Audibility of linear distortion in loudspeakers

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Outline

- Introduction: what can we hear and what should we measure?
- Audibility of resonances in loudspeakers
- Audibility of phase mismatch
Introduction

• Floyd Toole: “Frequency response is the single most important aspect of the performance of any audio device.”

• In the case of loudspeakers, what frequency response?
  – On-axis, off-axis, both?
  – Magnitude only, or does phase matter?

• What are the measurements that are the most useful to predict what we can hear?
Introduction (cont’d)

• Factors affecting loudspeaker response
  – Transducer bandwidth
  – Diffraction
  – Directivity pattern
  – Cross-over
  – Resonances
  – Non-linear distortion
Time/frequency analysis

- Cumulative spectral decay (CSD)

\[ CSD(\tau, f) = \int_{\tau}^{\infty} h(t) e^{-j2\pi ft} dt \]

Dyreby & Choisel, 2007
Time/frequency analysis

- Period-based cumulative spectral decay (PCDS)

\[ \text{PCSD}(p, f) = \int_{\frac{P}{f}}^{\infty} h(t) e^{-j2\pi ft} dt \]

Dyreby & Choisel, 2007
Audibility of resonances

• Summary of literature
  – Peaks more audible than dips
  – High Q factor less audible than low Q
  – High-frequency resonances less audible than low-frequency ones
  – Stimulus type
  – Test environment
Listening test

- Selection of “typical” resonances

Uprichard & Choisel, 2008
Listening test – factors

• Resonances
  – Low freq. (700-1000 Hz) – Low Q (8)
  – High freq. (6-8 kHz) – High Q (30)

• Programme material: pop/classical

• 3 acoustic environments
  – Headphones
  – Listening room
  – Car

• 12 subjects

Uprichard & Choisel, 2008
Listening test – GUI

You are listening to stimulus...

1 2 3

The different stimulus is...

1 2 3

Your last answer was...

Correct

Click NEXT or hit the SPACE BAR when done.
Listening test – procedure

• 3-alternative forced choice

Uprichard & Choisel, 2008
Listening test – results

- Resonances are more audible at a lower Q
- Frequency has a small effect
- Acoustic Environment has a significant effect for Classical music

Uprichard & Choisel, 2008
Audibility of phase distortion

- **Ohm (1843):** The relative phase of the harmonic components has no audible effect.
- **Hartmann:** In general the relative phase between two signal components should be irrelevant if the two components are separated by more than a critical bandwidth.
- **Blauert and Laws (1978):** Group delay thresholds between 1 and 3.2 ms.
- **Lipshitz et al. (1982):** Even quite small midrange phase nonlinearities can be audible on suitably chosen signals.
Audibility of phase distortion

• Toole: within very generous tolerances, humans are insensitive to phase shifts. Under carefully contrived circumstances, special signals auditioned in anechoic conditions, or through headphones, people have heard slight differences. [...] When auditioned in real rooms, these differences disappear.

• Summary
  – Absolute phase distortion difficult to hear in realistic conditions
  – BUT relative phase distortion (between channels) may be more audible!
Phase mismatch

Choisel & Martin, 2008
Listening test

• 8 subjects
• Procedure: 3-AFC
• Broad-band pink noise, or
• Octave-band filtered pink noise (3rd order)
  – 8 bands centred at 63, 125 ... 8000 Hz
  – Same centre frequency as phase mismatch
• 2 playback conditions:
  – Headphones
  – Loudspeakers

Choisel & Martin, 2008
Part 2 – Results

- **Narrow-band vs. broadband**

![Graph showing frequency mismatch and maximum phase difference for narrow-band and broadband headphones.](image)

Choisel & Martin, 2008
Part 2 – Results

• Narrow-band vs. broadband

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Choisel & Martin, 2008
Discussion

• Narrow-band vs. broad-band
  – Higher thresholds for narrow-band noise at high freq. →
    cues at lower frequencies were used in Part 1
  – Comparable thresholds at low frequencies → refutes the
    hypothesis of informational masking
  – Decrease in sensitivity might be level-dependent

• Loudspeakers vs. headphones
  – At low frequencies, higher thresholds for loudspeakers →
    spatial cues, lessened by cross-talk and room
  – At high frequencies, higher thresholds for headphones →
    interaural (spatial) cues cannot be used, timbral cues used
Implications

• Very low phase mismatch (7 deg) can be heard in headphones, this has implications on
  – Transducer matching
  – Headphone equalisation

• In loudspeakers placed in a listening room, the thresholds are much higher (50 deg. on average)
  – But very large differences between subjects – training increases sensitivity
Questions?