

Overview of Olson H. and May E.'s 1953 Paper on Electronic Sound Absorber

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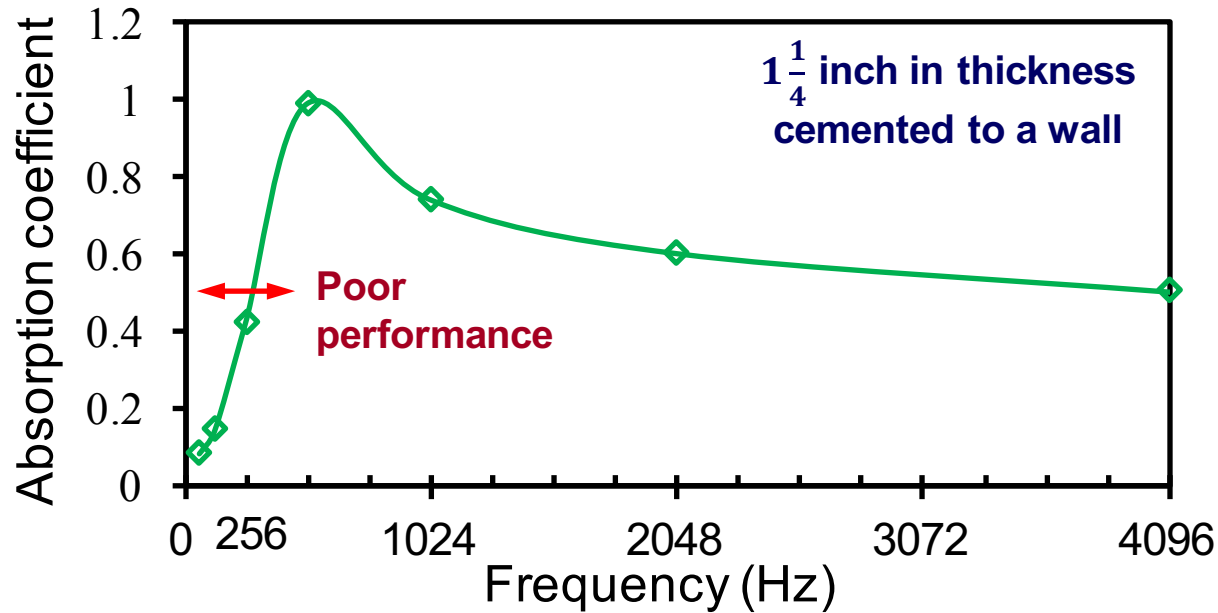
Aug 27, 2013



- **Problem Statement**
- **Overview of Electronic Sound Absorber**
 - ✓ Theory and concepts
 - ✓ System performance analysis
 - ✓ Thrust potential applications
- **Modern Active Noise Control (ANC) System**
 - ✓ Feedback and feedforward control strategies
 - ✓ Digital filter with adaptive algorithms (FXLMS)
- **Trend of ANC Applications in Auto Industry**
 - ✓ Active sound tuning of powertrain and exhaust noises
 - ✓ Active attenuation of tire-road noise
- **Concluding Remarks**

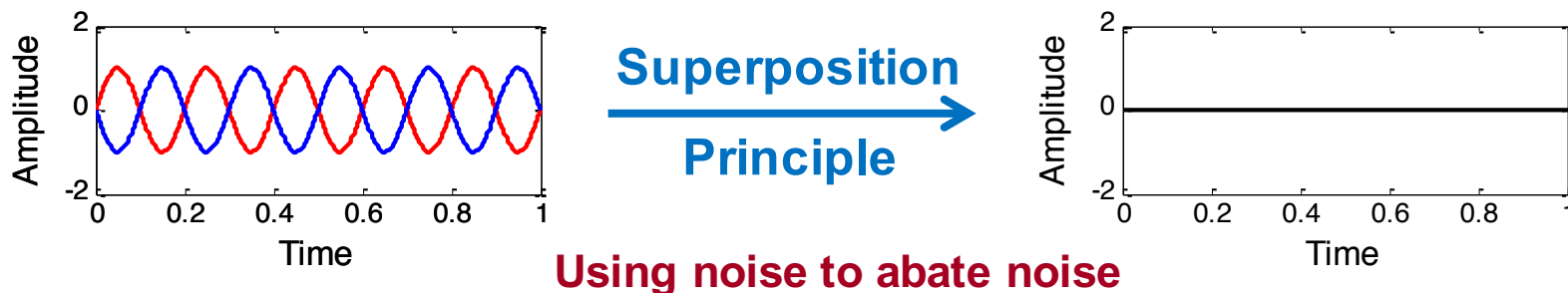
Concept of Active Noise Control

- Traditional passive noise control, via blocking or absorbing sound waves, tends to become very bulky for low-frequency noise.

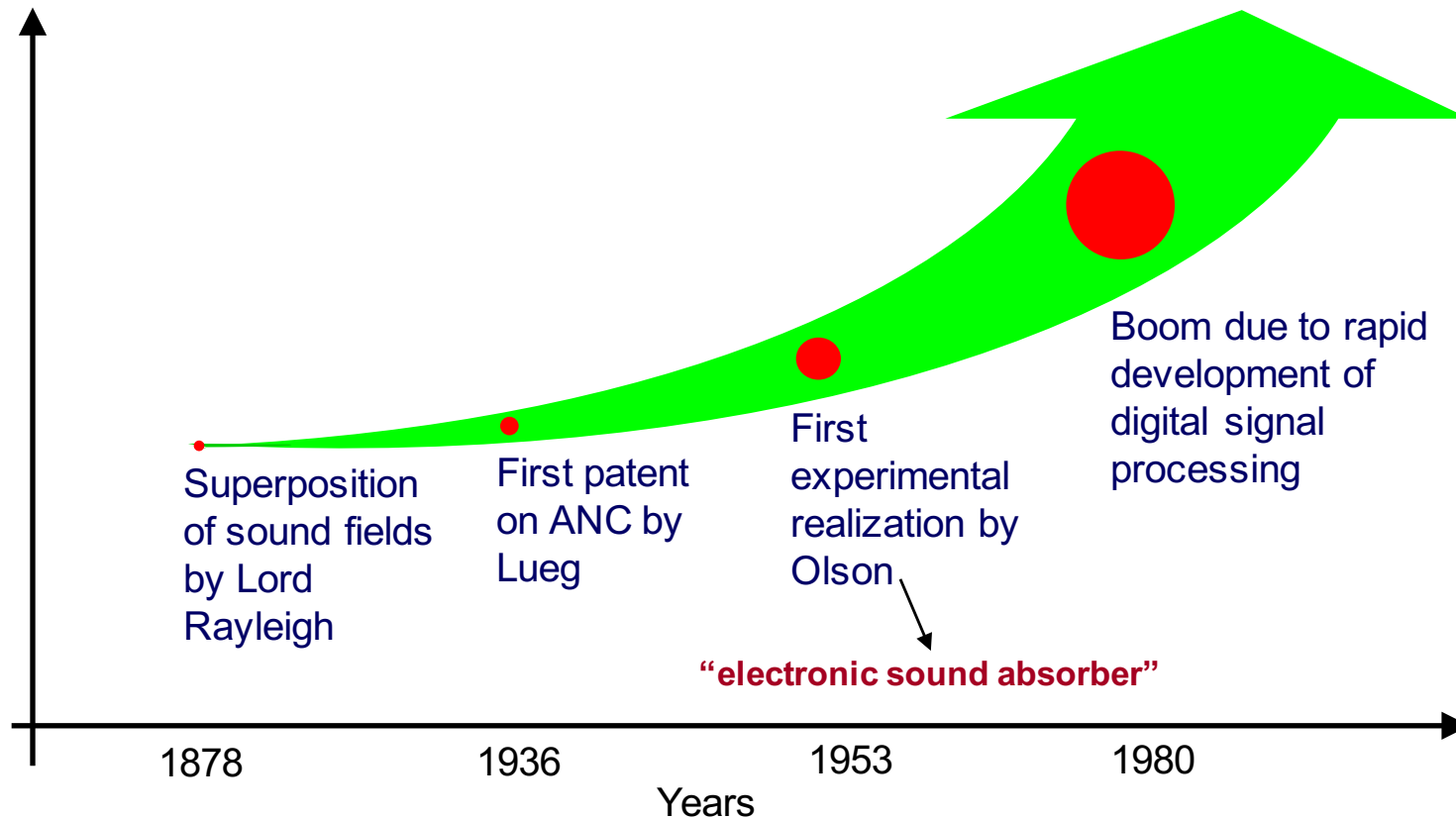


Absorption coefficient of a typical sound absorbing material
(reproduced from Olson's paper)

- Active noise control is an alternative way by injecting an “anti-noise”:



Development of Active Noise Control

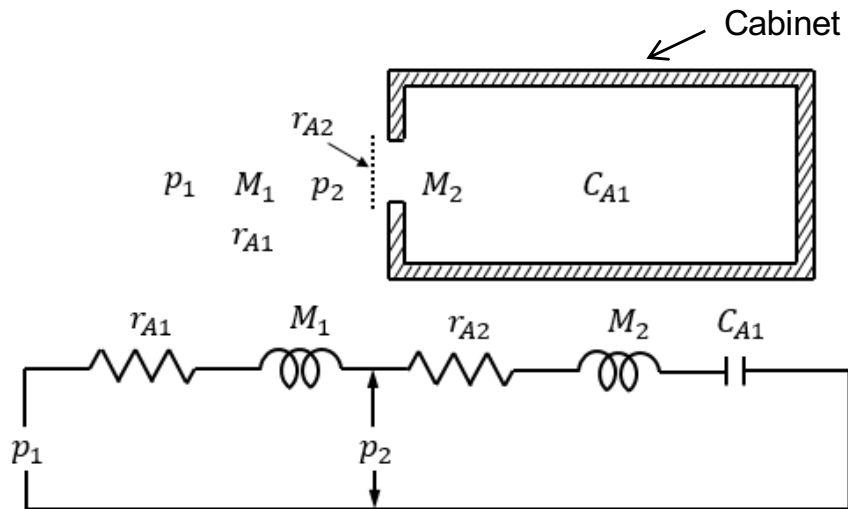


- In 1953, Olson first realized the idea of ANC in real environment.
- This pioneering work has a tremendous influence on subsequent ANC R&D in various areas, such as automobile, aircraft, HVAC and appliances.

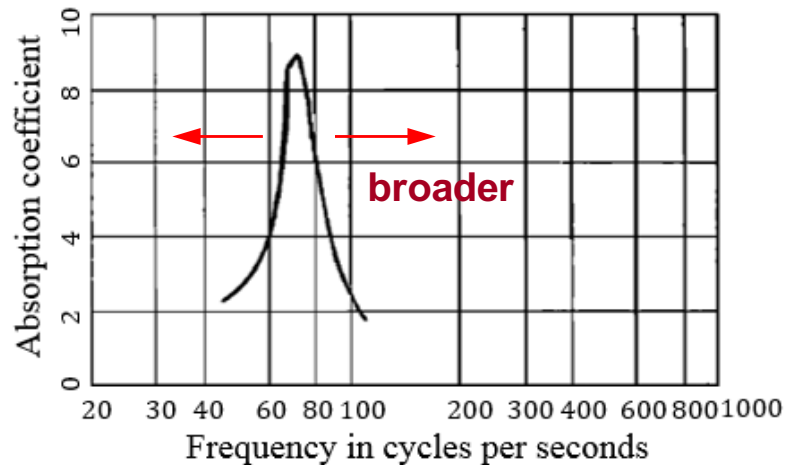
Concept of Electronic Sound Absorber

- Multiple Helmholtz resonators for absorbing broader low-frequency range.

Passive sound absorber



Acoustical network



Active sound absorber

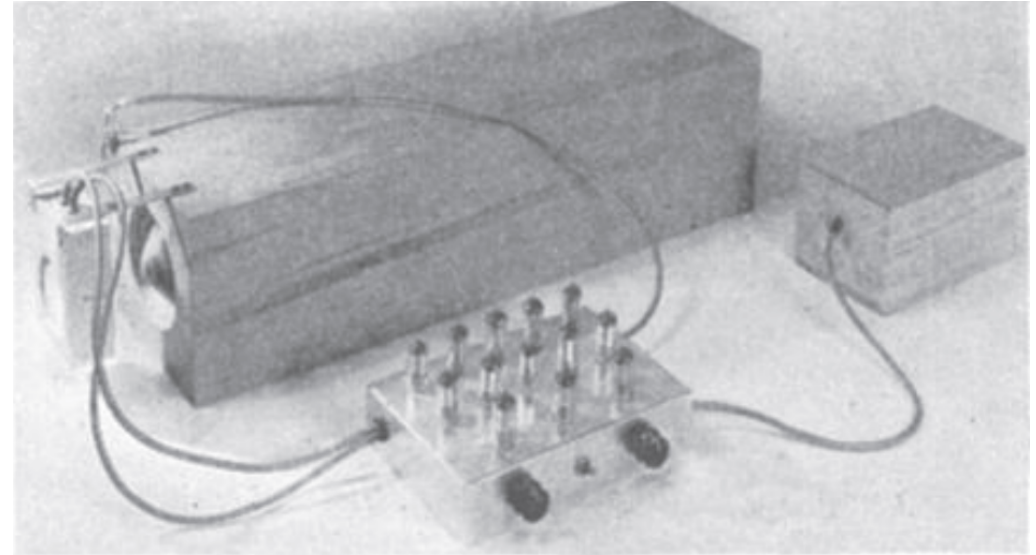


FIG. 6. Electronic sound absorber.

Figure is clipped from Olson's paper

- Alternatively, the active sound absorber provides a way to cancel the low-frequency noise without increasing weight and easy for practical installation.

Theory of Active Sound Absorber

- The electronic sound absorber is a negative feedback control system to reduce the sound pressure p_3 :

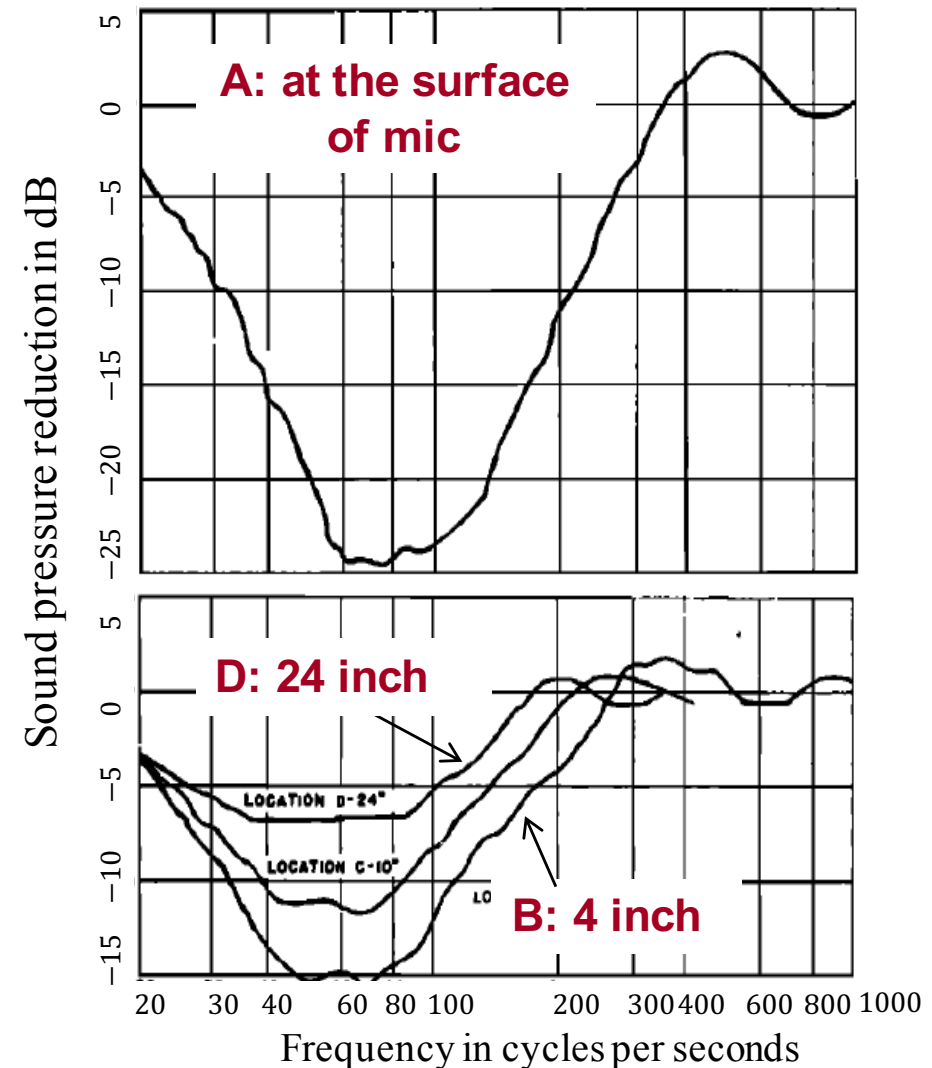
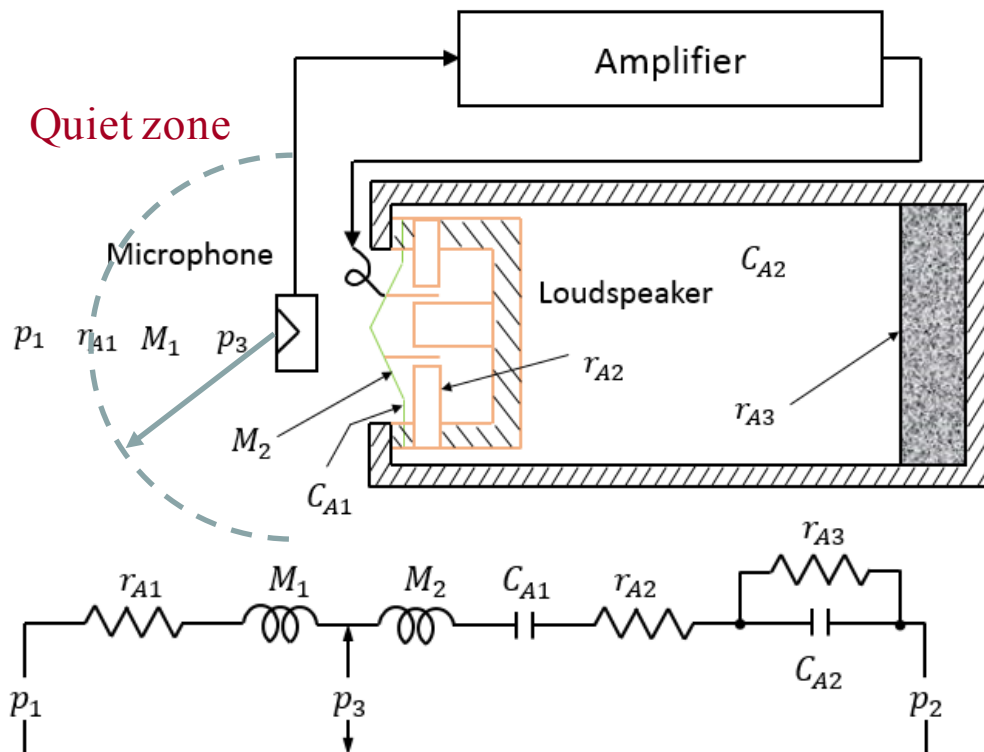
$$p_3 = p_1 f(A, \lambda, \phi, d).$$

where $A = p_2/p_1$: amplifier gain

λ : wavelength of the sound wave

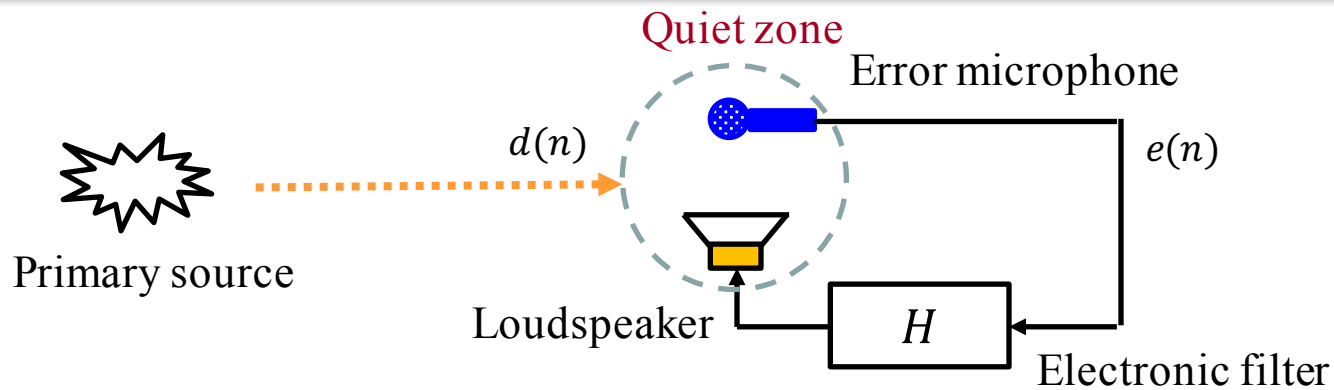
ϕ : phase shift in the system

d : distance between mic and speaker

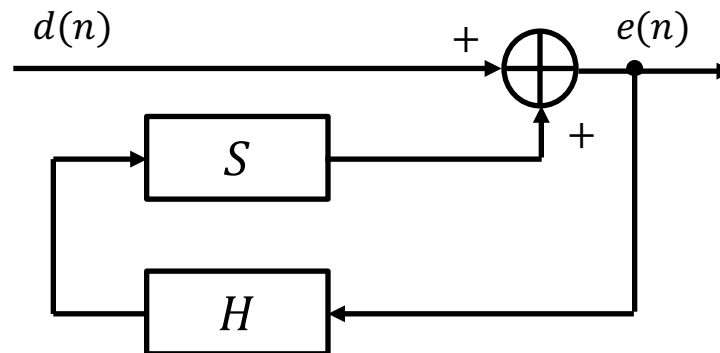


- Quite large zone of reduction
- However, the distance d will significantly affect system's performance.

Performance Analysis of Feedback ANC System



An ANC system using feedback control and its equivalent electrical block diagram



- The transfer function of complete feedback loop:

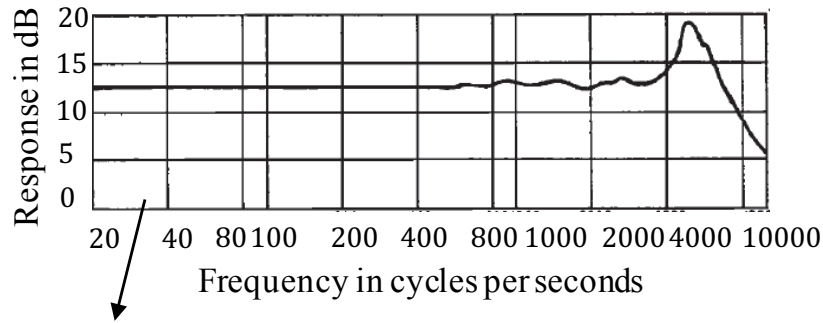
$$\frac{E(j\omega)}{D(j\omega)} = \frac{1}{1 - H(j\omega)S(j\omega)}$$

Here $S(j\omega)$ is the transfer function contains electroacoustic response of loudspeaker, acoustic path between loudspeaker and microphone, and the electroacoustic response of microphone.

For Olson's system, it was assuming $S(j\omega)$ is flat, $H(j\omega) = -A$. Hence, the larger the amplifier gain, the better the system's performance.

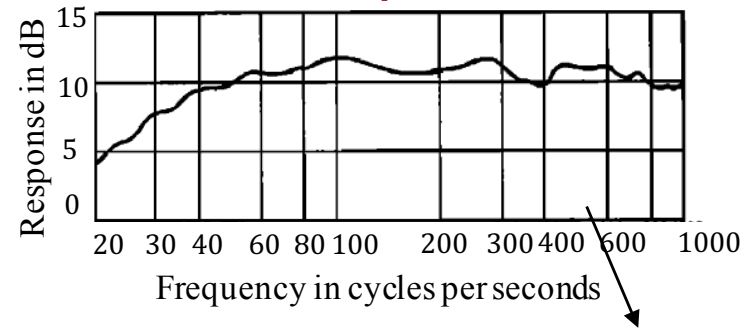
Components Design of the Active Sound Absorber

Electronic microphone



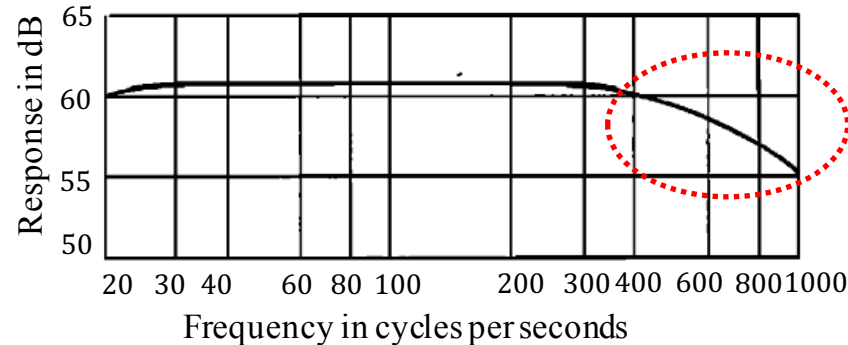
Also, the variation in phase angle is less than 2° from 20 to 400 cycles.

Loudspeaker



Size is one-half cubic foot

Amplifier

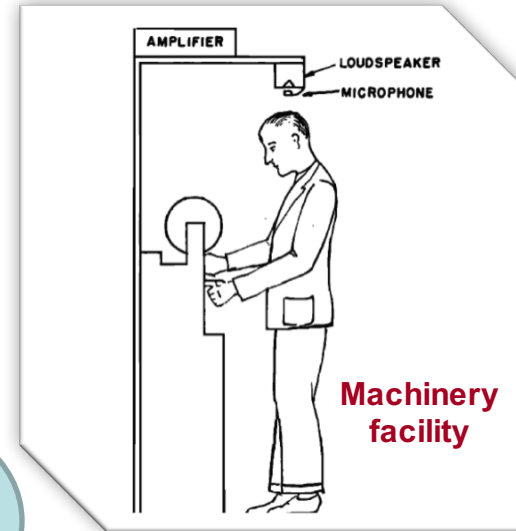
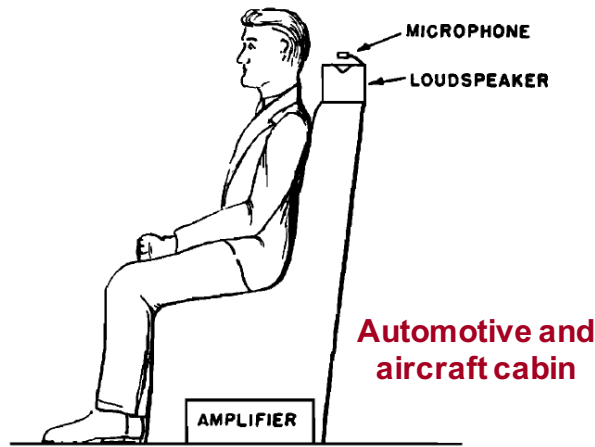


Reduced gain to avoid instability

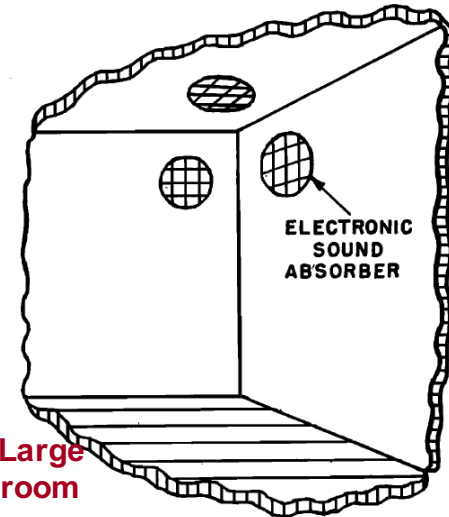
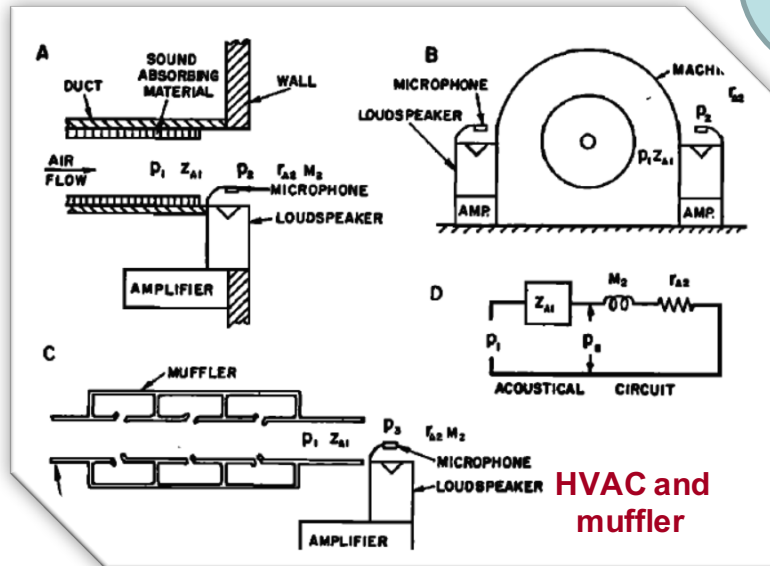
Figures are adopted from Olson's paper

- Very special precautions in the choice and design of the components
 - ✓ Flat response and free of phase shift of the secondary path (from loudspeaker to error microphone)
 - ✓ Reduced response of the amplifier to avoid positive feedback in the high frequency range

Potential Applications of the Active Sound Absorber



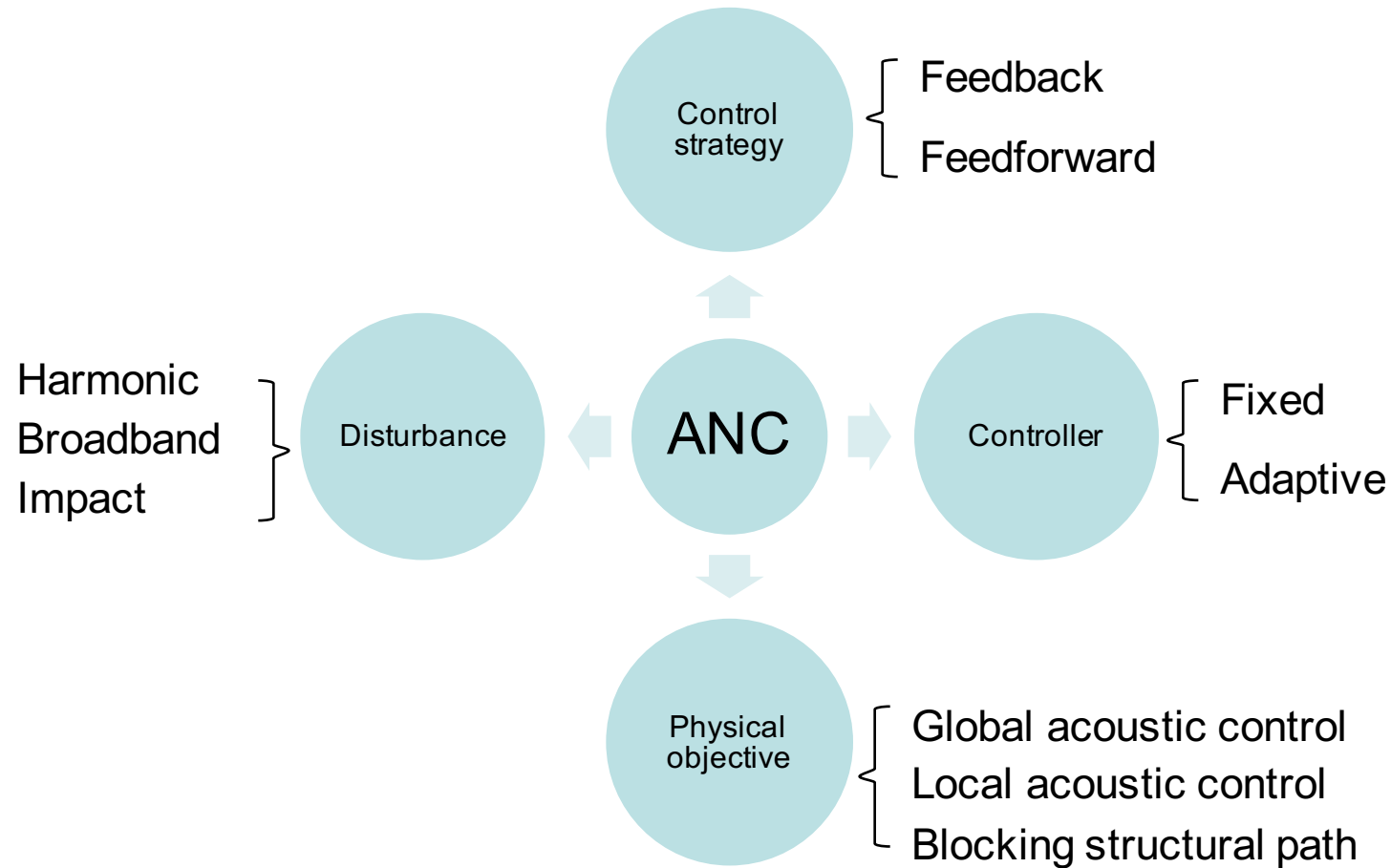
Electronic sound absorber



Figures are snipped from Olson's paper

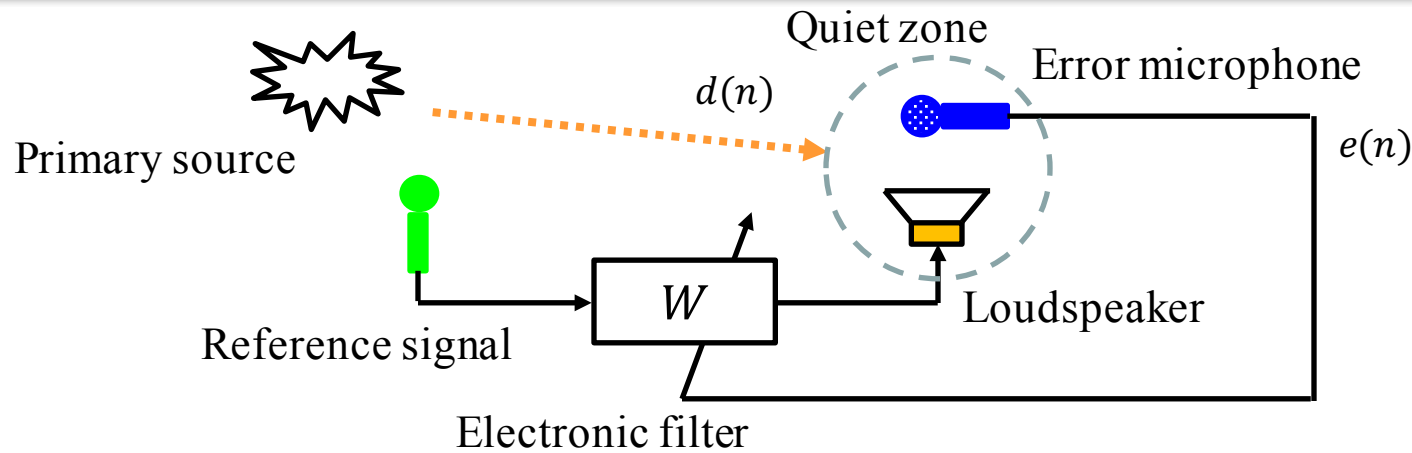
- The potential applications of the active sound absorber have been widely investigated by subsequent researchers, especially several practical commercialization in auto industry.

Modern Active Noise Control (ANC) System



- The boom of electronic hardware and software in 1980s leads to rapid development of modern ANC system (**feedforward control using digital filter with adaptive filtered-x least mean square (FXLMS) algorithm**).
- The modern ANC system tends to have more robustness to time-varying environment and dynamic disturbances.

Comparison of Control Strategies



Type of control

Feedback

Active damping

- Simple to implement and fewer computation
- Does not require accurate model of the plant
- Guaranteed stability when actuators and sensors are collocated

Disadvantages

- Effective only near resonance

Model-based

(LQG , H_∞ , etc)

- Global method
- Requires accurate model of the plant
- Attenuate all disturbance within bandwidth

- Limited bandwidth
- Requires low delay for wide bandwidth
- Spillover

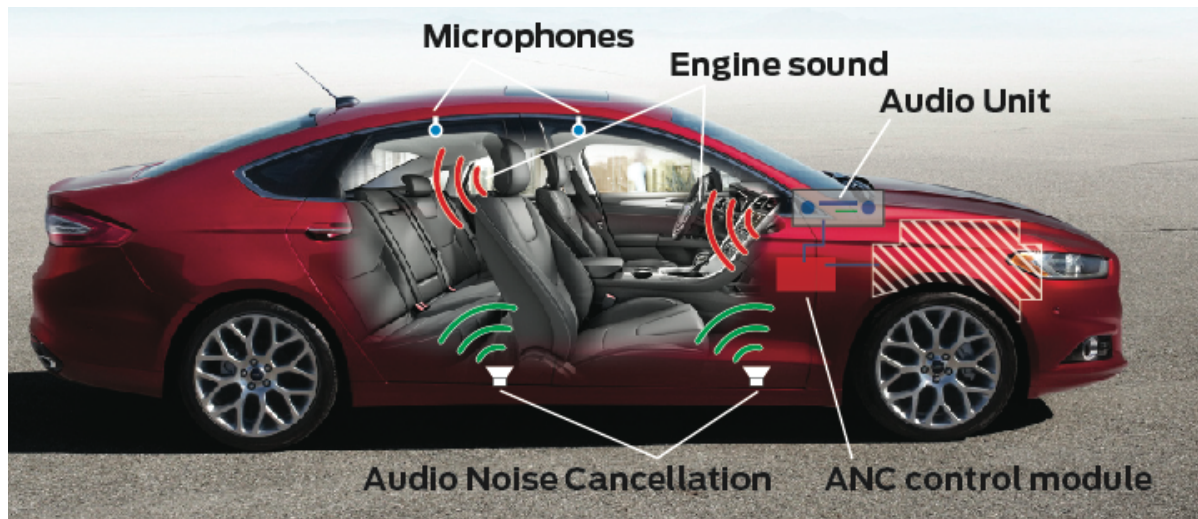
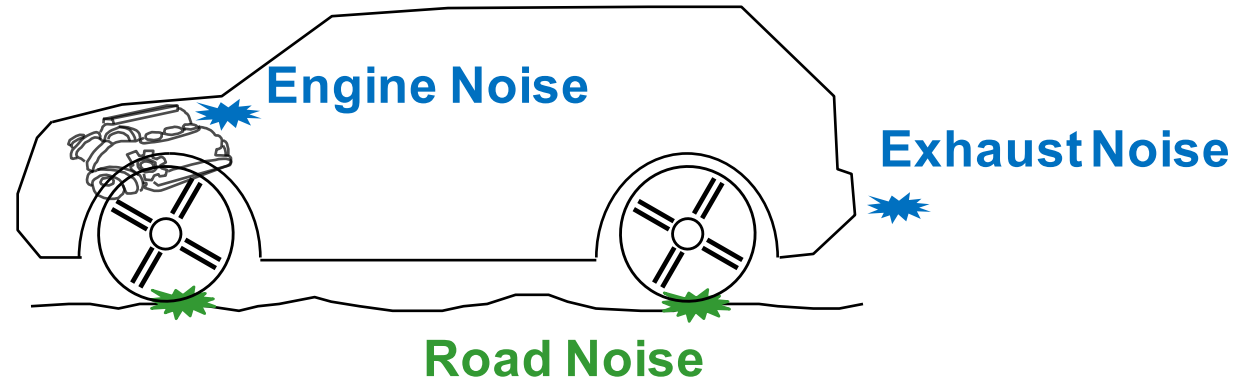
Feedforward

Adaptive filtering of reference (x-filtered LMS)

- Unnecessary precise modeling
- Large stability bounds
- More effective for narrowband disturbance

- Reference/error signal is required
- Local method and may amplify noise somewhere else

ANC Applications for Vehicle Interior or Exterior Noise



Concept of ANC for vehicle interior noise

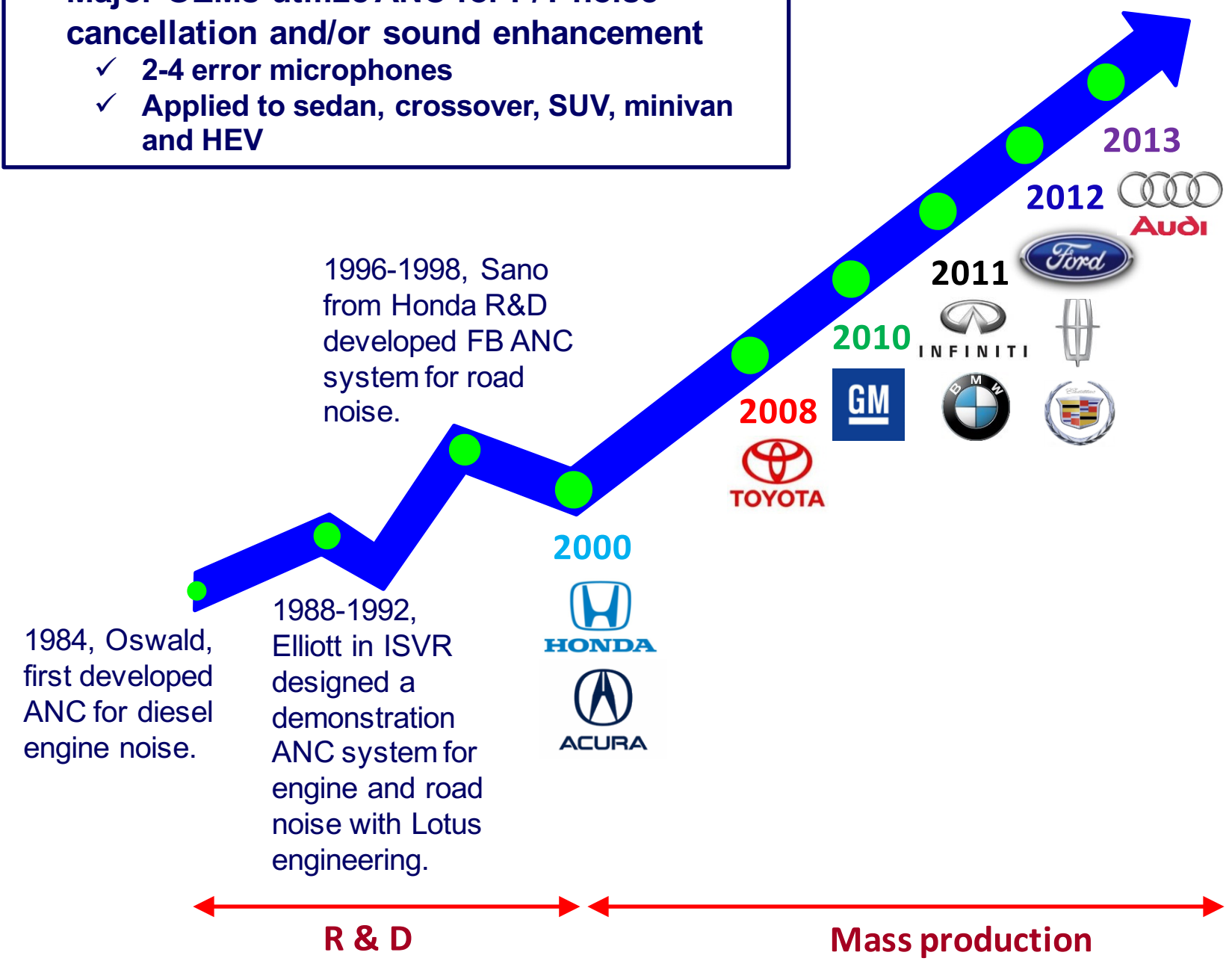
- **Dominant low-frequency vehicle interior noise is caused by engine noise and road noises.**
- **Traditional passive noise control uses heavier/thicker materials (poor fuel efficiency).**

Refs.: Elliott, S. J. (2008). A review of active noise and vibration control in road vehicles.

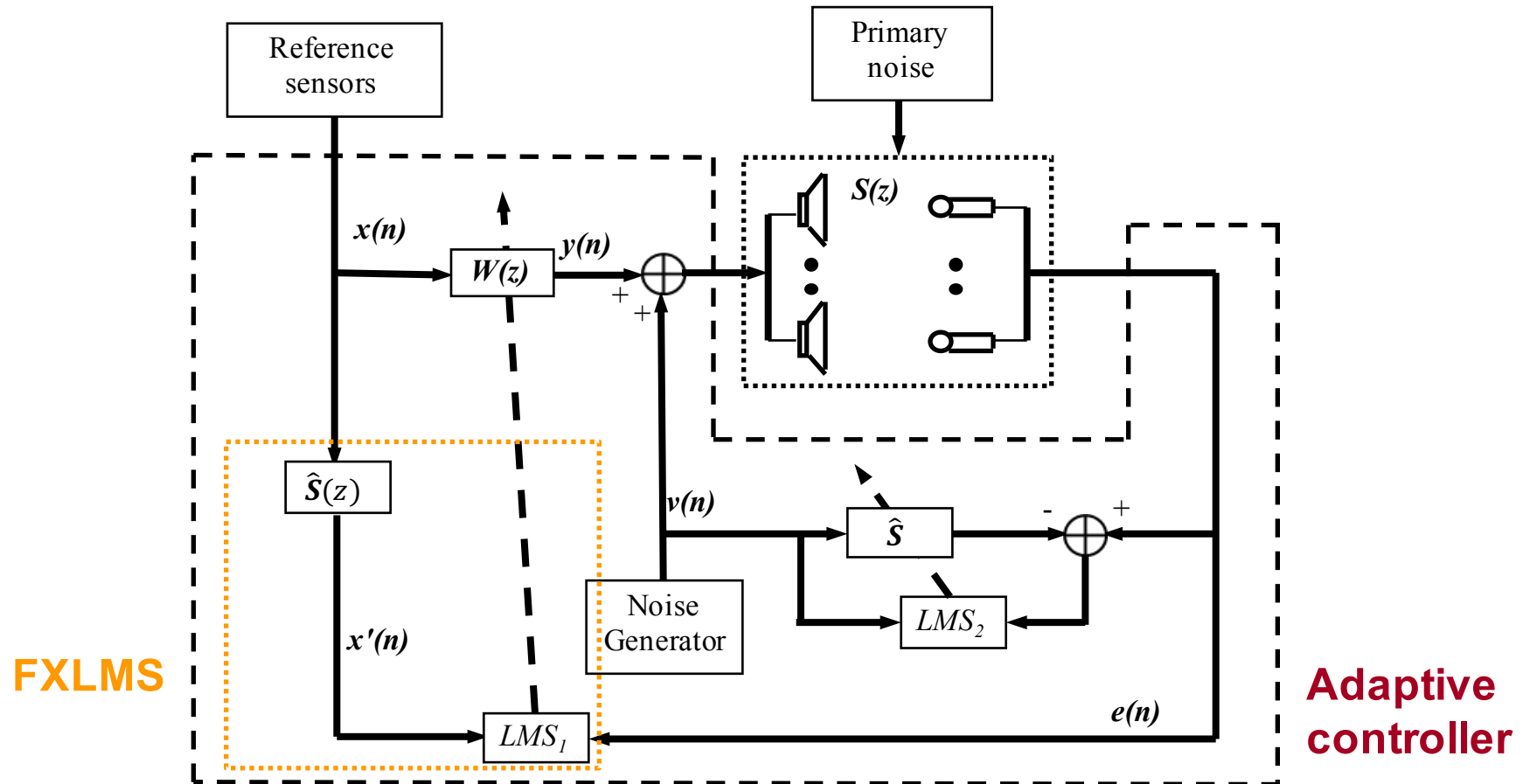
Li, M. D., Jie; Lim, Teik C. (2010). Active Noise Cancellation Systems for Vehicle Interior Sound Quality Refinement. *Recent Patents on Mechanical Engineering*, 3(3), pp.163-173.

Commercialization Trend in Automotive Industry

- Major OEMs utilize ANC for P/T noise cancellation and/or sound enhancement
 - ✓ 2-4 error microphones
 - ✓ Applied to sedan, crossover, SUV, minivan and HEV



Active Noise Control System Flow Diagram



FXLMS weight update:

$$W(n+1) = W(n) + ue(n)[\hat{S}(n) * X(n)]$$

$$u \propto \frac{2}{L(x * s)^2}$$

L is filter order

LMS :

$x(n)$:

$y(n)$:

$e(n)$:

$S(z)$:

$\hat{S}(z)$:

$v(n)$:

$W(z)$:

least mean squares algorithm

reference signal

control input signal

sound pressure response at microphone

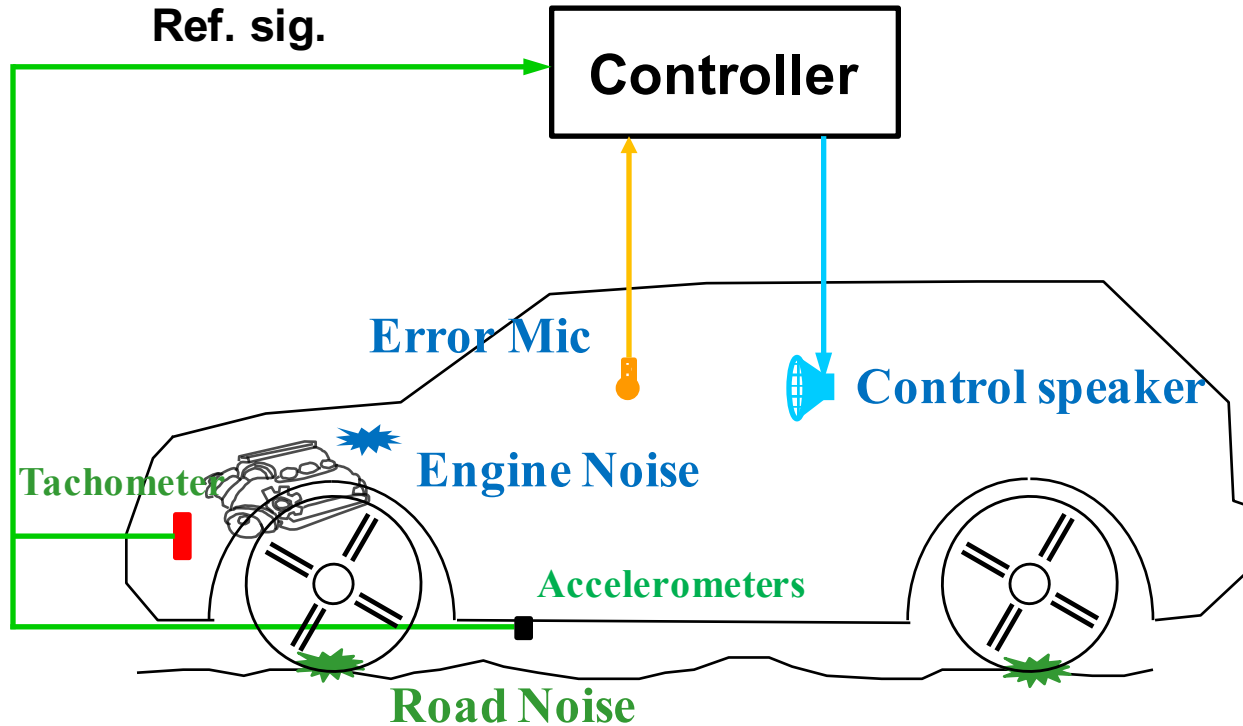
secondary path transfer function (relates control speaker driving signal to sound pressure response at microphone)

estimated secondary path transfer function

white noise

adaptive controller

UC ANC Work on Vehicle Powertrain and Road Noise



Several efficient algorithms have been proposed:

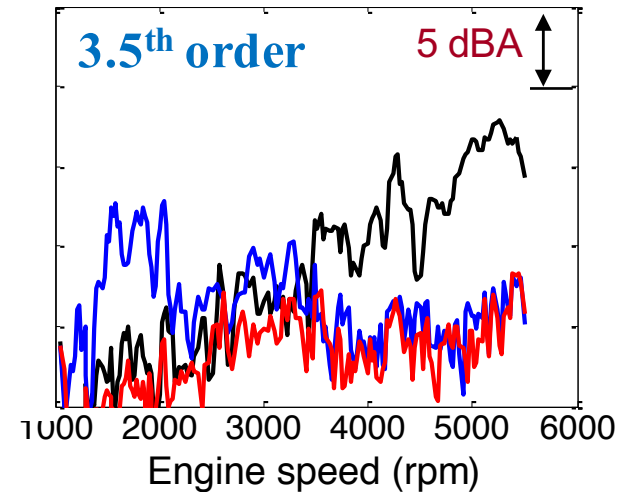
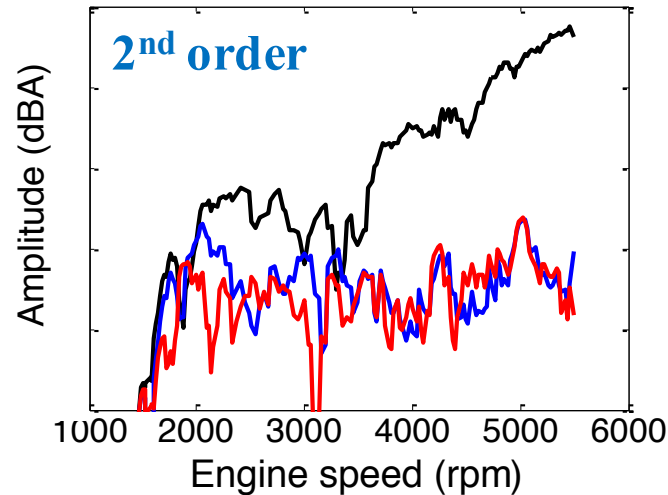
Engine Noise

- Twin-FXLMS algorithm (deal with odd & even order)
- Virtual secondary path algorithm (equalization)
- Time-frequency FXLMS algorithm for active sound tuning (cost efficient)

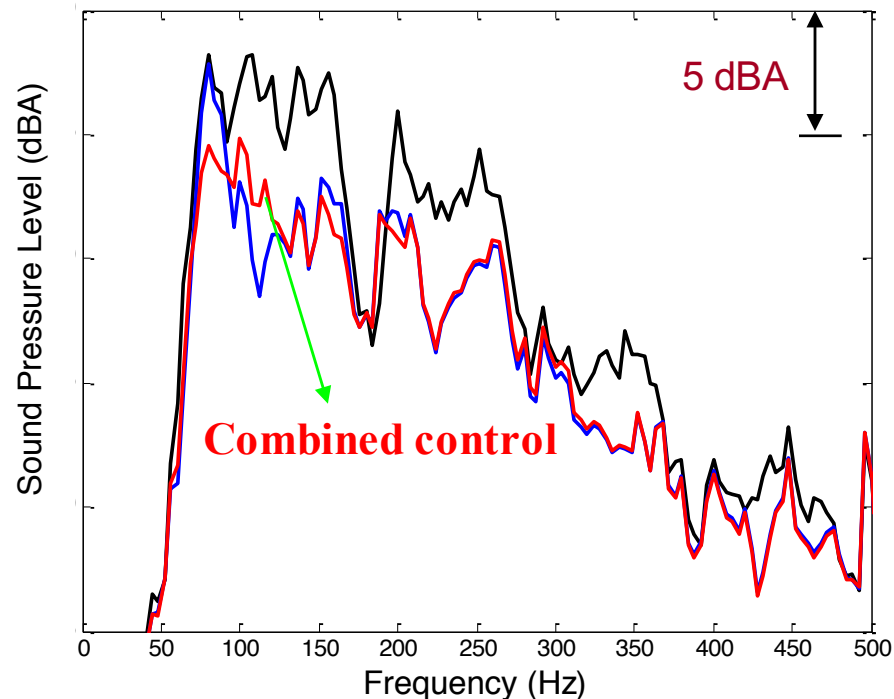
Road Noise

- Combined FF and FB system
- Subband algorithm (faster convergence for color noise)
- Channel equalization algorithm (balanced performance)

Powertrain and Road Noises Control Results



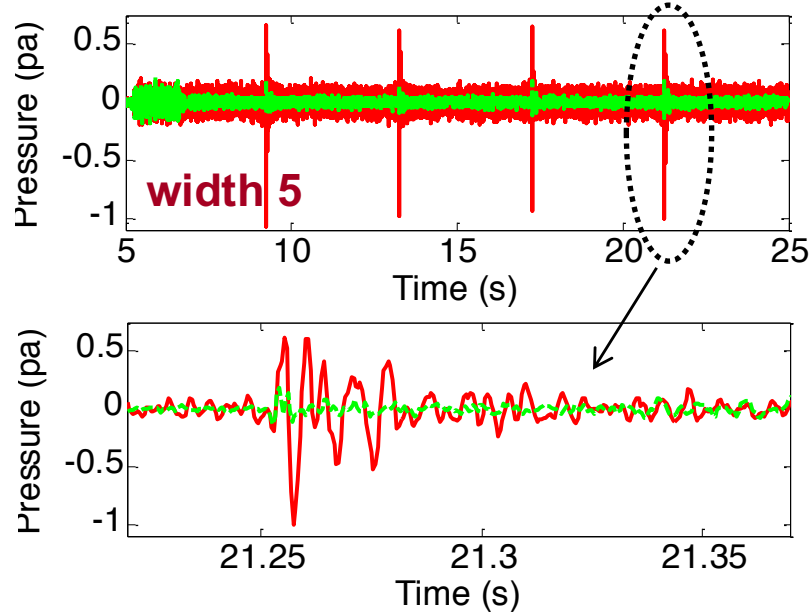
— **Baseline** — **ANC on, FXLMS algorithm** — **ANC on, Twin-FXLMS algorithm**



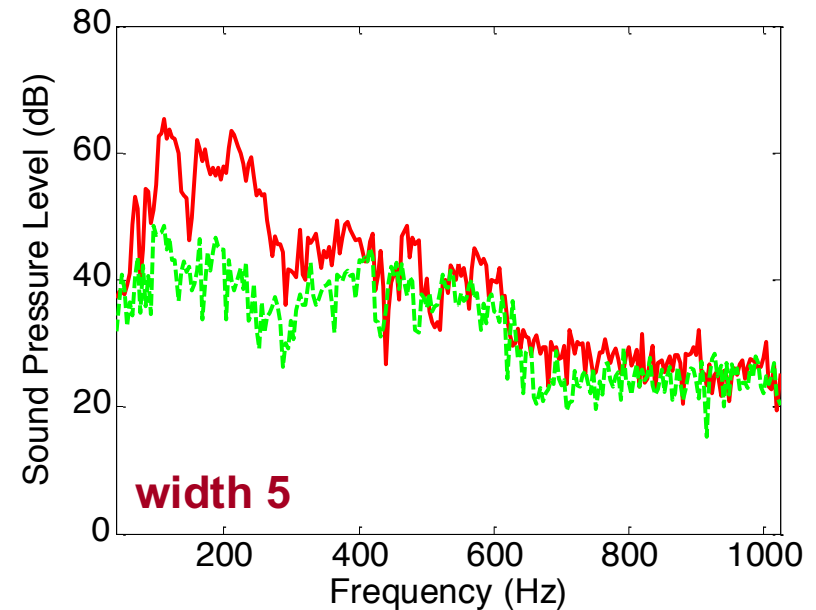
Combined control versus feedforward control only

Combined feedforward-feedback control strategy is able to achieve more reduction than feedforward or feedback control alone

Modified FXLMS Algorithm for Impact Acoustic Noise

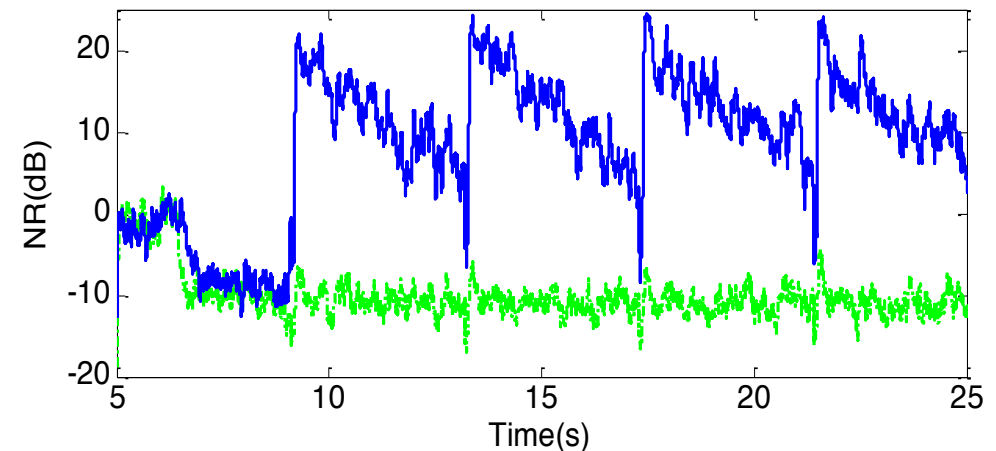


— ANC off - - - MFXLMS — FXLMS



Averaged spectra of the impact responses

- **Obvious reductions are achieved at both Gaussian noise and impulses. The introduction of threshold in the MFXLMS algorithm increases the robustness and stability of the ANC system.**



Noise reduction comparison of FXLMS and MFXLMS algorithms

1. Sun, G., Li, M., Lim, T., Lee, M. et al., "Experimental Study on Enhanced FXLMS Algorithm for Active Impulsive Noise Control," *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.* 6(2):2013.
2. Sun, G., Li, M., Lim, T., "Experimental Investigation of Convergence Behavior of Modified FXLMS Algorithm for Impact Noise Control", *Noise-Con 2013 & Wind Turbine Noise 2013*, Denver, CO, USA, Aug 27-30.

Concluding Remarks

- **This presentation gives an overview on the first experimental work by Olson (1953) to develop an electronic sound absorber. This pioneering research work has a tremendous influence on subsequent research and implementation of ANC technology.**
- **Most of the potential applications of the electronic sound absorber as discussed in this paper have been implemented and extended using modern control strategy for further commercialization of ANC system.**
- **The trend of ANC applications in automotive industry has been highlighted, which can be considered as thrust applications of the work by Olson and May.**

Thank you!



Thank you!