A constrained optimal hear-through filter design approach for earphones

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PURDUE MECHANICAL ENGINEERING

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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.

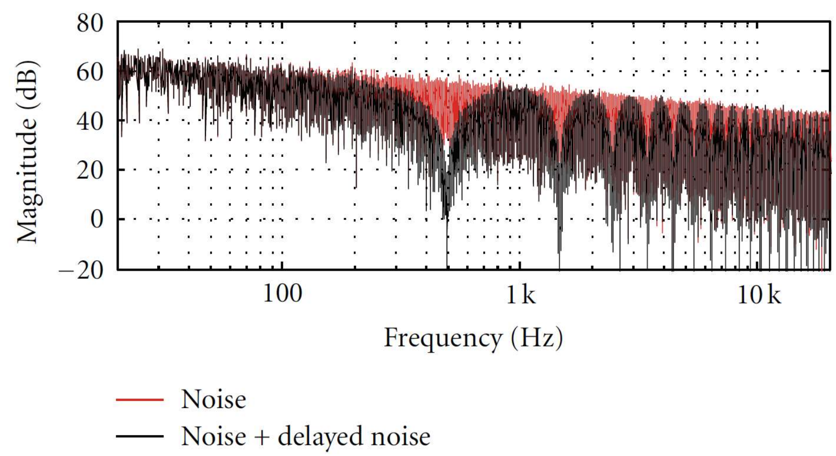
❑ Applications of hear-through function

- 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

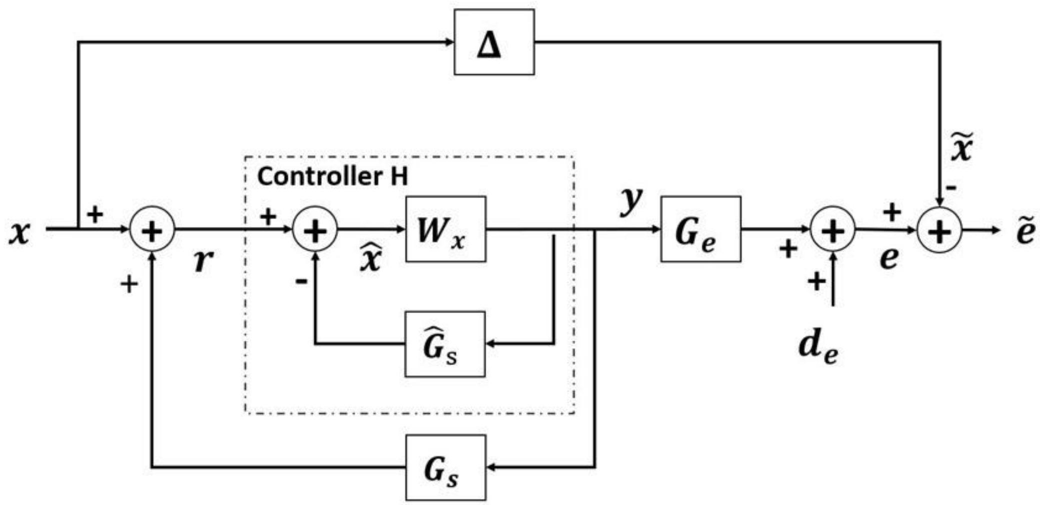
- The leakage sound from environment can be attenuated to reduce comb-filtering effect.
- Many ANC algorithms can be applied in a similar way

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

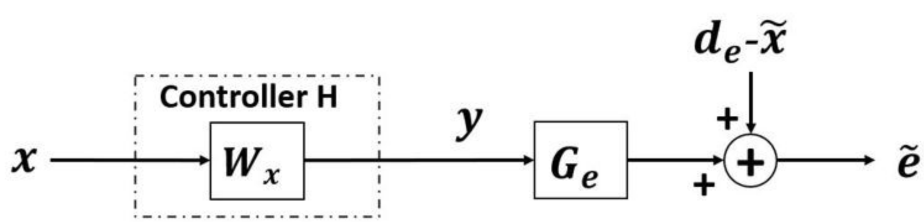
Proposed Method

- ❑ 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 $\boldsymbol{\hat{G}_s}$

$\boldsymbol{H_2/H_\infty}$ 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: $\boldsymbol{M}$**-** $\boldsymbol{\Delta}$ **structure and small gain theory:**

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

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

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

$\boldsymbol{H_2/H_\infty}$ Formulation

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Nyquist criterion, on the right of -1 point

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

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H_2/H_∞ Formulation

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Filter response:

$$|W_x(f_k)| \le C(f_k)$$ ➡ **The magnitude of frequency response**

$\boldsymbol{H_2/H_\infty}$ Formulation - Summary

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- Δ 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.

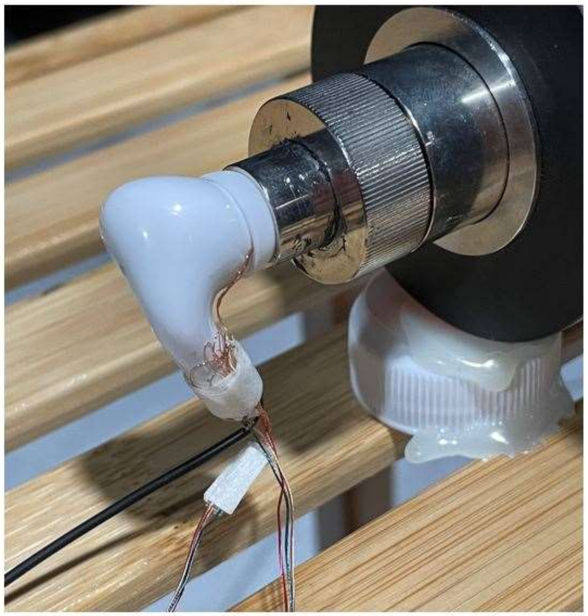
San Diego, CA
NOISE-CON 2019
2019 August 26-28

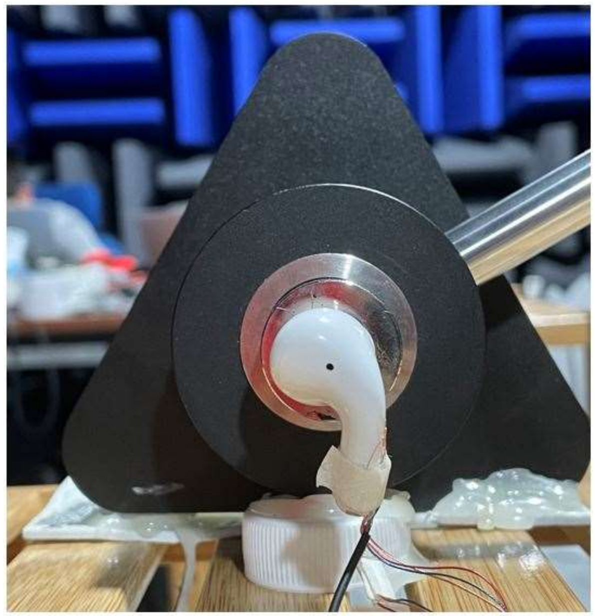
Study on the Cone Programming Reformulation of Active Noise Control Filter Design in the Frequency Domain

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 $\boldsymbol{G_e}$

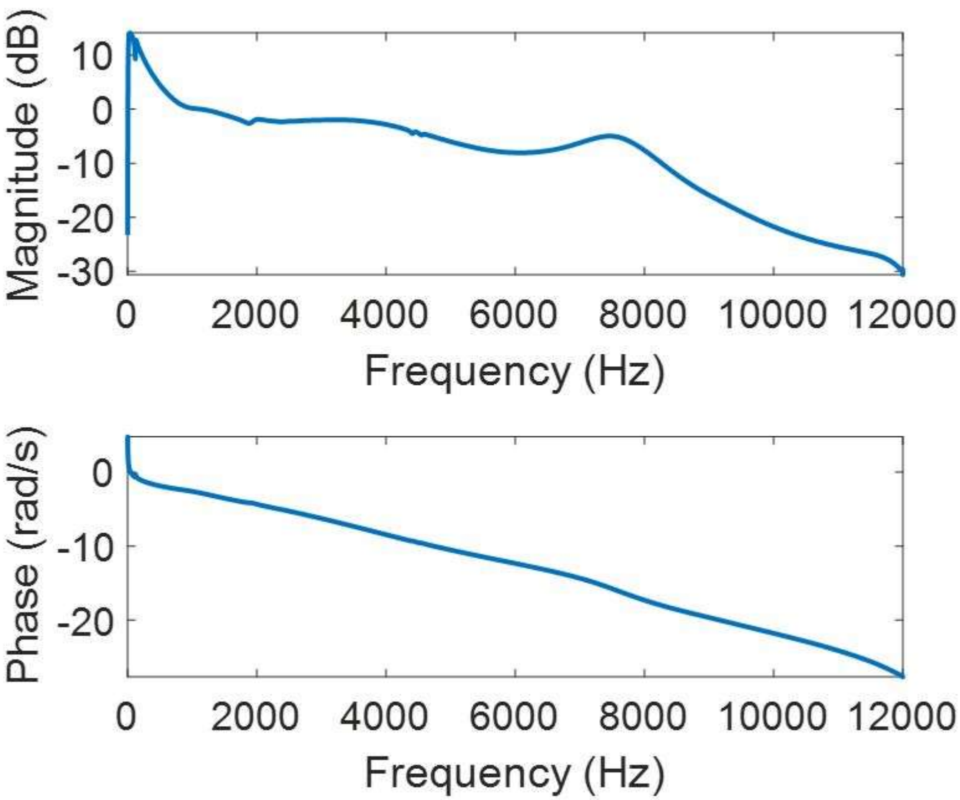




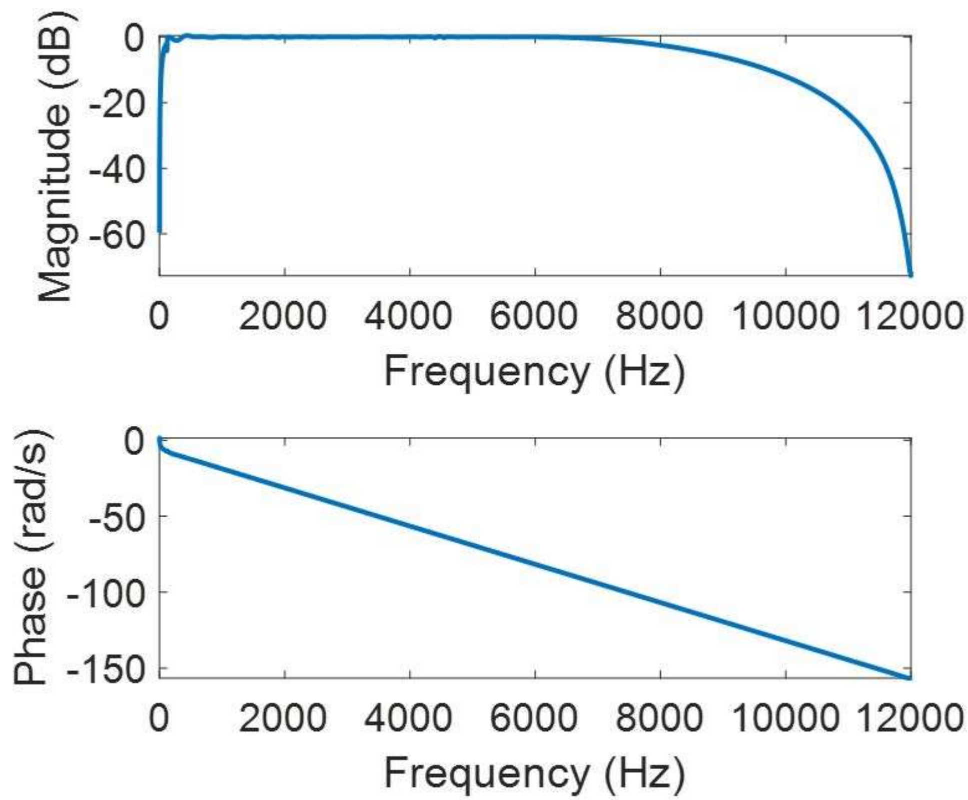
Experiment description:

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

Results – comb-filtering effect



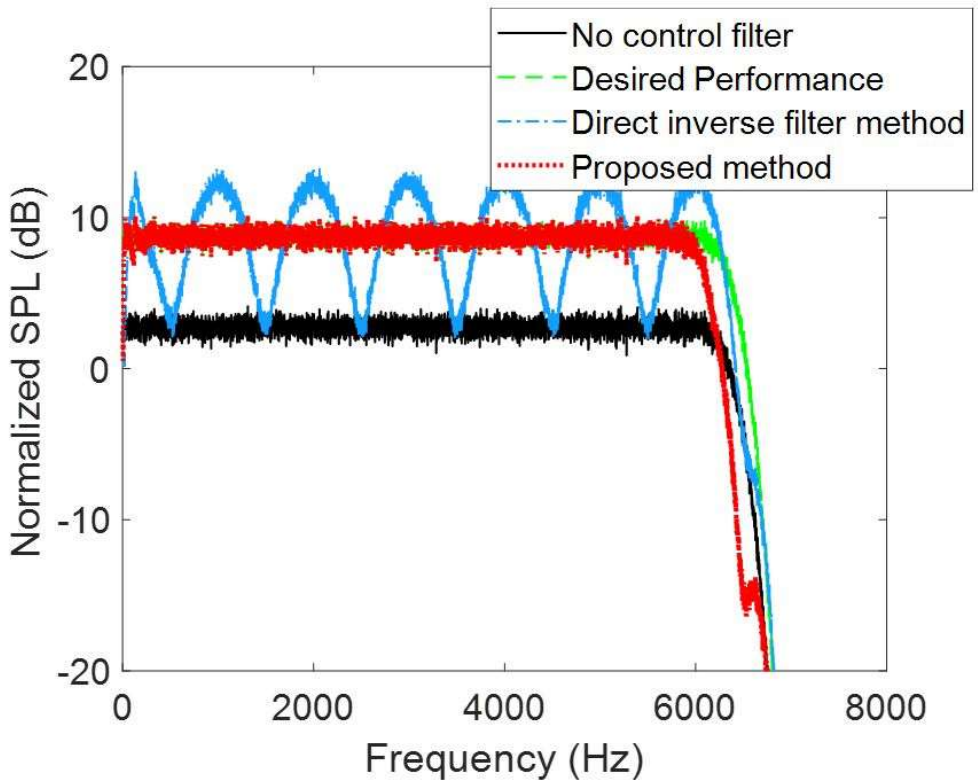
Measured secondary path $\boldsymbol{G_e}$



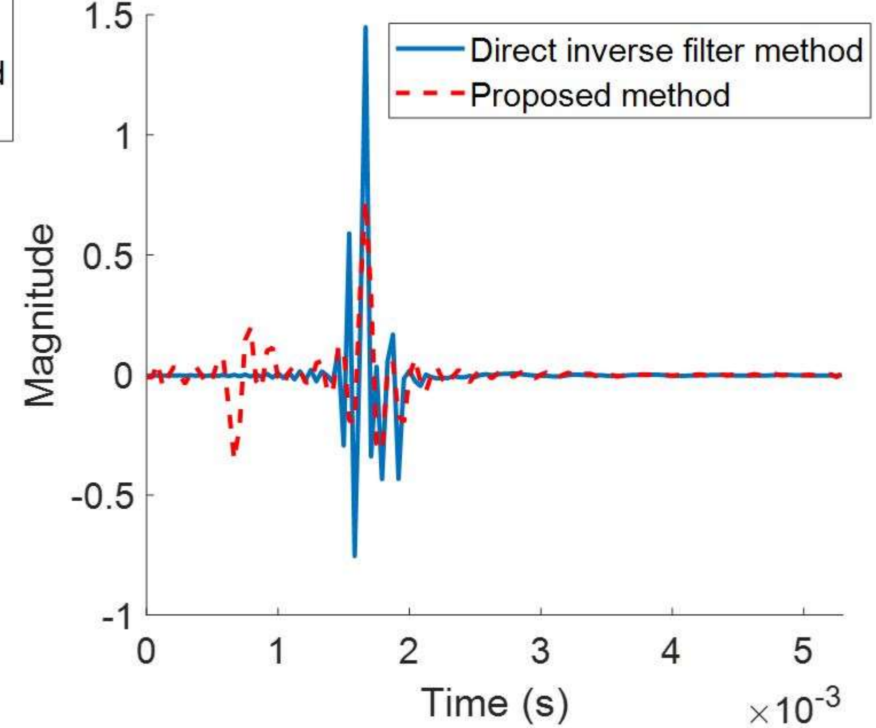
Direct inverse filter design, frequency response of $\boldsymbol{G_e W_x}$

Results – comb-filtering effect

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



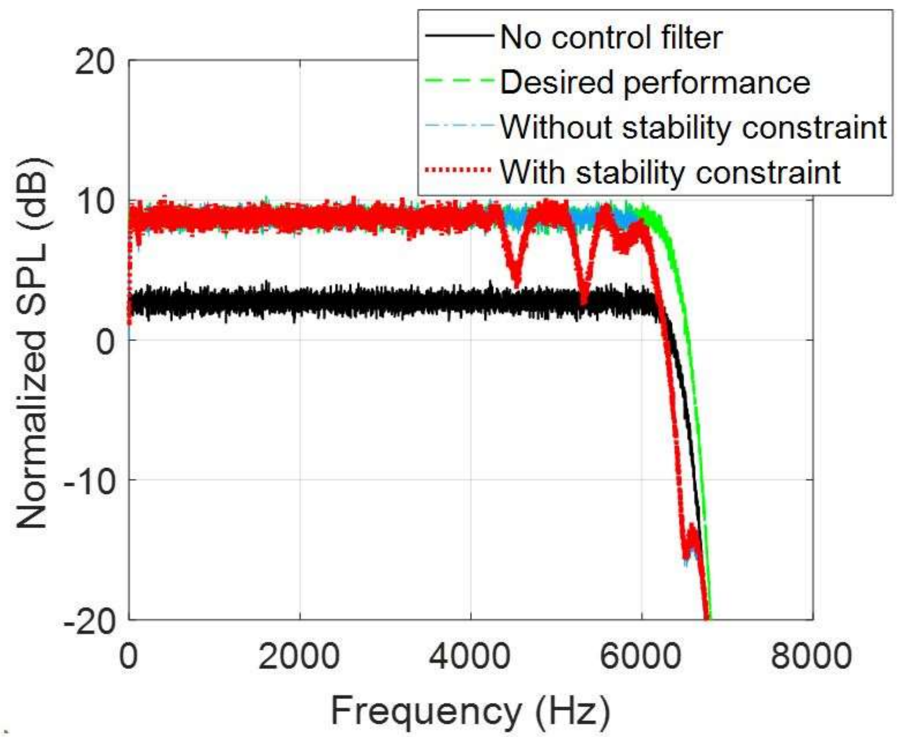
Performance in frequency domain



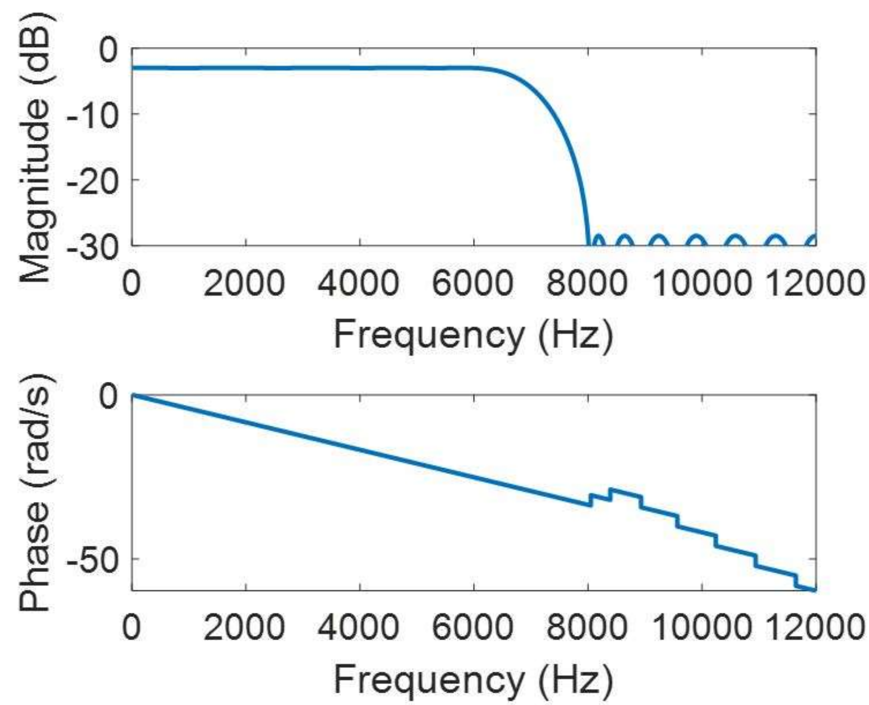
Impulse response of designed filter

Results – Stability constraints

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



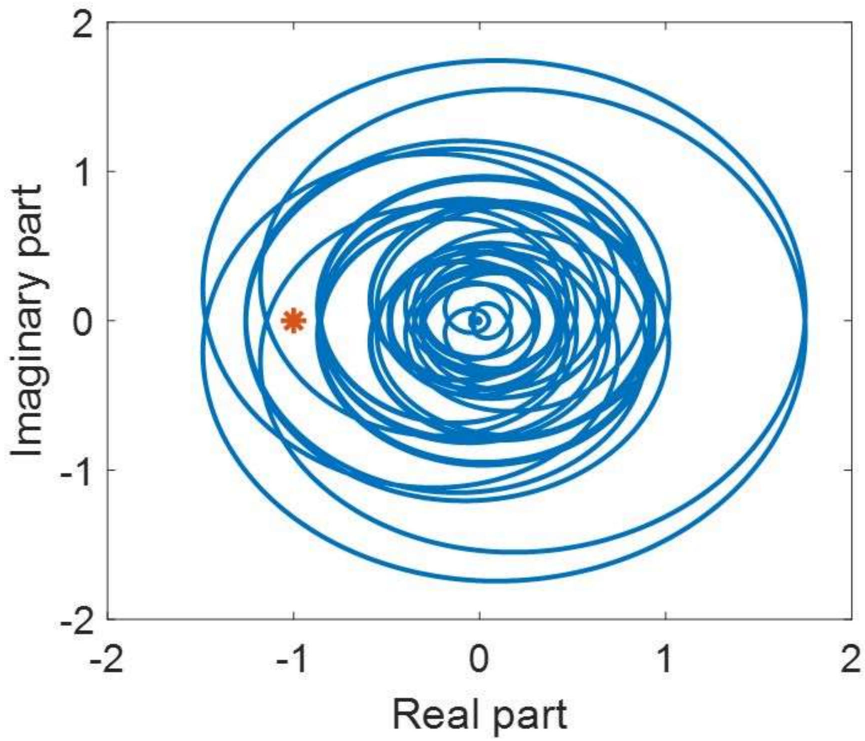
Performance in frequency domain



Frequency response of acoustic feedback path G_s

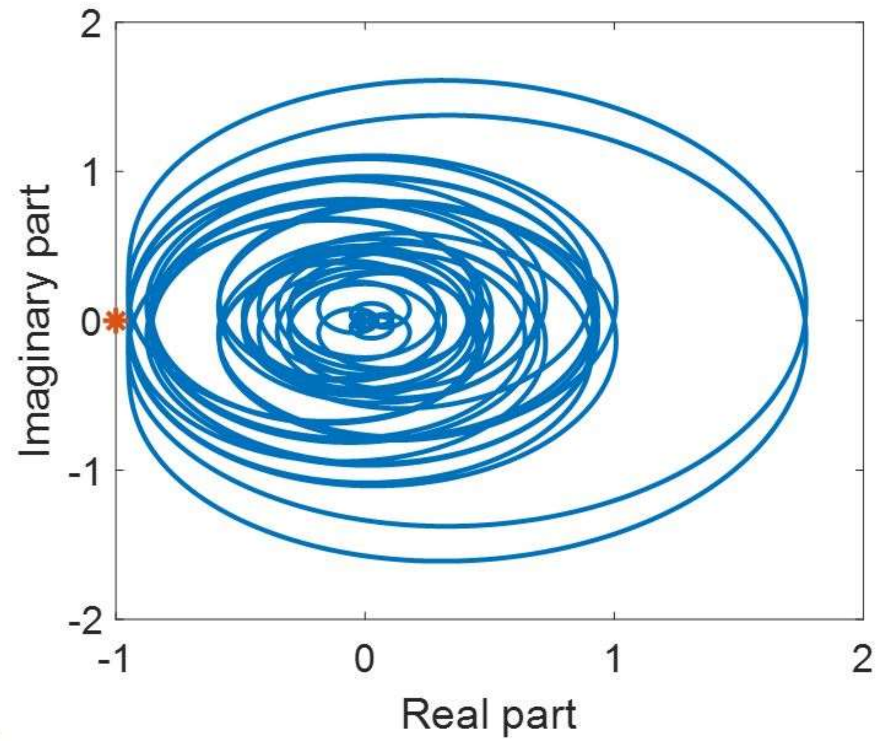
Results – Stability constraints

Nyquist plot



(a)

Without applying stability constraint



(b)

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 !