ADINSTRUMENTS

This technique note was compiled by ADInstruments Pty Ltd. It includes figures and tables from S.S. Young (2001): "Computerized data acquisition and analysis for the life sciences". For further information on any of the following topics, please refer to this textbook.

SUMMARY

Filters play a vital role in data acquisition systems to remove selected frequencies from an incoming signal and minimize artifacts (i.e. baseline wander, mains interference and noise).

Analog/hardware filters are used to filter the incoming, continuous signal before it is sampled by the analog to digital converter (ADC). These filters are included in ADInstruments front-ends (Bio Amps, Bridge Amps etc) and in some of the PowerLab units themselves.

ADInstruments front-ends initially amplify the signal to a level suitable for filtering. The analog filters are then used to remove unwanted frequencies, following which further amplification is performed before digitization. Filtering the signal prior to full amplification is essential for biopotential measurements to improve the signal to noise ratio.

The analog/hardware filters included in the S, SP and 30 series PowerLabs provide additional filtering to remove high frequency components (anti-aliasing low-pass filters) before the signal is digitized.

Additional Digital/Software filters are included in Chart and filter the data after it has been sampled and recorded by the PowerLab.

Digital filters are used post data acquisition and are advantageous because:
- It is possible to design digital filters that are impractical to make in analog form
- They are stable over time and provide consistent, reproducible signal filtering
- In Chart, they can be applied post data acquisition while the raw data is retained

However, a disadvantage of post-acquisition, digital filtering is that unless analog/hardware filters have also been used prior to digitization, any noise or baseline offset present in the signal has also been amplified and will have a negative effect on signal resolution.

SignalFiltering–09A

Important Terminology:

To understand the basics of filtering, it is first necessary to learn some important terms used to define filter characteristics. While these terms apply to all types of filters, for simplicity the following examples will only refer to low-pass filters.

- Cut-Off Frequency (f_c): Also referred to as the corner frequency, this is the frequency or frequencies that define(s) the limits of the filter range(s). It is the desirable cut-off point for the filter.
- Stop Band: The range of frequencies that is filtered out.
- Pass Band: The range of frequencies which is let through and recorded.
- Transition Band: The range of frequencies between the passband and the stopband where the gain of the filter varies with frequency.

Low-Pass Filter:

A low-pass filter allows signal frequencies below the low cut-off frequency to pass and stops frequencies above the cut-off frequency. It is commonly used to help reduce environmental noise and provide a smoother signal.
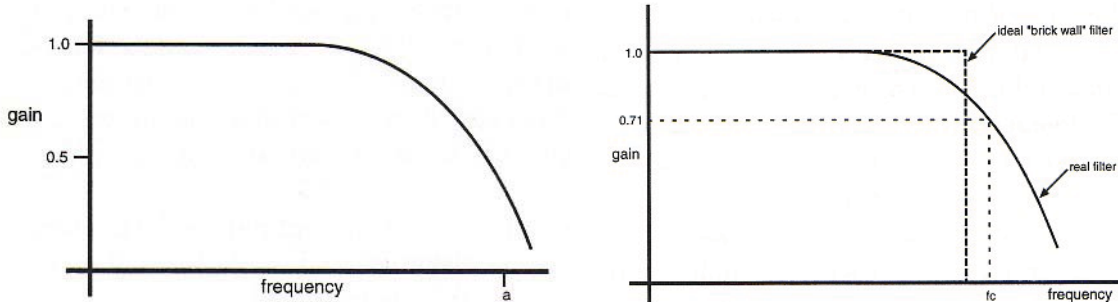

Figure 1. Effect of low-pass filtering on signal gain (S.S. Young, 2001).

A simple way to understand how a filter works is to plot signal frequency against signal gain (Figure 1). When a signal is unfiltered, it is recorded at a gain of 1, that is, the full signal is being recorded. However, when a signal is filtered, the gain (amount of signal recorded) is reduced (< 1). The frequency at which the gain starts to decrease by a reasonable amount is the cut-off (corner) frequency (f_c).

Ideally, low-pass filters would provide a gain of 1 below the cut-off frequency and a gain of zero above this cut-off value (i.e. no signal is recorded). However, filters are imperfect and some level of the signal is always recorded. This reduction in signal gain after the cut-off frequency is commonly referred to as signal attenuation and is commonly presented in decibel (dB) units. While signal attenuation is progressive rather than an ideal "all-or-none" process, all low-pass filters have a frequency (f_a; Figure 1) above which the gain is very small (the signal is virtually non-existent).

Note: Decibels are not units of measurement in the conventional sense (ie meter or joule) but represent a ratio, thereby describing how much bigger or smaller one thing is compared to another.
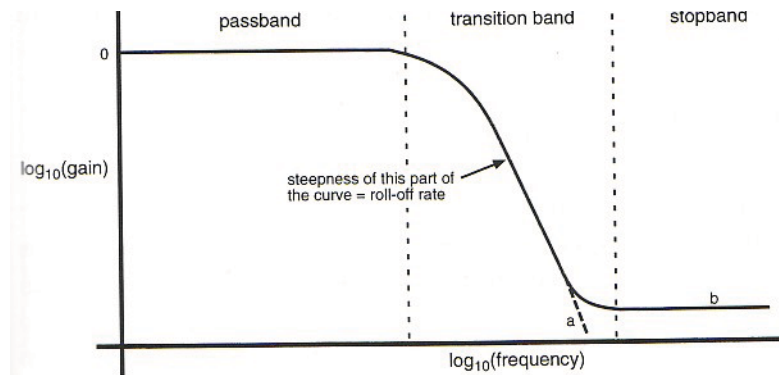
Figure 2. Filter Bands (S.S. Young, 2001).

All signal frequencies <u>below</u> the cut-off frequency are referred to as the passband (Figure 2).

All signal frequencies <u>above</u> the cut-off frequency are referred to as the stopband.

The region between the pass- and stop-bands is referred to as the transition band or transition width. This width (in Hz) depends on how sharply the filter response drops from the pass band to the stop band. Related to this is the roll-off rate, which, for low-pass filters is the rate at which the signal gain decreases when the signal is above the cut-off frequency. The narrower the transition band, the steeper the roll-off.

Other Filter Types:

High-Pass Filters:

A high-pass filter allows frequencies higher than the cut-off frequency to pass and removes any steady direct current (DC) component or slow fluctuations from the signal. Such filters are often used to stabilize the baseline of a signal (i.e. minimize baseline drift in an ECG signal). A useful comparison of the effects of a low-pass filter in comparison to a high-pass filter is presented in Figure 3.
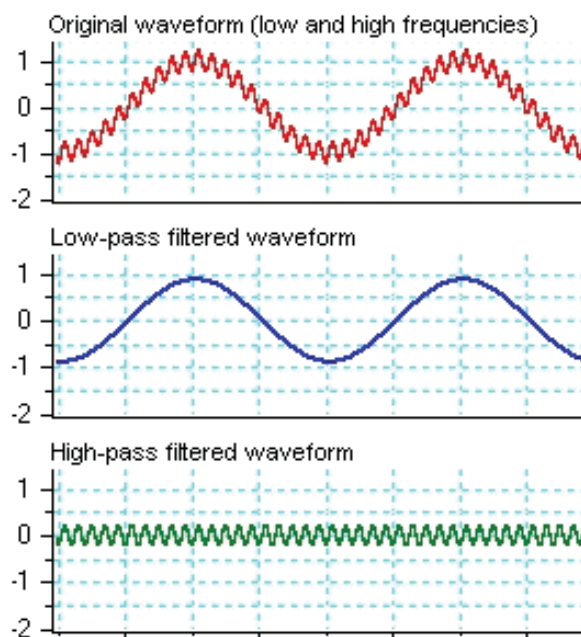

Figure 3. Effects of low and high pass filters on a signal waveform.

Mains Filters:

Mains interference (50/60 Hz) from power lines etc is not static and may vary during the day with the degree of variation greater in some countries than others. Therefore, to remove mains noise from a signal use the adaptive mains filter in the PowerLab. This filter tracks and removes the mains noise (including the harmonics of the fundamental) with minimal distortion to the recorded signal. Mains filters are digital and included in Chart versions for use with PowerLab /10, /20, /25 and /30s.

Notch Filters:

A notch filter removes a particular frequency from a signal and has a frequency response that falls to zero over a narrow range of frequencies (i.e. a 50 Hz notch may block signals from 49.5 – 50.5 Hz). Notch filters are available in all ADInstruments Bio Amps (Animal [ML136], Single [ML132], Dual [ML135] and Dual Bio/Stim [ML408]).

Narrow Band-Pass Filters:

Narrow band-pass filters are used to remove all signal frequencies except for a particular band (i.e. to record 8 – 12 Hz activity in EEG recordings). Frequencies either side of this band are not passed.

Band-Pass Filters:

A band-pass filter may be used to pass a larger range of frequencies (i.e. 0 – 100 Hz EEG activity). Frequencies either side of this band are not passed.

Band-Stop Filters:

A band-stop filter blocks a certain range of frequencies and allows frequencies either side of this range to be passed (i.e. You may wish to block Beta [ß1: 16 – 32 Hz] activity from an EEG recording but record all other frequencies between 0 – 15 Hz and 33 – 100 Hz).

Cut-Off Frequency and Center Frequency

For low-pass filters, the cut-off frequency is the frequency at which higher frequencies are blocked and lower frequencies are passed. For high-pass filters, the cut-off frequency is the frequency at which higher frequencies are passed and lower frequencies are blocked. Band-pass and band-stop filters have two cut-off frequencies (representing lower and upper limits).

For notch filters, the center frequency is the component frequency which is removed when the filter is applied to a waveform. For narrow band-pass filters, the center frequency is the frequency which is allowed through.

Transition Width (Filter Sharpness or Roll-off)

As mentioned earlier, all filters are imperfect. For example, a 200 Hz low-pass filter might leave frequencies up to 150 Hz untouched, reduce a 200 Hz signal to half its original amplitude and reduce the amplitude of higher frequencies more and more. However, it is not an "all-or-none process".

The transition width, or filter sharpness, is the band of frequencies for which the output amplitude is between certain percentages of the input amplitude (between 1% and 99% in the case of Chart's digital filters). In some situations, a narrow transition width or "sharp" filter is desirable. However, if the transition width is too small it can take too long to compute the filtered output. Furthermore, if a signal has sharp steps (such as a square wave), a small transition width can cause ringing in the step response.

The digital filters feature in Chart provides definition of transition width in 1 of 3 modes:
- Auto-Adjust
  Adjusts the transition width to 20% of the cut-off frequency unless this means an excessive calculation time, in which case the transition width will be increased, thereby resulting in a filter that is less sharp.
- Set to 20% of cut-off frequency
  Sets the transition width to 20% of the cut-off frequency.
- User-Defined
  Allows the user to specify a transition width (subject to absolute limits) in the "transition width" dialog.

1) ECG:

Range:	10 – 20 mV
Sampling rate:	
Mouse	4 kHz
Rat	2 – 4 kHz
Rabbit	1 – 2 kHz
Guinea Pig	1 – 2 kHz
Dog	400 Hz – 1 kHz
Pig	400 Hz – 1 kHz
Human	400 Hz – 1 kHz

*Should be 15-30 sample points in the QRS Complex

ECG signals contain limited information above 100 Hz

• High Pass:	0.3Hz to minimize iso-electric (baseline) drift
• Low Pass:	≤ 25 – 50 % sampling rate
	(typically 200 – 1 kHz low-pass cut-off)
• Notch:	Do NOT use as may distort ECG signal.
• Mains:	Will suppress electrical interference without distorting signal.

2) EEG/ECoG:

Range:	200 – 500 µV
Sampling Rate:	400 – 1000 Hz

EEG signals contain limited information above 50 – 100 Hz (Humans, Rat, Mice, Lambs)

• High-Pass:	0.1 or 0.3
• Low-Pass:	100 – 200 Hz cut-off
• Notch:	No (unless the user is aware of affect on signal)
• Mains:	Yes

Frequencies of Particular Interest:

• Delta:	0.5 – < 4 Hz
• Theta:	4 – < 8 Hz
• Alpha:	8 – < 12 Hz
• Spindles:	12 – 14 Hz
• Sigma:	12 – < 16 Hz
• Beta: (ß1)	16 – 32 Hz
• Beta: (ß2)	30 – 60 Hz

3) EOG

Range:	200 – 500 µV
Sampling Rate:	400 Hz – 1 kHz

EOG signals contain limited information above 50 Hz (Humans, Rat, Mice, Lambs)
- •High-Pass: 0.1 or 0.3
- •Low-Pass: 100 Hz cut-off
- •Notch: No (unless the user is aware of affect on signal)
- •Mains: Yes

4) EMG

Range:	Variable between species and muscle types.
Sampling Rate:	2 – 4 kHz

EMG signals contain variable frequencies; however, most common frequency bands recorded are 0.3 Hz – 1 or 2 kHz.
- •Notch: No (unless the user is aware of affect on signal)
- •Mains: Yes

Removing ECG artifacts, particularly in intrathoracic recordings (ie esophageal EMG) often requires difficult template matching (not available in Chart). If you need to remove low frequency artifacts > 2 Hz (i.e. respiratory or ECG artifacts) prior to recording/digitizing the signal, then the high-pass filters available in the Animal Bio Amp (ML136), Bio Amp (ML132), Dual Bio Amp (ML135) or Dual Bio Amp/Stim (ML408) are required.

5) Blood Pressure

Typical Heart Rates:
- • Humans: 80 – 200 bpm (max 4 Hz)
- • Guinea Pigs/Rats: 200 – 400 bpm (max 7 Hz)
- • Mice: 500 – 700 bpm (max 12 Hz)

For accurate reproduction of dicrotic notches and BP harmonics, sampling speeds of 50 to 100 times the heart rate (in Hz) are desirable. As a minimum, the low-pass filter frequency should be 10 times the heart rate (in Hz) and half the sampling rate.

Sampling Rates
- • Humans: 400 Hz
- • Guinea Pigs/Rats: 2 kHz
- • Mice: 2 kHz

Recommended Low Pass Cut-Off Frequency
- • Humans: 100 – 200 Hz
- • Guinea Pigs/Rats: 100 Hz – 1 kHz
- • Mice: 100 Hz – 1 kHz