ELEC-5630 Acoustics and Audio Technilogy Seminar

Headphone acoustic coupling to the ear and equalization methods for binaural reproduction

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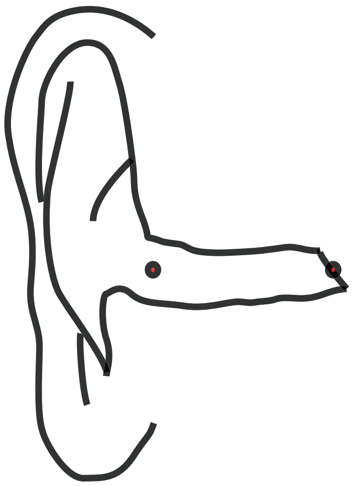
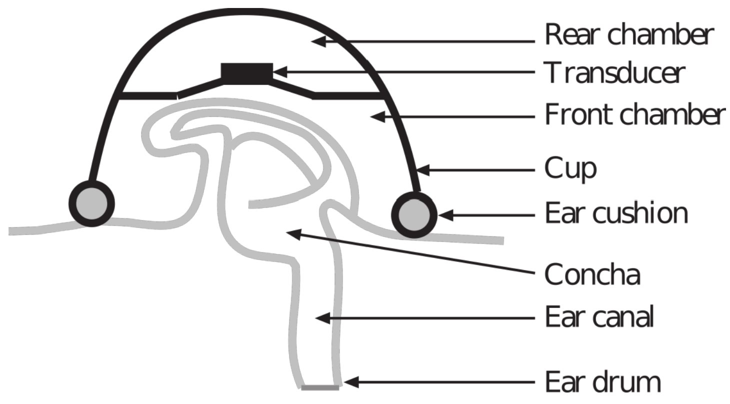
hefio

Outline

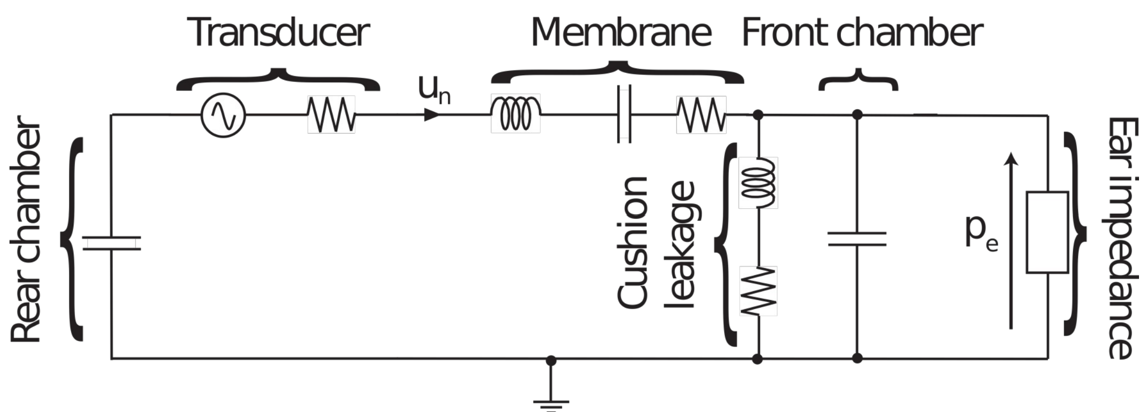
- Acoustic system description
  - Pressure chamber principle
  - Transmission line model
- Equalization for binaural rendering
  - Model of the external ear
  - Binaural filter design
    - Headphone response inversion
    - Binaural filters post-EQ
- Hefio self-calibrated headphones



Acoustic system

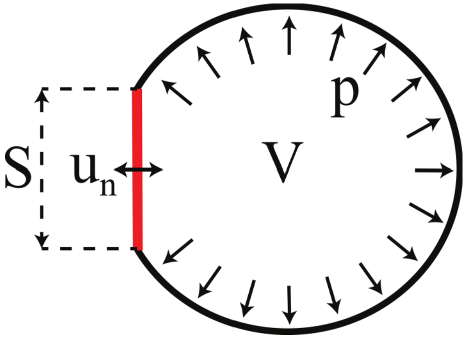


- Radiating element is close to the ear
- Ear is somehow enclosed
- All elements of the headphone may affect its acoustic properties
- Shifting of the headphone position may change its response
- Different type of headphones requires different approaches

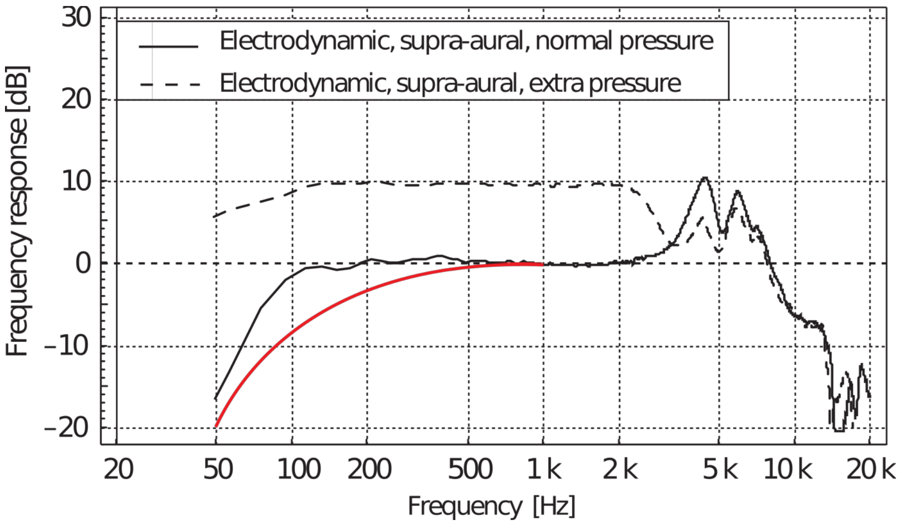


Pressure chamber principle

- Wavelength >> maximum dimension
- γ ratio of specific heats
- p_o atmospheric pressure
- Pressure inside V is proportional to the velocity of the vibrating surface
- Pressure is uniformly distributed
- Sensitive to leakage

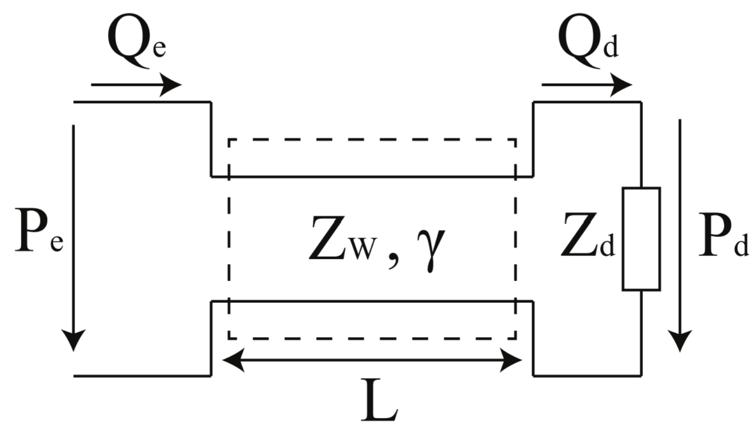


$$p = j\frac{\gamma\, p_0\, S}{\omega V} u_n$$



Transmission line model

- Models the ear canal
- Wavelength > diameter of ear canal
  - Plane wave propagation
- γ propagation coefficient
- L length of the ear canal



- L is not constant with frequency
- γ contains absorption that is hard

to model/measure

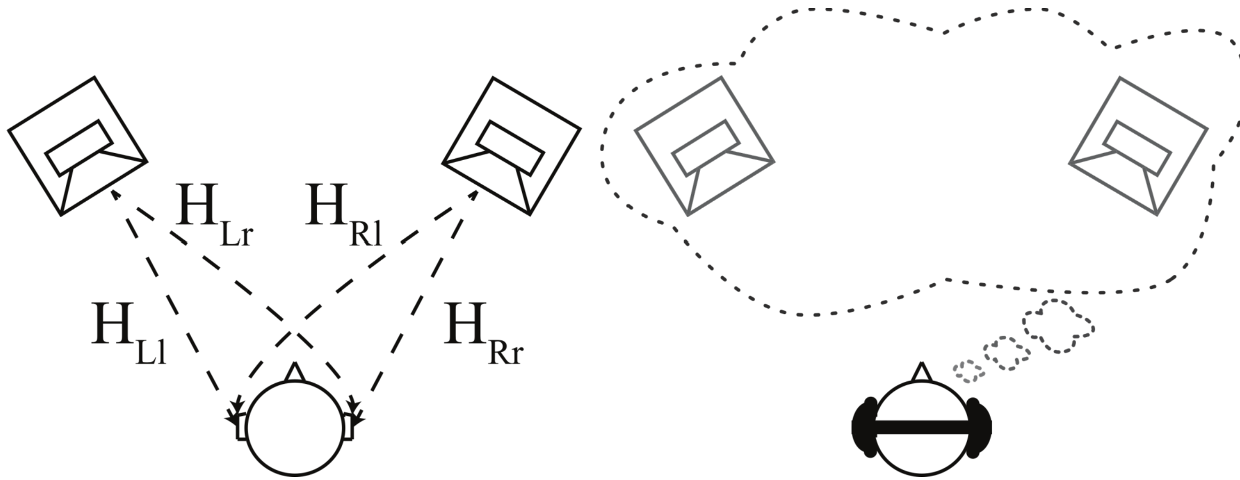
- Z_d is unknown

$$\begin{bmatrix} P_e \\ Q_e \end{bmatrix} = \begin{bmatrix} \cosh(\gamma L) & Z_w \sinh(\gamma L) \\ \frac{1}{Z_w} \sinh(\gamma L) & \cosh(\gamma L) \end{bmatrix} \begin{bmatrix} P_d \\ Q_d \end{bmatrix}$$

$$\gamma = \alpha + jk\omega$$

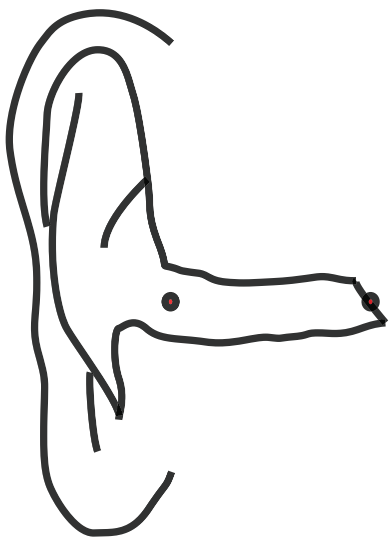
Equalization for binaural rendering

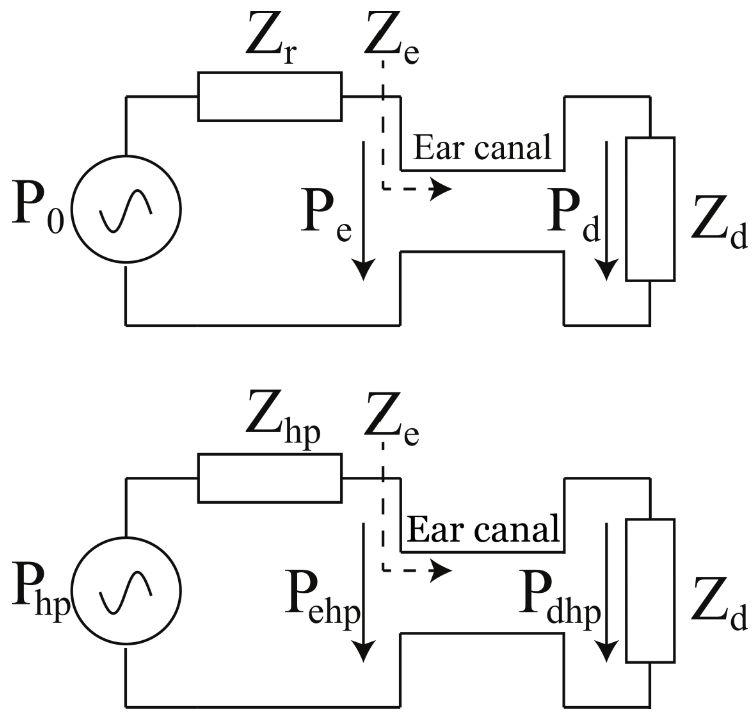
- Synthesis of sound signals at the listener's ears for emulating the auditory impression of real sources
- Using measured or simulated binaural responses (HRTF, BRIR), or binaural recordings



Model of the external ear [1]

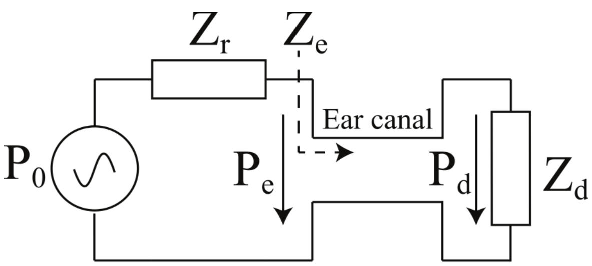
- P_o and P_{hp} are the sound signals at the entrance of the blocked ear canal for the free-air and headphone cases
- Z_r and Z_{hp} is the radiation impedance of the ear for both cases





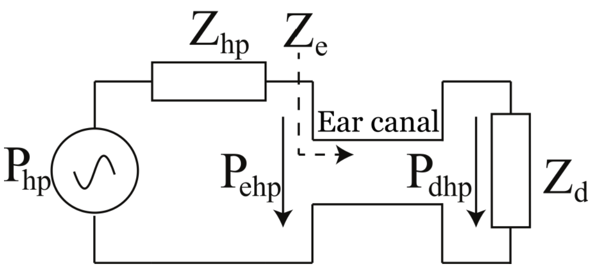
Binaural filter design [1]

- P_o , P_e, and P_d can be a HRTF, BRIR, or binaural recordings (Individual vs generic)
- P_{hp}, P_{ehp}, and P_{dhp} (HpTF) should be inverted
- **Inversion may be a problem**



- *Ideal case:*

$$H_D = \frac{P_d}{P_{d_{hp}}}$$



- *Blocked ear:*

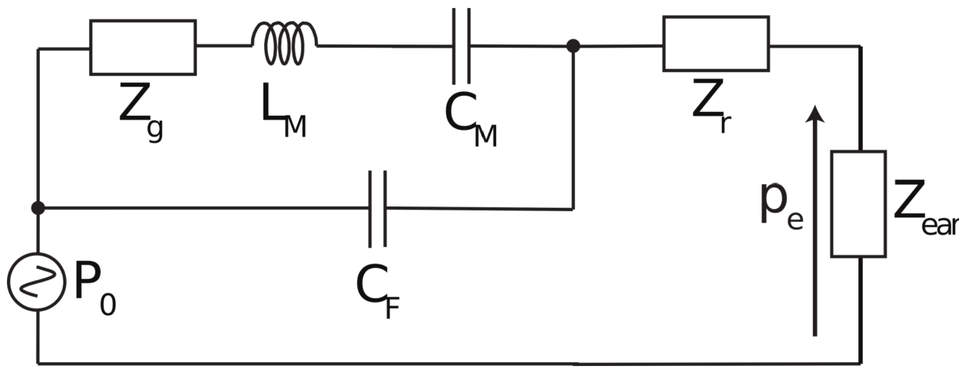
$$H_B = \frac{P_0}{P_{hp}}$$

- *Open ear:*

$$H_E = \frac{P_e}{P_{e_{hp}}} = \frac{P_0}{P_{hp}} \frac{Z_r + Z_e}{Z_{hp} + Z_e} = \frac{P_d}{P_{d_{hp}}}$$

Binaural filter design

- **Blocked ear:**
  - If $Z_{hp} = Z_r$, the headphone is Free-air equivalent coupling (FEC) compliant



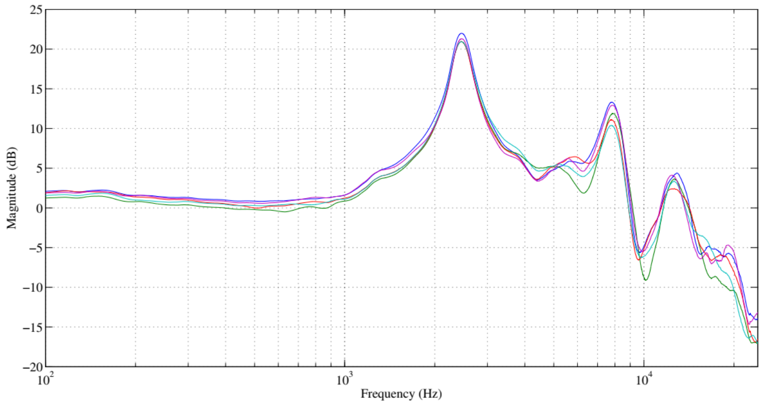
and $H_B = H_D$

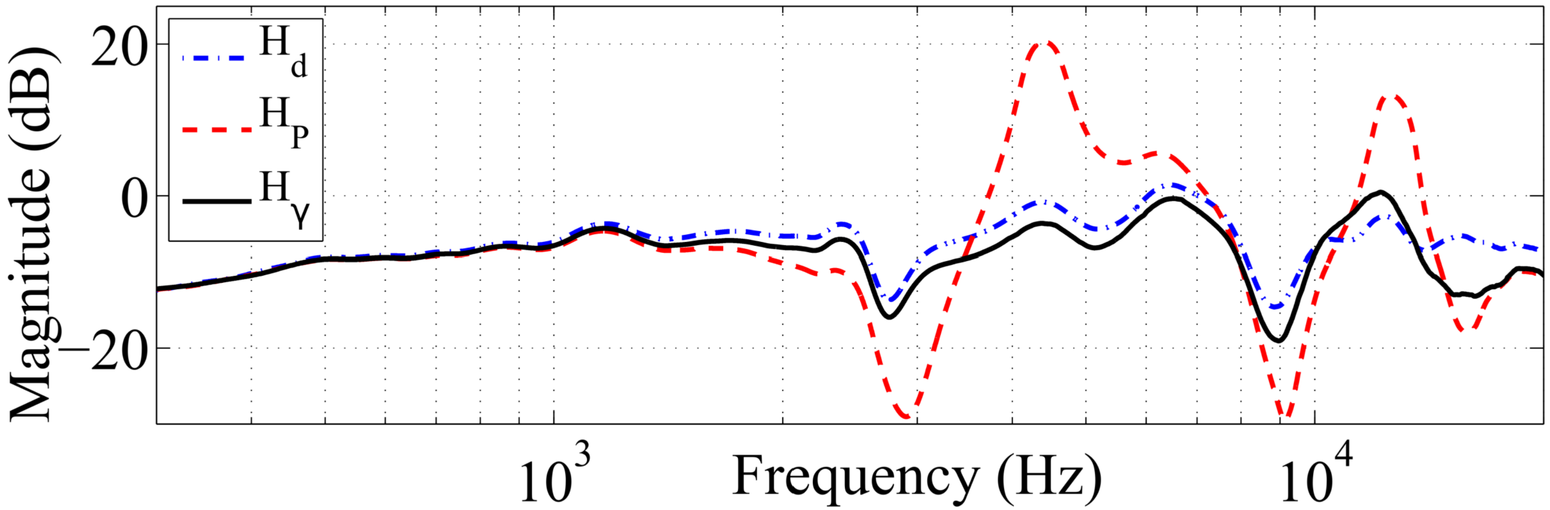
  - But only few headphones are close to be FEC compliant

Binaural filter design

- **Open ear:**
  - Entrance position is hard to define
  - If P_{ehp} position changes with respect

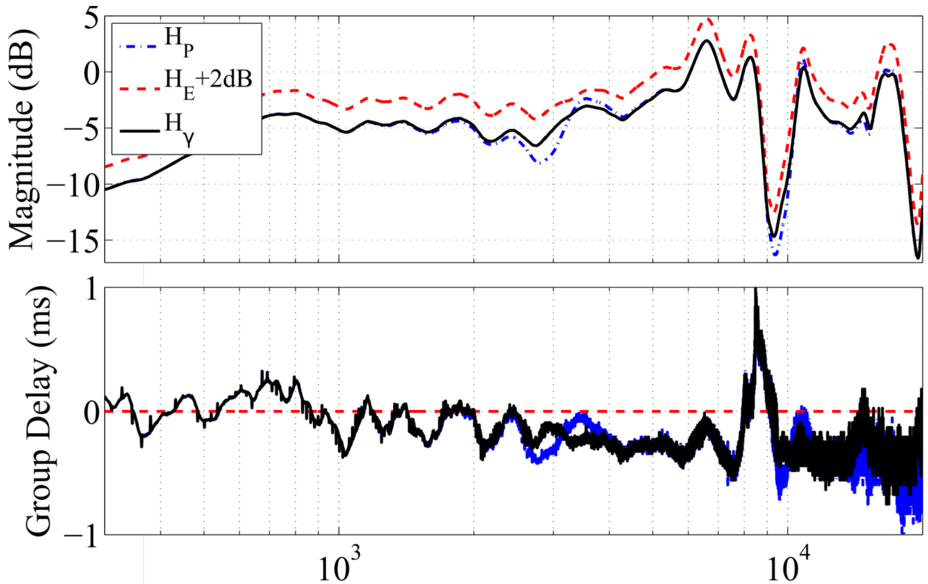
to P_e large errors can occur





Binaural filter design [2] [3]

- **At eardrum:**
  - Hazardous in practice
  - Can be estimated if P_e and U_e are known: → Microflown
  - Immune to microphone shift (till some degree)



$$|P_d| = \sqrt{|P_e|^2 + |Z_o U_e|^2}$$

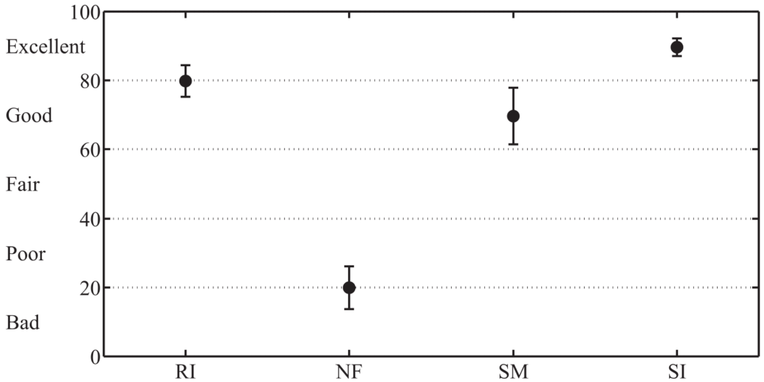
$$\gamma_L = atanh\left(\frac{Z_o}{Z_e}\right)$$

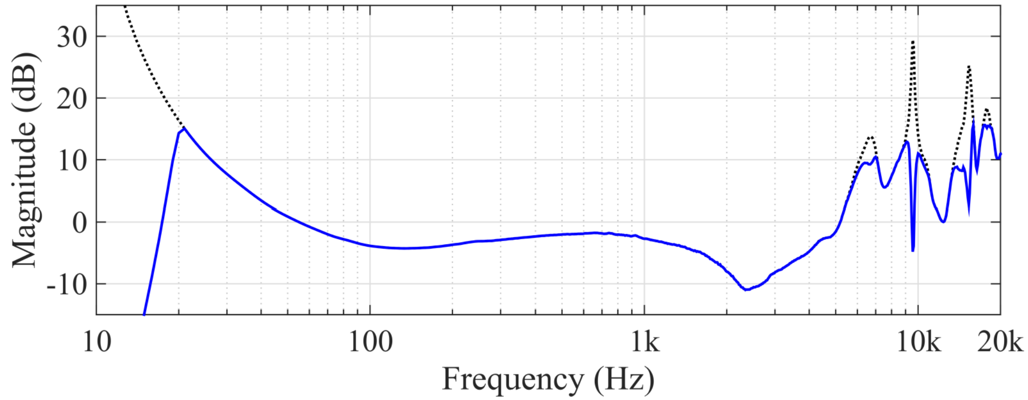
$$P_d = P_e \cosh(\gamma_L) - Z_0 U_e \sinh(\gamma_L)$$

Headphone response inversion

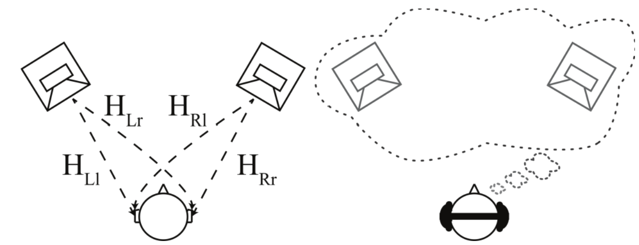
- When inverting the HpTF, large notches should be avoided to minimize errors due to repositioning or mic displacement
- Typical methods: Regularized inversion, HpTF Smoothing, statistical smoothing
- **Sigma regularization**: automatic regularization factor [4]

$$HpTF^{-1} = \frac{\widetilde{HpTF}}{\left|HpTF^{2}\right| + \left(\alpha + \sigma^{2}\right)}$$

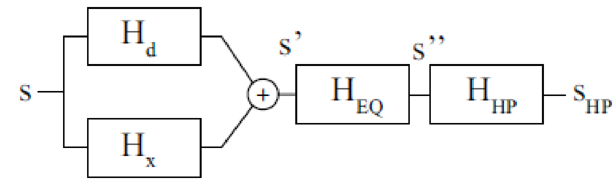




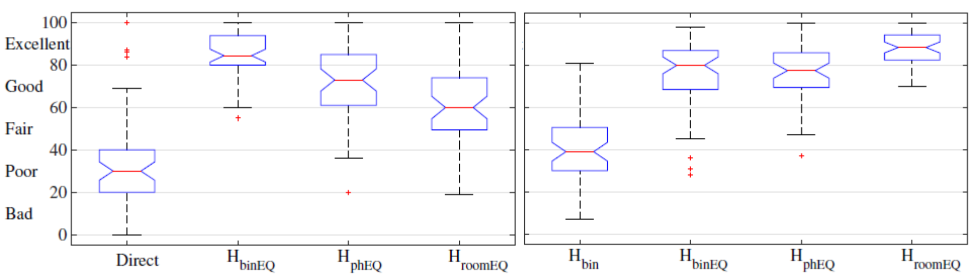
Binaural filters post-EQ

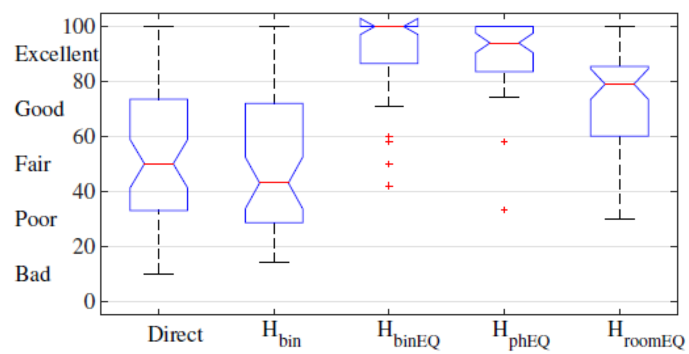


- Post-EQ of binaural filters for better sounding
- **Stereo enhancements:**
  - Add spatial information to the sound
  - Based in some type of binaural rendering
  - Timbre is affected



- Method to preserve the sound quality of the headphone [5]
  - Flatten the sum of the cross-talk to maintain the headphone sound characteristics





Bibliography

[1] H. Møller, *"Fundamentals of binaural technology"*, Applied Acoustics '92.

[2] M. Hiipakka, M. Karjalainen, and V. Pulkki, *"Estimating pressure at eardrum with pressure-velocity measurement from ear canal entrance,"* WASPAA '09.

[3] J. Gómez Bolaños, and V. Pulkki, *"Estimation of pressure at the eardrum in magnitude and phase for headphone equalization using pressure-velocity measurements at the ear canal entrance,"* WASPAA '15.

[4] J. Gómez Bolaños, A. Mäkivirta, and V. Pulkki, *"Automatic regularization parameter for headphone transfer function inversion,"* JAES '16.

[5] J. Gómez Bolaños, A. Mäkivirta, and V. Pulkki, *"Headphone stereo enhancement using equalized Binaural responses to preserve headphone sound quality,"* AES Headphone Conference '16.

Hefio

- Design of a self-calibrated headphone
  - Founded by D.Sc (Tech) Marko Hiipakka
  - Headphone measures the user's ear acoustics and flattens its response at the eardrum

Hefio One: (obsolete)

- Mobile/PC App
- DSP in server
- Flattens response at eardrum
- Introduce a "natural" target function

Hefio

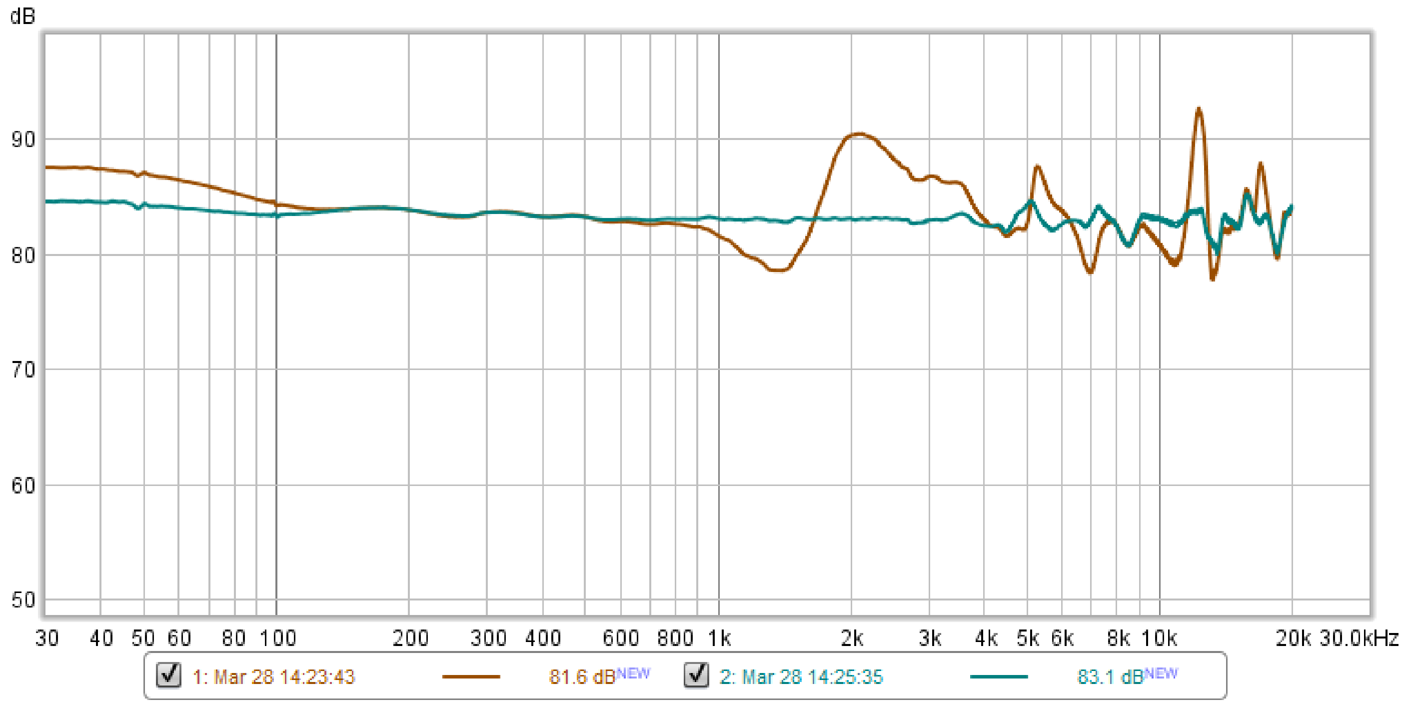
Hefio Play:

Intended for professionals who want a portable "studio" (or configurable) sound

- Autonomous system
- USB powered
- DSP embedded
- Flattens response at eardrum
- GUI for configuration
- Introduce selectable target function
- Selectable binaural stereo filters
- 3-bands EQ
- Extra functionality:
  - Sound level meter
  - Sound level exposure time

Hefio

Response at the eardrum of an artificial ear after calibration on human's ear (brown) and on artificial ear (green)



Thanks for your attention!

Any question?

Do you want to test the demo?