8-5-2021

# A Constrained Optimal Hear-Through Filter Design Approach for Earphones

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# A constrained optimal hear-through filter design approach for earphones

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# Introduction



## ❑ Hear-through function

- Sound can be altered when transmits through an earphone.
- People will hear unnatural environment sound when wearing an earphone.
- Hear-through function reproduces the environment sound using earphone speakers.

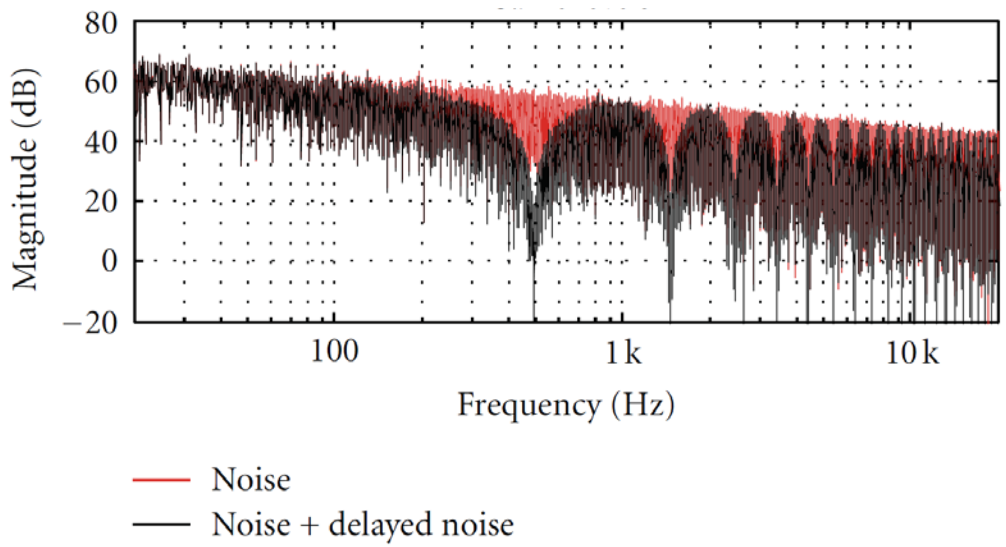
## ❑ Applications of hear-through function

- One popular function in many earphones.
- An important technique in achieving better augmented reality audio (ARA) performance.

# Two Main Design Approach Categories

## ❑ Direct inverse filter approach

- Flattening the attenuation curve caused by the earphone and/or the ear canal.
- Reproduced sound will combine with leakage environment sound to cause a **comb-filtering effect**.




[Rämö and Välimäki, 2012]

## ❑ Design using an active noise control structure

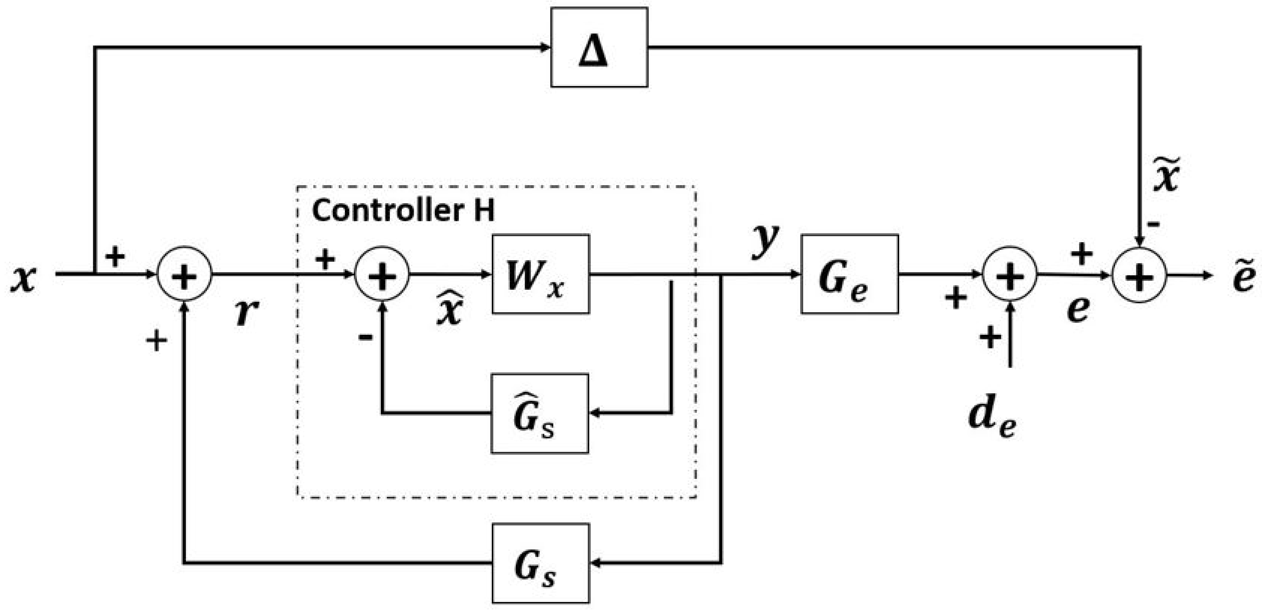
- The leakage sound from environment can be attenuated to reduce comb-filtering effect.
- Many ANC algorithms can be applied in a similar way

For both methods, since sound from speaker will propagate to reference microphone, thus, **robust stability** should be considered

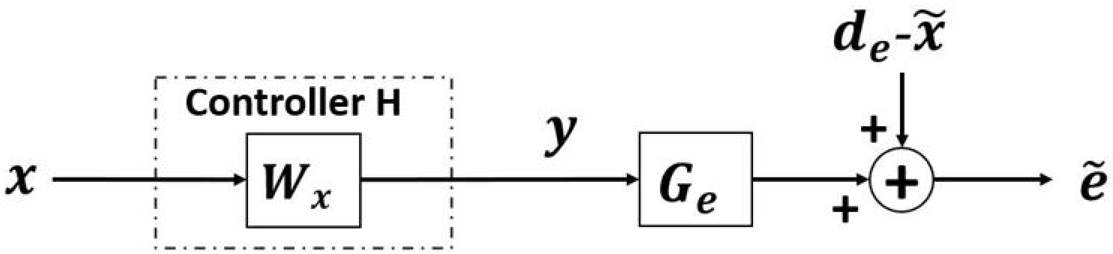
# Proposed Method

- Alleviate comb-filtering effect by using ANC structure
- Constraints like robust stability can be considered
- The desired delay of reproduced sound can be specified if a spatial sound impression is desired.
- Designed hear-through filter can be directly implemented in an ANC system.

# Control System




(a)




(b)

(Non-adaptive control is considered in the current work)

- Minimize the power of $\tilde{\boldsymbol{e}}$
- $\Delta = e^{-j2\pi f\delta}$ is the specified delay between desired sound and reference signal
- The robust stability considered is the closed loop $\boldsymbol{W_x}\ \boldsymbol{\hat{G}_s}$
- Assume a perfect feedback path model $\boldsymbol{\hat{G}_s}$

# $H_2/H_\infty$ Formulation

## Cost function:

$$\sum_{k=1}^{N_f} \mathrm{E}[\tilde{\boldsymbol{e}}(f_k)\tilde{\boldsymbol{e}}^*(f_k)]$$

→ **Total power of $\tilde{e}$ cross all frequencies**

**Constraints:**

Stability: **Use Nyquist criterion:**

$$\mathrm{Re}\{W_x(f_k)\hat{G}_s(f_k)\} > -1$$

Robustness: ***M*- Δ structure and small gain theory:**

$$\left| W_x(f_k)\hat{G}_s(f_k) \right| B(f_k) \leq 1$$

Filter response: **The magnitude of frequency response:**

$$|W_x(f_k)| \leq C(f_k)$$

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**Nyquist criterion, on the right of -1 point**

Robustness: $\boldsymbol{M}$- $\boldsymbol{\Delta}$ **structure and small gain theory:**

$$\left|W_x(f_k)\hat{G}_s(f_k)\right| B(f_k) \leq 1$$

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➡ ***M*- Δ structure and small gain theory**

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$$\left| W_x(f_k)\hat{G}_s(f_k)\right| B(f_k) \leq 1$$

## Filter response:

$$|W_x(f_k)| \leq C(f_k)$$ → **The magnitude of frequency response**

# $H_2/H_\infty$ Formulation - Summary

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## Original Problem

**Cost function:** **Total power of $\tilde{e}$ :**

$$\sum_{k=1}^{N_f} \mathrm{E}[\tilde{\boldsymbol{e}}(f_k)\tilde{\boldsymbol{e}}^*(f_k)],$$

**Constraints:**

Stability: **Use Nyquist criterion:**

$$\mathrm{Re}\{W_x(f_k)\hat{G}_s(f_k)\} > -1$$

Robustness: **$M$- $\Delta$ structure and small gain theory:**

$$\left| W_x(f_k)\hat{G}_s(f_k) \right| B(f_k) \le 1$$

Filter response: **The magnitude of frequency response:**

$$|W_x(f_k)| \le C(f_k)$$

By using the method proposed in previous conferences,
This optimization problem can be solved efficiently.

NEXT WAVE IN NOISE CONTROL ENGINEERING
CATCH THE NOISE-CON 2019
AUG. 26-28
SAN DIEGO, CA

San Diego, CA
NOISE-CON 2019
2019 August 26-28

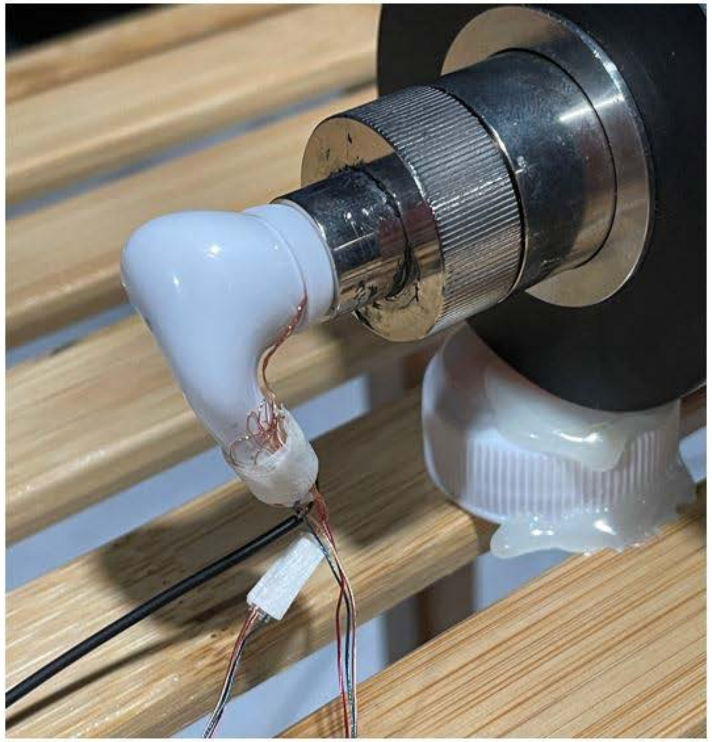
**Study on the Cone Programming Reformulation of Active Noise Control Filter Design in the Frequency Domain**

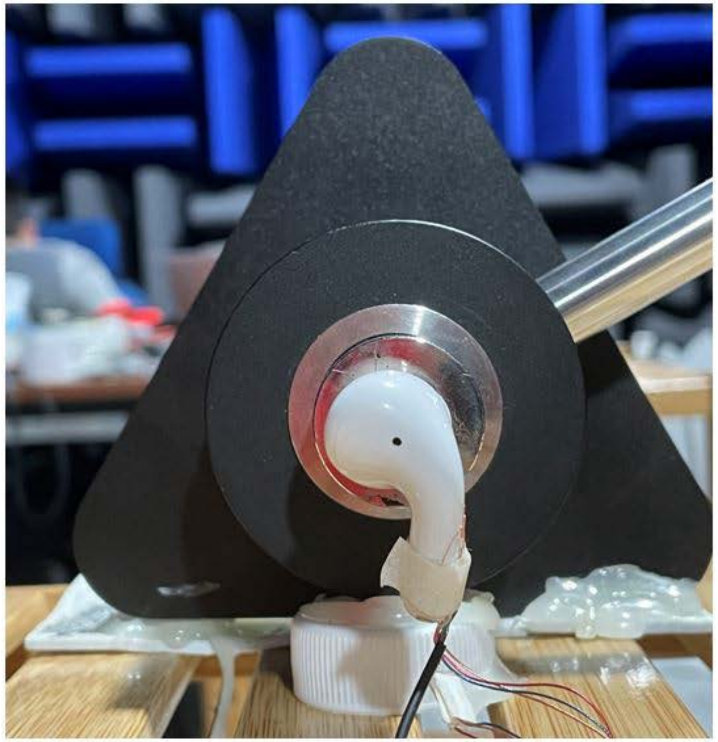
Seoul inter-noise 2020 23-26 AUGUST

**Development and application of dual form conic formulation of multichannel active noise control filter design problem in frequency domain**

# Experiments

Off-line Simulation based on experimentally measured secondary path $\boldsymbol{G_e}$

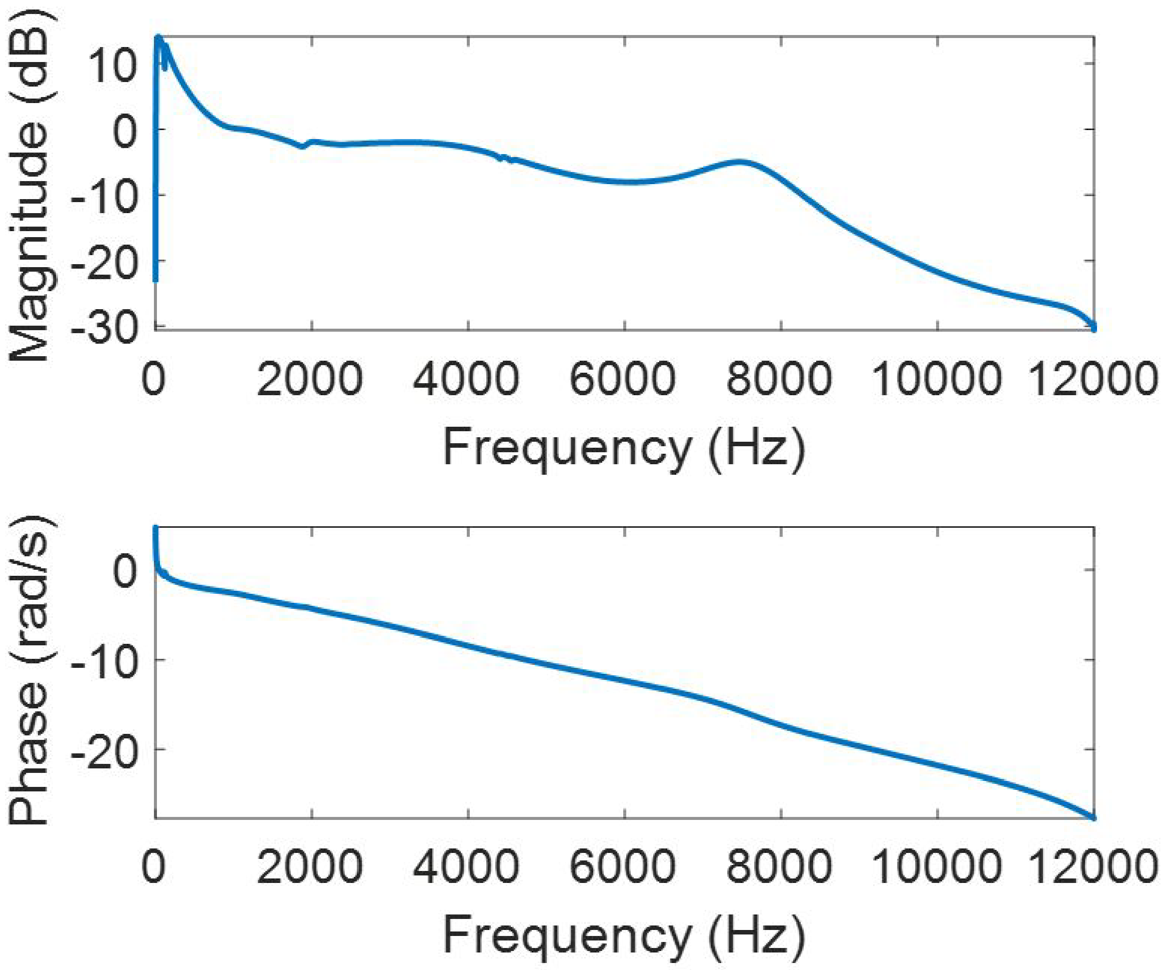




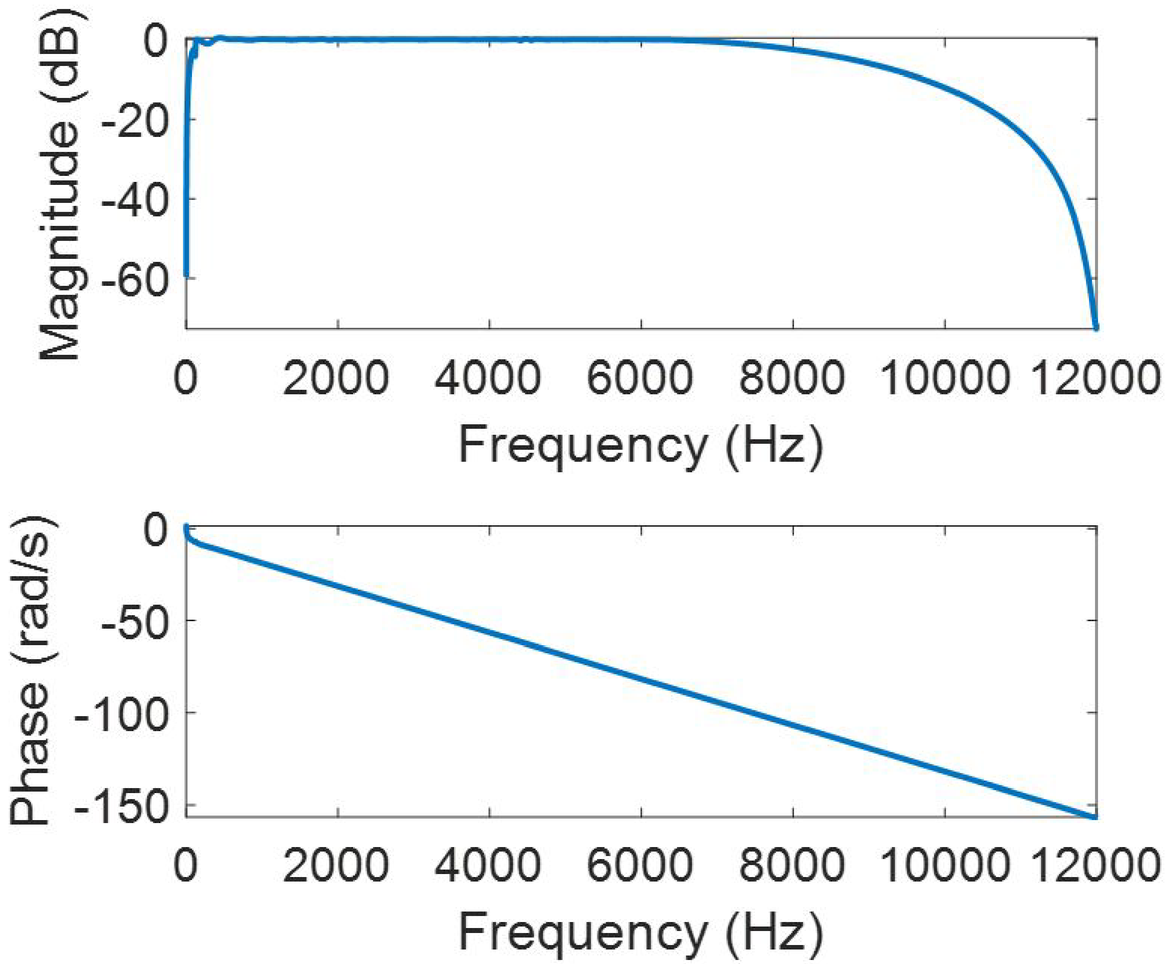
Experiment description:

- sampling rate: 24000 Hz
- FIR filter length: 128
- Hear-through band: 0 - 6000 Hz
- Desired delay: 2 ms

# Results – comb-filtering effect



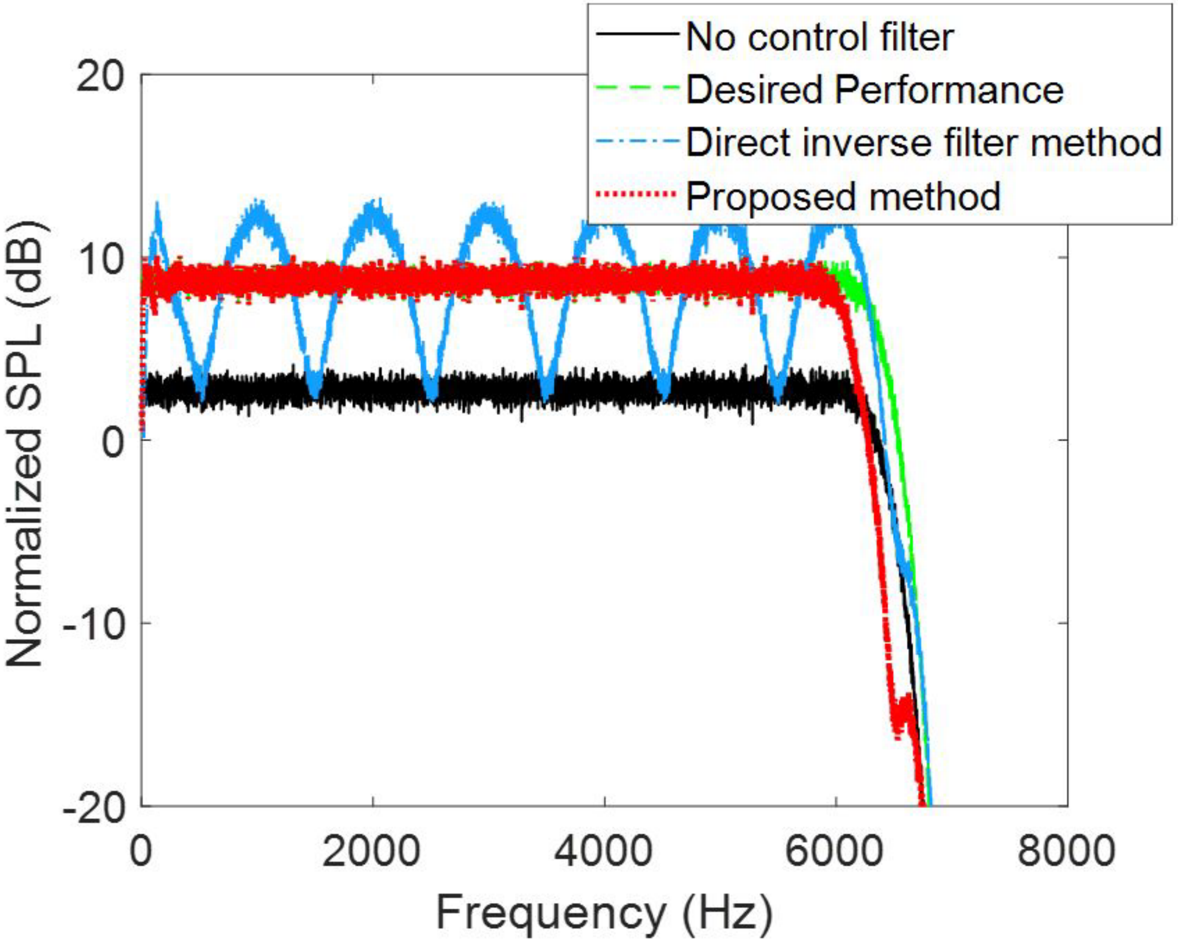

Measured secondary path $G_e$



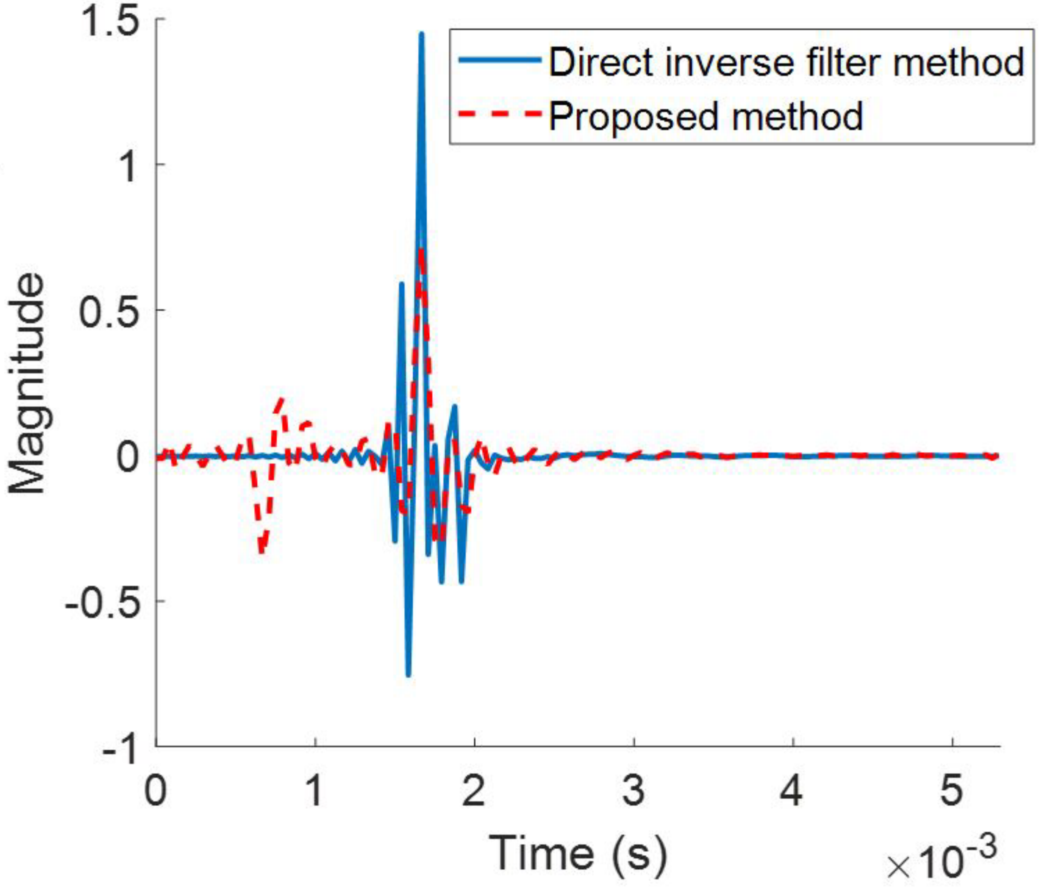

Direct inverse filter design, frequency response of $G_eW_x$

# Results – comb-filtering effect

Assume environment sound is 6 dB lower and 1 ms lag after transmit through earphone



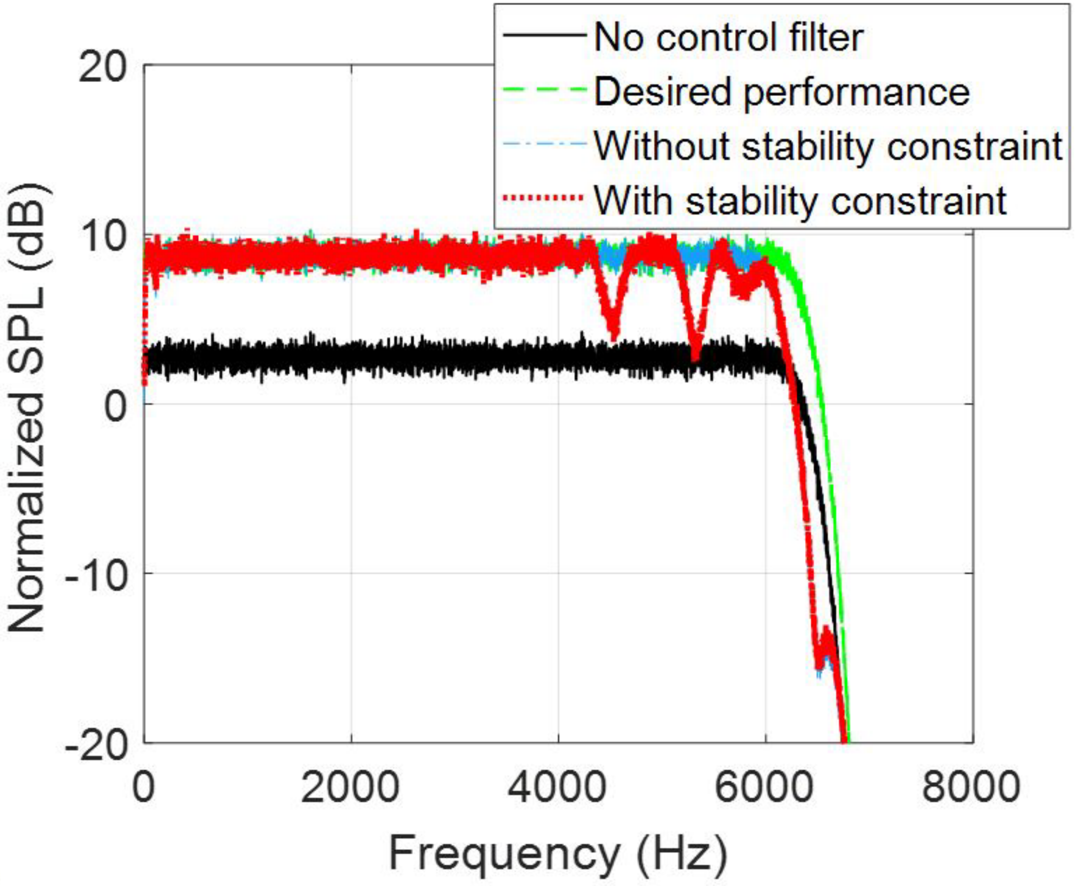

Performance in frequency domain



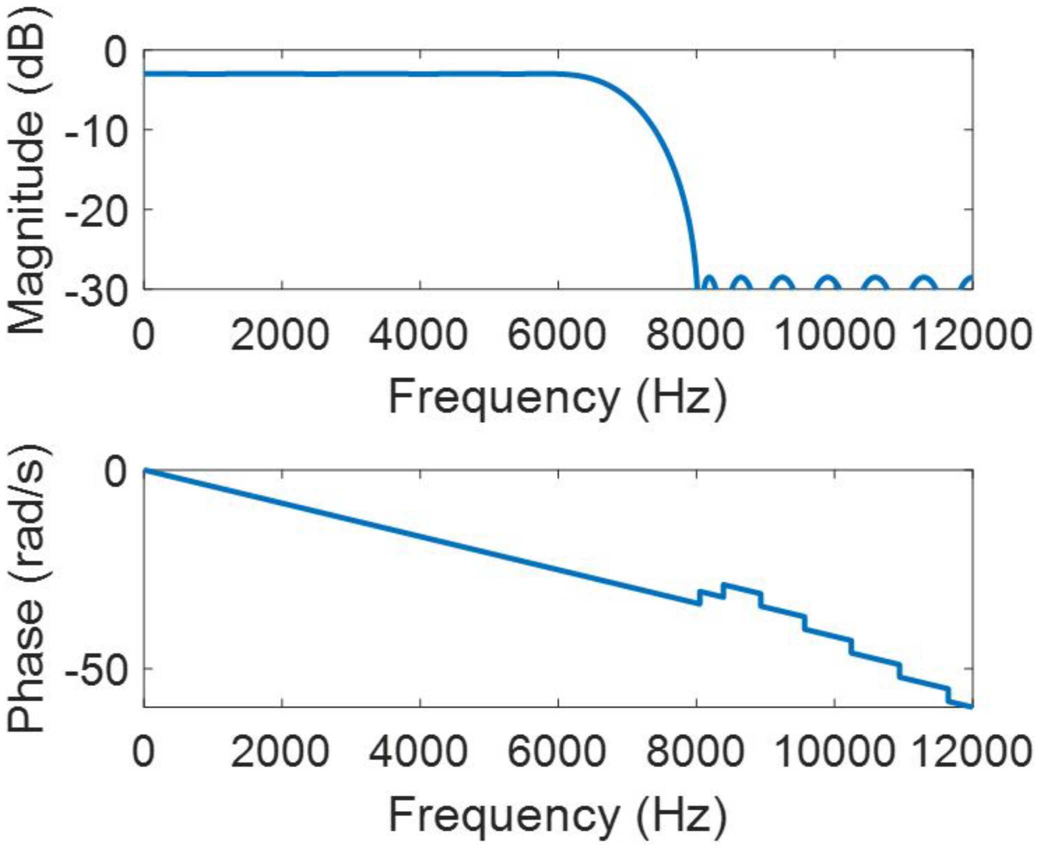

Impulse response of designed filter

# Results – Stability constraints

Assume an acoustic feedback path also 3 dB attenuation and 1 ms lag



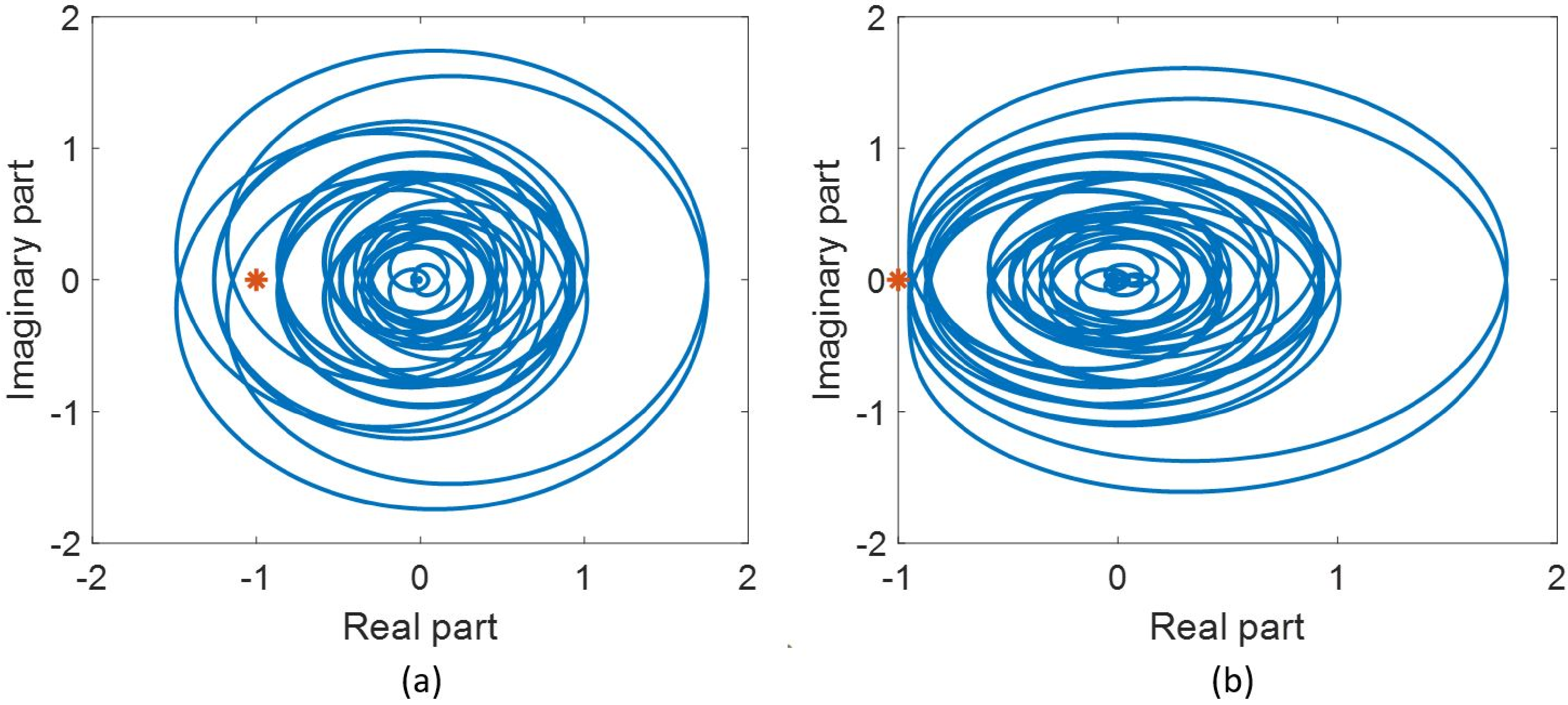

Performance in frequency domain




Frequency response of acoustic feedback path $G_s$

# Results – Stability constraints

Nyquist plot




Without applying stability constraint

After applying stability constraint

# Conclusions

- The proposed method can alleviate the comb-filtering effect by attenuating the leakage sound from environment.
- Robust stability constraint can be applied when using proposed method.
- Desired delay can be specified.
- The proposed method has the potential to be expanded to multi-channel situations which has a wider application besides earphone, e.g., the hear-through function in an automobile.

# Thank you !

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