Electroacoustic Measurements of Headphones

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Overview
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- Orthotelephonic & Diffuse Field Responses
- Acoustic Impedance
- Couplers, Ear Simulators & Manikins
- Electroacoustic Measurements
  - Electrical Impedance
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  - 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

Including distance attenuation and obstacle effect of the head
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
This is the typical target for
headphones measured at DRP

Random Incidence OR
Power Sum of ALL HRTFs in 3D
Acoustic Impedance

Thévenin Equivalent

Norton Equivalent

Ohm's Law

\[ Z_A = \frac{p}{U} \] [ N·s/m² (mks acoustic ohms)]

Low \( Z_s \) Pressure Source
High \( Z_s \) Volume Velocity Source

\[ \therefore Z_A \cdot f \propto \frac{1}{V_{Equivalent}} \]

The Effect of Leakage on Response

...assuming a high acoustic impedance source

Outer Ear & Pinna

Darwin's Tubercle
Anti-Helix
Crest of Helix
Crus
Canal
Tragus
Lobe
Earphone Types

<table>
<thead>
<tr>
<th>Earphone Type</th>
<th>Circumaural</th>
<th>Supra-aural</th>
<th>Supra-concha</th>
<th>Intra-concha</th>
<th>Insert</th>
</tr>
</thead>
</table>

Acoustic Couplers

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

A Brief History of some Legacy Couplers:

- **NBS 9A (6cc) Coupler**
  - ca. 1950
  - ca. 1968 (standardized)

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

- **Braun Coupler**
  - ca. 1953
  - DIN standard ca. 1969

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

- **NBS 9A (6cc) Coupler**
  - Hearing Aid & Insert Earphone QC/QA
  - Audiometer Calibration

- **Braun Coupler**
  - DIN standard ca. 1969
  - Telephone Handset Testing (Legacy)

Artificial Ear

IEC 60318 (ITU-T Type 1)

- ca. 1962-68 (standardized 1973)

- *Ear Reference Point or Concha bottom*

- Audiometer Calibration
- Telephone Handset Testing (Legacy)

Ear Simulators

- **IEC 60711 Ear Simulator**
  - 1973, standardized 1979

- **ANSI S3.25-1989 Ear Simulator**
  - a.k.a. Zwischen Coupler, 1971

- Measurement Microphone Diaphragm is at DRP!
**IEC 60711 Ear Simulator**

**Acoustic Transfer Impedance**

- Frequency [Hz]
- Acoustic Transfer Impedance (ATZ) [dB]

**Pinna Simulators**

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

- Type 3.2
- Type 3.3
- Type 3.4

**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)

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)

HATS Free Field Response

KEMAR Free Field Response with Zwislocki Coupler
**Test System**

(adapted from IEC 60268-7)

- Headphones or earphone to be measured
- Pinna simulator
- Free or Diffuse Field Correction, if necessary
- A weighting filter, if necessary

**Electrical Impedance**

For $R \ll 0.1 |Z_{MIN}(f)|$ (typically 0.1 $\Omega$):

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

**Electrical Impedance**

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

**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 source impedance (120 ohms), across the input connector of the headphone. This is the SPL for 1 mW input.

\[
V = IR, P = VI
\]

\[
P = \frac{V^2}{R} = \frac{V^2}{Z_0}
\]

\[
V^2 = PZ_0
\]

\[
V = \sqrt{PZ_0} = \sqrt{0.001 \times Z_0}
\]

\[
V = 0.0316\sqrt{Z_0}
\]

- **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.

**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!**

**IEC 60268-1 Simulated Program Spectrum**

**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 (500 Hz – 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**

\[
\begin{align*}
H_{DFC}(f) &= H(f) - H_{DF}^{0,0}(f) \quad \text{[in dB]} \\
H_{FFC}(f) &= H(f) - H_{FF}^{0,0}(f) \quad \text{[in dB]}
\end{align*}
\]

This is the Insertion Gain!

**Left-Right Tracking**

\[
L(f) = 10 \log_{10} \left( \frac{\sum_{i=1}^{N} 10^{\left( L_i / 10 \right)}}{N} \right)
\]

Responses 1/3 octave power averaged

**Crosstalk**

- 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 (\( \leq -10 \text{ dB} \) in each band)
- Can measure sequentially – Best measured simultaneously

\[
C_{CL}(f) = G_{CL}(f) - G_{LR}(f) \quad \text{[in dB]} \quad \text{for signal applied to RIGHT Ear}
\]
Harmonic Distortion at Rated Voltage

- Frequency [Hz]
- dB SPL
- Fundamental
- 2nd Harm.
- 3rd Harm.

THD vs. Frequency

- THD = \( \sum A_i^2 / \sum A_i^0 \)
- Frequency [Hz]
- dB
- 0.01 %
- 0.1 %
- 1 %
- 10 %

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
- \( \Delta f \) 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

Intermodulation Dist.
- \( f_1 \) 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: \( f_{\text{MAX}} / N \)
where \( N \) = Harmonic order
Underestimates distortion at high frequencies

Noise Isolation

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

90 dB SPL 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

Open Ear Response

Noise Isolation - 3

G1 (f) Noise Cancelation OFF!

Noise Isolation - 4

G1 (f) Noise Cancelation ON!
### Noise Isolation

- Passive Attenuation
- Active + Passive Attenuation
- Active Attenuation Only

\[
L_{\text{Passive}}(f) = G_1(f) - G_{\text{Open Ear}}(f) \quad \text{[in dB]}
\]
\[
L_{\text{Active + Passive}}(f) = G_2(f) - G_{\text{Open Ear}}(f) \quad \text{[in dB]}
\]
\[
L_{\text{Active}}(f) = L_{\text{Active + Passive}}(f) - L_{\text{Passive}}(f) \quad \text{[in dB]}
\]

### Conclusion

- **Insertion Gain** – *This is the TARGET!*
- Orthotolephonic & 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!

### References

- J. Borwick, Loudspeaker and Headphone Handbook 3rd Ed. 2001