A Parallel Analog and Digital Adaptive Feedforward Active Noise Controller

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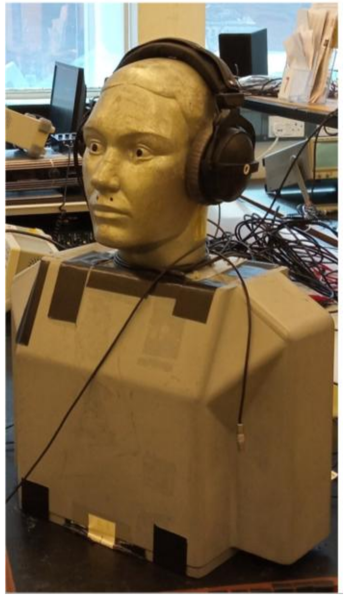
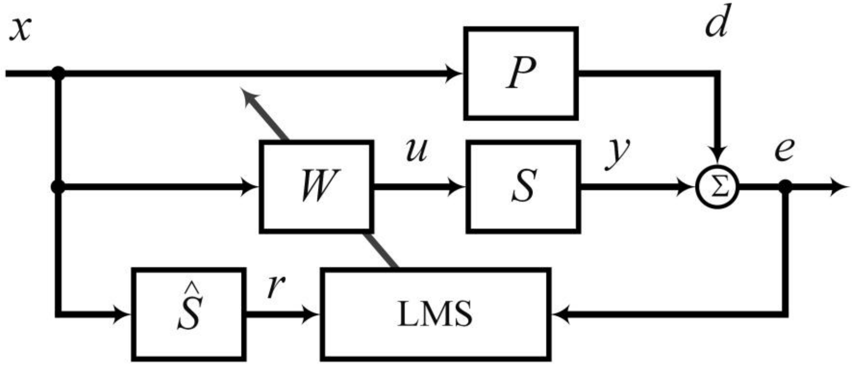
The Sound of Silence

Institute of Sound and Vibration Research

Motivation



Adaptive Active Noise Control: The classic setup

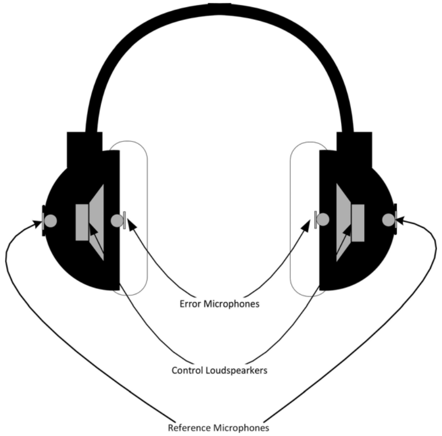


Systems:

P/S: Primary/Secondary acoustic path (LTI)

$W(z) = \sum_{k=0}^{K-1} w_k z^{-k}$: FIR controller

$\hat{S}$: Secondary path model



Signals:

d: undesired noise

x: reference

u: control signal

y: control action

e: measured error

r: filtered reference

Adaptation law using the Filtered Reference - Least Mean Squares method (Fx-LMS)

$$w_k[n+1] = w_k[n] - \mu r[n-k]e[n]$$

$$r[n] = \hat{S} * x[n], 0 < \mu < \frac{2}{\max(\sigma_{rr})}$$

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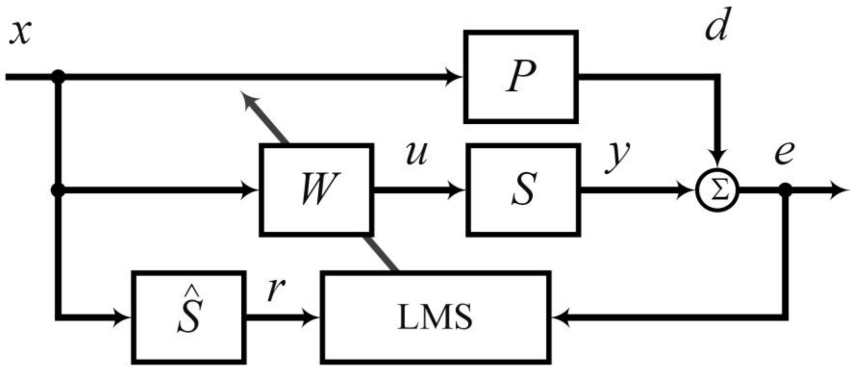
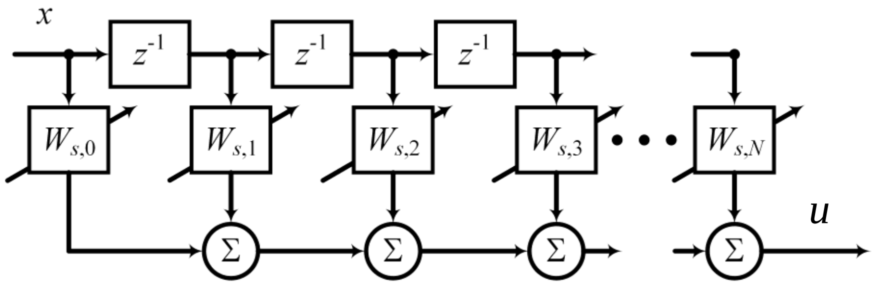
Sampled Filtered reference LMS Active Noise Control

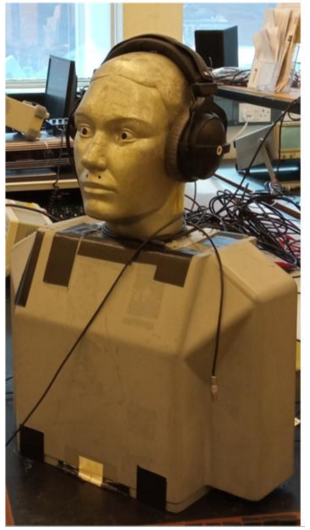
In theory

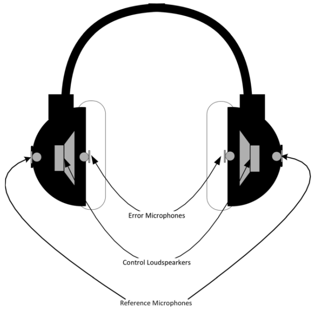




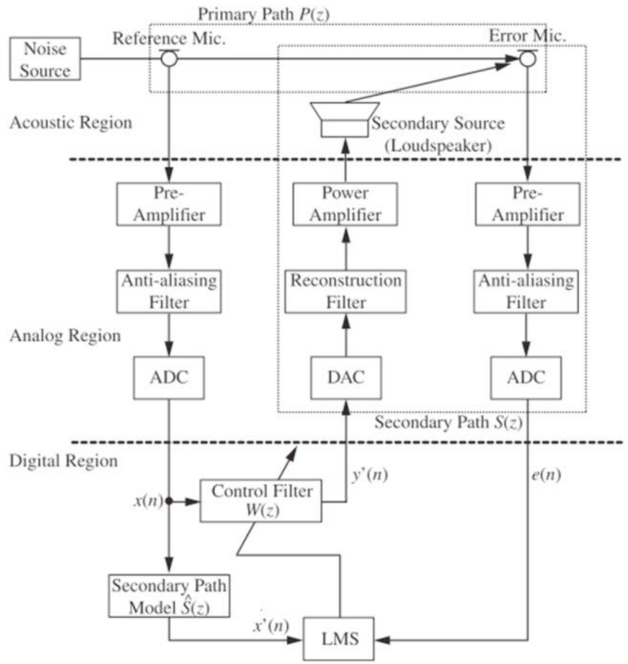
LMS adaptation law

$$w_k[n+1] = w_k[n] - \mu r[n-k]e[n]$$





In reality



B. Lam et al. Building and Environment (2021)

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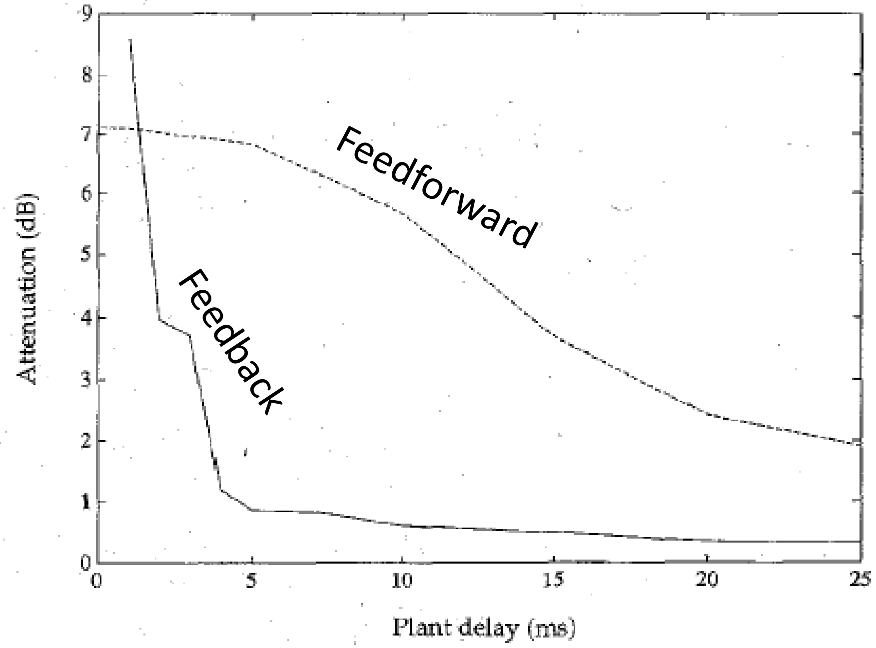
Effect of secondary path delay



S. J. Elliott and T. J. Sutton (1996)

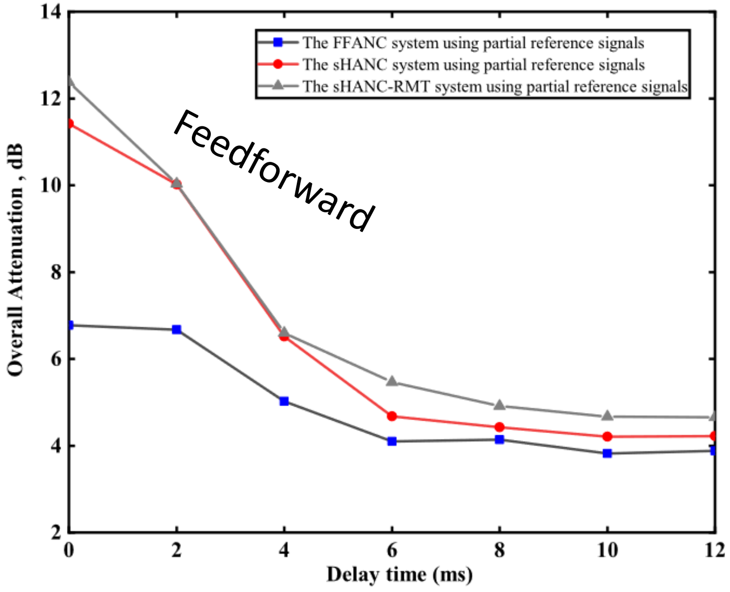


Fig. 11. The delay characteristics of different ANC system.

X. Zheng et al., Applied Acoustics (2023)

There is no magic fix

Causality condition for feedforward control

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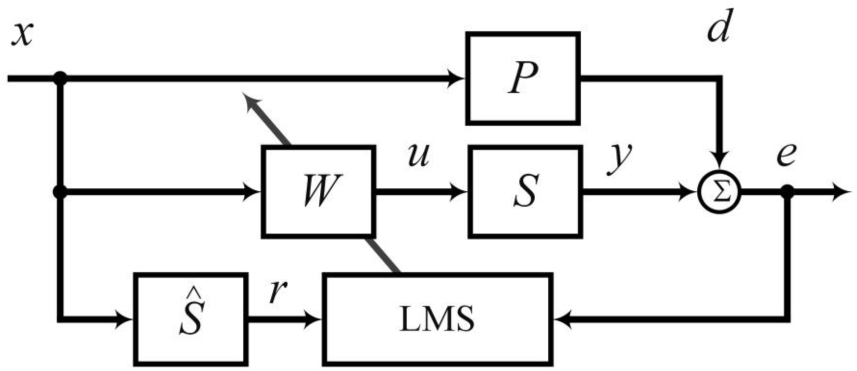
To obtain good performance:

$$\Delta t_P > \Delta t_S + \Delta t_D$$

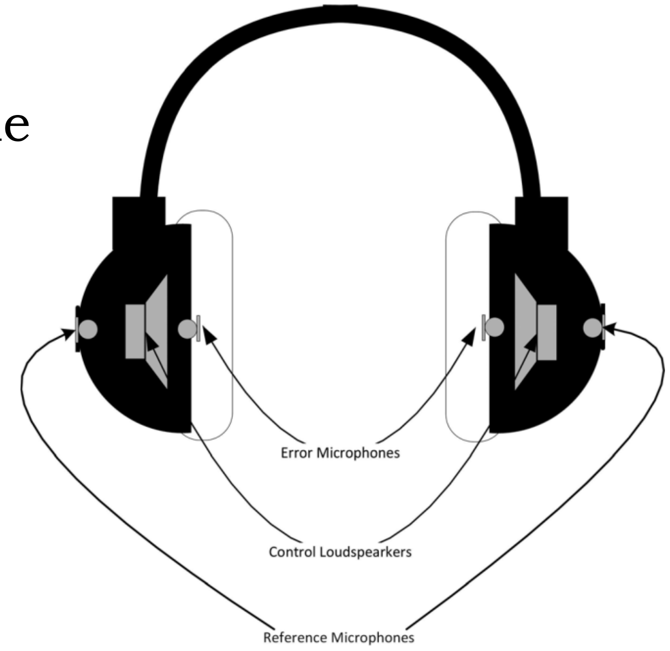


- Δt_P- the time of flight from the reference sensor to the error microphone

  a function of the sensors' positions
- Δt_S- the time of flight from the loudspeaker to the error microphone

  a function of the loudspeakers' positions
- Δt_D- the time delay due to filtering and sampling

  a function of the sample rate and filters' bandwidth

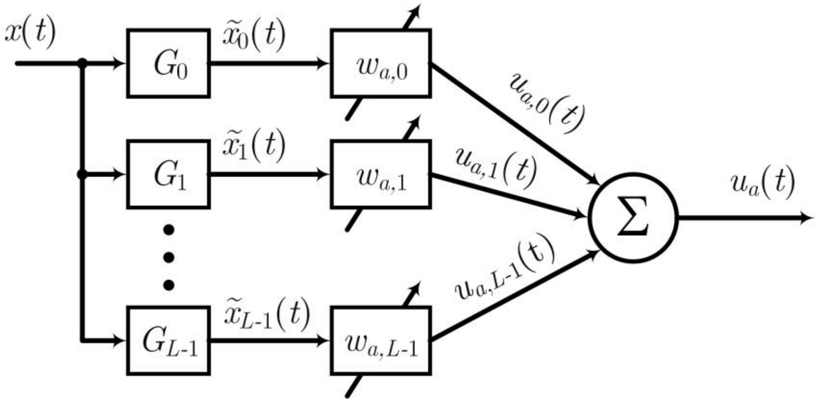


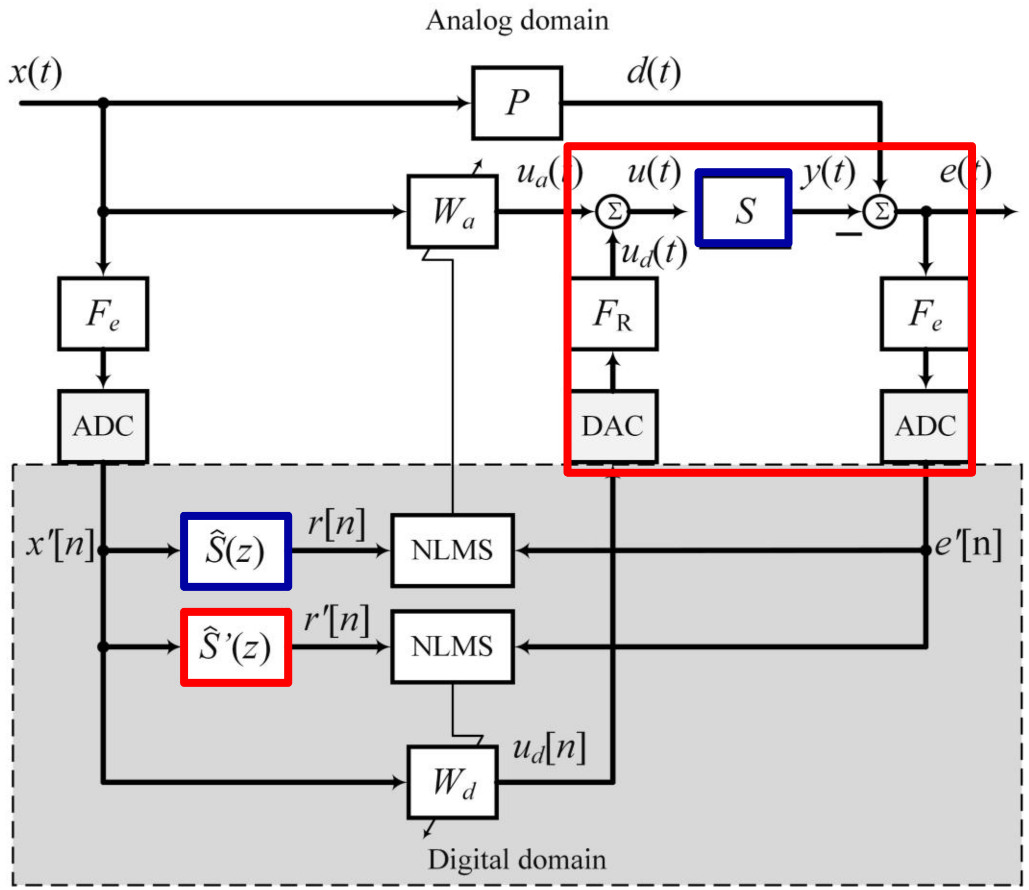
Parallel Analog–Digital Adaptive Active Noise Control

$$\Delta t_P > \Delta t_S + \Delta t_D$$

Objective: minimize the time delay of the sampling: Δt_d

Proposed solution: add an adaptable analog filter parallel to the sampled one





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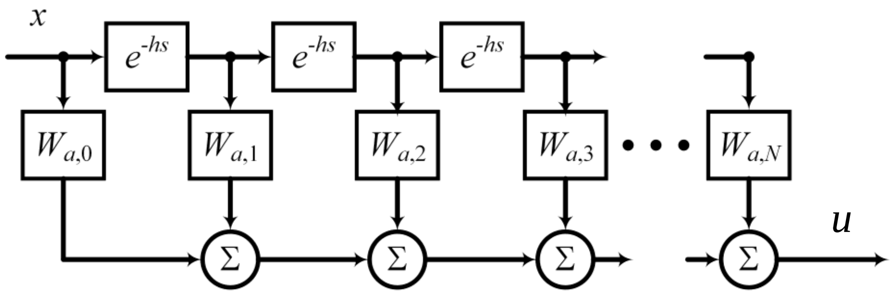
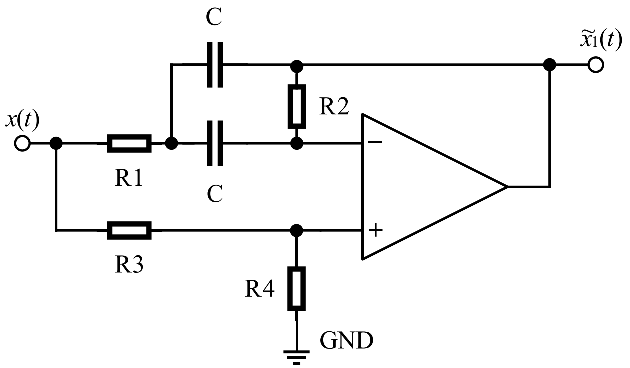
Idea: Analog tapped delay with configurable individual weights



Realization of delay element as 2nd order all-pass filter

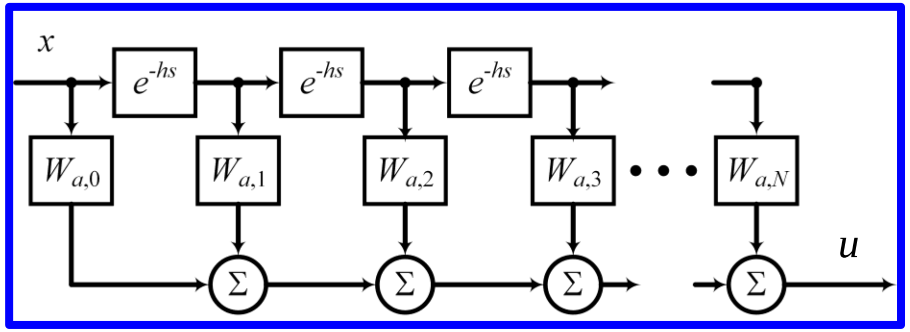
$$G_l(s) = e^{-(lh)s} \approx \frac{1}{4}\,\frac{s^2 - 6(lh)^{-1}s + 12(lh)^{-2}}{s^2 + 6(lh)^{-1}s + 12(lh)^{-2}}$$

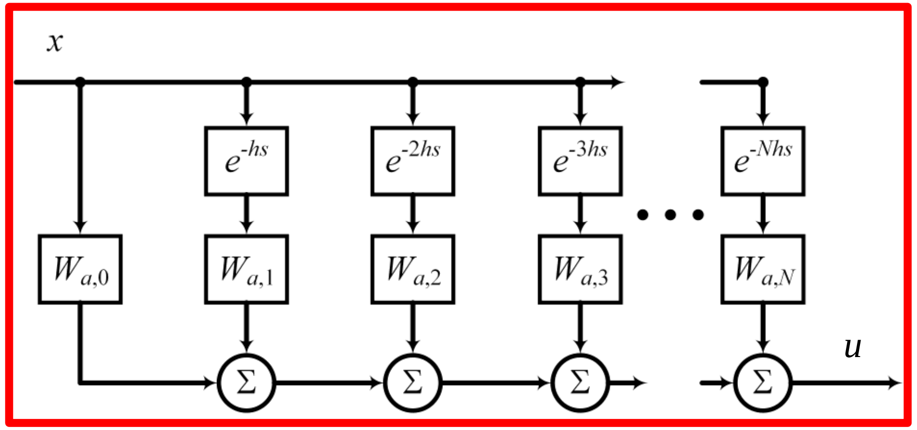


$$\mathrm{R}_1 = \mathrm{R}_3 = lh/4\mathrm{C}$$
$$\mathrm{R}_2 = lh/3\mathrm{C}$$
$$\mathrm{R}_4 = lh/12\mathrm{C}$$

Analog adaptable controller design

Idea: Analog tapped delay with configurable individual weights



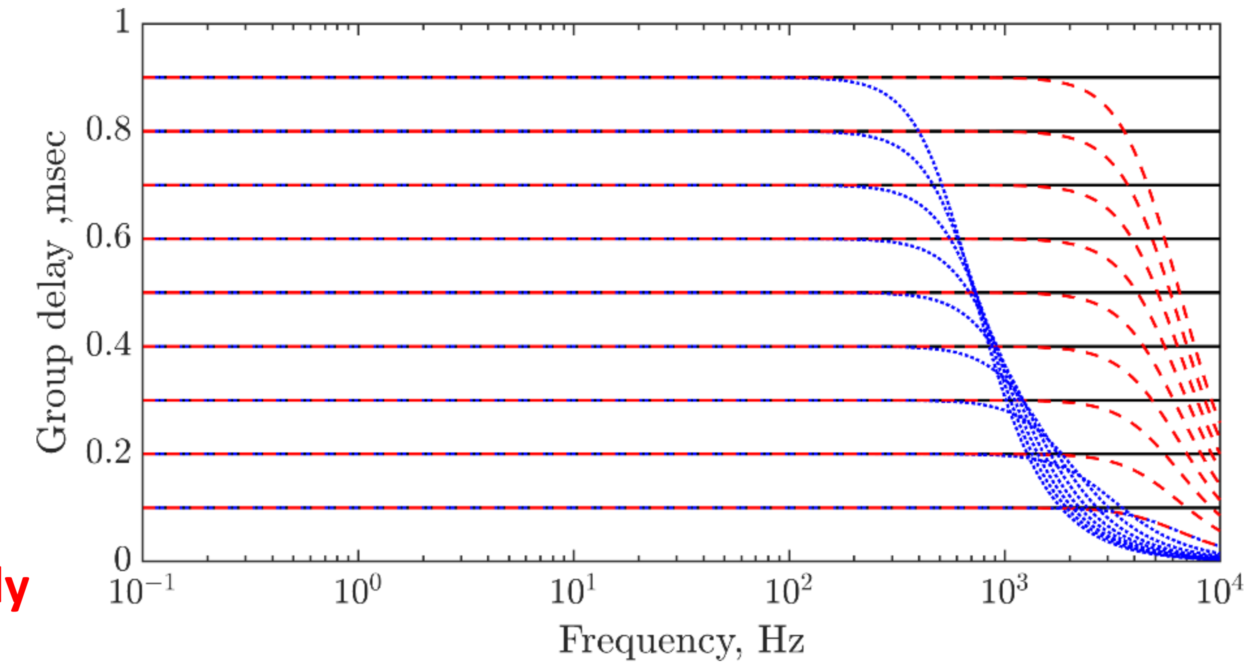


BLUE: Concatenating the base delay filter

RED: Each delay filter is implemented individually

$$G_l(s) = e^{-(lh)s} \approx \frac{1}{4}\frac{s^2 - 6(lh)^{-1}s + 12(lh)^{-2}}{s^2 + 6(lh)^{-1}s + 12(lh)^{-2}}$$

Group delay $\tau_g(\omega) \equiv -\dfrac{\partial \angle G(\omega)}{\partial \omega}$

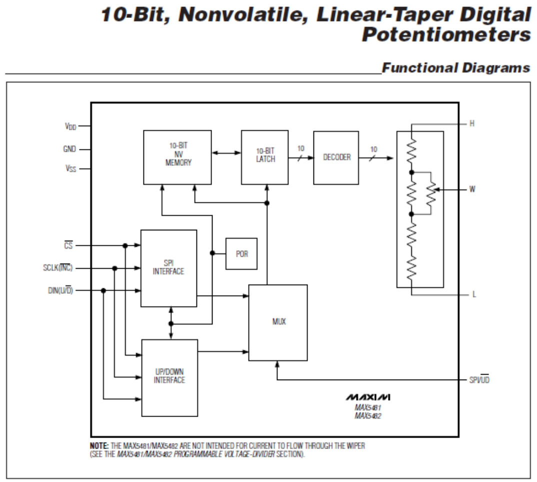


Experimental verification

$$u_{a,0}x(t) = \frac{a_0}{1023}x(t)$$

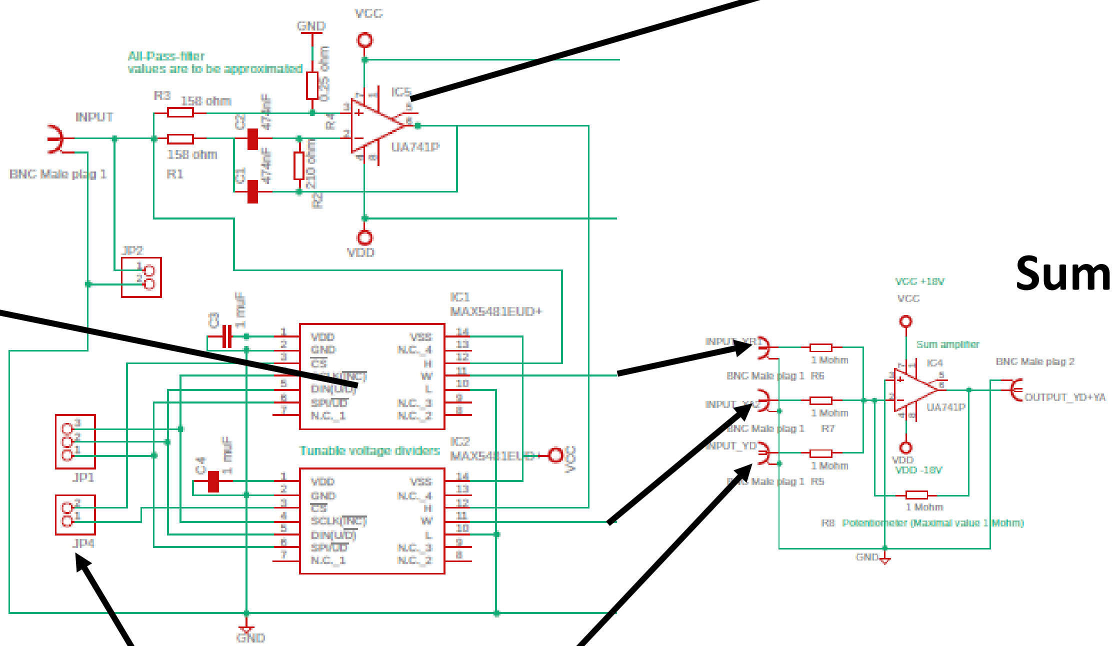
$$u_{a,3}x(t) \approx \frac{a_3}{1023}x(t-3h)$$

Adaptable weights realization



2 states analog controller

$$G_3(s) = e^{-(3h)s} \approx \frac{1}{4}\frac{s^2 - 6(3h)^{-1}s + 12(3h)^{-2}}{s^2 + 6(3h)^{-1}s + 12(3h)^{-2}}$$



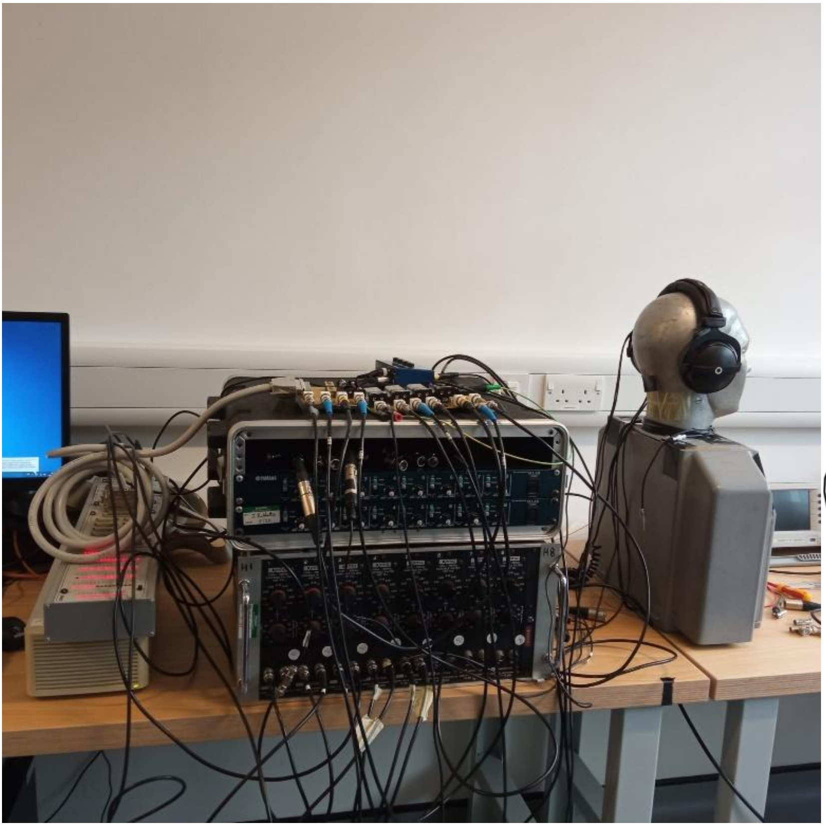
Summing circuit

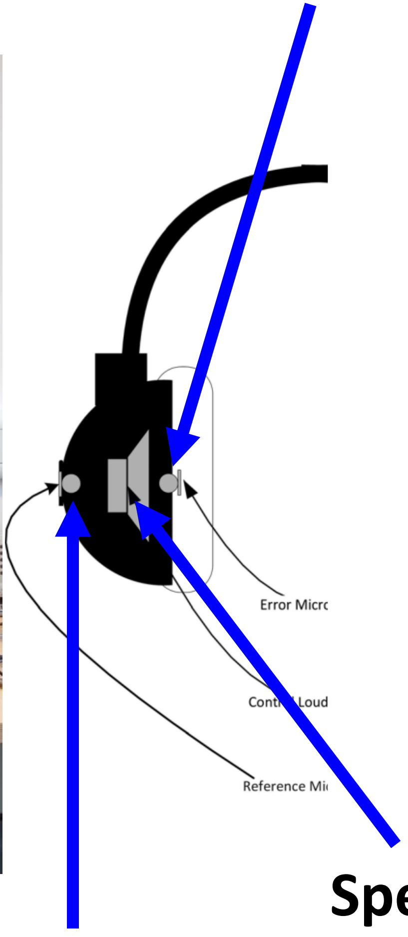
$$u = \frac{1}{3.9}u_{a,0} + \frac{1}{4}u_{a,3} + u_d$$

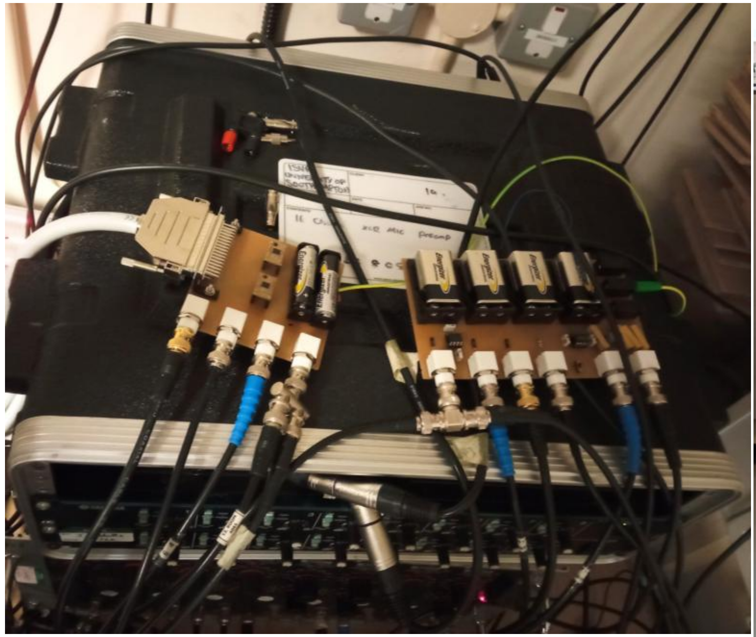
dSPACE 1003
Digital controller
and adaptation

Experimental verification

Error mic



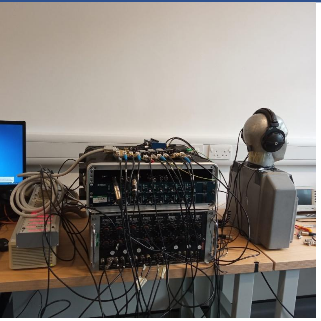




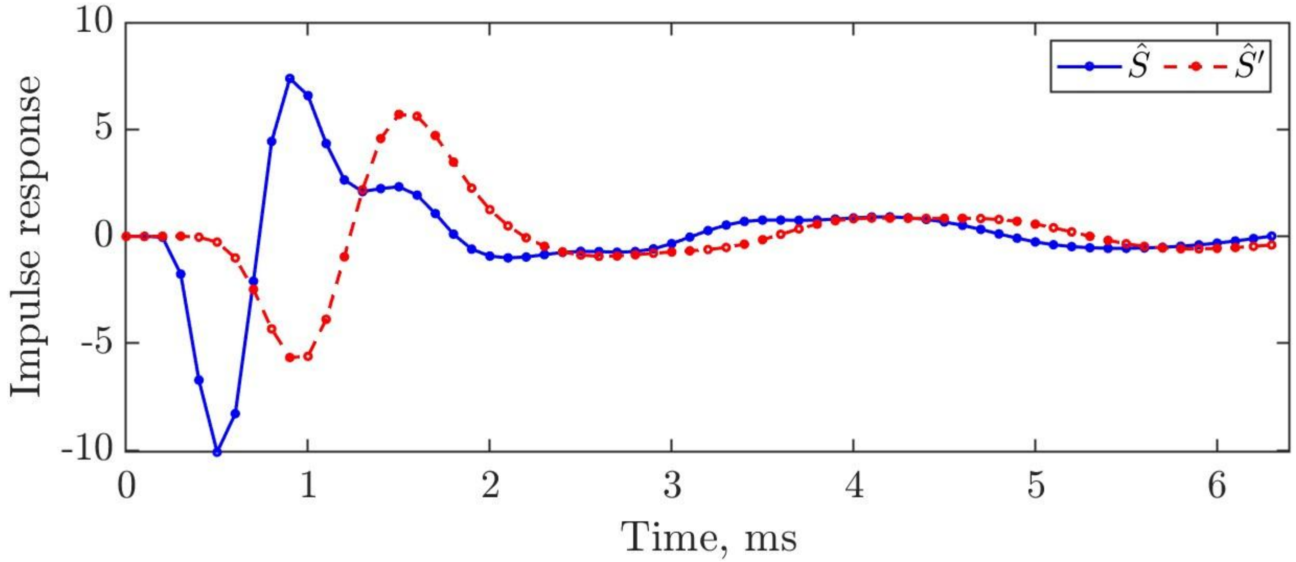
Speaker (Secondary source)

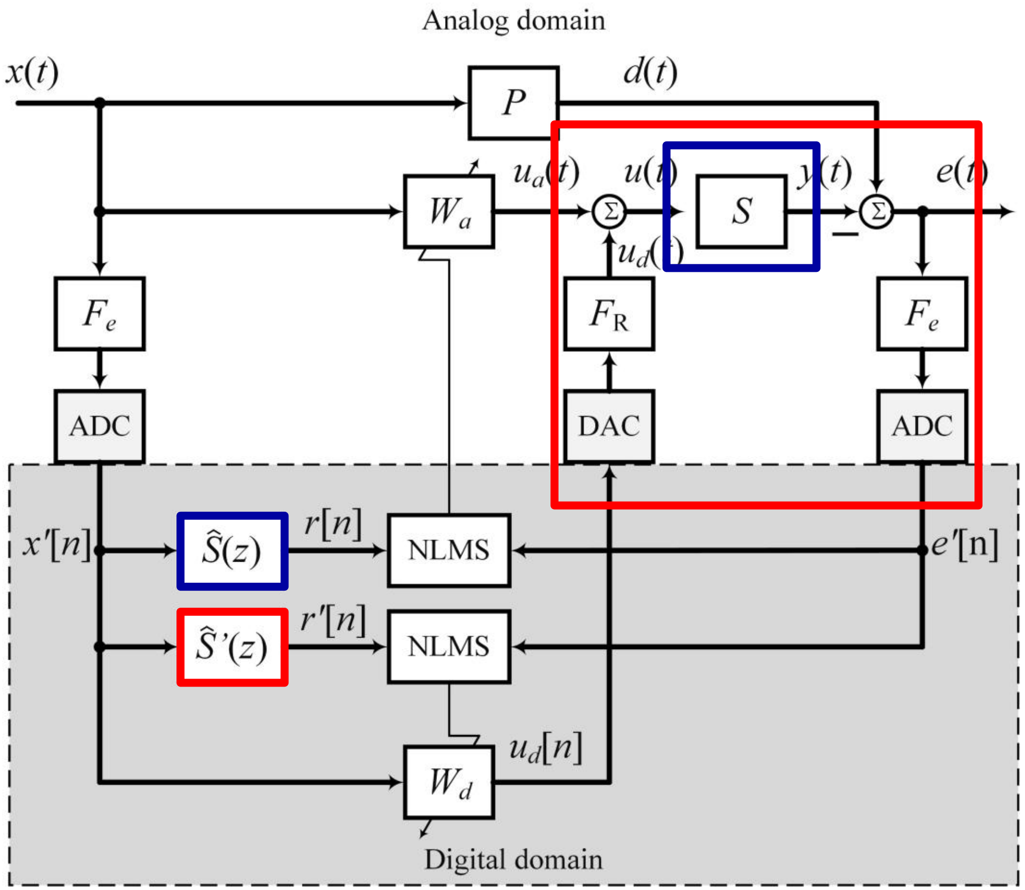
Reference mic

Secondary path models

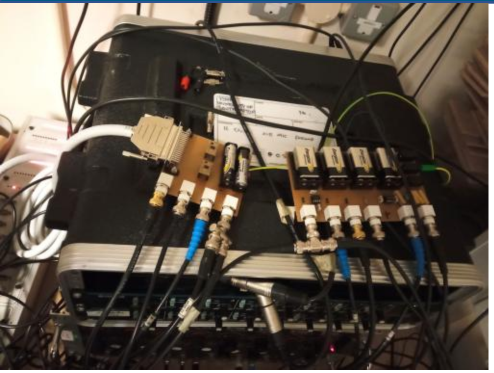


BLUE: Physical analog secondary path model
RED: Sampled digital secondary path model

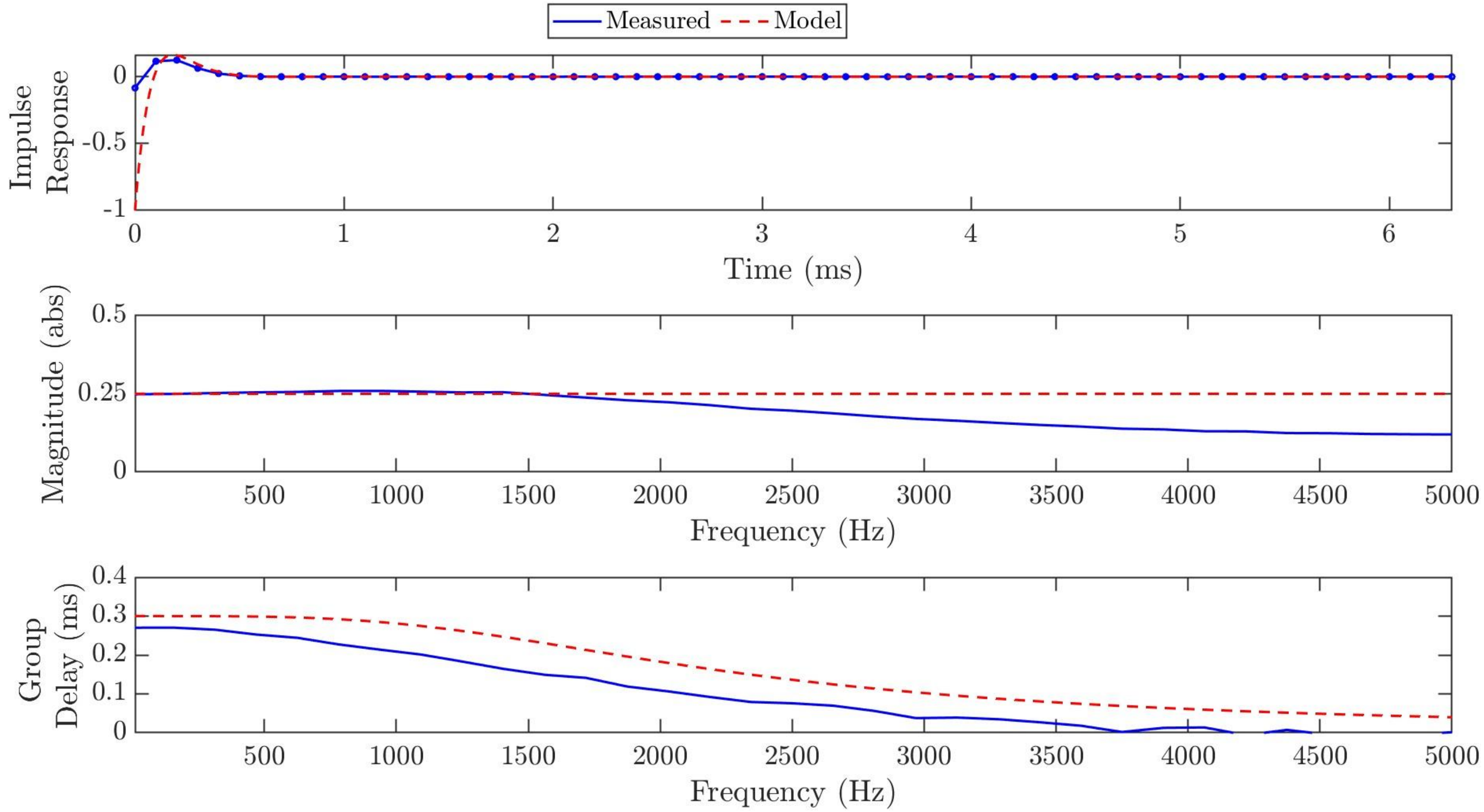




Padé all-pass filter



$$G_3(s) = e^{-(3h)s} \approx \frac{1}{4}\,\frac{s^2 - 6(3h)^{-1}s + 12(3h)^{-2}}{s^2 + 6(3h)^{-1}s + 12(3h)^{-2}}$$

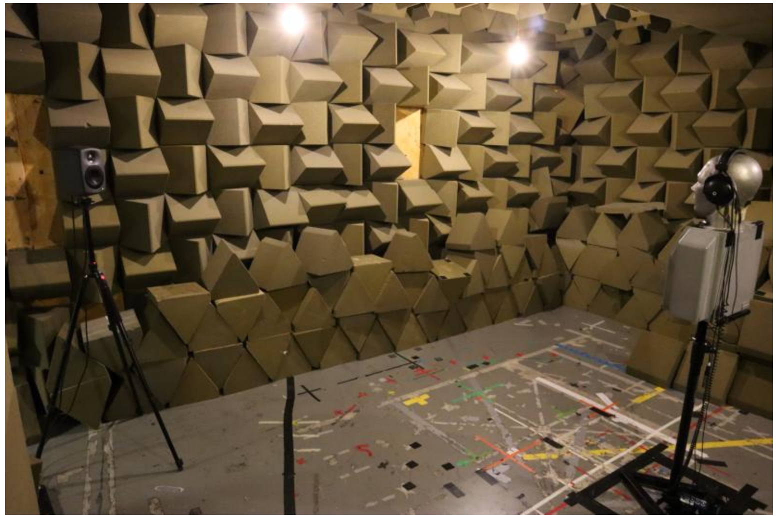


BLUE: Measured
RED: Model

Anechoic chamber experiments

Best case scenario

Worst case scenario



$\Delta t_P > \Delta t_S$

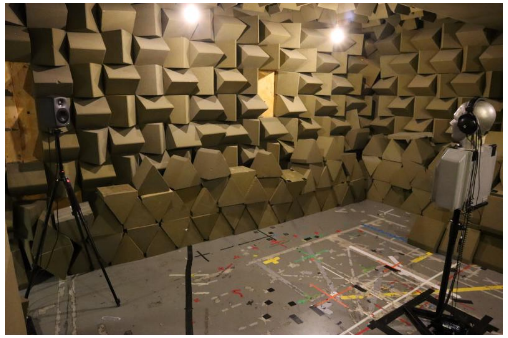
$\Delta t_P \approx \Delta t_S$

Anechoic chamber experiments – NR

Noise reduction between 20 – 2000 Hz

$\boldsymbol{\theta = -90}$	u_d	$u_d + u_{a,0}$	$u_d + u_{a,3}$	$u_d + u_a$
NR [dBA]	12.2	13.3	18.6	17.6

$\boldsymbol{\theta = -45}$	u_d	$u_d + u_{a,0}$	$u_d + u_{a,3}$	$u_d + u_a$
NR [dBA]	11.6	12.8	17.4	17.2



$\boldsymbol{\theta = 0}$	u_d	$u_d + u_{a,0}$	$u_d + u_{a,3}$	$u_d + u_a$
NR [dBA]	11.3	13.5	16.3	16.4

Concluding Remarks

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- A parallel adaptive analog and digital controller was designed to minimize the sampling delay
- The adaptable analog controller was designed using digital potentiometers and 2nd-order all-pass filter
- Experimental results indicate great improvement when using the parallel controller
- The additional analog tap, $u_{a,3}$, is required to obtain near-optimal performance. The direct feedthrough $u_{a,0}$ by itself is not enough.

Thank you for your attention