Chapter 3
Time-domain Filtering for Removal of Artifacts

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Time-domain filters

- Synchronized averaging
- Moving-average filters
- Derivative-based operators to remove low-frequency artifacts

Problem:

- Propose a time-domain technique to remove random noise given the possibility of **acquiring multiple realizations** of the signal or event of interest

Synchronized averaging

- Linear filters fail
  - When the signal and noise spectra overlap
  - Synchronized signal averaging can separate a repetitive signal from noise w/o disturbing the signal
- **Alignment** of the waveforms is important
- No frequency-domain filtering is necessary
- If **noise is random with zero mean and uncorrelated** with the signal averaging will improve SNR

ERP & SEP

- ERP: Event-related potential
  SEP: Somatosensory evoked potential
- The **somatosensory system** is the sensory system of somatic sensation.
  - The sense of touch is mediated by the **somatosensory system**. **Touch** may simply be considered one of five human senses; however, when a person touches something or somebody this gives rise to various feelings: the perception of pressure (hence shape, softness, texture, vibration, etc.), relative temperature and sometimes pain. Thus the term "touch" is actually the combined term for several senses. In medicine, the colloquial term "touch" is usually replaced with **somatic senses**, to better reflect the variety of mechanisms involved.

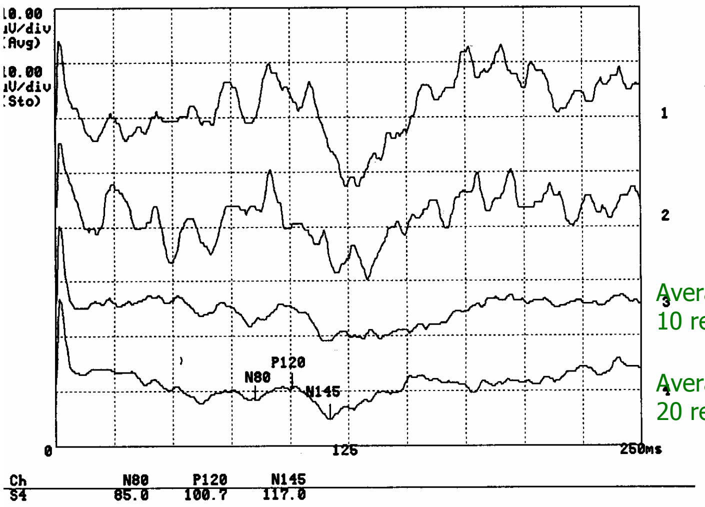
Examples:

- ERPs and SEPs
  - Epochs obtained a number of times by repeated application of the stimulus
  - Stimulus is used to align the epochs
  - Averaging is then performed
- ECG signals
  - filtered by detecting the QRS complexes and their position to align the waveforms

Algorithm

- M repetitions -> SNR increase by a factor $\sqrt{M}$
- Obtain a number of realizations
- Determine a reference point
  - Trigger if external stimulation
  - Repetitive events
    - QRS complexes in the ECG or S1 and S2 in the PCG
- Extract parts corresponding to events and add them to a buffer
- Divide the results in the buffer by the # of events added

Example: Visual ERPs

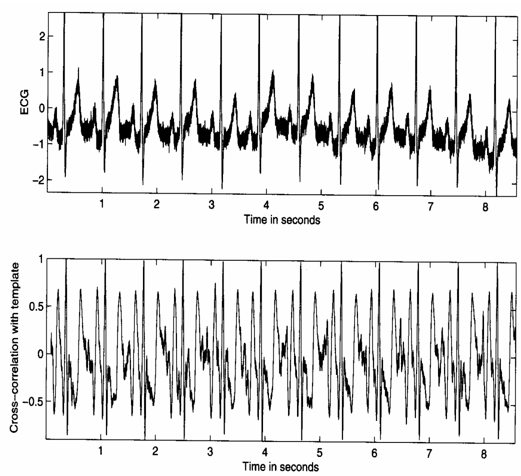


Averaging over 10 repetitions

Averaging over 20 repetitions

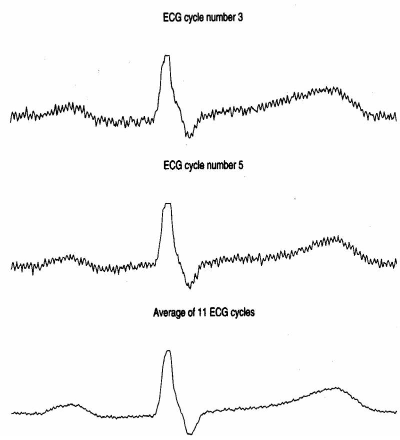
Example: Noisy ECG signal

- Sample QRS complex
  - First beat used as a template (86 ms)
- Template matching
  - Normalized cross-correlation
- Cross-correlation peaks (value is 1) at the locations of QRS
- Choose an appropriate threshold (be careful!)



Example: Noisy ECG signal

- Two ECG cycles extracted using trigger points from cross-correlation function
- Synchronized averaging performed
  - 11 cycles averaged



Problem:

- Propose a time-domain technique to remove random noise given "**only one realization**" of the signal or event of interest.

Solution: Moving-average filters

- Temporal averaging for noise removal
- $y[n] = \Sigma\, b_k\, x[n-k]$
  - b_k: filter coefficients, k = 0 … N
  - N: order of the filter
  - The effect of division by the number of samples used is included in the values of filter coefficients

MAF

- $H(z)=b_0+b_1z^{-1}+b_2z^{-2}+\ldots+b_Nz^{-N}$

Special MAF: Hanning filter

- $H(z)=(1/4)[1+2z^{-1}+z^{-2}]$
  - Double zero at z=-1

Advantages and attributes of MAF

- h[k] has a finite number of terms
- FIR filter
  - No recursion, no feedback
- The output depends only on the present input sample and a few past input samples
- Filter is a set of tap weights of the delay stages
- No poles except at z=0
  - Inherently stable
- Linear phase
  - Symmetric or antisymmetric tap weights

Hanning Filter

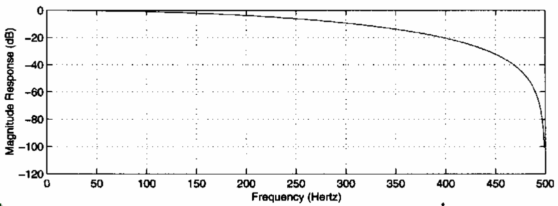
- $H(w)=(1/4)[1+2e^{-jw}+e^{-j2w}]$
- $H(w)=(1/4)[\{2+2\cos(w)\}e^{-jw}]$

Hanning filter

Magnitude response = |(1/2){1+cos(w)}|

- Lowpass filter with linear phase

- Magnitude and phase response assist in undestanding the effect of the filter on the frequency components of the signal and noise



Phase response = -w

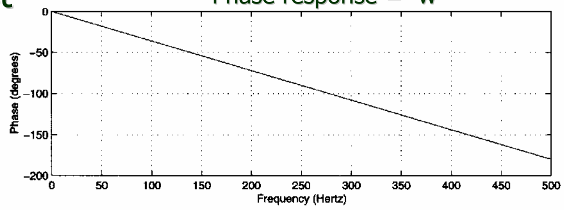
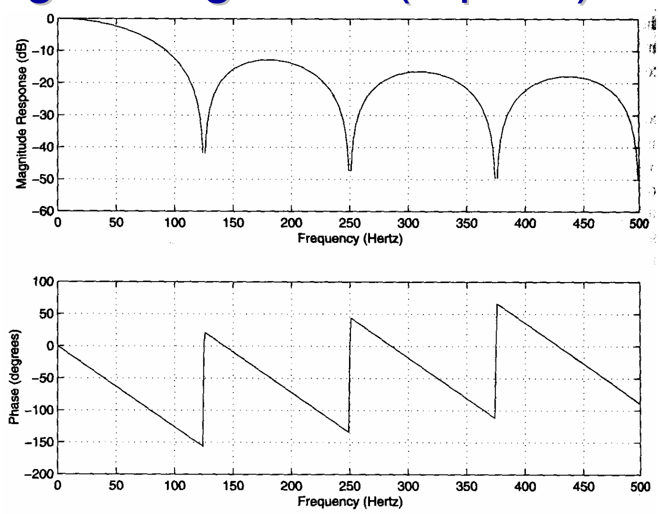


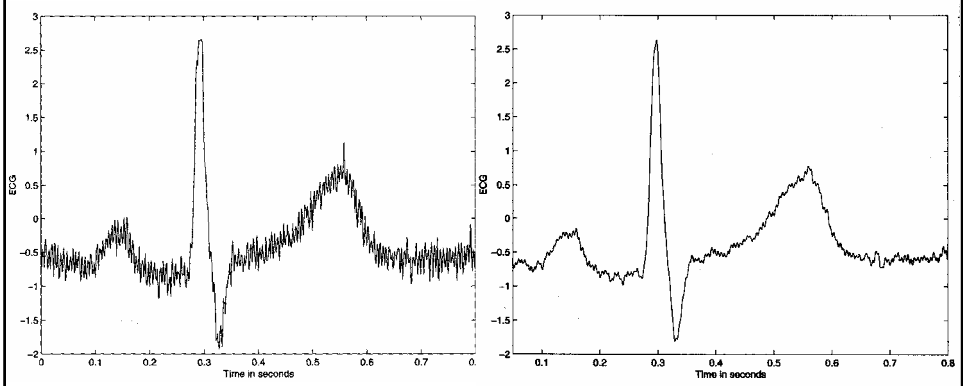
Figure 3.17 Magnitude and phase responses of the Hanning (smoothing) filter.

Moving average filter (8-point)



H(w) = (1/8) Σ exp(-jwk) =
(1/8) [1+ exp(-j4w) {1+2cosw+2cos2w+2cos3w}]

Illustration of application: Filtering with 8-point MA



Problem

- Develop a time-domain technique to remove base-line drift in the ECG signal

Derivative-based operators to remove low-frequency artifacts

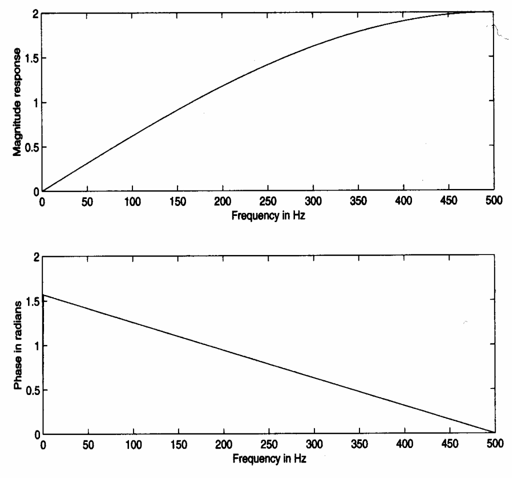
- Derivative operator in time-domain
  - Removes parts that are constant
  - Large changes in the input -> high values in the output
    - Boost HF components and suppress LF components

Derivative operator

- d/dt -> multiplication by jw or j2*pi*f
- Gain of the freq response, H(w)=jw
  - starts with 0 and increases linearly
- Second-order derivative operator d^2/dt^2
  - $H(w) = -w^2$
  - Quadratic increase in gain for HF components

First-order difference operator

- y[n]=(1/T) [x[n]-x[n-1]]
- H(z)=(1/T) [1-z^{-1}]
- H(w)=(1/T) exp(-jw/2) [2j*sin(w/2)]
- |H(w)|=(2/T) |sin(w/2)|
- Phase = pi/2 – w/2
- HF noise will be amplified
  - **Noise-amplification problem**



Three-point central-difference operator

- Average of two successive output values
- y3[n]=(1/2) [y[n]+y[n-1]]
- y3[n]=(1/2T) [x[n]-x[n-2]]
- H(z)=(1/2T) (1-z^{-2})
  =(1/T) (1-z^{-1}) (1/2) (1+z^{-1})
- First-order-diff operator + 2-point MA filter
- Bandpass filter

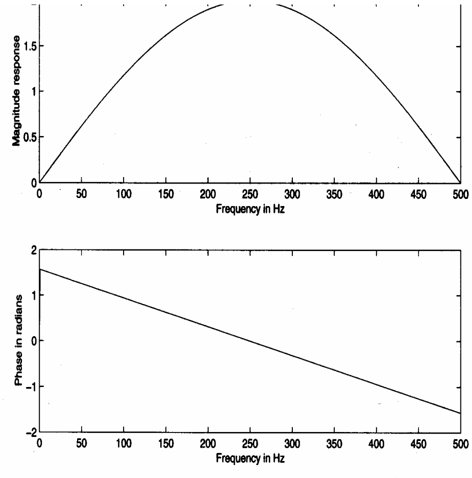
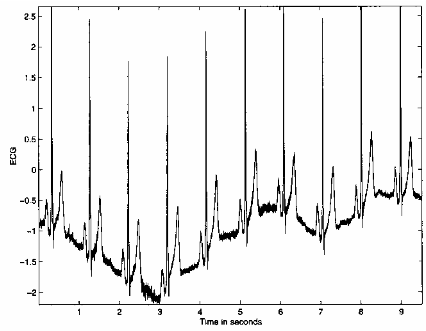
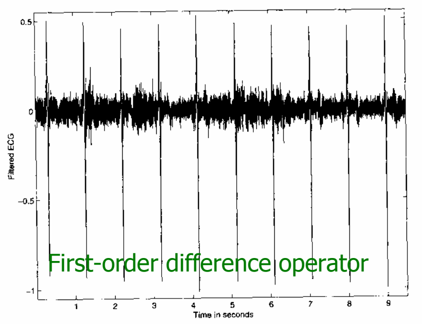
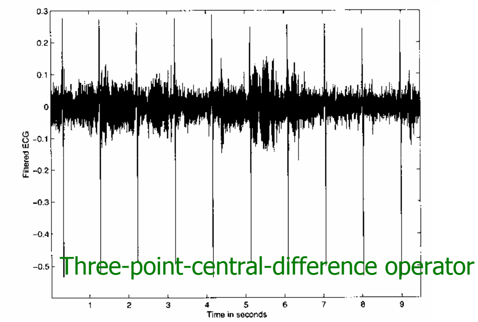


Illustration of Application: Removal of LF noise







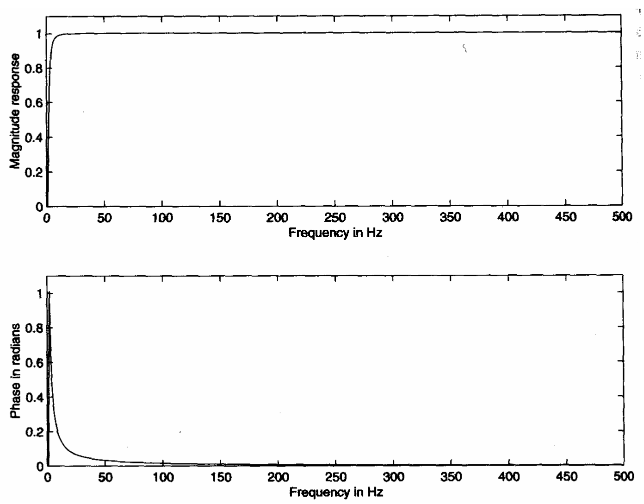
Problem

- How could we improve the performance of the basic first-order difference operator as a filter to remove LF noise or baseline wander w/o distorting the QRS complexes?
- We would like the gain of the filter to be close to unity after a certain frequency.

Solution

- To obtain high gain in the low frequencies place a pole on the real axis (zero) frequency at z=0.995 pole
- $H(z)=(1/T)[(1-z^{-1})/(1-0.995z^{-1})]$
- $H(z)=(1/T)[(z-1)/(z-0.995)]$
- $y[n]=(1/T)(x[n]-x[n-1])+0.995y[n-1]$

Magnitude and phase response



Removal of wander