Wide-band audio vibration suppression using passband adaptation in disturbance observer

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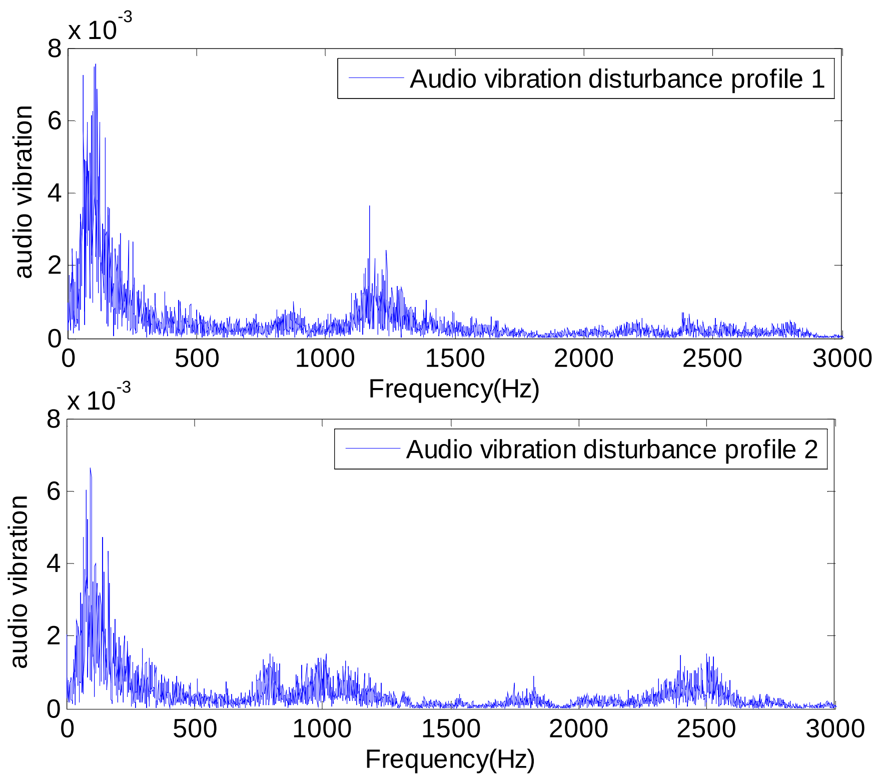
Contents

- Problem description
- DOB structure for audio vibration
  - Local loop shaping (LLS) technique
- Adaptive Q filter design in DOB
  - Frequency identification
  - Passband optimization
- Simulation results

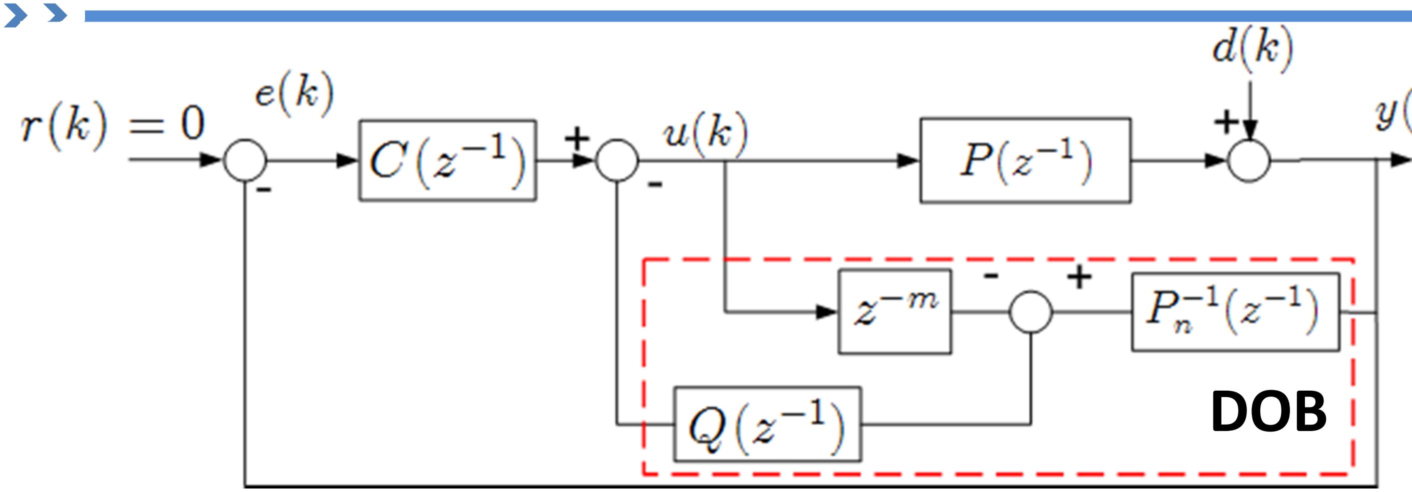
Problem description



Audio Vibration Disturbance Spectrum

- Challenges
  - Wide spectral peaks
  - Wide frequency range
  - Environment-dependent
    - Center frequencies shift
    - Peak widths change

DOB structure for disturbance suppression



$$S_0 = \frac{1}{1+PC}$$

$$G_{d2y} = \frac{(1 - Qz^{-m})}{1 + PC + Q(P_n^{-1}P - z^{-m})}$$

$\ll 1$

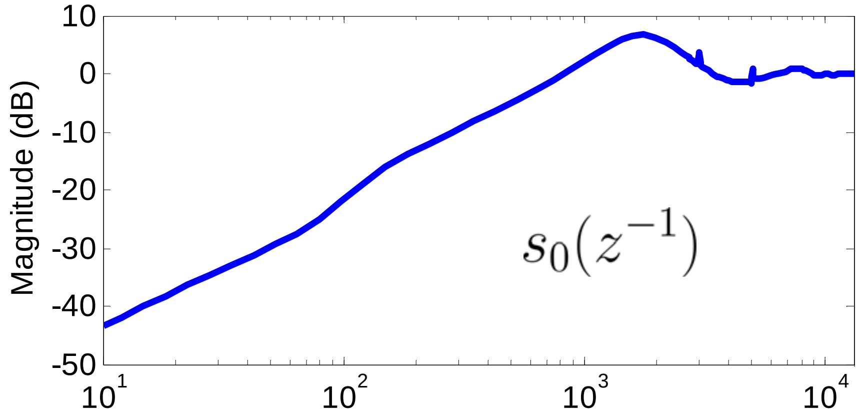
$$S \approx \frac{1 - Qz^{-m}}{1+PC} = (1 - Qz^{-m})S_0$$

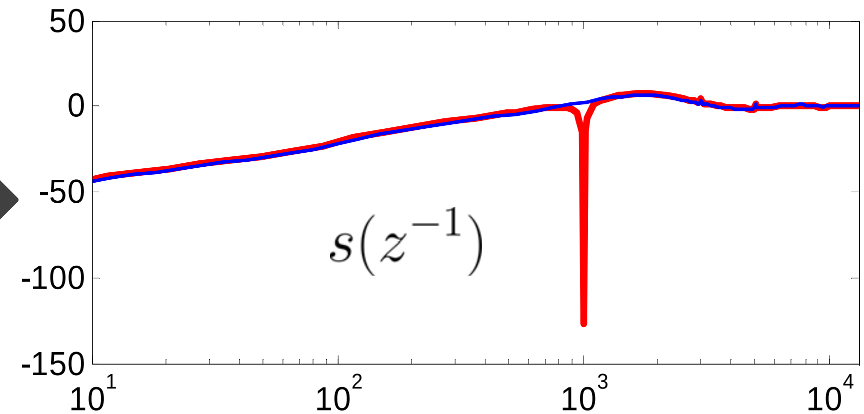
- $C(z^{-1})$ - baseline controller
- $P(z^{-1})$ - HDD plant
- $P_n(z^{-1})$ - nominal model w/o delay
- $Q(z^{-1})$ - bandpass filter
- z^{-m} - plant delay
- $S_0(z^{-1})$ - baseline sensitivity function
- $d(k)$ - disturbance

Local loop shaping

$$S(z^{-1}) \approx \{1 - Q(z^{-1})z^{-m}\} S_0(z^{-1})$$

Let $1 - Q(z^{-1})z^{-m} = J(z^{-1}) N(z^{-1})$ ← notch filter





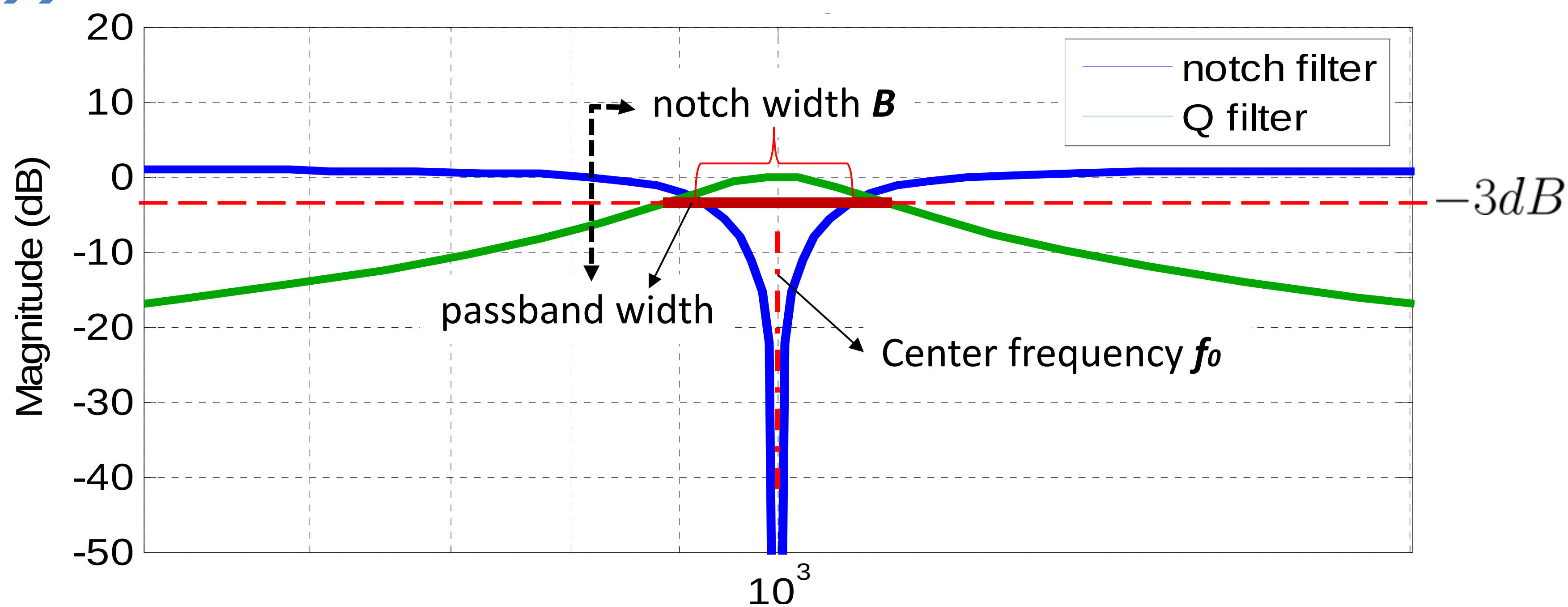
Design Q filter based on notch filter

$$1 - \frac{B_Q(z^{-1})}{A(z^{-1})} z^{-m} = \frac{B_N(z^{-1})}{A(z^{-1})} J(z^{-1}) \longrightarrow$$

Diophantine Equation

$$A(z^{-1}) = B_Q(z^{-1}) z^{-m} + B_N(z^{-1}) J(z^{-1})$$

Q-filter design based on notch filter



For environment-dependent audio vibration,

- Center frequency → Frequency identification
- Passband width → Passband optimization

Notch filter structure in lattice form

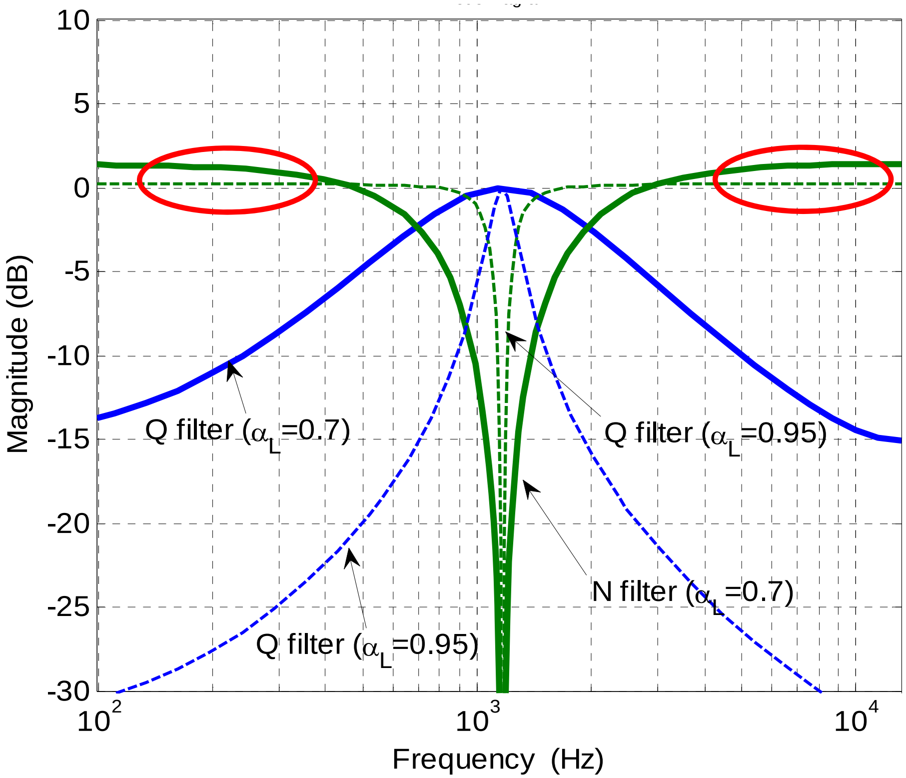
Lattice form notch filter

$$N_L(z^{-1}) = \frac{1 - 2\cos w_0 z^{-1} + z^{-2}}{1 - (1+\alpha_L)\cos w_0 z^{-1} + \alpha_L z^{-2}} = \frac{B_L(z^{-1})}{A_L(z^{-1})}$$

$B_L(z^{-1})$ → Notch location

$A_L(z^{-1})$ → Notch width ***B***

$$B = 2arctan\frac{1-\alpha_L}{1+\alpha_L}$$

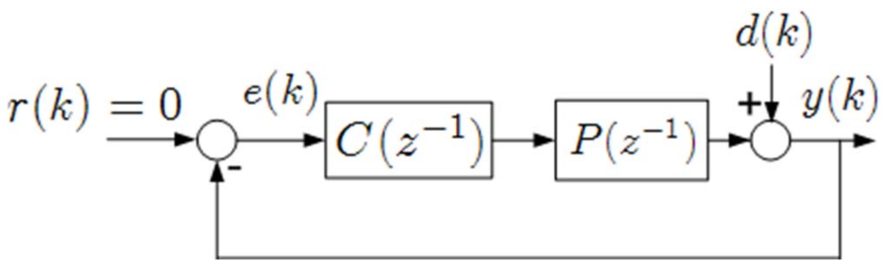


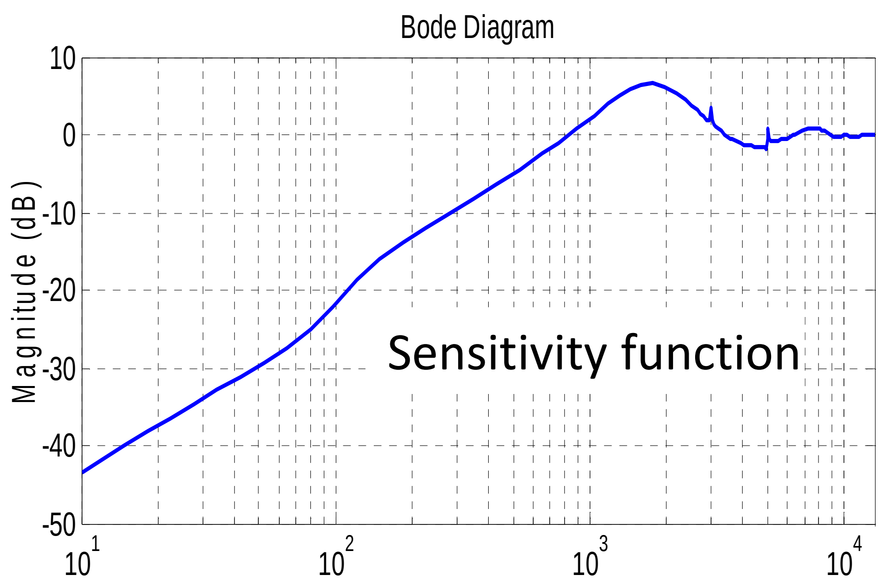
Advantages

- Symmetric
  - Amplifications are evenly distributed at low and high frequencies
- Notch width adaptable
  - filter is bilinear w.r.t. $\cos\omega_0$ and α_L

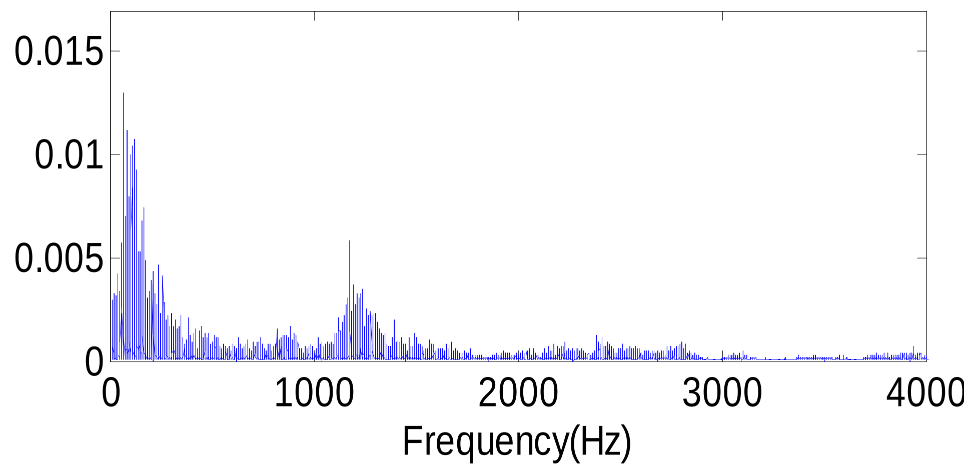
Simulation result I

--- Performance with baseline PID

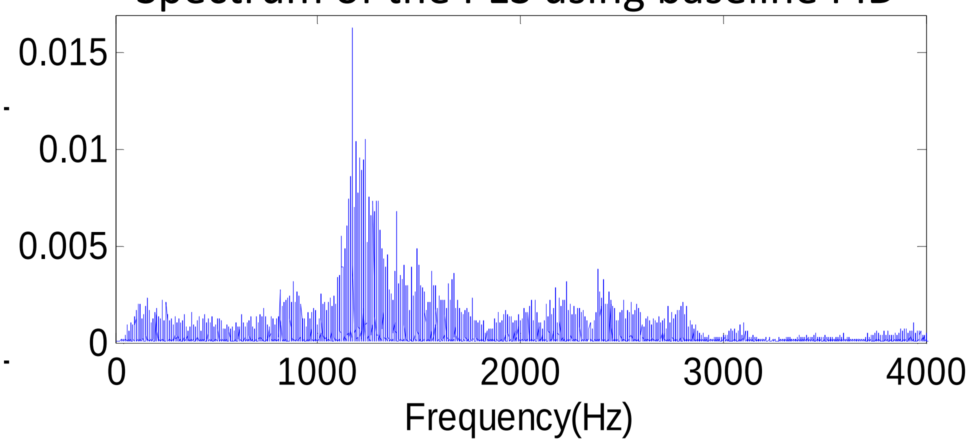




Spectrum of the audio vibration disturbance

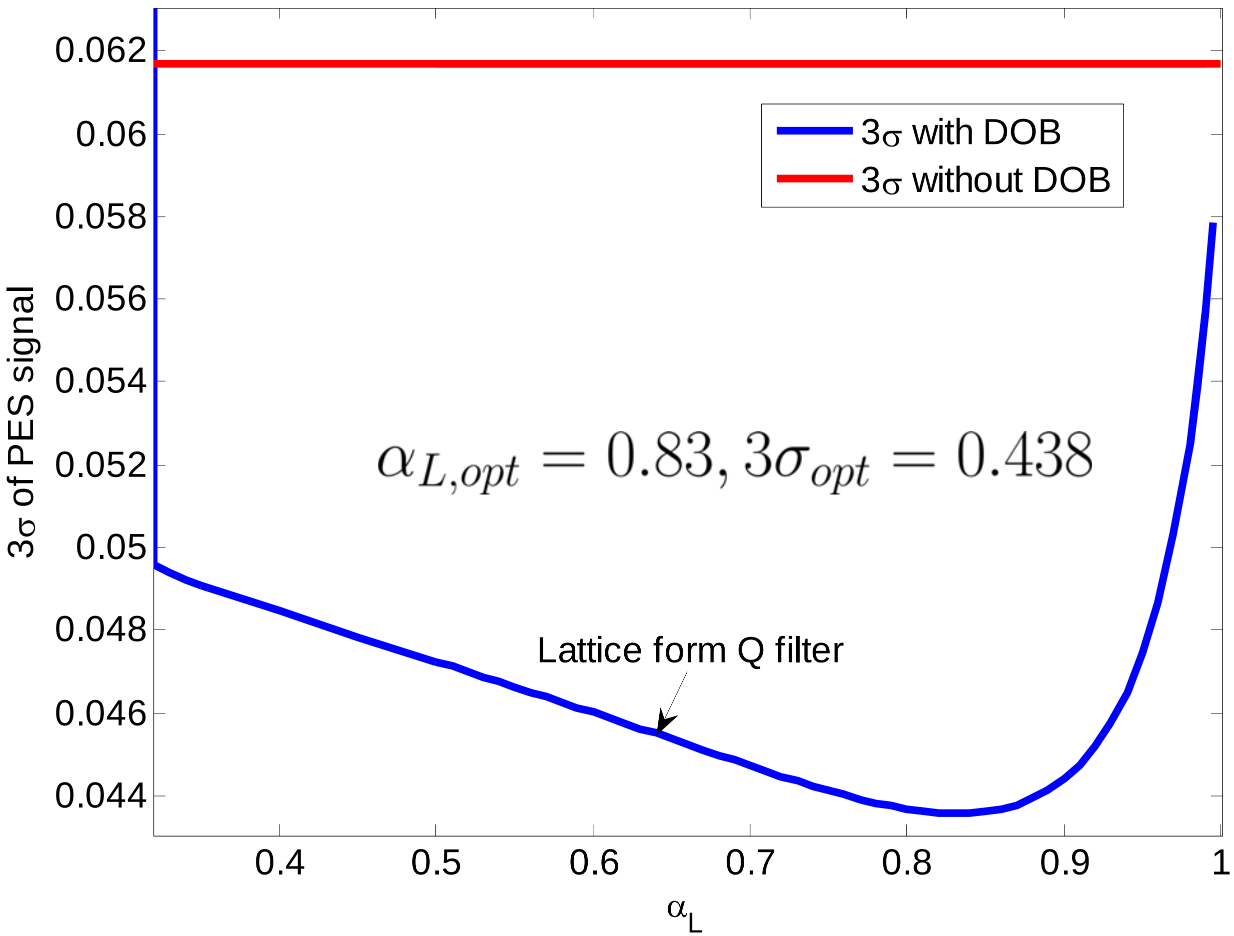


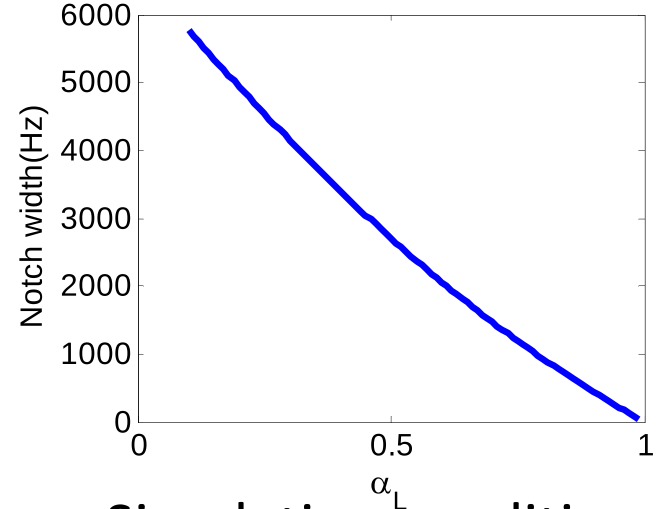
Spectrum of the PES using baseline PID



Simulation result II

--- Relationship between width and PES

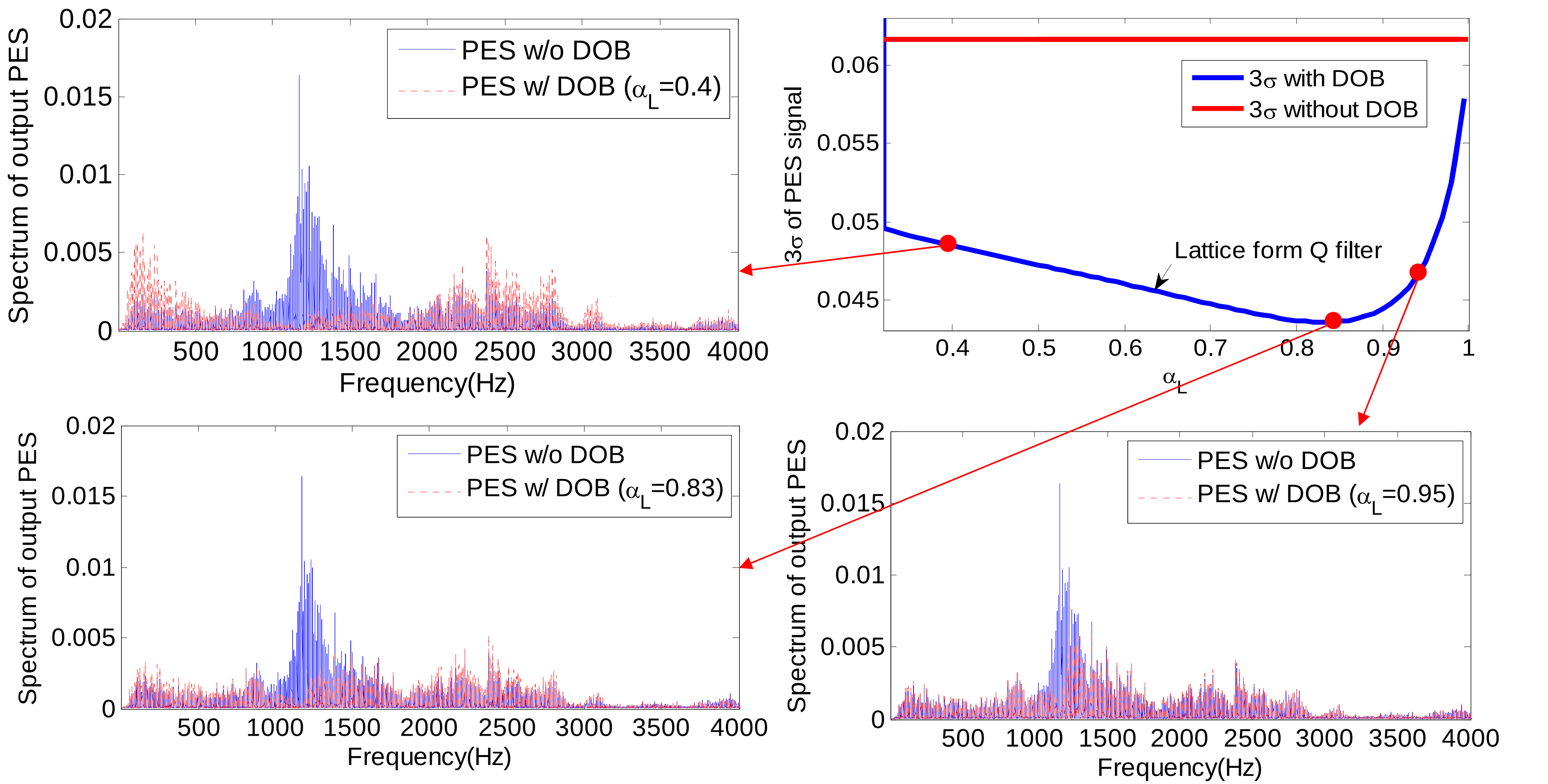




- Simulation condition
  - delay *m=3*
  - $P_n(z^{-1})$
    second order
    nominal model

Simulation result II

--- Relationship between width and PES



Two-stage adaptation

$$N_L(z^{-1}) = \frac{1 - 2\beta z^{-1} + z^{-2}}{1 - (1+\alpha_L)\beta z^{-1} + \alpha_L z^{-2}}, \beta = \cos w_0$$

production term

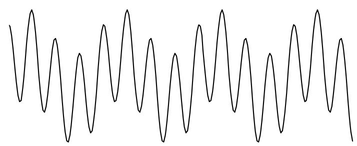
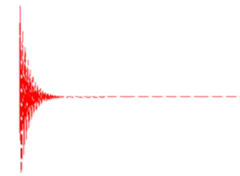
Input-output relation of the notch is not linear w. r. t. α_L and β, thus a two-stage adaptation is designed.

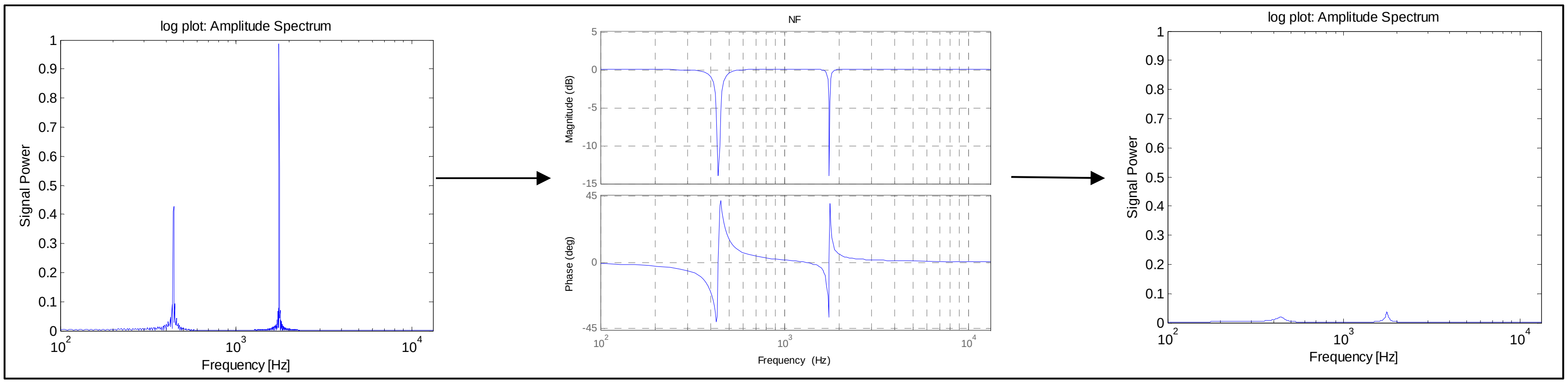
- Stage I: frequency identification[1]
- Stage II: passband width optimization

1. X. Chen, M. Tomizuka, unknown multiple narrow-band disturbance rejection in hard disk drives–an adaptive notch filter and perfect disturbance observer approach, 2010 ASME Dynamic Systems and Control Conference, September 13-15, 2010, Cambridge, Massachusetts, USA.

Two-stage adaptation

--- Stage I: frequency identification

Intuition:  $\longrightarrow \boxed{N\left(q^{-1}\right)} \longrightarrow e^{o}\left(k\right)$ 



Take a single notch filter for example

$$N\left(z^{-1}\right)=\frac{\frac{1+\alpha_L}{2}\left(1-2\beta z^{-1}+z^{-2}\right)}{1-\left(1+\alpha_L\right)\beta z^{-1}+\alpha_L z^{-2}}$$

$\beta=\cos w_0$

$\omega_0=2\pi T_s\Omega_0$

Ω_0 in Hz

α_L fixed

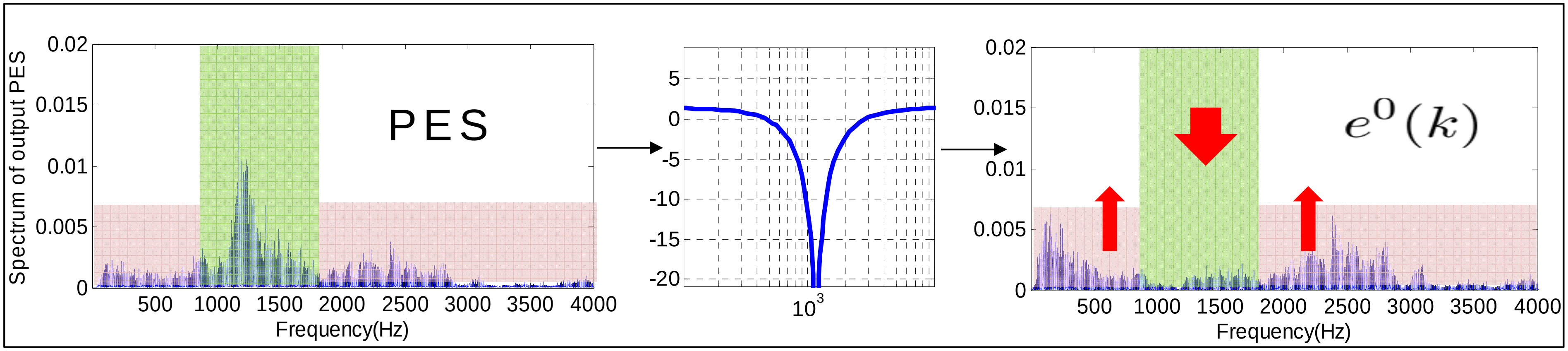
Unknown parameter β

Objective $\min\ V_k\left(\beta\right)=\sum_{j=1}^{k}\frac{1}{2}\left[e^{o}\left(j\right)\right]^2$

Two-stage adaptation

--- Stage II: passband optimization

Intuition: utilize "waterbed effect" to adaptively tune the optimal passband width



Take a single notch filter for example

$$N_L\left(z^{-1}\right) = \frac{1 - 2\beta z^{-1} + z^{-2}}{1 - (1+\alpha_L)\beta z^{-1} + \alpha_L z^{-2}}$$

$\beta = \cos w_0$ is identified in stage I

Unknown parameter α_L

Objective $\min \; V_k(\alpha_L) = \sum_{j=1}^{k} \frac{1}{2}\left[e^o(j)\right]^2$

Adaptation algorithm

--- Recursive prediction-error method(RPEM)

Objective:

$$\min \ V_k(\theta) = \sum_{j=1}^{k} \frac{1}{2} \left[e^o(j) \right]^2$$

Stage I: $\theta = \beta$

Stage II: $\theta = \alpha_L$

$$\hat{\theta}(k+1) = \hat{\theta}(k) + F(k)\psi(k)e(k)$$

$$e(k) = \frac{e^o(k)}{1 + \psi^T(k)F(k)\psi(k)}$$

$$F(k+1) = \frac{1}{\lambda(k+1)} \left\{ F(k) - \frac{F(k)\psi(k)\psi^T(k)F(k)}{\lambda(k+1) + \psi^T(k)F(k)\psi(k)} \right\}$$

$$e^o(k) = B_N(\hat{\theta}(k-1))y_{pes}(k) + A_N(\hat{\theta}(k-1))e(k)$$

$$\psi(k) = -\partial e^o(k) / \partial \hat{\theta}(k)$$

$$N_L(z^{-1}) = \frac{1 - 2\beta z^{-1} + z^{-2}}{1 - (1+\alpha_L)\beta z^{-1} + \alpha_L z^{-2}} \triangleq \frac{B_N(z^{-1})}{1 - A_N^*(z^{-1})}$$

$$\lambda(k) = \lambda_{end} - \left[\lambda_{end} - \lambda(k-1) \right] \lambda_0$$

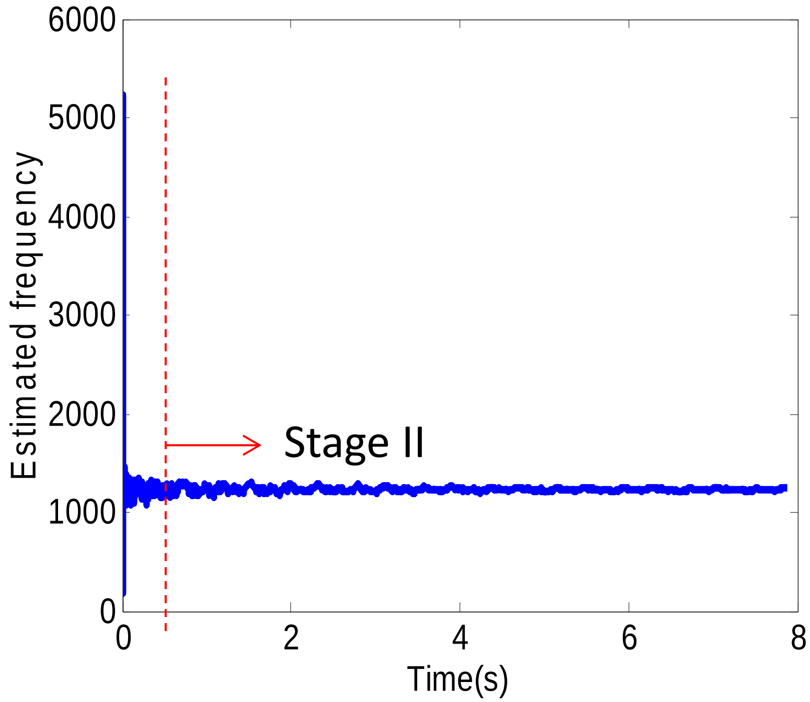
Gang Li, 1997, A Stable and Efficient Adaptive Notch Filter for Direct Frequency Estimation, IEEE TRANSACTIONS ON SIGNAL PROCESSING, VOL. 45(8), pp. 2001-2009.

Bor-Sen Chen, Tsang-Yi Yang, and Bin-Hong Lin, 1992, Adaptive notch filter by direct frequency estimation, Signal Processing, Vol. 27, pp. 161-176.

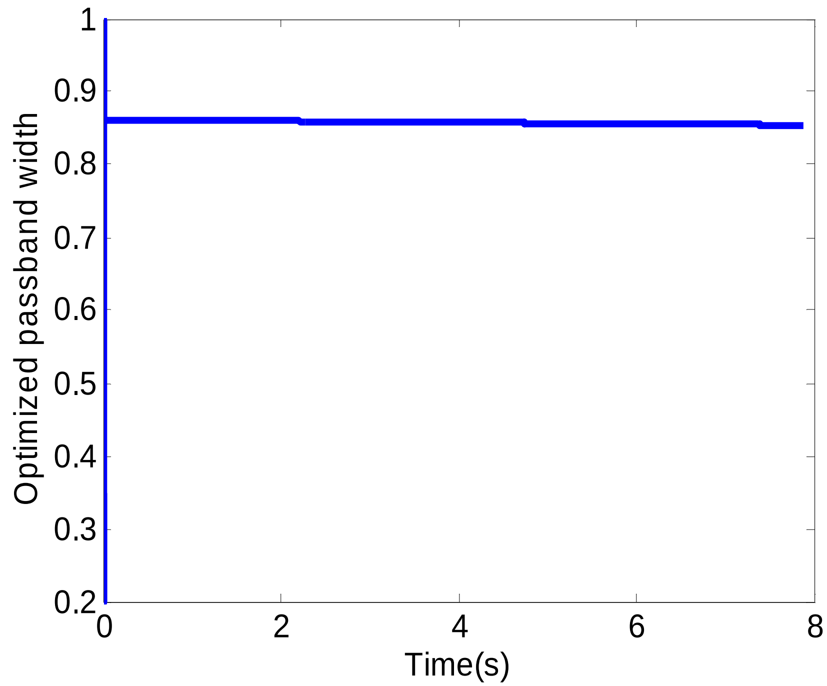
Simulation result III

--- Performance with adaptive passband width

Frequency estimation

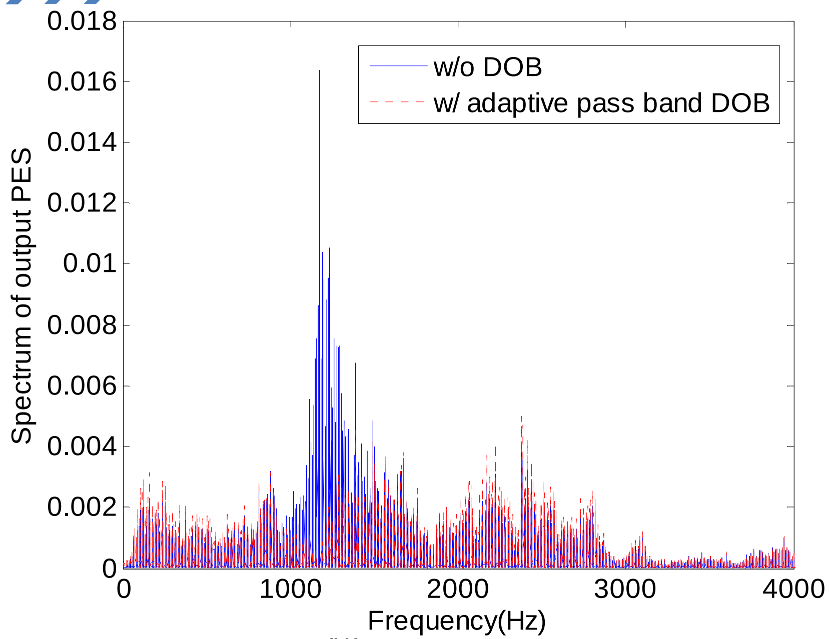


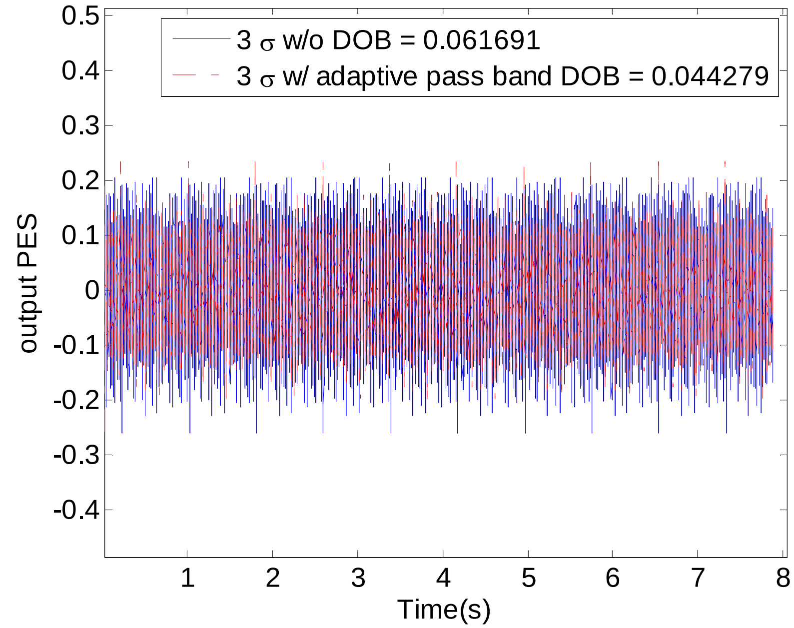
Passband width optimization

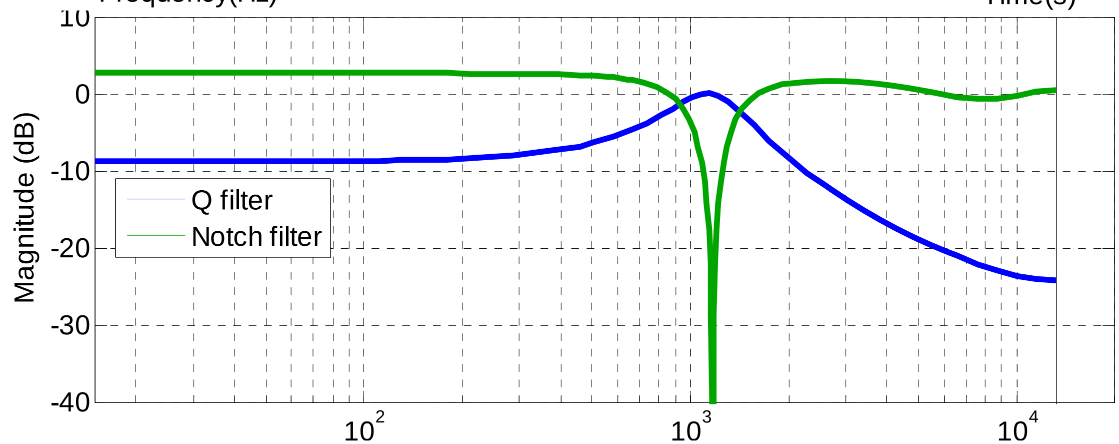


Simulation result III

--- Performance with adaptive passband width







Future work

- Multiple bands
- Frequency-shaped passband-adaptive Q filter
- Simultaneous optimization
  – Center frequency
  – Passband width
- Youla-Kucera parametrization with adaptive passband width
- Experimental tests