Aalto University
School of Electrical Engineering

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Active Noise Control

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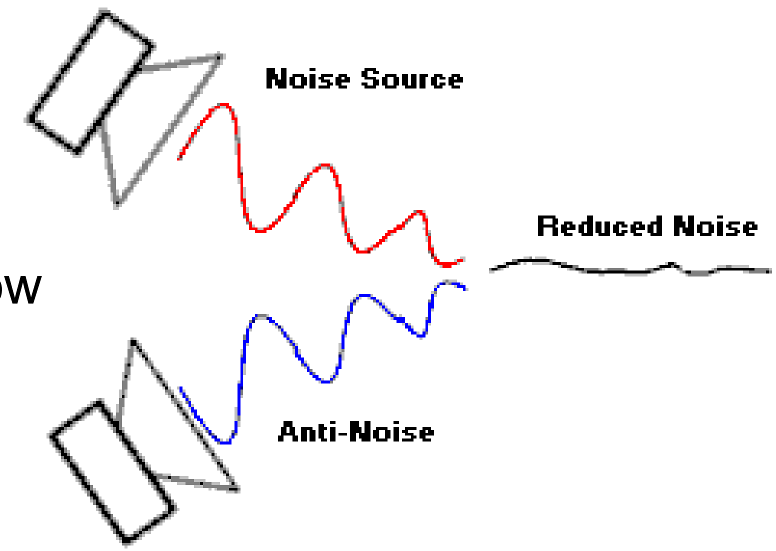
Active Noise Control – Contents

- Fundamentals of active noise control
- Adaptive filtering
- Interference cancellation
- Applications
  - Ventilation duct, headphones, transportation

Active Noise Control Basics

- Electronics is faster than sound!
  - Detect noise with a microphone
  - Produce anti-noise, play with speaker
  - Noise and anti-noise will cancel out
- Main advantage: good attenuation at low frequencies
- An acoustic transfer function modeling problem
  - How does noise propagate from mic to the area to be silenced?
- Size of silent area depends on geometry
  - In 1-D case: perfect, in 3-D case: small



ANC = Active Noise Control

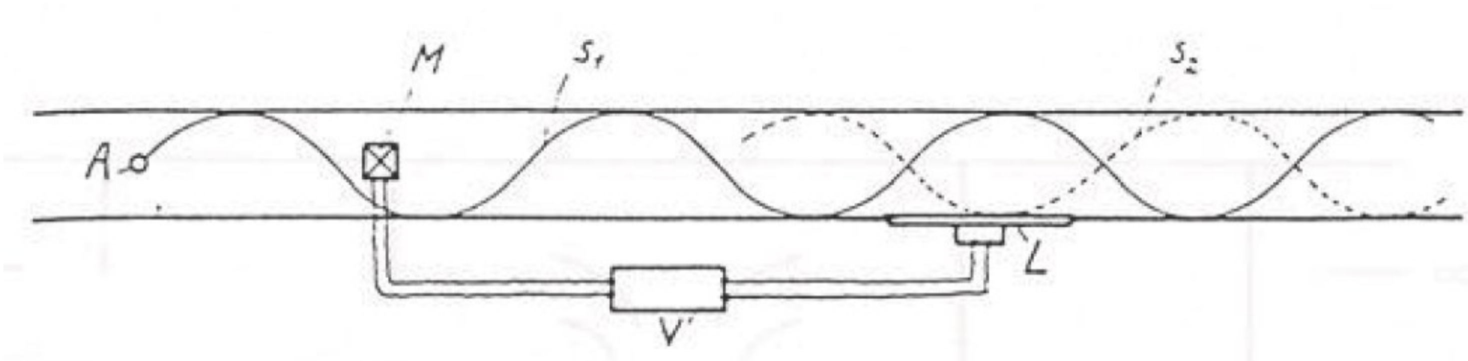
https://en.wikipedia.org/wiki/Active_noise_control

A Short History of ANC

- Paul Lueg's invention in Germany in 1930s
- Practical implementation become possible only decades later
  - Manual systems in the 1950s
  - Automatic control of analog ANC systems in the 1960s
  - Digital ANC systems in the 1980s
- First textbook in 1992
  - P. A. Nelson and S. J. Elliott (ISVR, University of Southampton, UK), "*Active Control of Sound*"
- Industrial applications in 1990s
  - Active hearing protectors, attenuators for ventilation ducts, household appliances, cars, aircrafts

Principle of ANC in a Duct

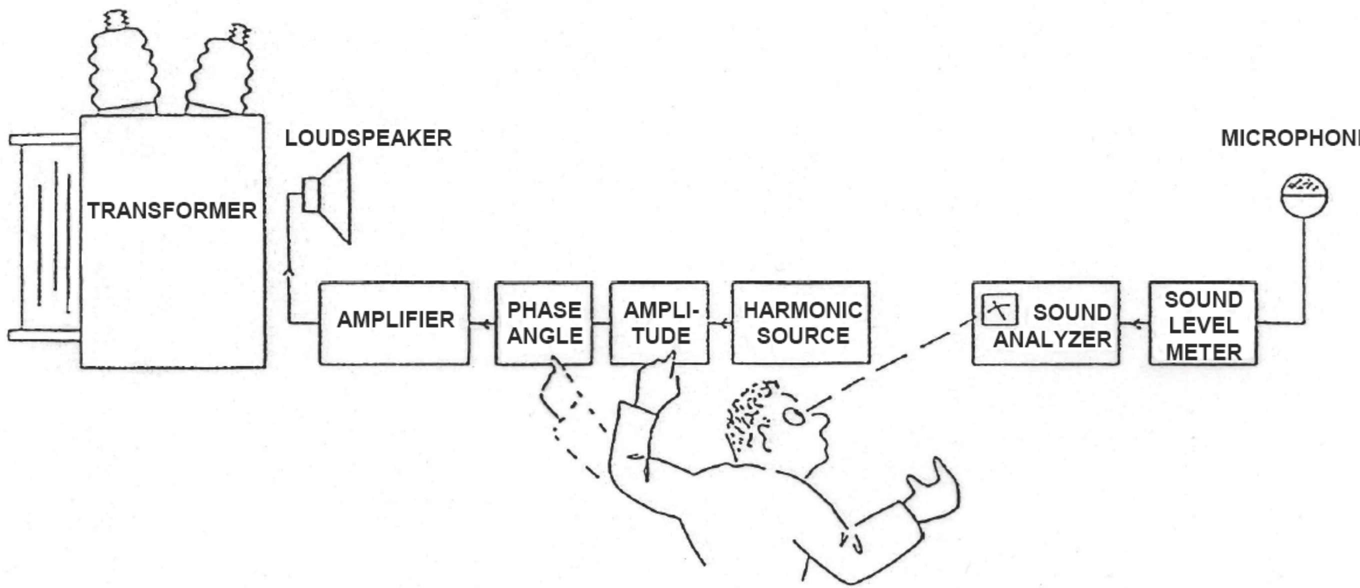
- Paul Lueg's invention in Germany in 1930s
  - Patented in Germany in 1936
  - About 50 years ahead of its time



Ref: P. A. Nelson and S. J. Elliott, "Active Control of Sound," 1992.

Manual ANC of the 1950s

- Conover's manual noise control system for a transformer



Ref: P. A. Nelson and S. J. Elliott, "Active Control of Sound," 1992.

Audio Examples

Vacuum cleaner

Transformer

Audio examples taken from: David Crawford, 1996, http://www.spd.eee.strath.ac.uk/~david

Practical applications of ANC

- Ventilation systems in offices and in industry
- Active hearing protectors and headphones
  - Combination of passive and active noise control gives the best result
- Vehicle cabins in cars, trains, aircrafts
  - Passanger comfort!
- Stealth submarines
- Snoring suppression systems
  - At least 2 commercial systems developed in the US (1992, 2004)

    (Ref. Personal communication with Prof. Scott C. Douglas, Southern Methodist Univ., Dallas, TX)
- In most applications, the ANC system must be adaptive
  - The acoustic transfer function is affected by changes in temperature, humidity, dirt, flow, speakers, microphones

Experimental Snore ANC System

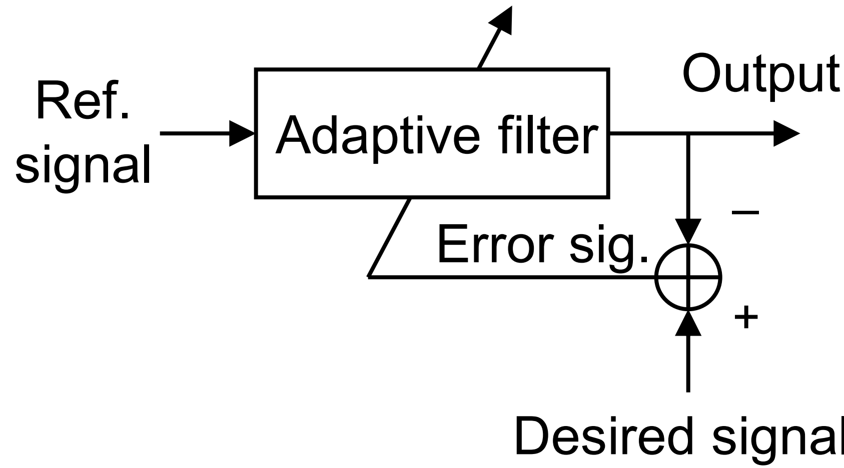
Picture taken from Kajikawa et al. 2012

Introduction of Adaptive Filtering

- Coping in a changing environment requires adaptation
  - General principle in nature: adapt or die
- An adaptive filter is necessary, when the desired response of the filter varies over time
- Widrow and Hoff discovered **LMS algorithm** in 1959
  - LMS = least mean squares
- Related to the research that also lead to development of ADALINE, a neural network for pattern recognition

Basic Idea of Adaptive Filtering

```
repeat forever
    Filter one sample
    compute error
    Adjust parameters
end
```



- Must know the desired signal to define the error (here: error → silence)
- In ANC: desired signal = original noise
- A rule is needed to adjust the filter parameters to reduce the error

LMS Algorithm

- Rule to adjust FIR filter coefficients so that the least squares error is minimized (Widrow-Hoff algorithm):

  $$\mathbf{w}(n+1) = \mathbf{w}(n) + 2\mu\mathbf{e}(n)\mathbf{x}(n)$$

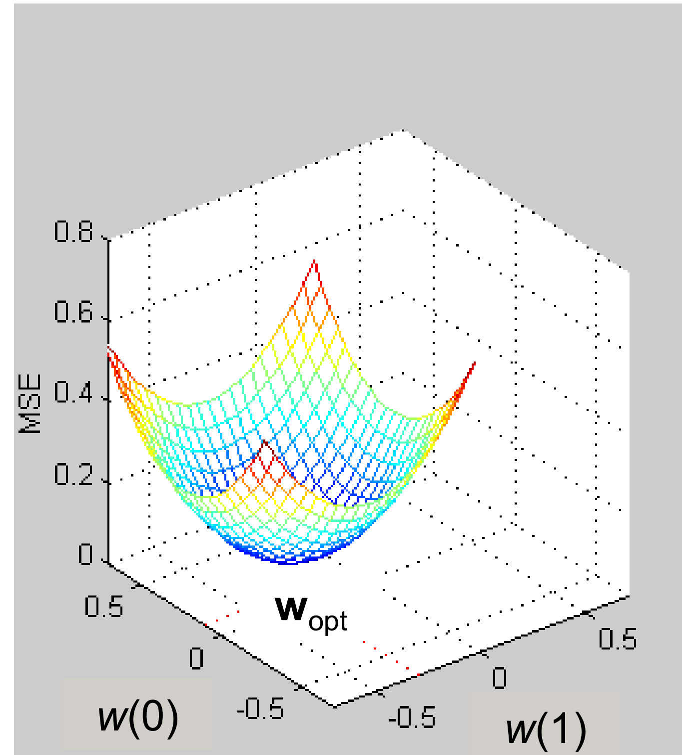
  where $\mathbf{w}(n)$ is the filter parameter vector,

  μ is an adaptation constant

  $\mathbf{x}(n)$ is the reference (input) signal vector

  $\mathbf{e}(n) = \mathbf{d}(n) - \mathbf{y}(n) = \mathbf{d}(n) - \mathbf{w}^T(n)\mathbf{x}(n)$ is the error signal, and

  $\mathbf{d}(n)$ is the desired signal
- Initial values of **w** don't matter



Pros and Cons of LMS Algorithm

Pros

- Simple and effective
- Small memory footprint (only delay lines and parameter values)
- Still a very popular algorithm
- Can be modified in various ways (frequency-domain version, sign-only version, apply filters in signals, among others)

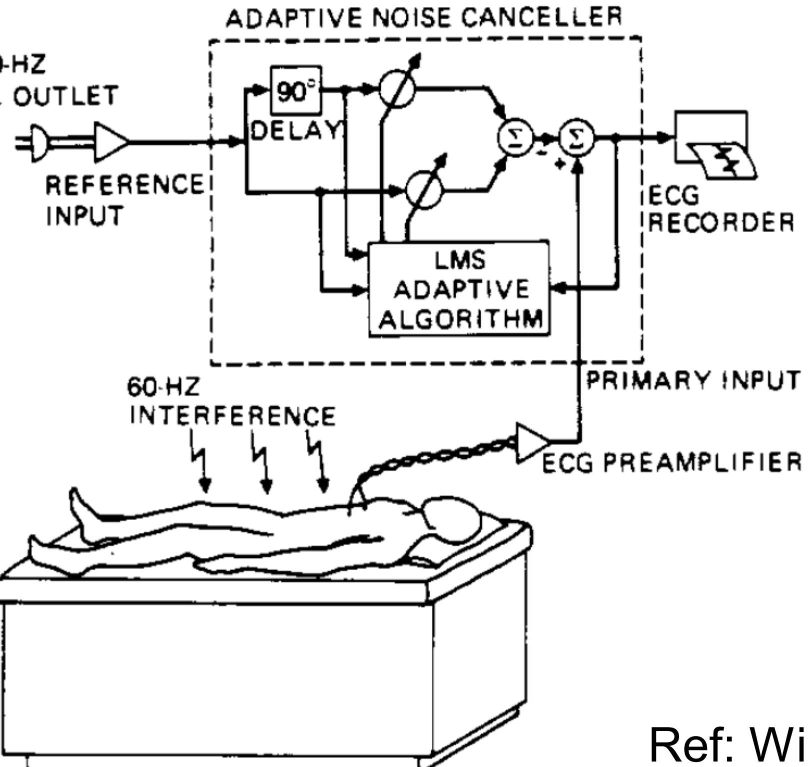
Cons

- Slow convergence
- Convergence speed depends on signal (power, spectral shape)
- Too ”heavy” for some low-cost applications

Adaptive Interference Cancellation

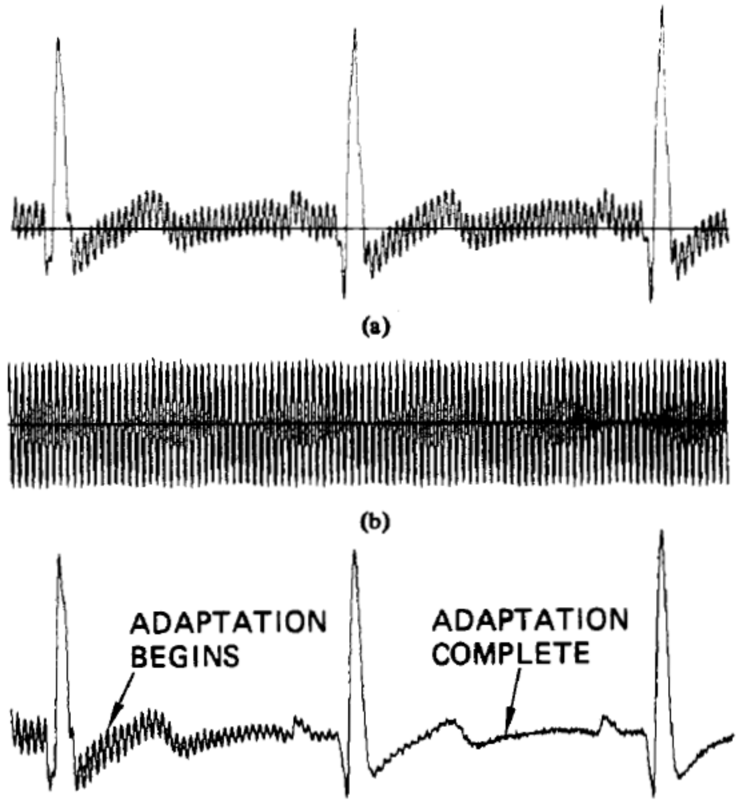
- Removal of disturbances from a digitized electronic signal
- The earlier application: remover of 60-Hz power grid disturbance from ECG measurements (electrocardiogram, heartbeat signal) (Widrow et al., 1975)
- Removal of background noise in communications systems
  - For example, smart phones, fighter and helicopter pilots, tanks…
- Removal of periodic disturbance without reference signal
  - If the frequencies are known, a synthetic reference signal can be generated
  - For example, removal of 50/60-Hz power-line hum from a recording
  - A delayed reference signal can be used as a reference signal, if it remains stationary
  - Special case: DC removal

Adaptive Interference Cancellation



Ref: Widrow *et al.*, 1975

Adaptive Interference Cancellation



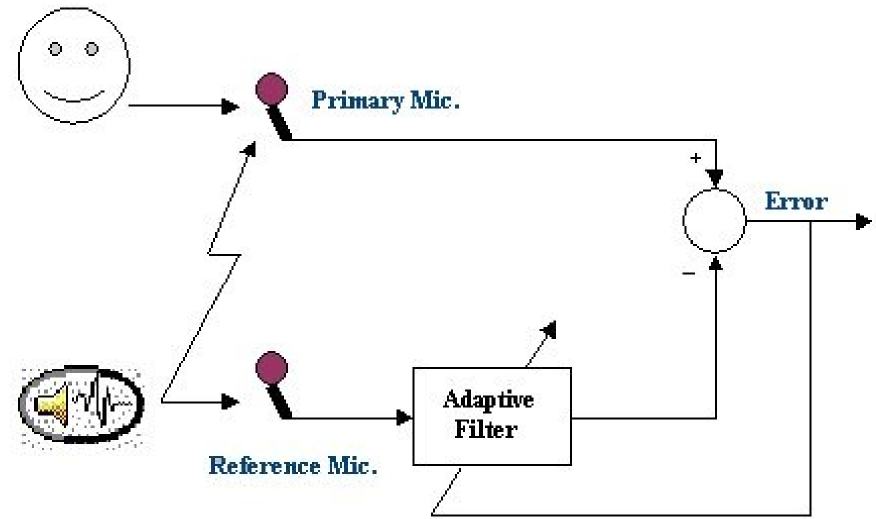
Ref: Widrow *et al.*, 1975

Noise Removal from Helmet Mic Signal

- Two mics are needed

1. Primary mic inside the helmet capturing the speech signal plus noise
2. Reference mic far away from the pilot to capture the ambient noise

- The adaptive filter will find the best parameters to remove reference signal (ambient noise) from the primary mic signal
- The error signal is sent to the receiver (less noisy than the primary mic signal)



Ref: http://www.eas.asu.edu/~dsp/grad/anand/java/ANC/ANCDesc.html

Interference Cancellation Demo

- A guitar played thinks that his recording is damaged, but an adptive filter can fix it!
  - A reference signal is needed, but it easy to acquire

Corrupted recording ("*La Foa*")

Interference only (50 Hz + harmonics)

After adaptive processing (N = 9; μ = 0,005)

After adaptive processing(N = 9; μ = 0,1 … 0,001)

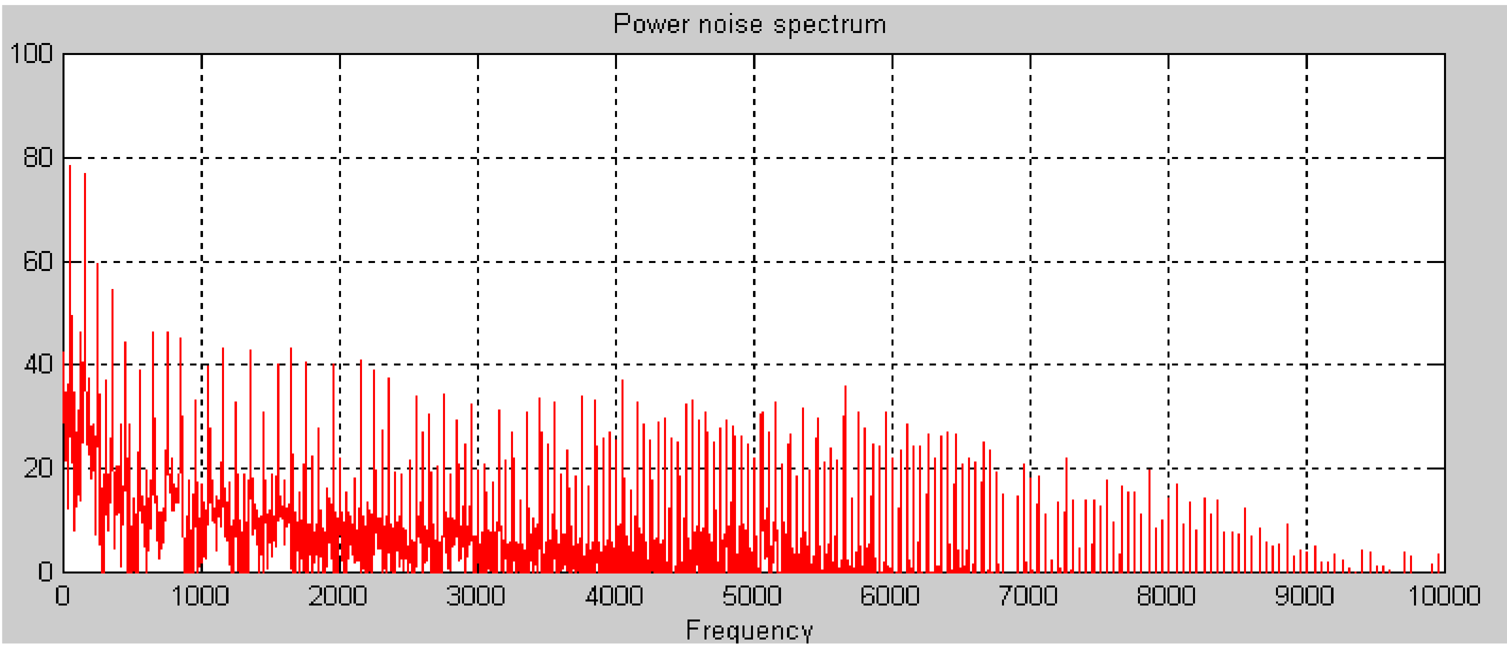
- First fast convergence, then slow

Original recording with interference ("*La Foa*")

Audio demo by Tommi Huotilainen and N. N. (2001)

Power Line Interference

- 50 Hz and its odd harmonics
- Wideband signal containing many peaks

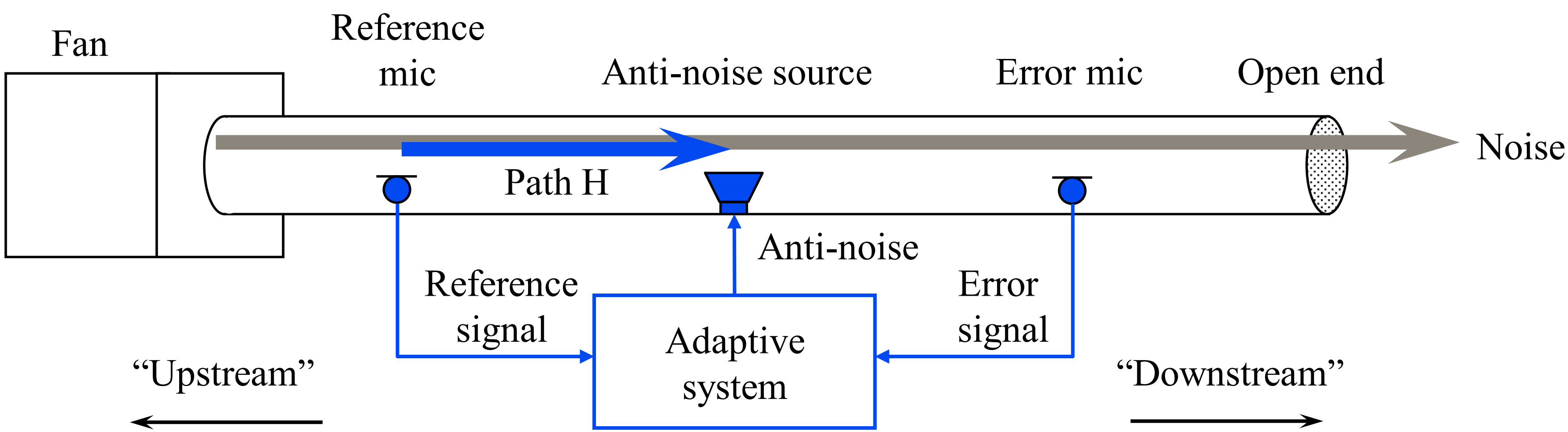


Duct ANC Project in Finland

- Particularly well suited topic for ANC
  - A fan causes noise propagating along the duct without attenuation
  - Passive attenuators are large and resist flow
  - 1-D case: ANC is ”easy” below the frequency limit of transversal propagation

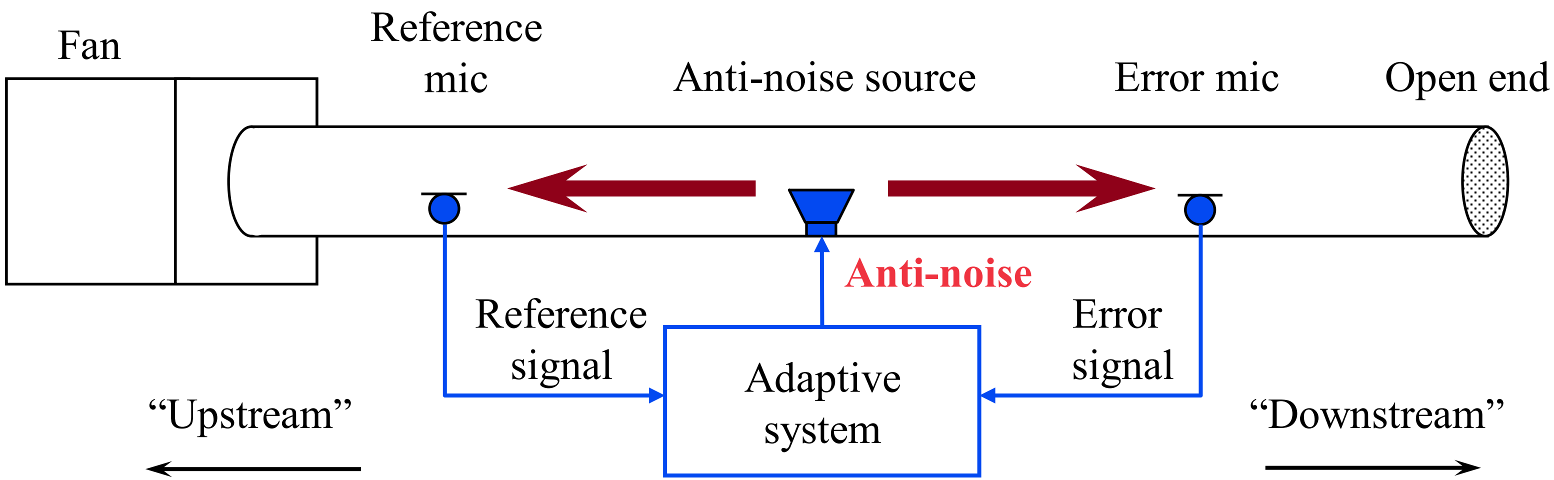
Duct ANC: Basic System

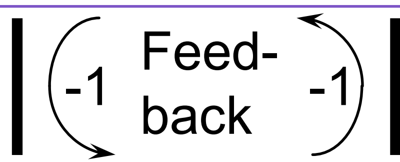
- Adaptive system produces the anti-noise by filtering a reference signal
  - Reference mic captures the noise: Reference signal
  - Adaptive system models the acoustic propagation path H and inverts the signal
  - Error mic used for checking whether the suppression succeeds
- However, problems arise using standard mics and loudspeakers!!!



Acoustic Feedback in ANC

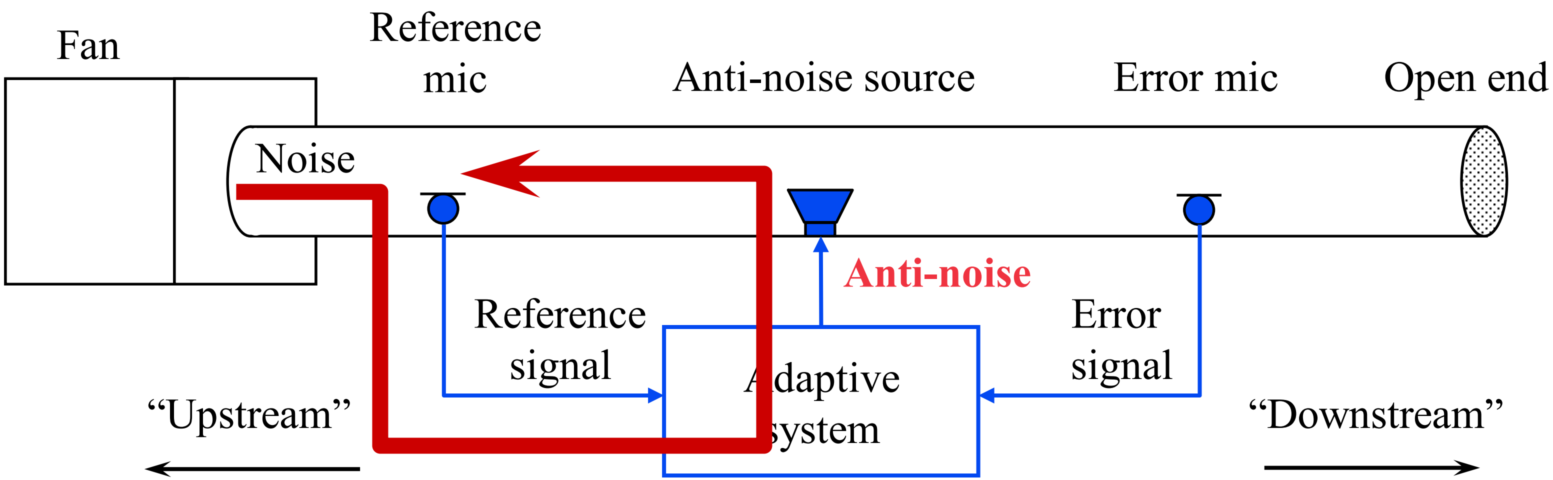
- A regular speaker radiates sound in both directions
- A regular mic hears hears equally well from both directions
  - Anti-noise gets mixed with the reference mic signal, reducing attenuation
- A high risk of howling caused by acoustic feedback!!!

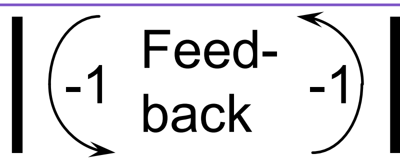




Problem from Upstream Direction

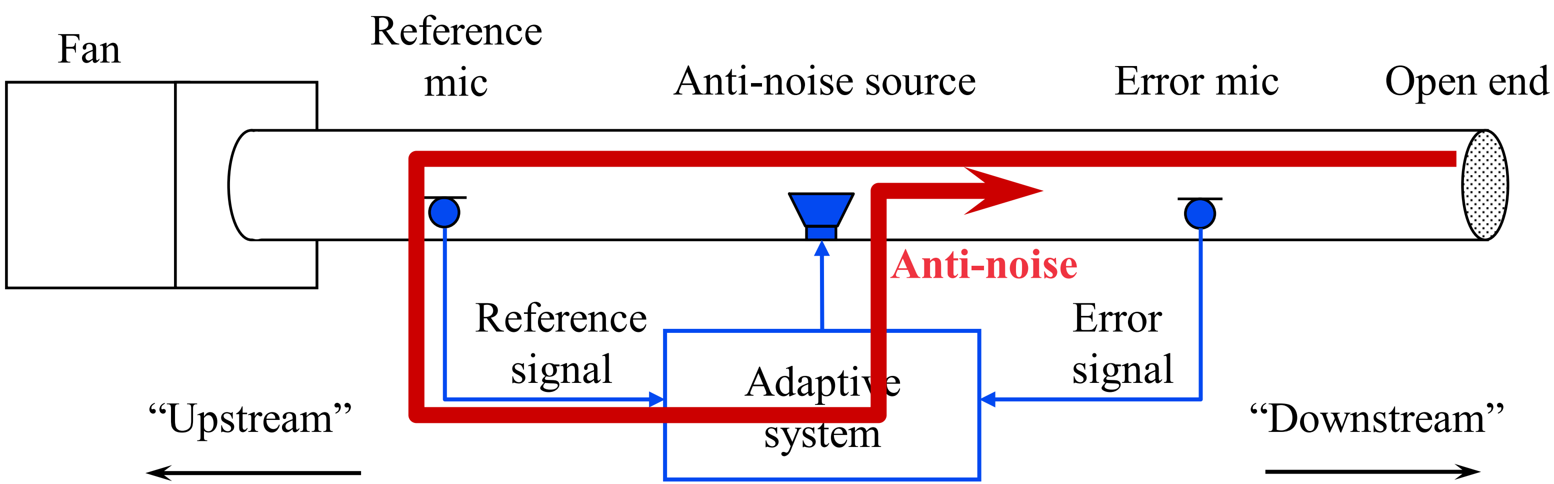
- The anti-noise speaker acts as a reflector
  - New standing waves are formed inside the duct because of the active system
  - Noise level is increased on the upstream side
  - The system can start howling (acoustic feedback)



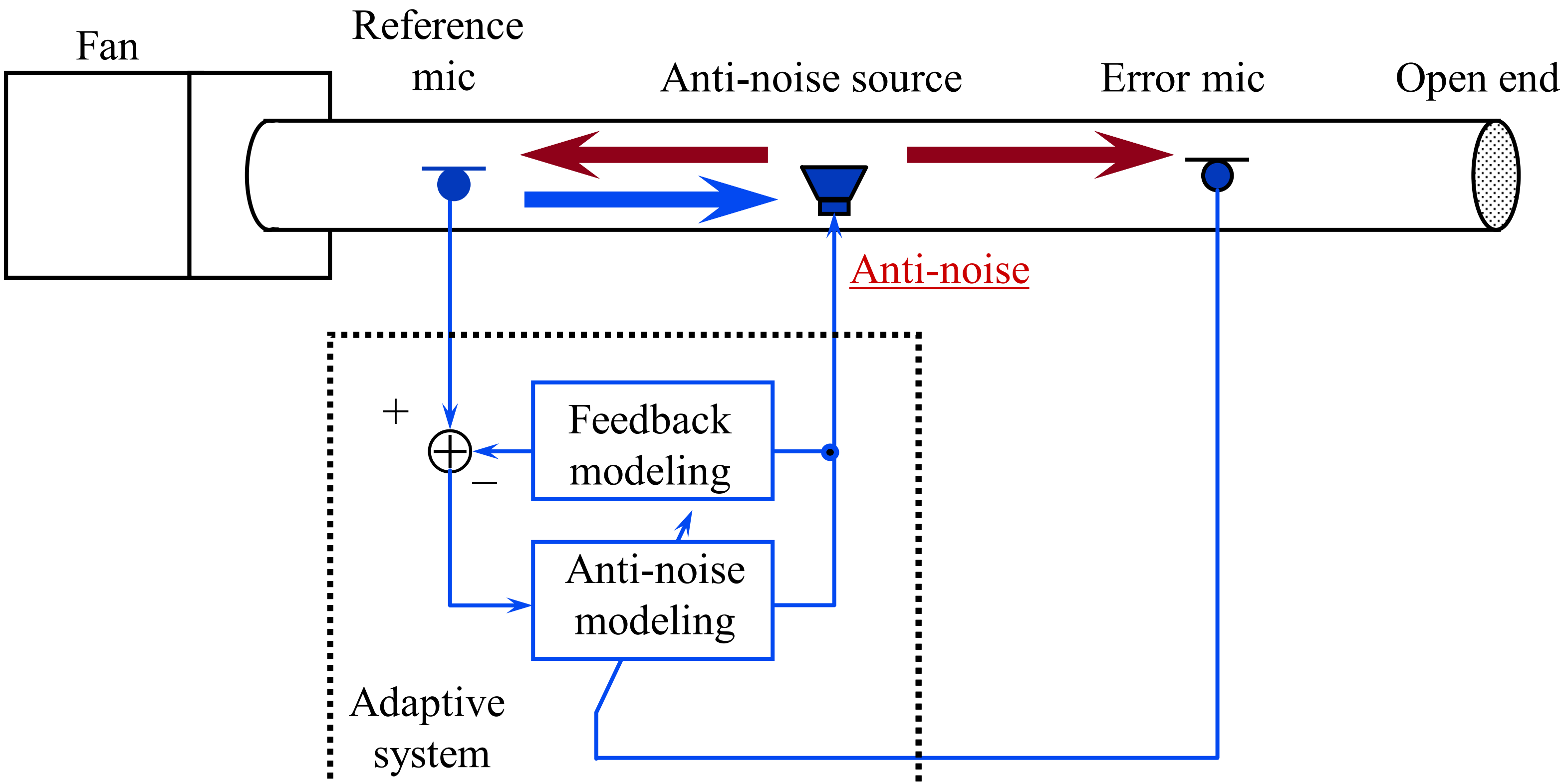


Problem from Downstream Direction

- The reference mic acts as a reflector
  - New standing waves are formed between the ref mic and the open end of the duct
  - Acoustic properties of the duct are changed and noise level may increase



A Solution: Feedback Cancellation

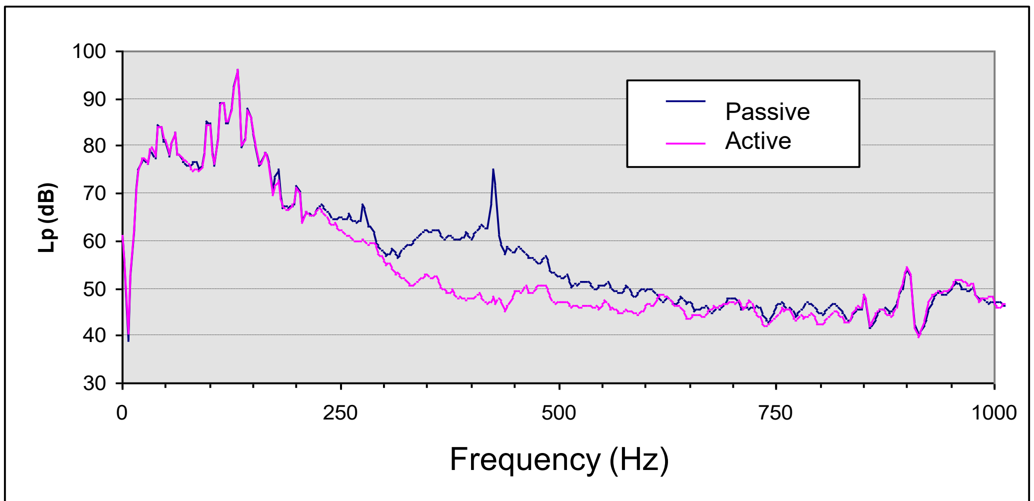


A Solution: Feedback Cancellation

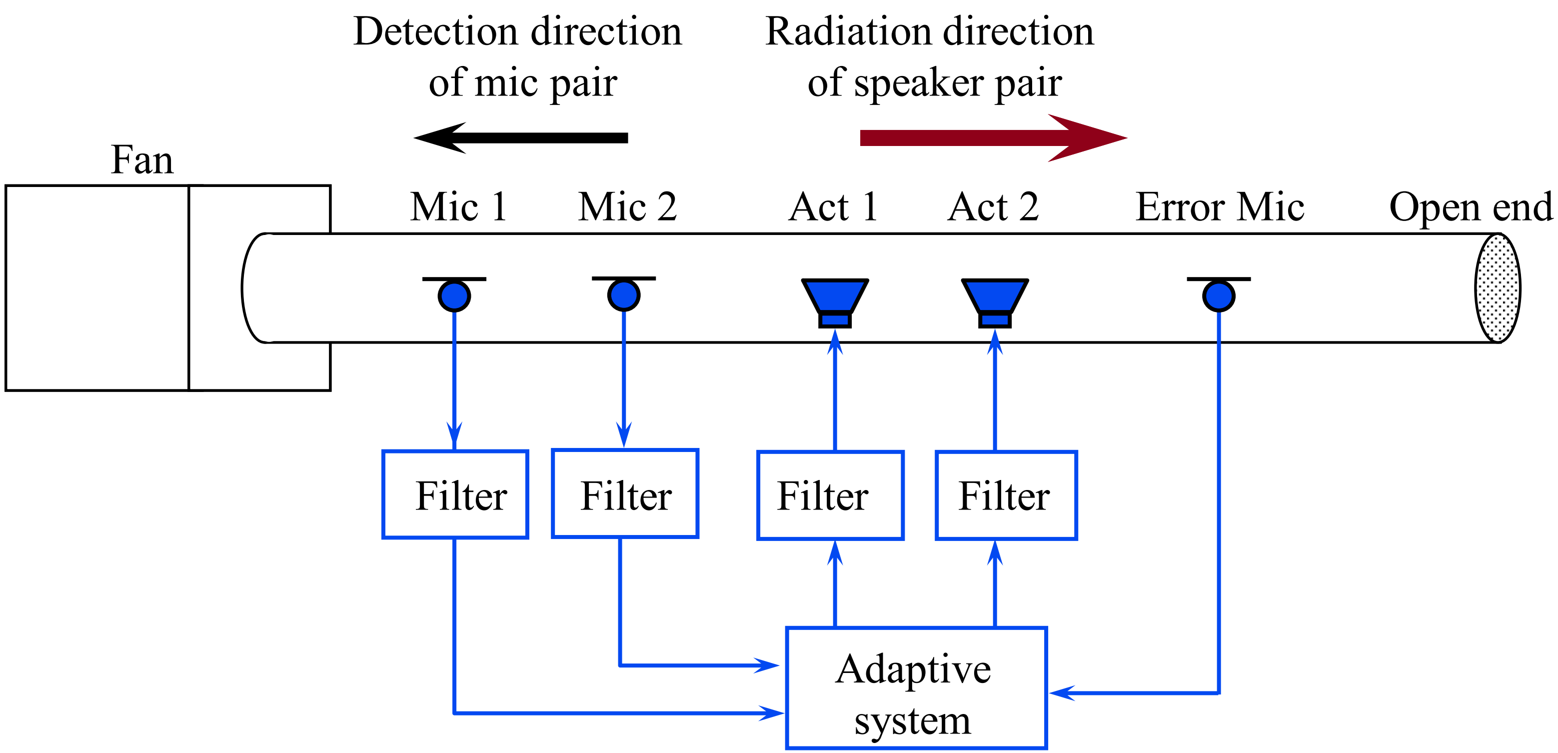
- The feedback is modeled with another adaptive filter and is cancelled
  - The same idea as “echo cancellation” in telephone systems
- The anti-noise system will not howl so easily ☺
- The ANC speaker still radiates in both directions ☹

Results with Feedback Cancellation

- A loudspeaker was used as the noise source
  - Air flow disturbs the ANC system
- Near the blade-passing frequency, attenuation was achieved on a wide band
  - Over 20 dB of attenuation at BPF, but only a few dB in average



More Advanced Solution: Unidirectional Mics and Speaker



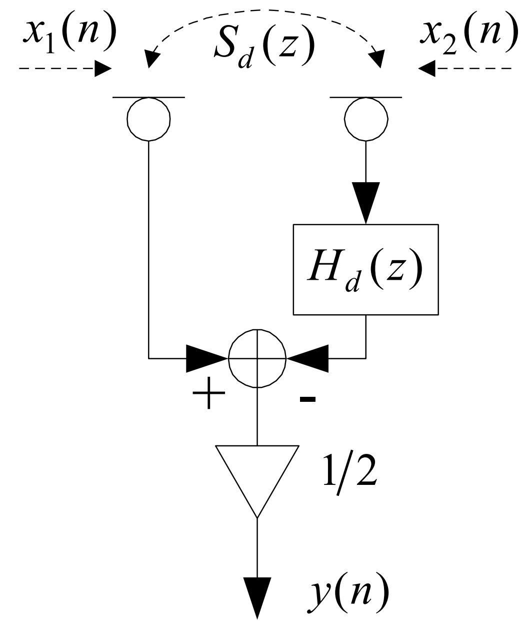
Advantages of a Unidirectional ANC System

- The unidirectional source does not radiate upstream ☺
  - The noise level does not increase in the upstream direction
- The unidirectional mic does not hear from downstream ☺
- This solution effectively suppresses acoustic feedback!
- Also isolates the anti-noise signal from the reference signal and can improve the performance of the ANC system

(Ref. Seppo Uosukainen, Doctoral dissertation, Helsinki Univ. of Tech., 1999)

Principle of the Unidirectional Mic Pair

- Originally developed for a speaker pair, but it is reversible
- The signal of one sensor is delayed appropriately
  - Cancels signal x_2 coming from downstream
  - Side effect: Signal x_1 coming from upstream gets highpass filtered
- The delay between sensors must be very accurate
  - Need a fractional delay filter or a measured impulse response between the sensors
- Assumption: Transfer function $S_d(z)$ is pure delay
  - Losses or reflections are not accounted for



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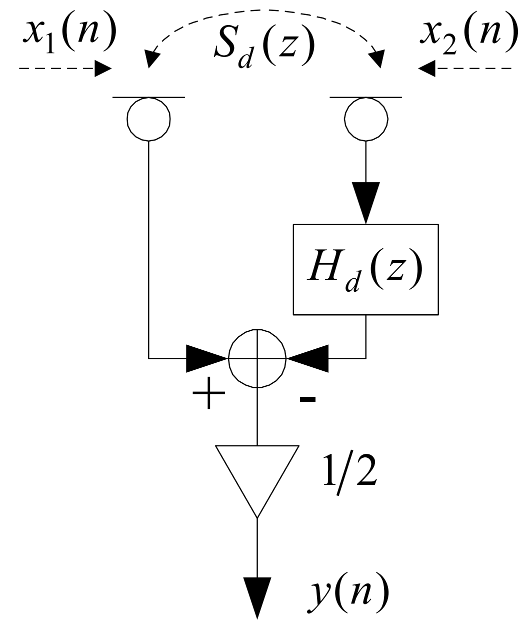
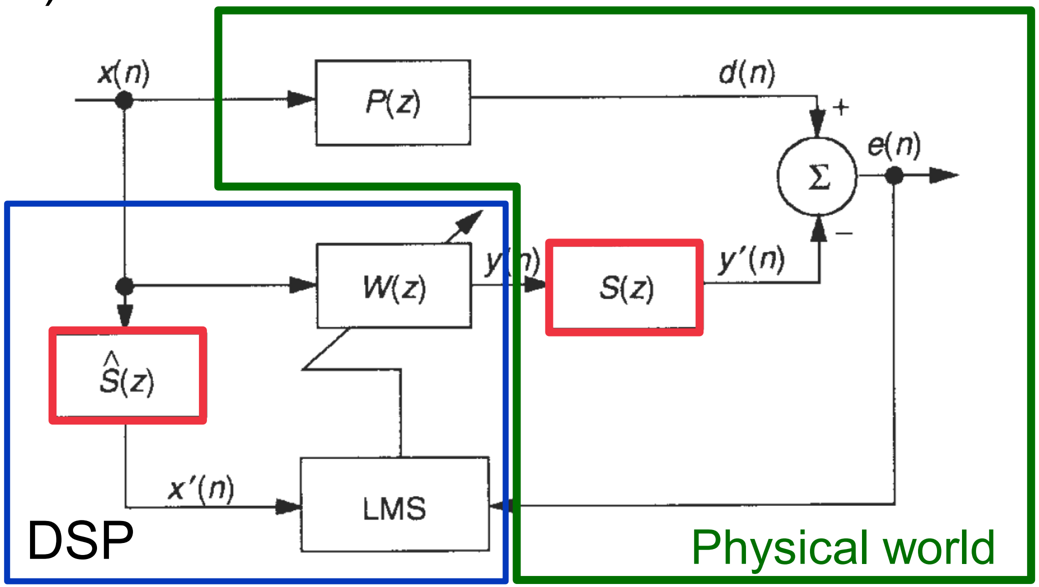
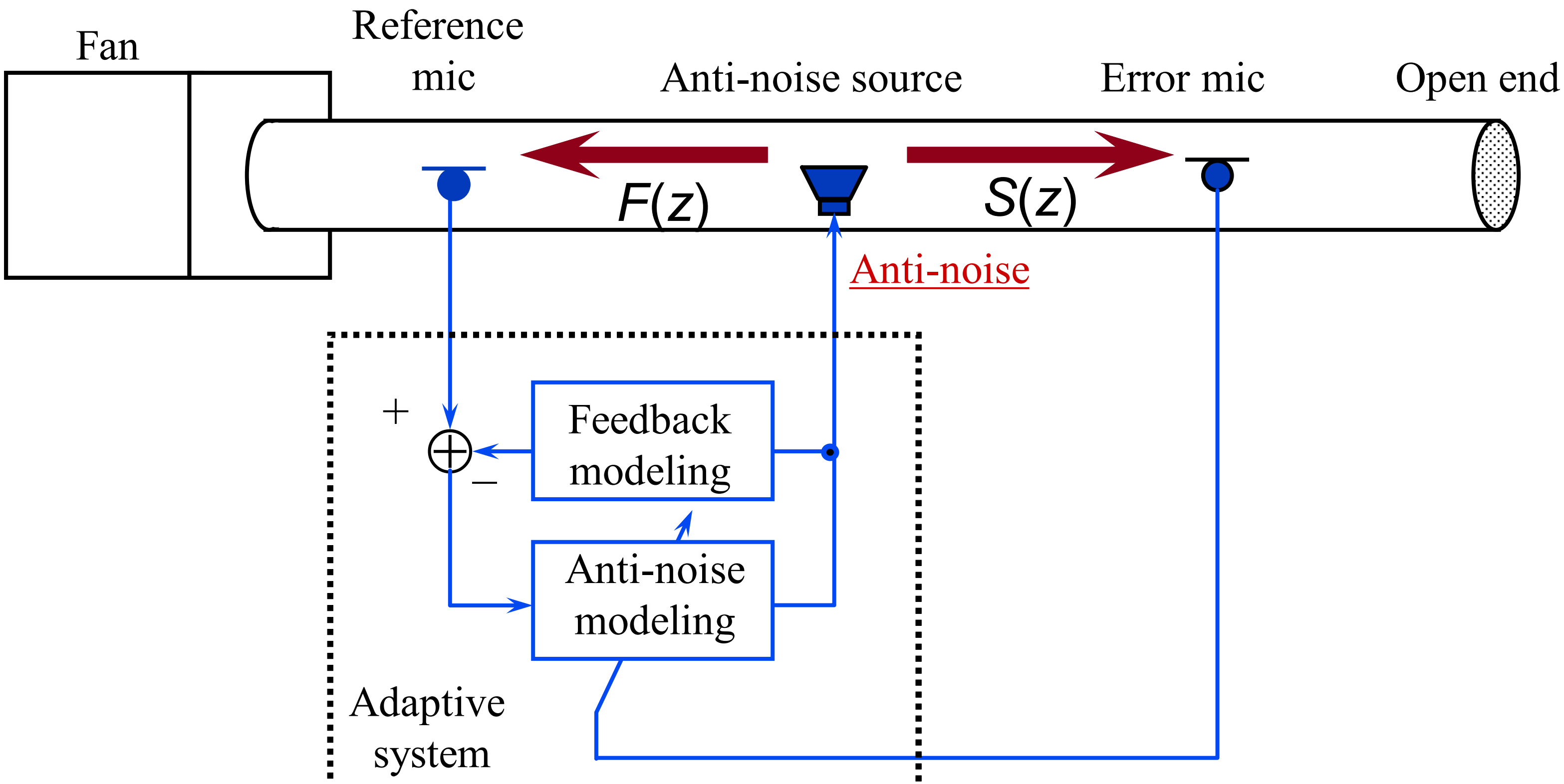


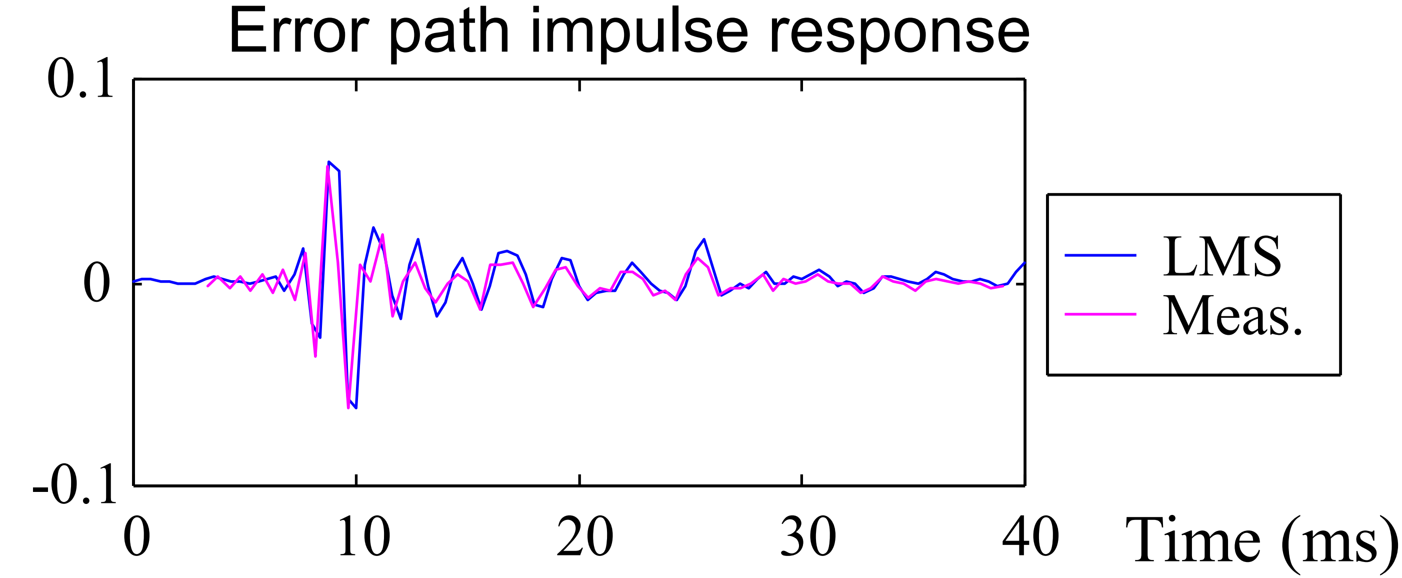
FXLMS Algorithm

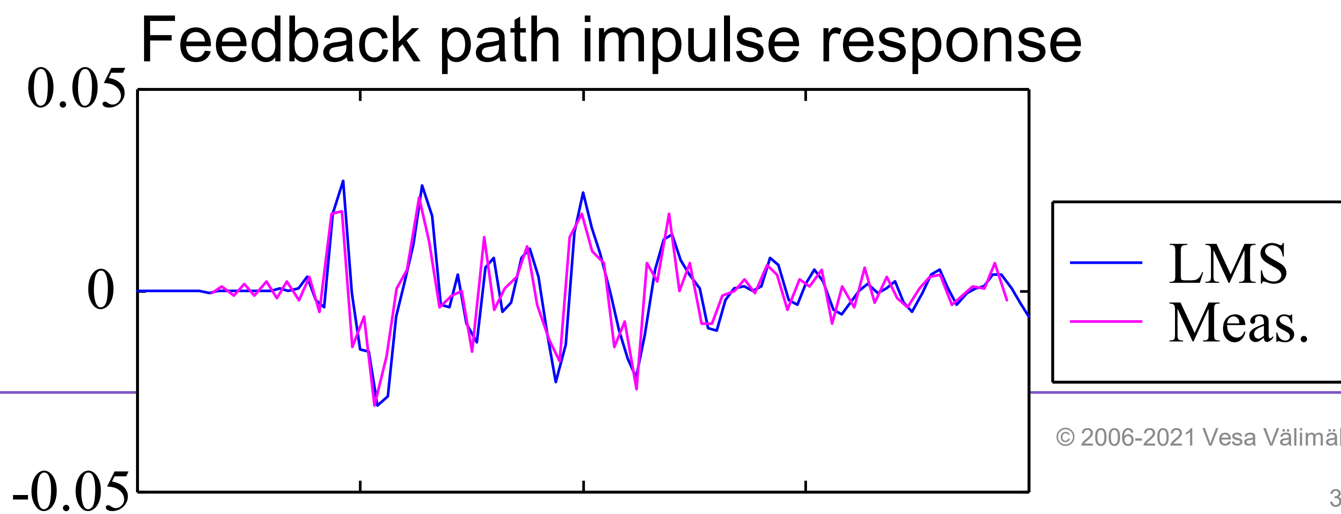
- FXLMS algorithm (Filtered-X LMS) uses a filter S(z) to approximate how the error signal is delayed and processes the reference signal in the same way (Morgan, 1981; Burgess, 1981; Widrow 1981)

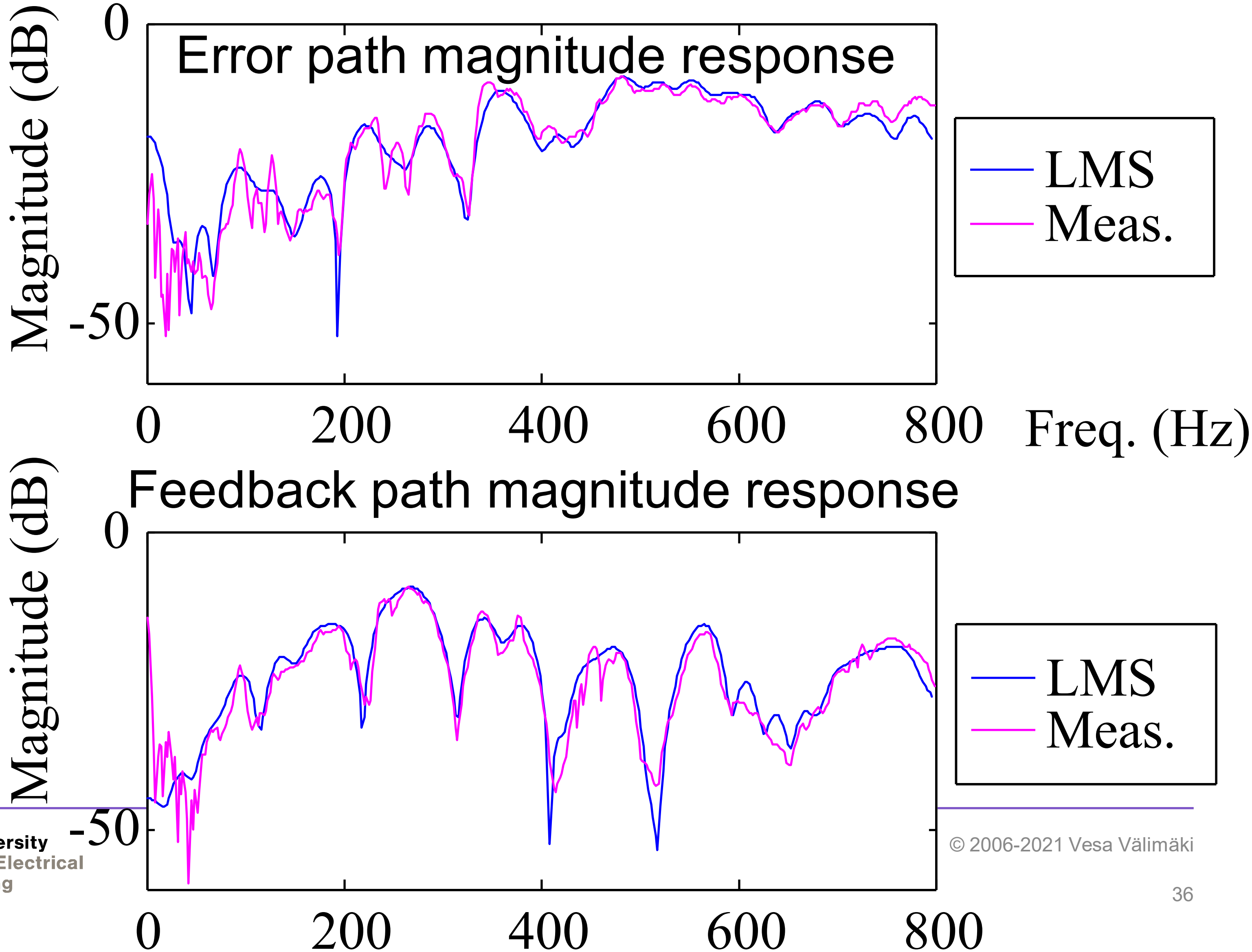


Error Path S(z) in Duct ANC System




Error path impulse response
0.1
0
-0.1
0
10
20
30
40
Time (ms)
LMS
Meas.

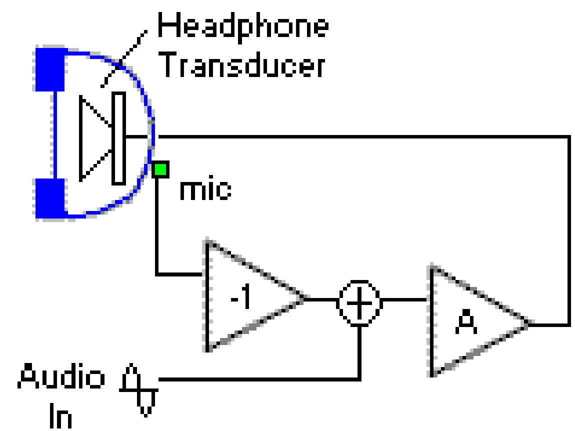

Feedback path impulse response
0.05
0
-0.05
LMS
Meas.


Error path magnitude response
Magnitude (dB)
0
-50
0
200
400
600
800
Freq. (Hz)
LMS
Meas.
Feedback path magnitude response
Magnitude (dB)
0
-50
0
200
400
600
800
LMS
Meas.

ANC Headphones

- A low-cost analog ANC headphone registers the ambient noise with a mic and uses an inverting amplifier to play it as anti-noise
  - Gain is tuned at factory (non-adaptive)
- Reduces low-frequency ambient noise about 10 to 20 dB, but only on a narrow band
  - Passive materials help at high frequencies
- Audio signal can be played at the same time, without interaction with the ANC function
- Audio demo by Jussi Rämö (Aalto Univ. 2011): Bose Quiet Comfort 2

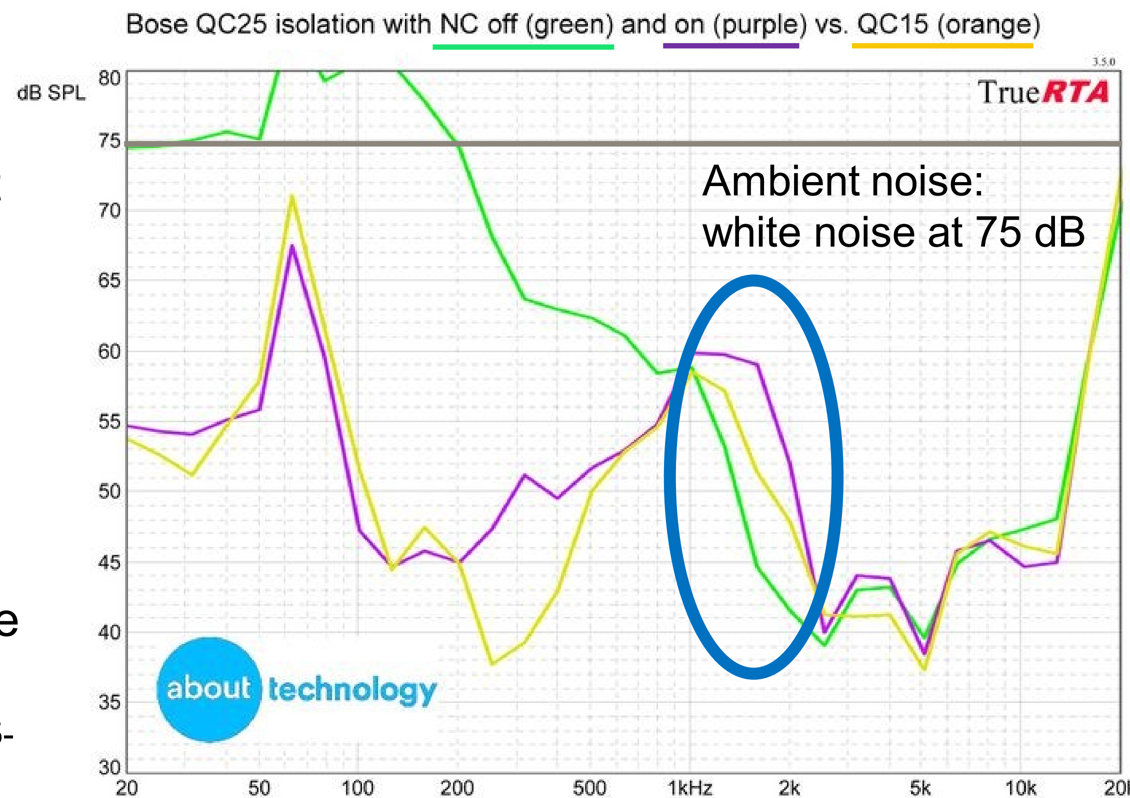
Ambient noise – Bose OFF – Bose ON



ANC Headphones

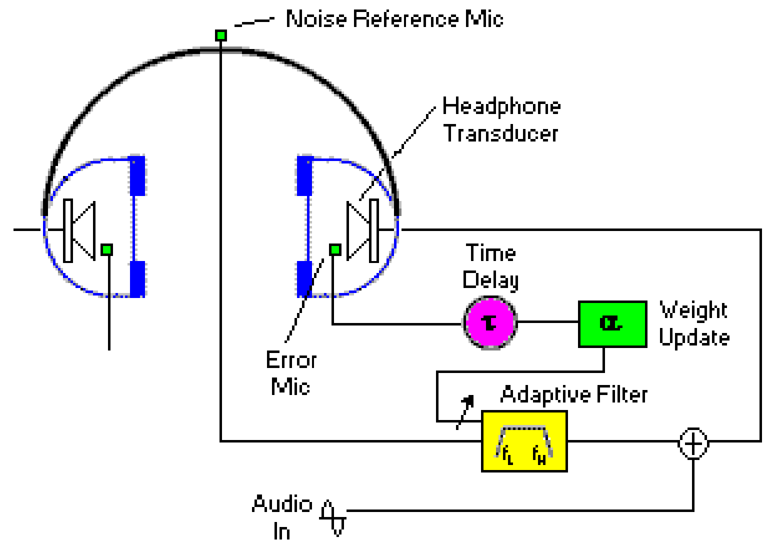
- ANC attenuates noise most effectively at low frequencies below about 200 Hz
- At higher frequencies, the wavelength of sound limits its functioning
- ANC can boost noise at some frequencies ("**waterbed effect**"), here between 1 and 2 kHz

Ref: https://www.lifewire.com/bose-qc25-review-specs-3134560



ANC Headphones

- A digital feedforward ANC headphone requires a **reference mic** outside the headphones
  - Often there are several reference mics, to capture ambient noise from certain directions
  - Another external mic or mic pair may be used to capture the user's own voice for smart phone use
- An **error mic** is needed inside each earpiece for adaptation

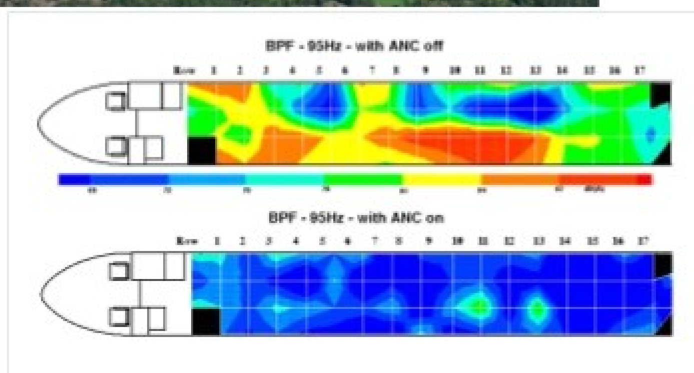


ANC in Airplanes

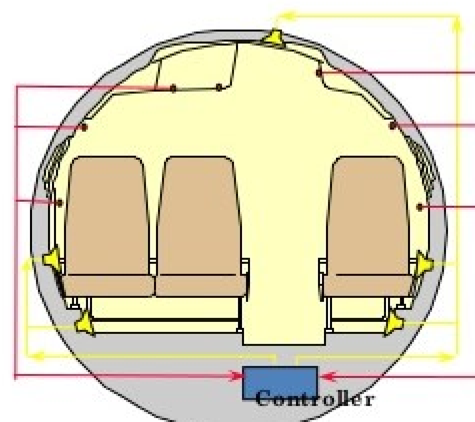
- The cabin of a modern turboprop airplane is fairly noisy
  - The blade-passing frequencies are fairly low and propagate easily through the fuselage
- Airplanes must be light, so passive attenuation of low-frequency noise is difficult
- ANC seems like a suitable solution
  - Also, the cost of an ANC system is reasonably small w.r.t. to the price of the aircraft

ANC in Airplanes

Saab 2000 and Gripen

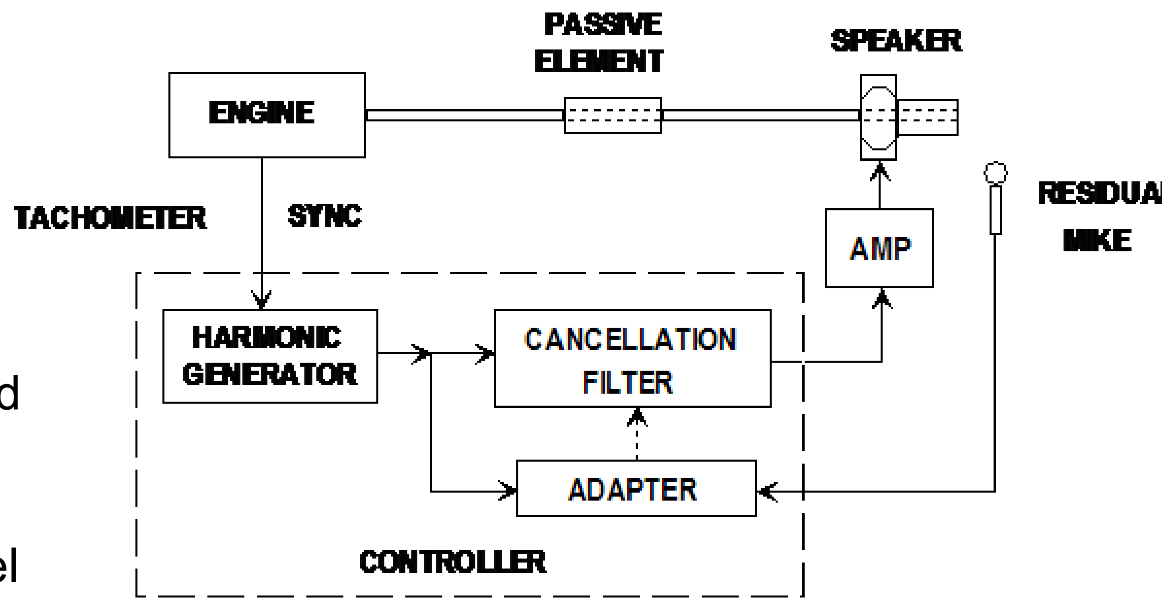


A 400M



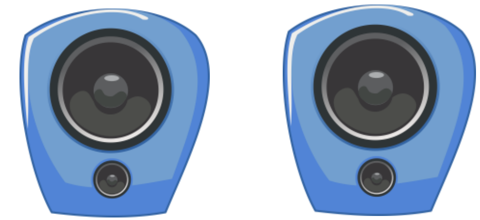
Active Muffler for Cars

- An ANC muffler uses synthetic engine harmonics to produce anti-noise
- A regular muffler reduces the engine power
- An active muffler would not reduce power that much
- Could it reduce the fuel consumption?

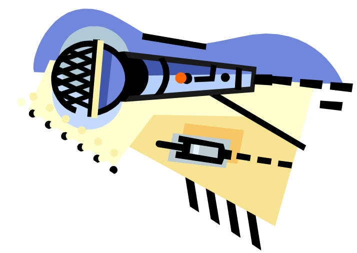


Ref: http://doctord.dyndns.org/Pubs/POTENT.htm

Adaptive Filtering Applications



- Automatic equalization of audio system
  - E.g. home theater systems
- Echo cancellation
  - Telephone systems (since 1965)
  - Hands-free communication systems
  - Teleconference systems

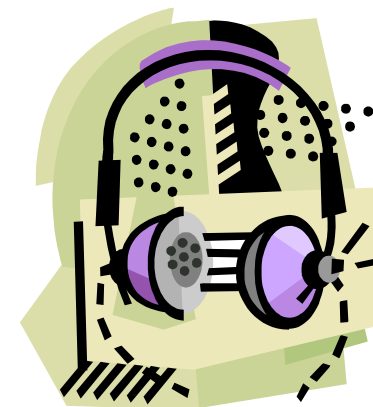


- Feedback cancellation in hearing aids
- Noise equalization
  - In working machines, it is necessary to reduce noise, but it must not disappear
  - In car cabins, the engine noise can be made more sporty

- Beam forming
  - E.g. mic arrays in teleconferencing or in SONAR (underwater sound radar)

Conclusion

- Active noise control is an old idea (1930s…)
- Used in combination with passive noise control
  - Active control work well at low frequencies, passive attenuation work best at high frequencies
- Active hearing protectors and headphones are the most successful application so far
- In the future, there may be more ANC applications
  - Many devices can have enough computing power, mics and speakers
  - ANC can bring increased **comfort or savings**
  - Environmental noise is becoming a major issue but there are still no ANC applications
  - Patents are expiring (US patents are valid for 20 years)



References

Readings for the exam

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