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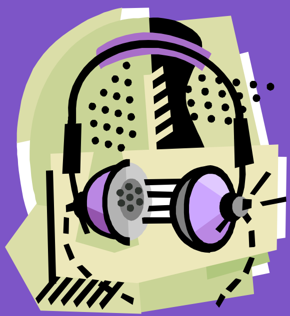
ELEC-E5640 Noise Control
27 Nov. 2023



Sound check

Active Noise Control

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Acoustics Lab, Dept. Information and Communications Engineering,
Aalto University

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Active Noise Control – Contents

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

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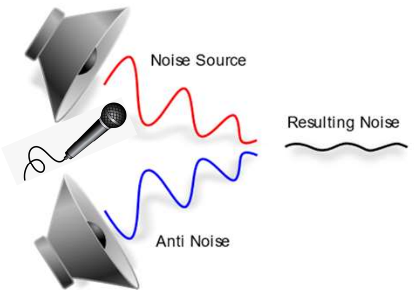
Active Noise Control Basics

- Electronics is faster than sound!
  - Detect noise with a microphone
  - Produce anti-noise
  - Play it with a speaker
  - Noise and anti-noise will cancel out
- Advantage: good attenuation at low frequencies
- Acoustic transfer function modeling
  - 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

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A Short History of ANC

- Paul Lueg's invention in Germany in the 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, Univ. of Southampton, UK), "*Active Control of Sound*"
- Industrial applications appeared in the 1990s
  - Active hearing protectors, attenuators for ventilation ducts, household appliances, cars, aircrafts

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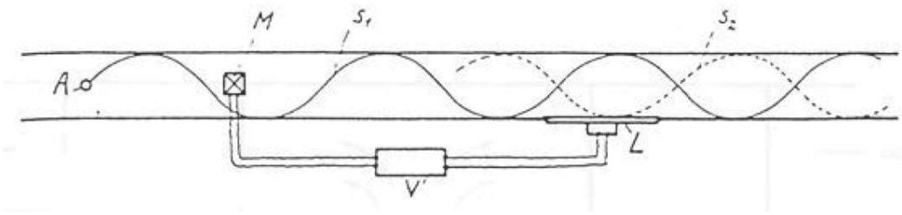
Principle of ANC in a Duct

- 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.

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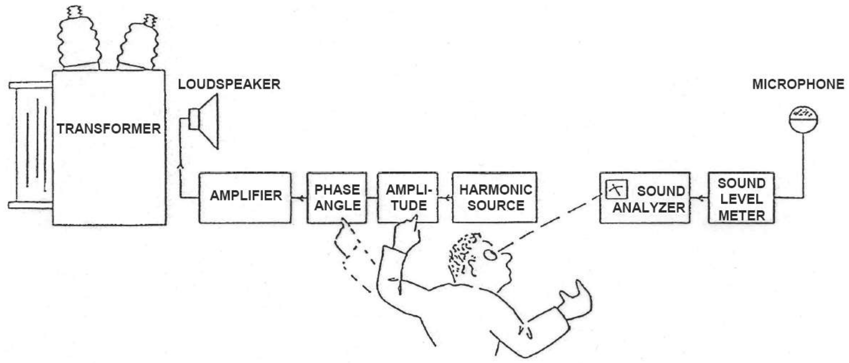
Manual ANC of the 1950s

- Conover's manual noise control system for a transformer



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

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Audio Examples

Vacuum cleaner

Transformer

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

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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
  - Passenger comfort!
- 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

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Experimental Snore ANC System

Picture taken from Kajikawa et al. 2012

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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 led to the development of ADALINE, a neural network for pattern recognition

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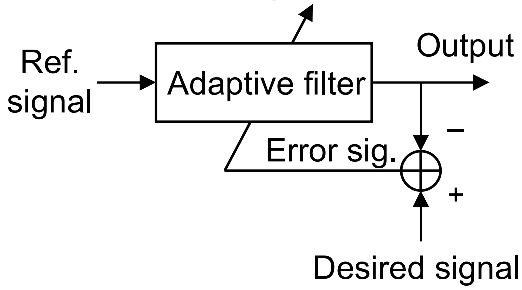
Basic Idea of Adaptive Filtering

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



- Must know the desired signal to define the error
- In ANC: desired signal = original noise
- A rule is needed to adjust the filter parameters to reduce the error
- After converge, the error signal should be close to zero (“silence”)

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LMS Algorithm

- Rule to adjust FIR filter coefficients, minimizing the least squares error (Widrow-Hoff algorithm):

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

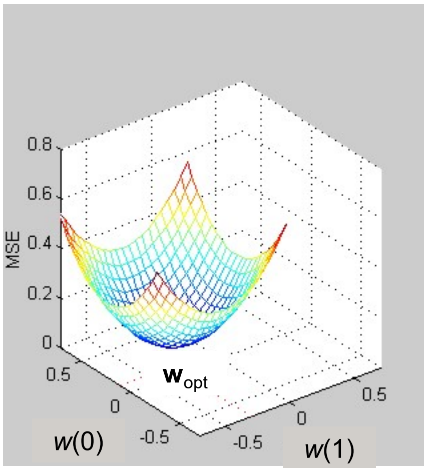
  where $\mathbf{w}(n)$ is the filter parameter vector,

  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
- Constant μ must not be too large or too small



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Pros and Cons of LMS Algorithm

Pros

- Simple and effective
- Small memory footprint (delay lines and parameters)
- 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 or when the impulse response is very long

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Adaptive Interference Cancellation

- Removal of disturbances from a digitized electronic signal
- An early 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, smartphones, airline pilots…
- 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, if it remains stationary
  - Special case: DC removal

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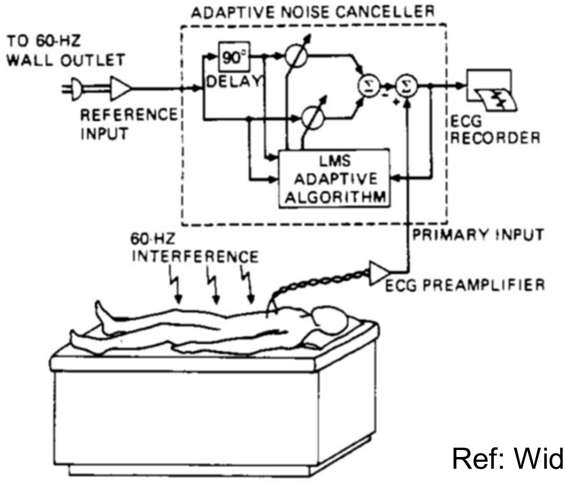
Adaptive Interference Cancellation



Ref: Widrow *et al.*, 1975

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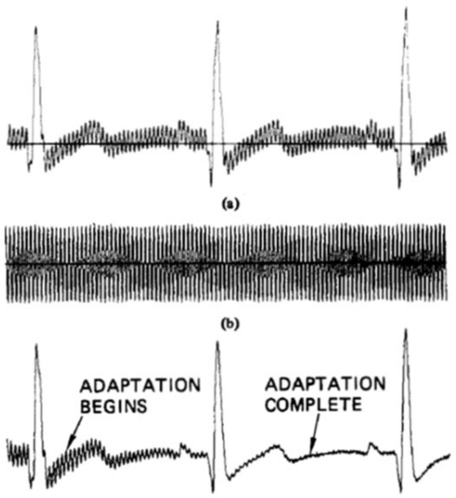
Adaptive Interference Cancellation



Ref: Widrow *et al.*, 1975

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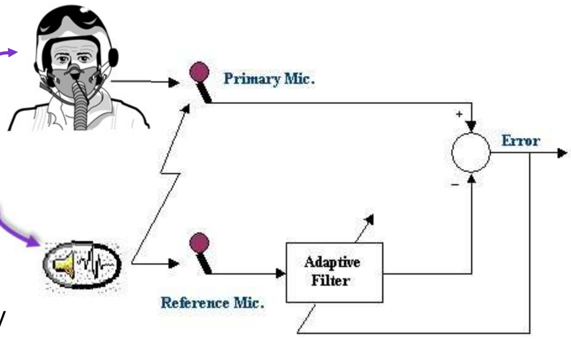
Noise Removal from Helmet Mic Signal

- 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 the 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

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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)

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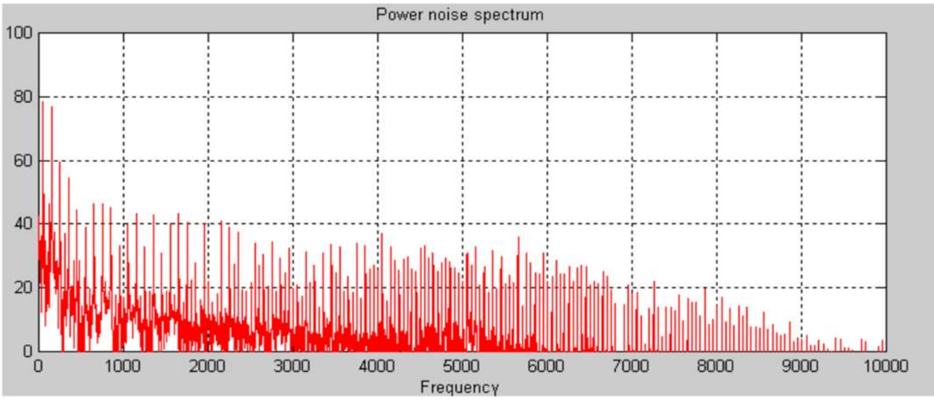
Power Line Interference

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



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Duct ANC Project in Finland

- Particularly well suited application for ANC
  - Fan noise propagates 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

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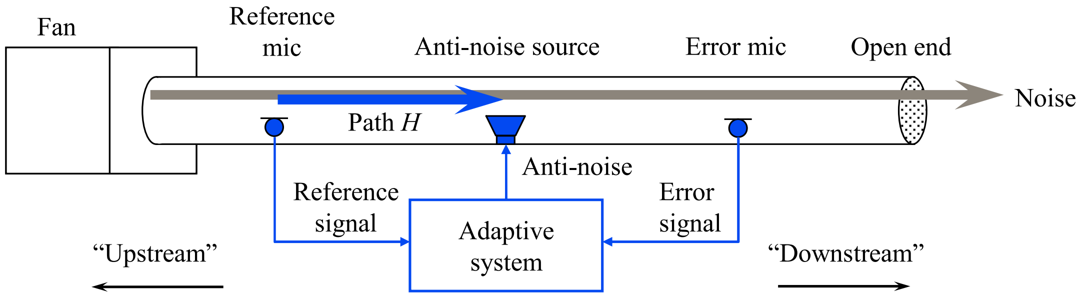
Duct ANC: Basic System

- 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 is used for checking whether the suppression succeeds
- However, problems arise using omnidirectional mics and loudspeakers!!!



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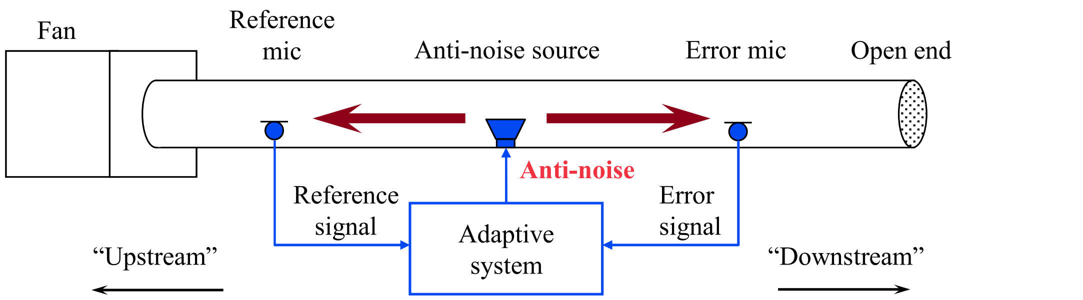
Acoustic Feedback in ANC

- 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!!!



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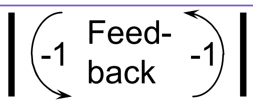

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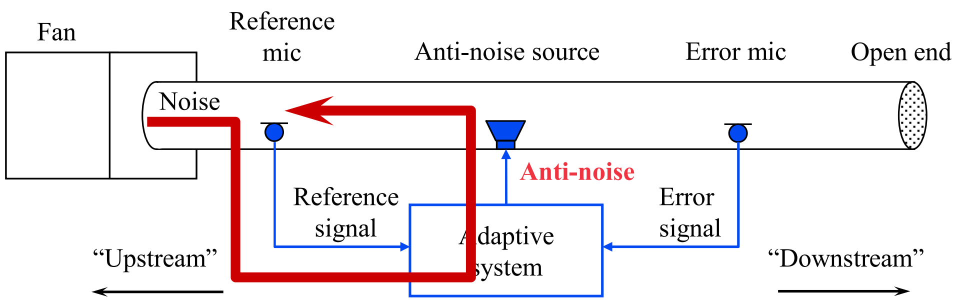
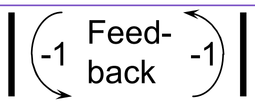
Problem from Upstream Direction

- 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)





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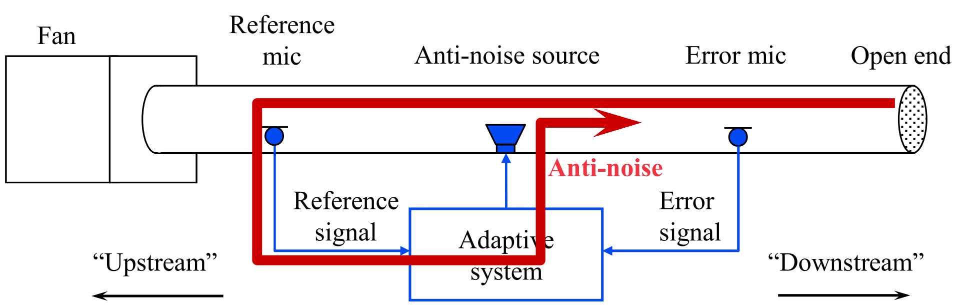
Problem from Downstream Direction

- 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



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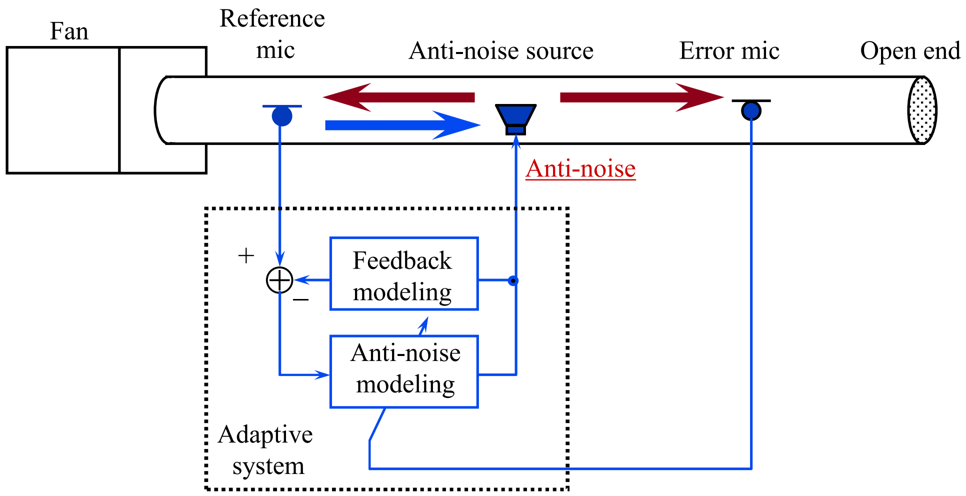
A Solution: Feedback Cancellation



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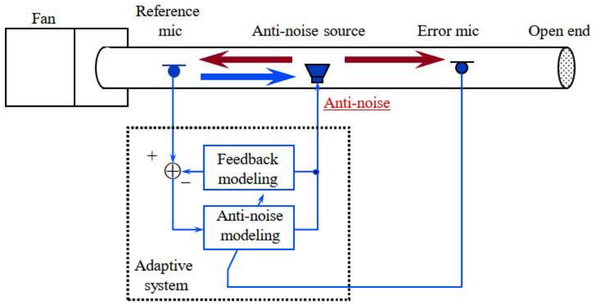
A Solution: Feedback Cancellation

- 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 ☹



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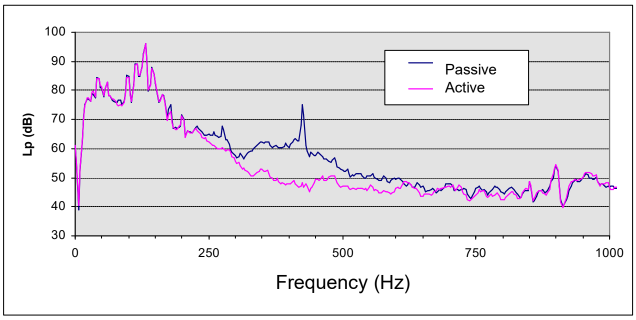
Results with Feedback Cancellation

- 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



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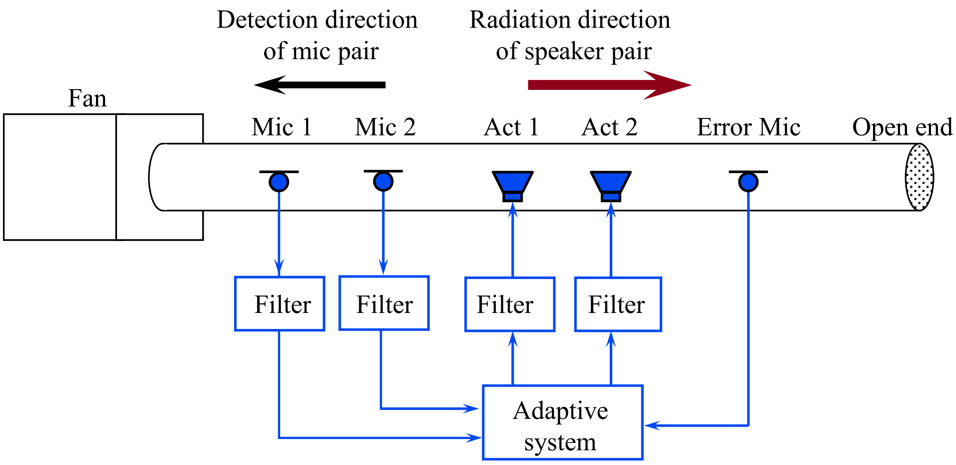
More Advanced Solution: Unidirectional Mics and Speaker



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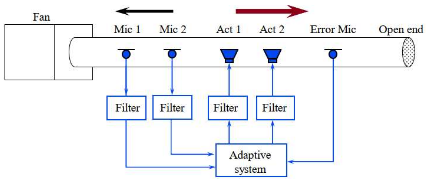
Advantages of a Unidirectional ANC System

- The anti-noise does not radiate upstream ☺
  - Noise level does not increase in the wrong place
- The unidirectional mic does not hear from downstream ☺
- Acoustic feedback is effectively suppressed! ☺
- Also isolates the anti-noise signal from the reference signal, improving the performance of the ANC system

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



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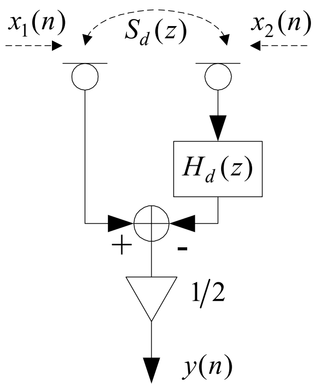
Principle of the Unidirectional Mic Pair

- 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

- In many acoustic ANC cases, the error signal cannot be measured directly
  - Error mic is not at the same location as the anti-noise source (speaker)
- However, the LMS algorithm does not converge, if the error signal is not synchronized with the reference signal
- The FXLMS algorithm (Filtered-X LMS) uses a filter estimate $S(z)$ for the error path
  - Reference signal $x(n)$ is filtered with $S(z)$ to compensate for the delay between the error and reference signals
- This algorithm was discovered by several researchers at the same time (Morgan, 1981; Burgess, 1981; Widrow 1981)

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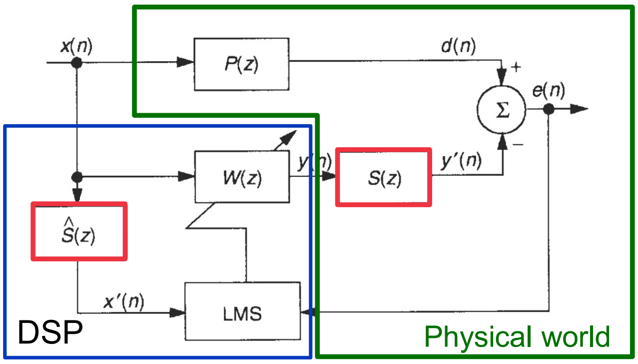
FXLMS Algorithm

- 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)



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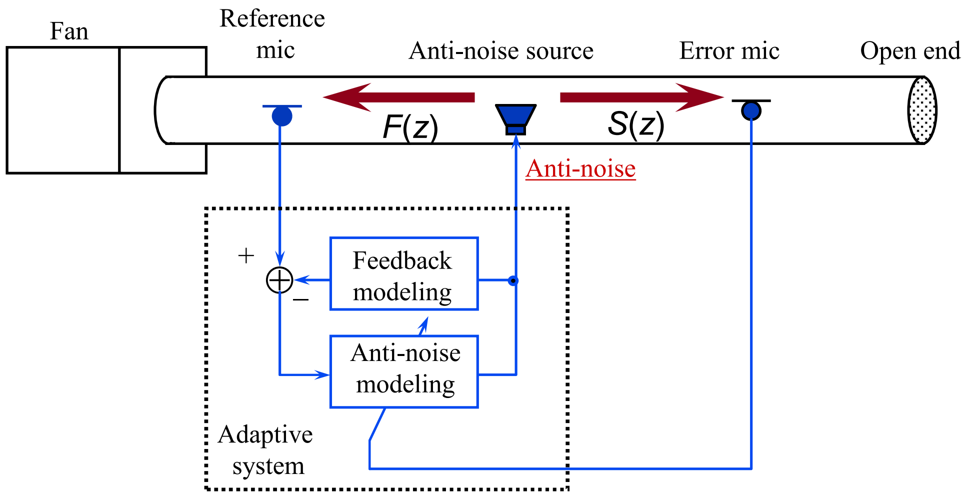
Error Path S(z) in Duct ANC System



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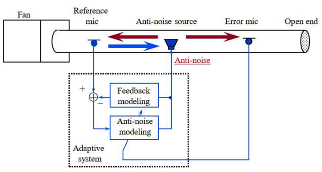

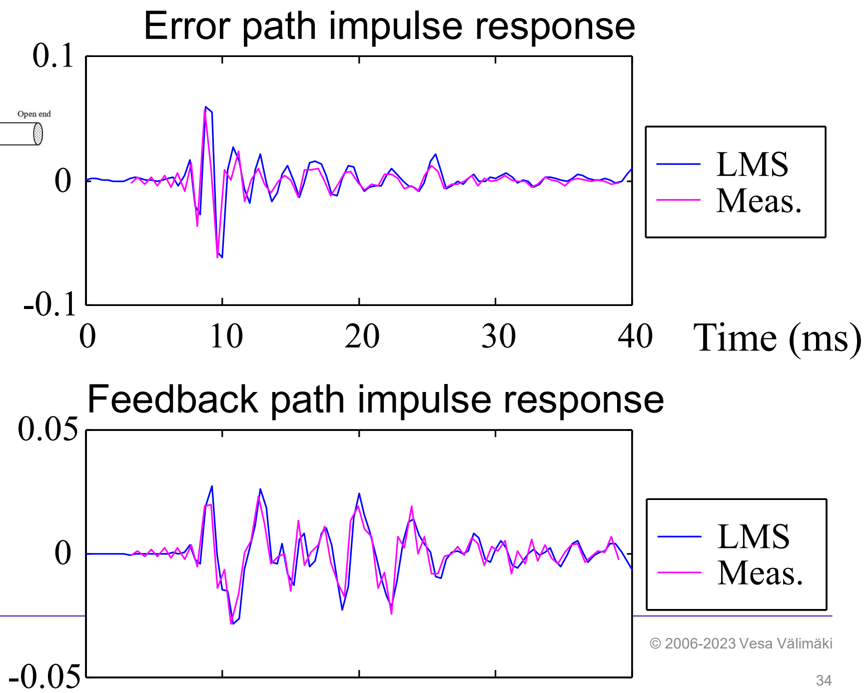

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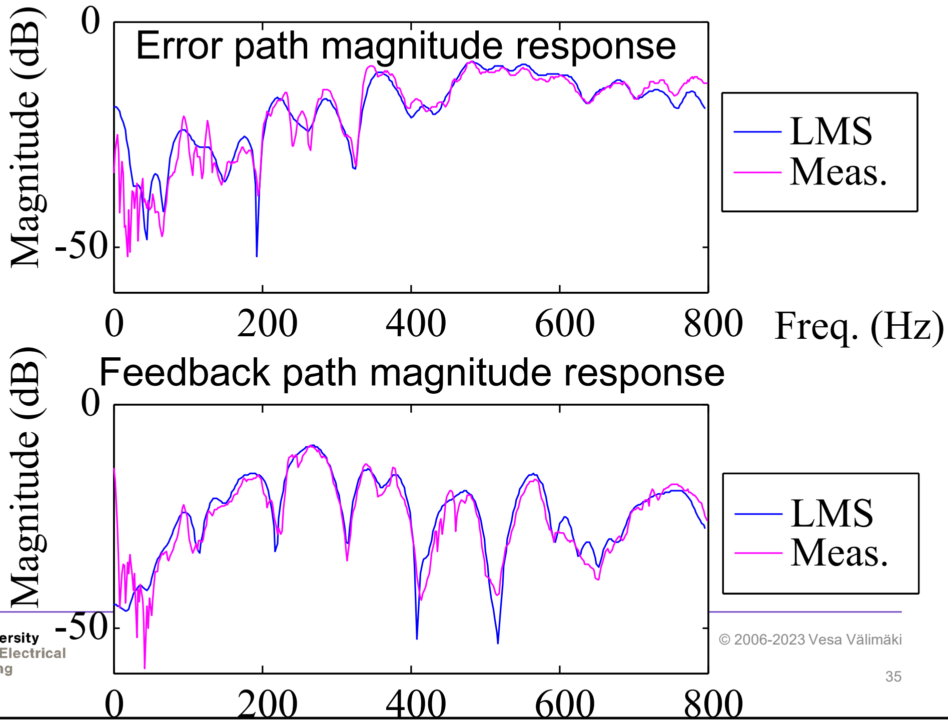

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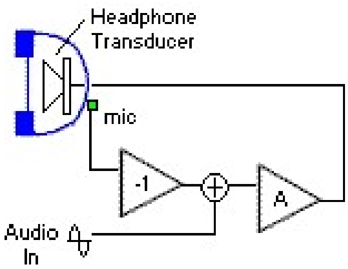
ANC Headphones

- 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



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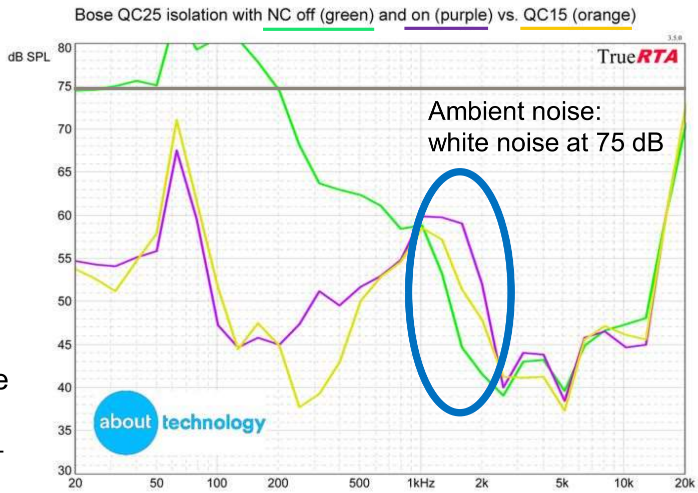
ANC Headphones

- 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 near its cutoff frequency (“**waterbed effect**”), here between 1 and 2 kHz

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



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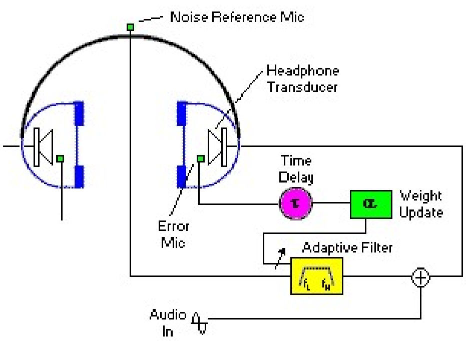
Digital ANC Headphones

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



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ANC in Airplanes

- The cabin of a modern turboprop airplane is fairly noisy
  - The blade-passing noise occurs at low frequencies and propagate easily through the fuselage
- Airplanes must be light, so passive attenuation of low-freq noise is hard
- ANC seems like a nice solution
  - ANC works best at low frequencies
  - ANC system does not add much to the weight of the aircraft
  - The cost of an ANC system is reasonably small w.r.t. to the price of the aircraft

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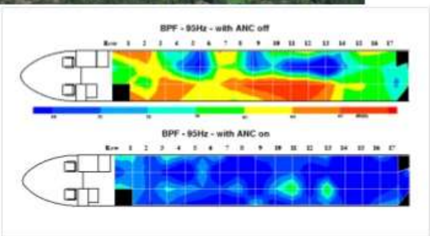
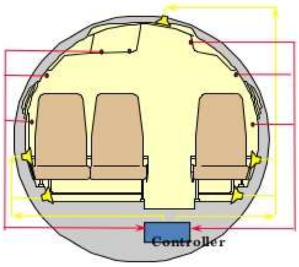
ANC in Airplanes

Saab 2000 and Gripen

A 400M





Vesa Välimäki

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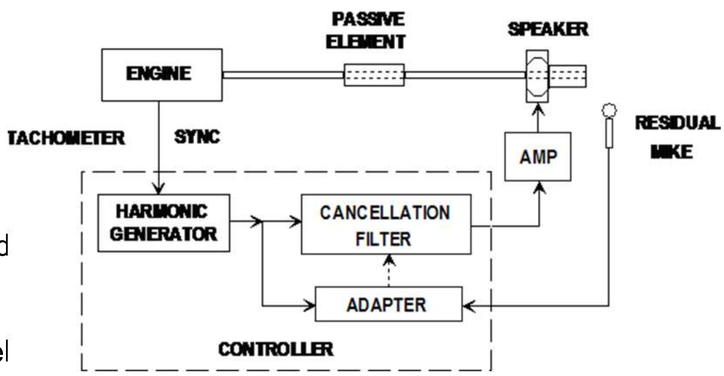
Active Muffler for Cars

- 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

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Use Cases of Adaptive Filtering

1) Transfer function modeling
   - Adaptive filter learns a (time-varying) frequency response
   - For example, active noise control
2) Inverse modeling
   - Adaptive filter cancels of transfer function
   - For example, automatic equalization of a loudspeaker
3) Prediction
   - Adaptive filter learns to ”predict” the output signal of a system
   - For example, predictive coding, ADPCM, spectral envelope models
4) Interference cancellation
   - Adaptive filter ”subtracts” an interference from a corrupted signal

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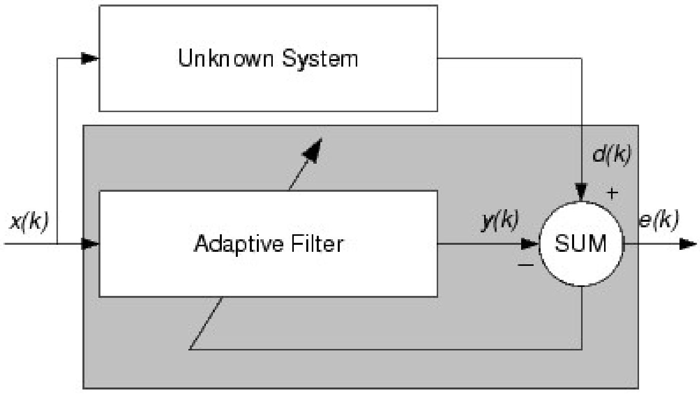
Transfer function modeling

- Adapt the filter so that the filter responses become equal (i.e. error signal becomes zero)



Ref: http://www.mathworks.com/access/helpdesk/help/toolbox/filterdesign/adaptiv4.shtml

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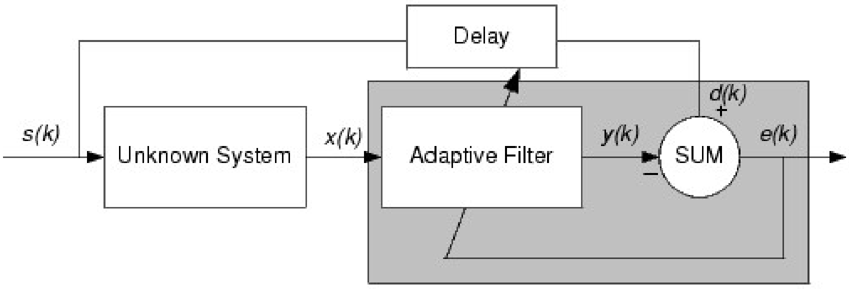
Inverse modeling

- Adaptive filter learns to cancel the response of a system
- A **modeling delay** must be included!



Ref: http://www.mathworks.com/access/helpdesk/help/toolbox/filterdesign/adaptiv5.shtml

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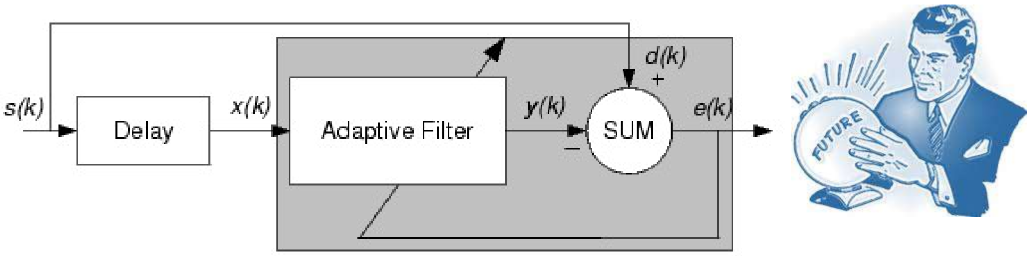
Prediction

- Adaptive filter learns to make the best guess of next signal value
- Learning correlation properties is equivalent to spectral estimation



Ref: http://www.mathworks.com/access/helpdesk/help/toolbox/filterdesign/adaptiv7.shtml

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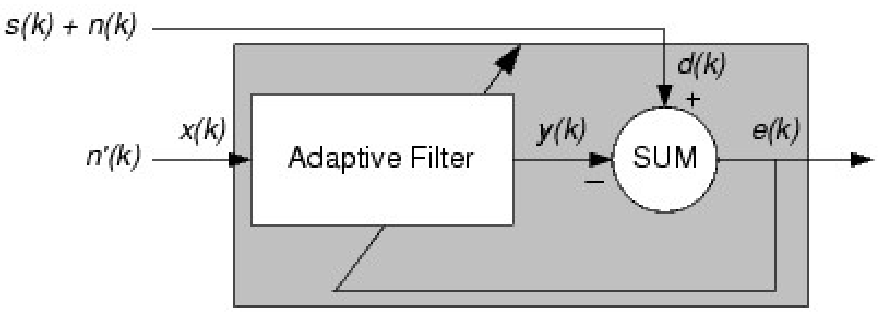
Interference Canceling

- Subtract the filtered interfering signal $n'(k)$ from the mixture of desired signal and interference $s(k) + n(k)$



Ref: http://www.mathworks.com/access/helpdesk/help/toolbox/filterdesign/adaptiv6.shtml

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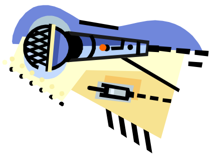
Adaptive Filtering Applications

- 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

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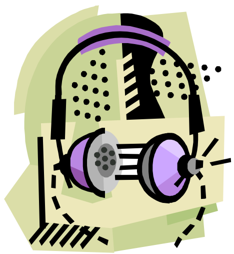
Conclusion

- 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 not many ANC applications (Lam *et al.*, 2021)
  - Patents are expiring (US patents are valid for 20 years)



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