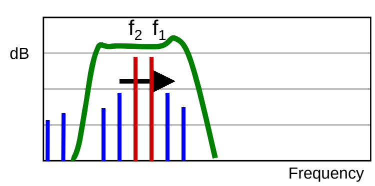
Intermodulation Dist.

- f_2 below passband *OR* IM products outside passband

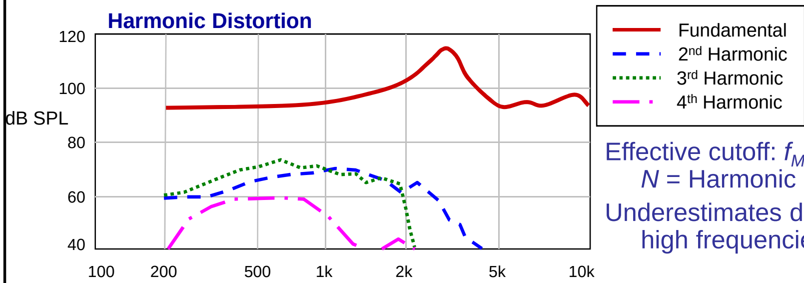


Difference Frequency Dist.

- Odd-order products within passband
- Even-order products may be inside or outside passband

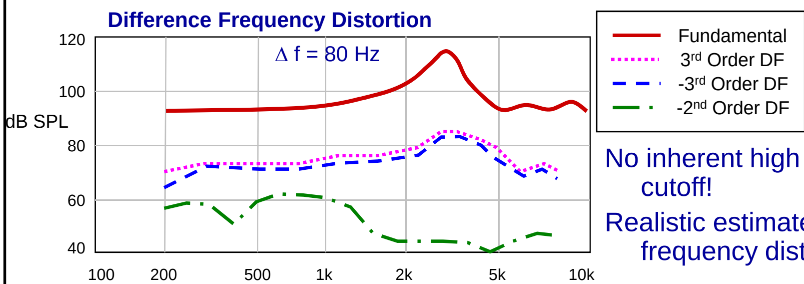


Diff. Freq. vs. Harmonic Distortion



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

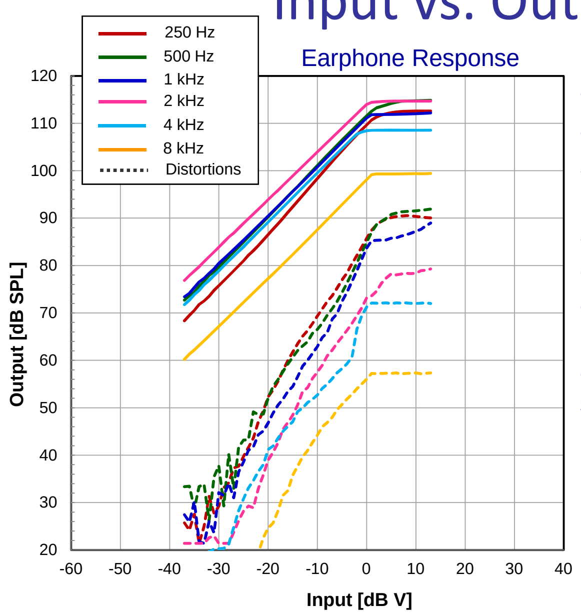
Underestimates distortion at high frequencies



No inherent high frequency cutoff!

Realistic estimate of high frequency distortion

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

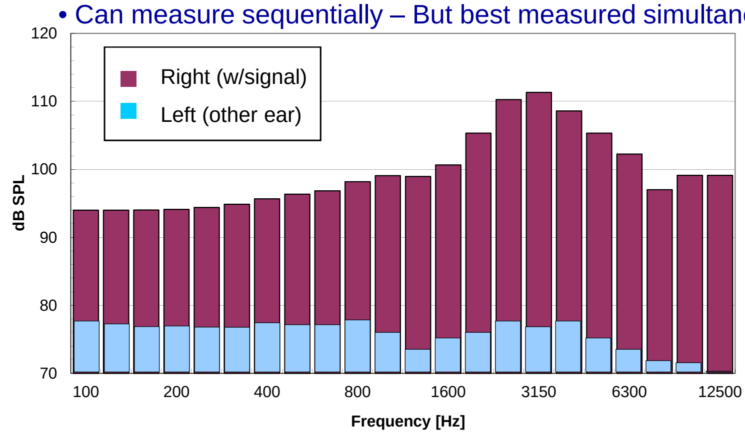
ANSI S3.7-2016

Crosstalk

In each 1/3 octave band:

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

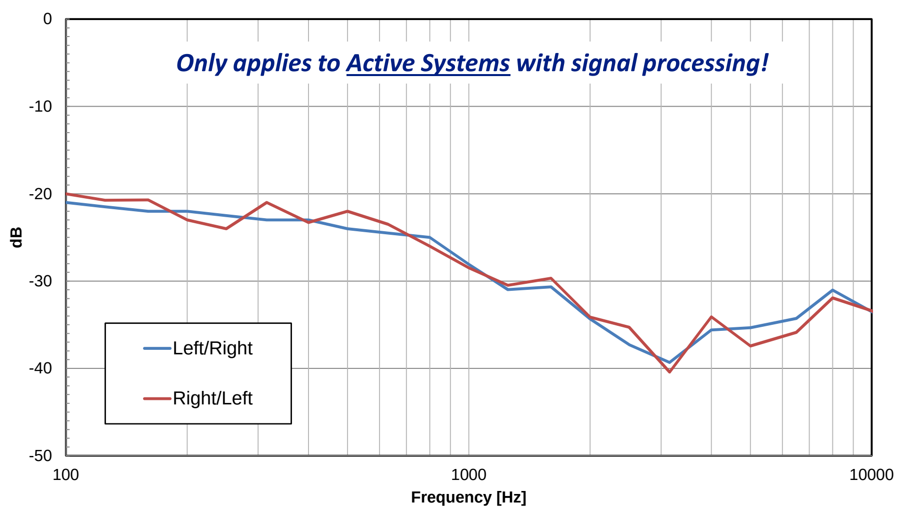
- Requires 2 Ear Simulators
- Measurement S/N is poor:
  - Use 94 dB SPL sinusoidal test signal
  - Convert to 1/3 octave as power summation*
  - Check background noise level (≤ -10 dB in each band!)
- Can measure sequentially – But best measured simultaneously



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*



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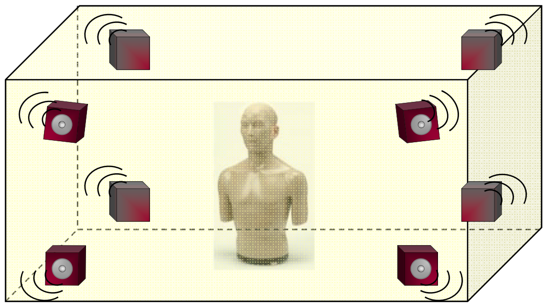
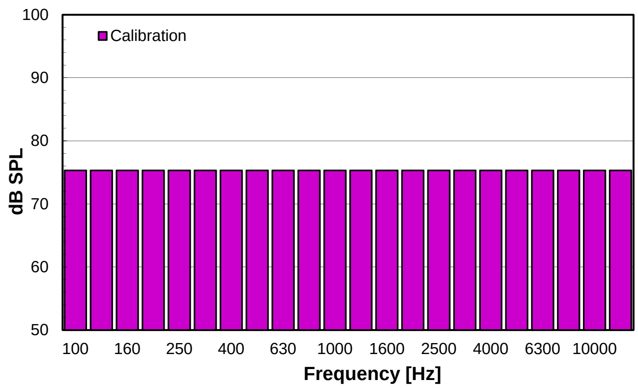
Noise Isolation



Diffuse Noise Field

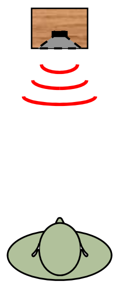
- Reverberant Room and/or Uncorrelated Sources
- 90 dB SPL at Test Point

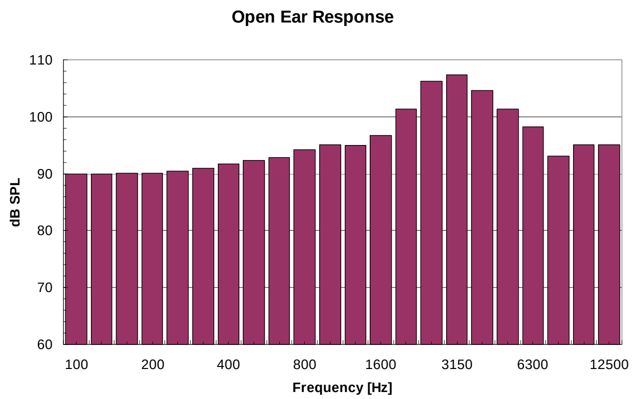
Noise Isolation - 1



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

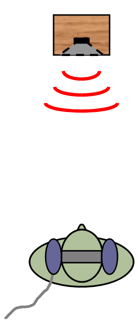
Noise Isolation - 2

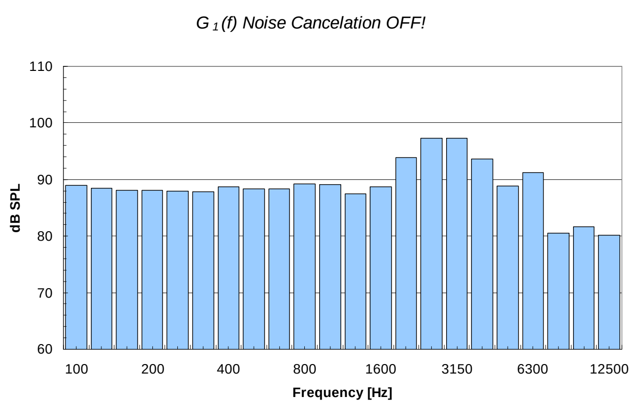




90 dBSPL Pink Noise w/ Real-time Filter Analysis *OR* FFT + 1/3 Octave Synthesis

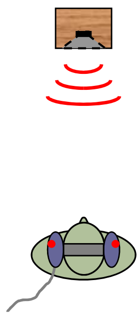
Noise Isolation - 3

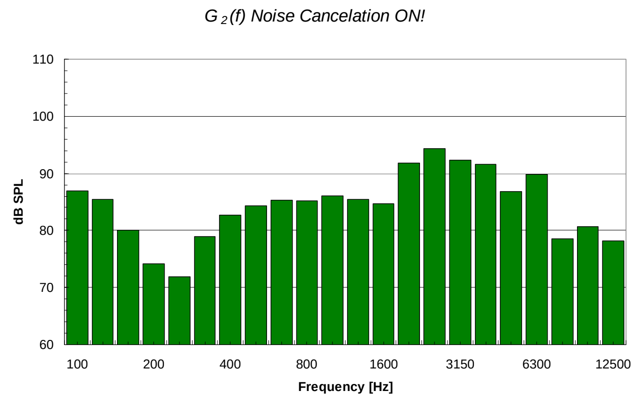




90 dBSPL Pink Noise w/ Real-time Filter Analysis *OR* FFT + 1/3 Octave Synthesis

Noise Isolation - 4





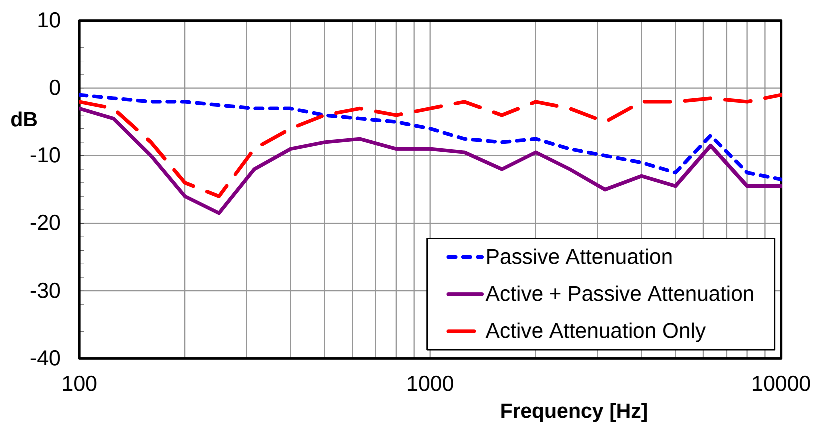
90 dBSPL Pink Noise w/ Real-time Filter Analysis *OR* FFT + 1/3 Octave Synthesis

Noise Isolation

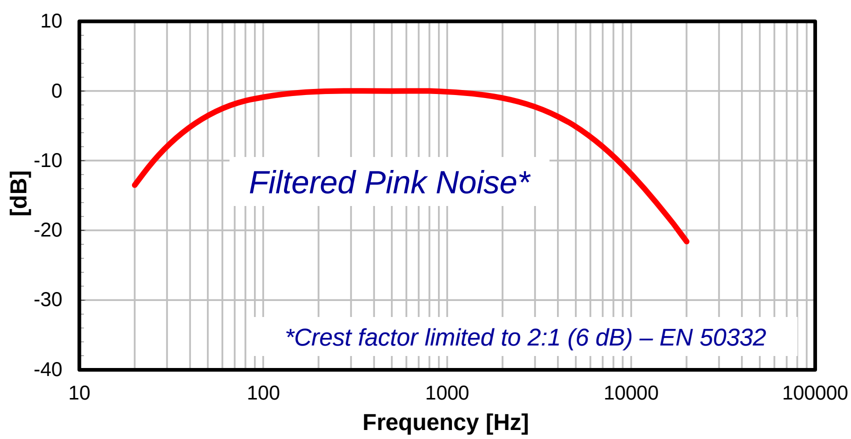
$L_{Passive}(f) = G_{NR\text{-}OFF}(f) - G_{Open\ Ear}(f)$ [in dB]

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

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

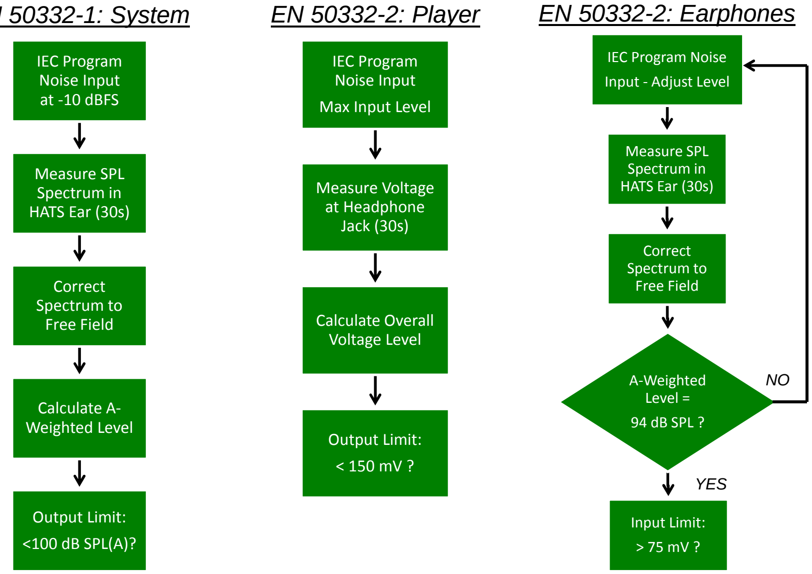


IEC 60268-1 Simulated Program Spectrum



EN 50332 Maximum Output

EN 50332-1: System *EN 50332-2: Player* *EN 50332-2: Earphones*



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

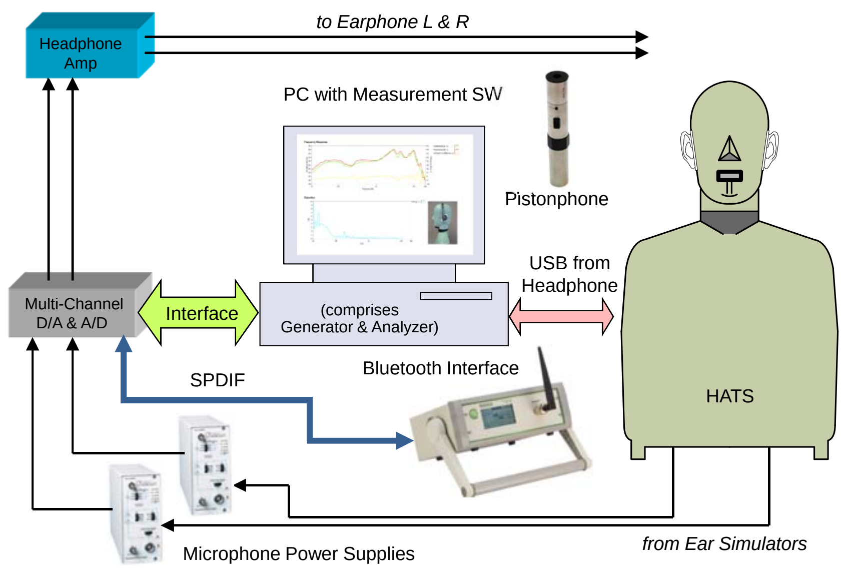
NOTE: THIS IS A DESTRUCTIVE TEST!

A Minimum Test Suite

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

[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)

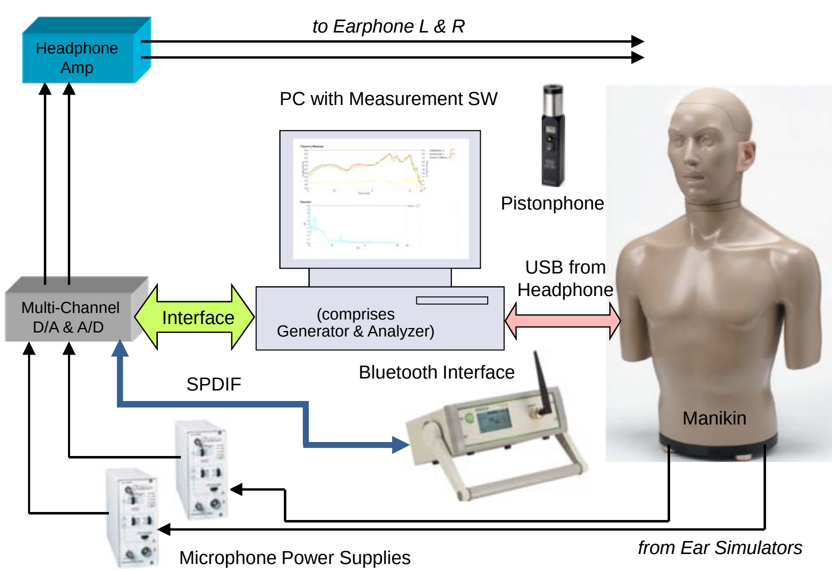
- Insertion Gain
  - A *FLAT INSERTION GAIN* is the target!
  - *This is 'corrected' from the measured response at DRP.*
- Acoustic Impedance
  - *Low Acoustic Z = Open*
  - *High Acoustic Z = Sealed*
- Test System and Tests
  - Requires a manikin equipped with calibrated ear simulator(s)
  - Sine *AND* 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

Headphone Test System



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).
- C. J. Struck and S. F. Temme, *"Headphone Response: Target Equalization Trade-offs and Limitations"*, presented at the Audio Engineering Society 139th Convention – New York, NY (2015 October 29 – November 1).
- C. J. Struck, *"Free Plus Diffuse Sound Field Target Earphone Response Derived From Classical Room Acoustics Theory"*, presented at the Audio Engineering Society 135th Convention – New York, NY (2013 October 17-20).
- 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.
- C. J. Struck, *"Evaluation of Headphone Performance with a Head And Torso Simulator"*, presented at the 13th International Congress on Acoustics - Zagreb, (1989 August 24-31).