Data acquisition
Objectives

1. Overview of the components and problems involved in data acquisition
2. More profound study of ADC/DAC
3. Multiplexing and sampling
4. Signal conditioning and filtering
5. Specific problems with grounding and isolation
6. Problems with the transmission of a signal and noise filtering
7. Digital signals and pulse trains

1 Introduction

In no matter what processing system measurements are the core of the process. Without measuring it is impossible to control the system. But measuring means dealing with signals and those signals have to be conditioned whether it is to transport the value or to be able to be perceived it by a human. Nowadays most processing systems are controlled by PC or mainframe. The evolution from electromechanical systems to PC based systems has also an impact on the signals themselves because they are to be digitalized which is an operation that already complicates the matter.

2 ADC

ADC is an acronym that stands for Analog to Digtal Convertor. These devices transform an analog voltage to an binary number. If we change a contiuous signal into a digital one we only have an approximation of the real value. This is a consequence of changing a continuous signal into a discrete one. How close this approximation is depends on the number of bits we use for the conversion. This is called the resolution. The (theoretical) resolution is put in a simple mathematical formula.

An n bit ADC has a resolution of one part in 2^n. For example, suppose we have a 16-bit ADC then we have resolution of $2^{16} = 65536$. So a 10V DC signal has a resolution of

$$\frac{10}{65536} = 0.000153V = 0.153mV$$

This resolution is also the value of the LSB or Least Significant Bit. Once we go below half of this value the ADC won't recognise this voltage and puts the value at 0. This is called the quantum value and the corresponding error is called the quantization error. Do not confuse resolution with accuracy! Accuracy has to do with different types of error and resolution only with how precise we can discretisize the analog value. Different types of error can occur during the conversion.

2.1 ADC error

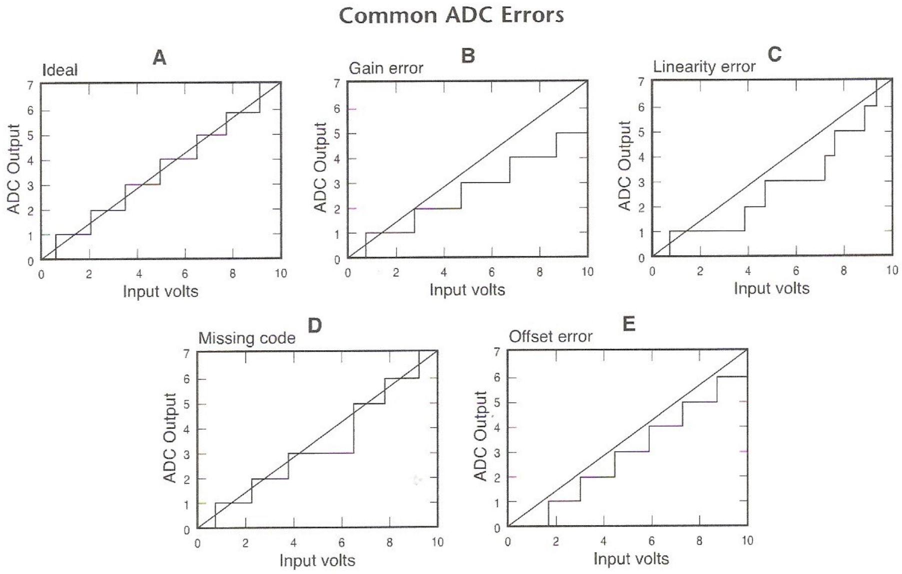

Figure 1: (source:data aqcuisition handbook,MCmeasurement computing)

We have

- Gain error: The gain has not been set to the correct value. This type of error can be avoided by calibrating before use.
- Offset error: Ther is an offset during the conversion. This type of error can also be avoided by calibration.
- Linearity error: Non linear phenomena can have an influence on the conversion. This type of error is almost impossible to avoid. The best way to decrease this type of error is to use the ADC in a small interval of conversion
- Missing code error:This means that the ADC is missing a piece of code which of course cannot be converted. It skips a certin piece of information thus cannot produce an accurate output.

Another problem that could occur is a certain level of noise that interferes with the signal. One method, and the most important, to decrease the noise level is to eliminate ground loops. They are an important source of noise. Another way to decrease noise is to filter the signal.

2.2 Types of ADC

There are different types of ADC, with each his advantages and its disadvantages.

- Succesive approximation ADC:This type of ADC has an ADC, control logic and a comparator in its circuit and works as follows. When the voltage to be converted is present at the input of the comparator the control logic sets all bits to zero. Then the ADC's MSB is set to 1 which forces the ADC output to half of its full scale. The comparator compares the analog input to the output of the ADC and the analog input and if the ADC output is lower then the input the bit remains at 1 else it is set to 0. Then the second bit follows, but at 1/4 of the scale until all bits are compared. These ADC are relatively slow but they are also inexpensive.
- Voltage-to-frequency ADC: Converts the analog input to a pulse train with frequency proportional to the amplitude of the input. The pulses are counted over a constant period and the frequency is measured. This frequency represents the digital value. The advantage of this type is its high noise rejection ratio.
- Integrating ADC:This type measures the time to charge and discharge a capacitor to determine the input voltage. The time needed to charge and/or discharge determines the digital value of the bit. This type is interesting for its accuracy and the reduction of noise. The disadvantage is that it is relatively slow.
- Sigma-Delta ADC: Is another type of integrating ADC, relatively inexpensive but high resolution and noise rejection.

3 Multiplexing and sampling

An ideal data acquisition system uses a single ADC for every single measurement. This is a very expensive way to do data acquisition. It is cheaper to use multiplexers. Multiplexing means switching among lines of multiple channels. The multiplexer (Mux) will switch among the measuting devices driving a single ADC. This means that the rate at which data can be acquired will decrease because of the time sharing but most for applications the sample of a multiplexing device will suffise. For example an ADC that can sample at 100 kHz will be sampled at 10 kHz if a 10 channel multipexer is used.

3.1 Disadvantages

- The high source impedance can combine with stray capacitance to increase settling time and generate cross talk.
- The impedance itself can degrade signals

3.2 Solid state switch versus relay

Both systems are used in multiplexers but both have advantages and disadvantages. Relays are relatively slow but can handle large input voltages up to several kV, while solid state switches can handle much higher sample rates but input voltages up to max 25V. Another difference is the 'on resistance' of the element. A electromechanical switch has an on resistance of 0.01 ohm while analog switches have 'on resistances' of 10 to 100 ohm. This resistance adds to the signals impedance and affects measurements accuracy. Analog switches showe another problem called charge injection. A small portion of input gate drive voltage is coupled to the analog input voltage and manifests as a spike in the output voltage which again can produce measuremants errors.

3.3 Fundamental concepts

- Sampling rate: Enough samples have to be made to ensure that the sampled signal can be faithfully reproduced in the time domain. (contiuous or discrete)
- Source impedance: Fast multiplexing rates require lower source impedance.
- Sample and hold circuit: To avoid time skew during the multiplexing we need to buffer the signal before the multiplexer. The buffer holds the signal's value while the multiplexer switches through the channel.
- Nyquist theorem: To reproduce a signal it must be sampled at a rate of twice the maximum frequency present in the sampled signal. Preferably the sampling frequency is set between five and ten times the frequency rate of the highest frequency component of the signal.
- Aliasing: When the sampling rate is less then Nyquist rate, signals lower in frequency than the signal being sampled can appear in the reconstructed signal. This is called aliasing. To prevent aliasing anti aliasing (low pass) filters are used. The problem using these filters is that desired low frequency signals could also be filtered.
- Fourier transform: to study periodic signals a mathematical tool, called Fourier transform, is widely used. There are three different types of Fourier transform namely
  - Standard Fourier transform(SFT):

    $$F(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} f(t) e^{-i\omega t} \, dx.$$

  - Fast Fourier transform(SFT):is an algorithm to calculate more efficiently and faster the discrete Fourier transform

  - Discrete Fourier transform(DFT):

$$X_n = \sum_{n=0}^{N-1} x_n e^{-}\frac{i2\pi}{N}kn$$

- Windowing: Real time measurements are taken over a limited time interval but Fourier transforms are calculated over infinite time intervals so this produces data that are only approximations. This means that at the beginning and the end of the time interval the signal will produce the largest oscillations, thus errors. For this reason windows functions will be used that rise and decrease gradually thus avoiding these oscillations.

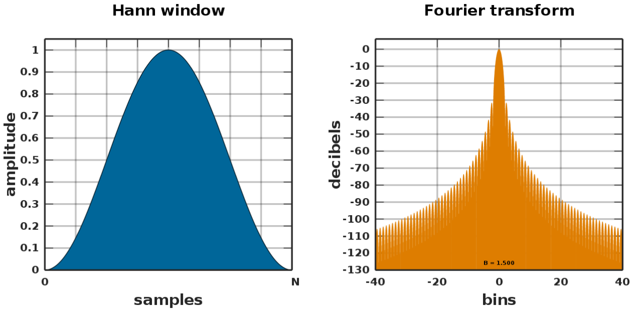

Figure 2: Hanning window;source:wikipedia.org

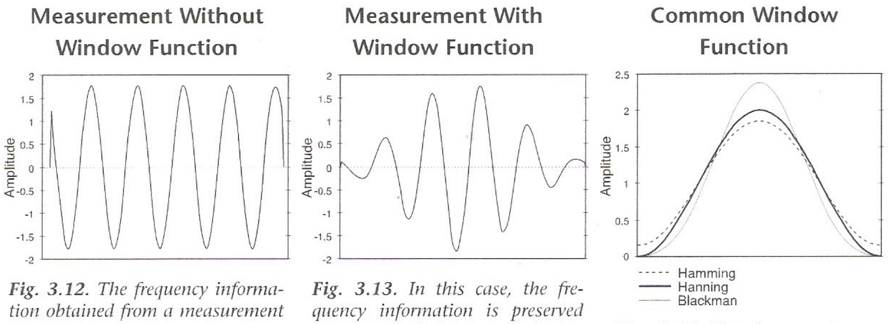

Fig. 3.12. The frequency information obtained from a measurement can be incorrect when the waveform contains abrupt beginning or ending points.

Fig. 3.13. In this case, the frequency information is preserved when multiplied by a windowing function. It minimizes the effect of irregularities at the beginning and end of the sample segment.

Fig. 3.14. The three most common types of window functions include Hamming, Hanning, and Blackman.

Figure 3: windowing (source:Data acquisition handbook, MC Measurement computing)

4 Signal conditioning and filtering

4.1 Amplification

The primary parameters concerning ADC are speed and resolution. Concerning speed we should respect a low source impedance. A Mux has a parasitic RC time constant due to a small parasitic capacitance from all types of signal input. When the switch closes and we have a parasitic capacitance of 100pF and a $10k\Omega$ source resistance the time constant will be $1\mu s$. When sampling rates of $10\mu s$ are used the capacitance is only charged to 86% of the value thus creating large errors. If we use a low source resistance of $1k\Omega$ the capacitance is faster charged thus leading to a more precise value.

Because some transducers use signal levels just a few microvolts high, there is a problem with ground loops and interference. These problems can be avoided by amplifying the signal. This type of amplifiers need to have

- Very low input current, drift and offset voltage
- Stable and accurate voltage gain
- High input impedance and common mode rejection

[1]

4.1.1 Common Mode Rejection Ratio(CMMR)

This value gives information over the way the circuit handles signals that are present over both the inputs. The device should reject non desired signal components. The CMMR is infinite if the device does not allow the undesired signal. This is however an ideal situation. Real values of CMMR lie between 70 and 120dB. Especially instrumentation amplifiers need to have large CMMR.(usually around 90dB)

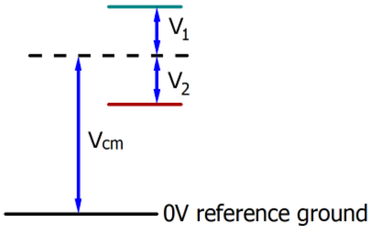

Figure 4: common mode voltage (https://infosys.beckhoff.com)

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[1] Most amplifiers have already been treated during previous lectures automatisation and electronics.

4.2 Filtering

In almost every data acquisition circuit you can find a filter. There are two different classes of filters which are active and passive filters. The difference is that in a passive filter circuit no active components like diodes or transistors are found. Only passive elements like capacitors, resistors and inductors are present in the circuit.

There are four different types of filters

- Low pass filter: only frequencies below a certain frequency, called cut off frequency, will pass.
- High pass filter: only frequencies above a certain frequency, called cut off frequency, will pass.
- Bandpass filter: only frequencies in between two frequencies will pass, frequencies outside this range will be rejected.
- Band reject filter: frequencies in between two frequencies will NOT pass, will be rejected.

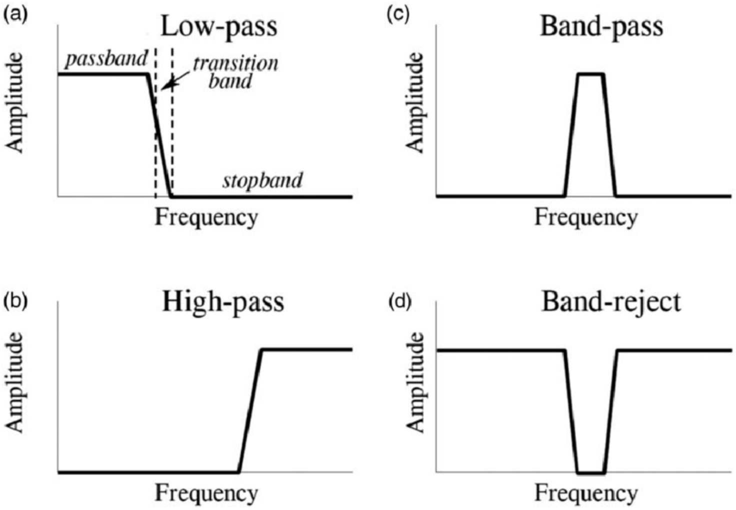

Figure 5: types of filter (source:https://www.nutsvolts.com)

The most well known and used filters are the Chebyshev filter, Butterworth filter, elliptic filter and the Bessel filter. Each type has its unique characteristics.

4.2.1 Chebyshev filter

The Chebyshev filter has a steeper attenuation then a Butterworth but shows a ripple in the passband. Phase response is much more non-linear then the Butterworth.

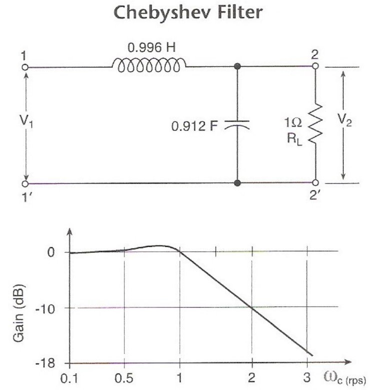

Figure 6: Chebyshev filter(source:Data Acquisition Handbook,MC measurement computing)

4.2.2 Butterworth filter

The Butterworth has a fairly flat response in the pass band and a steep attenuation rate. The phase response on the other hand is very non linear. To compensate for this slow attenuation response one needs to have a higher order filter.

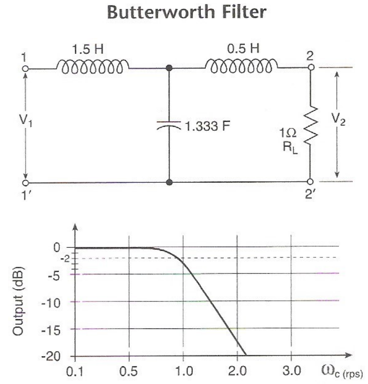

Figure 7: Butterworth filter(source:Data Acquisition Handbook,MC measurement computing)

4.2.3 Bessel filter

A Besselfilter has the best step response and the phase response is quite linear. On the other hand, the rate of attenuation is very slow.

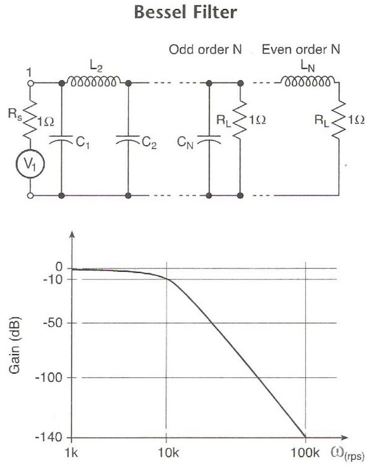

Figure 8: Bessel filter(source:Data Acquisition Handbook,MC measurement computing)

4.2.4 Elliptic filter

No filter of equal order has a faster attenuation rate from pass band to stop band. The ripple in each band can be adjusted independantly.

4.3 Attenuation

Usually data acquisition systems measure voltages between 5 and 10V. Voltages higher then this need to be atenuated. This can be done by a voltage divider. This however has two drawbacks. Either the input impedance is to low or the output impedance is to high. For a multiplexed system better solutions are present. When using buffered voltage dividers the low input impedance can be overcome. This means using transistors or opamps to have a large input impedance without losing accuracy.

5 Grounding and isolation

5.1 Isolation

A very important feature in control loops is the isolation between input and output circuit. Isolation is by definition the separation of two signals to avoid unintentional interaction. When data acquisition systems need to measure low voltages where high voltages are common as in control loops of motordrives, you might need isolation amplifiers to secure safety for the operators as well as the circuit itself. Another benefit is that the isolation amplifier also eliminates ground loops. Isolation modules come in both types analog as well as digital. The galavanic isolation of analog modules use three types of isolation optical, capacitive and magnetic. Main goal is to isolate input from output and thus withstand a large common mode voltage between input and output.

5.1.1 Capacitive isolation

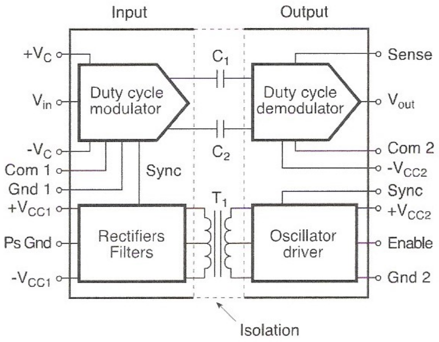

Figure 9: capacitive isolation circuit(source:Data Acquisition Handbook,MC measurement computing)

5.1.2 Optical isolation

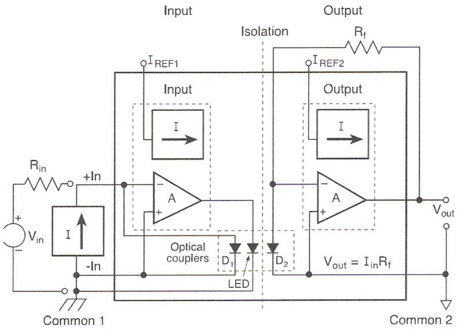

Figure 10: optical isolation circuit(source:Data Acquisition Handbook,MC measurement computing)

5.1.3 Magnetic isolation

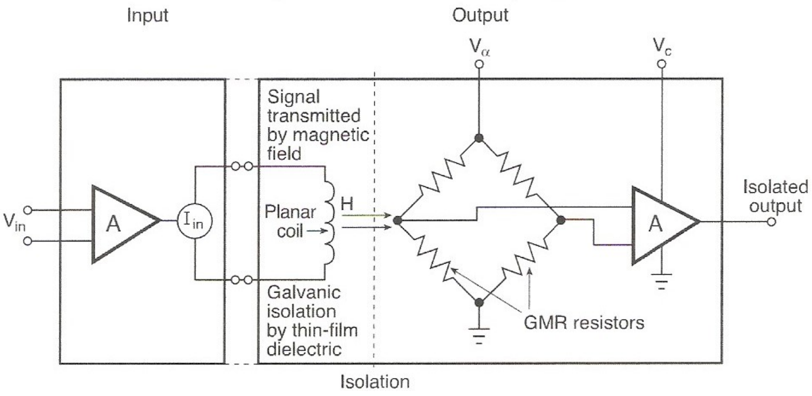

Figure 11: magnetic isolation circuit(source:Data Acquisition Handbook,MC measurement computing)

5.1.4 Digital isolation

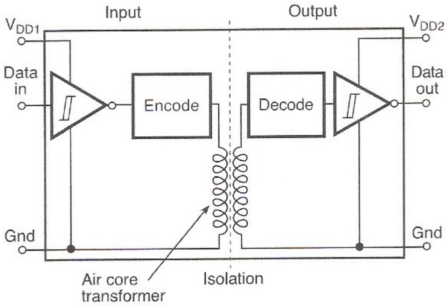

Figure 12: digital isolation circuit(source:Data Acquisition Handbook,MC measurement computing)

There are some more technical problems that cannot be overlooked.

First there is risk of overload. The circuit could be exposed to voltages of over 10v. A current limiting resistor will be connected in series to avoid high current.

Then there is electrostatic discharge that has to taken in consideration. Most important is grounding but this is not sufficient. Controlling humidity and slightly ionising air is very effective.

5.2 Grounding

Grounding is an essential part for the safety of circuits. But not only safety, also avoiding noise in your data acquisition is a very important advantage of grounding your system. Grounding for safety means connecting all your electric appliances to a rod planted into the ground.

Avoiding noise by grounding is only a start. Using proper shielding, correct wiring and signal averaging is also necessary to avoid erronous signaling and as a consequence bad measuring signals. In instrument circuit usually shielded wring is used because of the low voltages involved. Already small currents can create high enough magnetic fields to disturb the measurements signals. Noise reduction can also be obtained by using signal averaging and filtering.

Modern ways of communication are wireless techniques and they will be used more and more. Bluetooth protocol being one of those techniques. But this goes far beyond the goals to be achieved in these lecture notes.

6 ANNEX: Filters

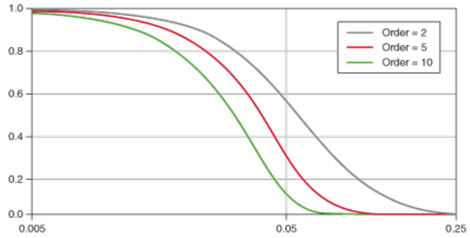

Figure 13: Bessel filter Bode diagram amplitude(source:wikipedia)

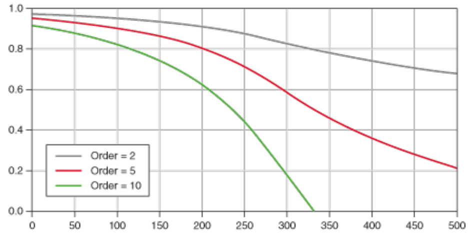

Figure 14: Bessel filter Bode diagram phase(source: wikipedia)

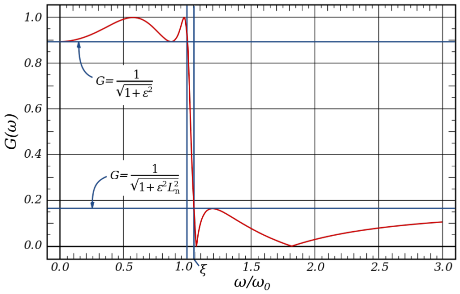

Figure 15: Elliptic filter 4th order(source wikipedia)

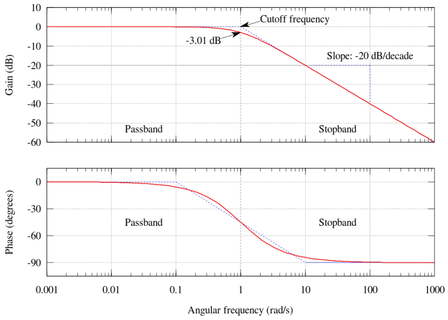

Figure 16: Butterworth filter Bode diagram(source:wikipedia)

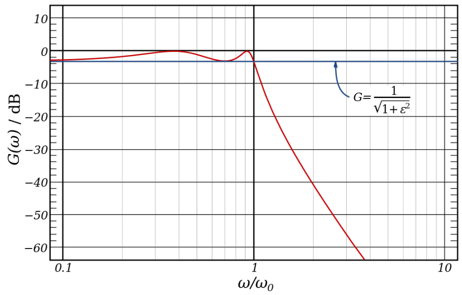

Figure 17: Chebyshev filter 4th order amplitude characteristic(soure: wikipedia)

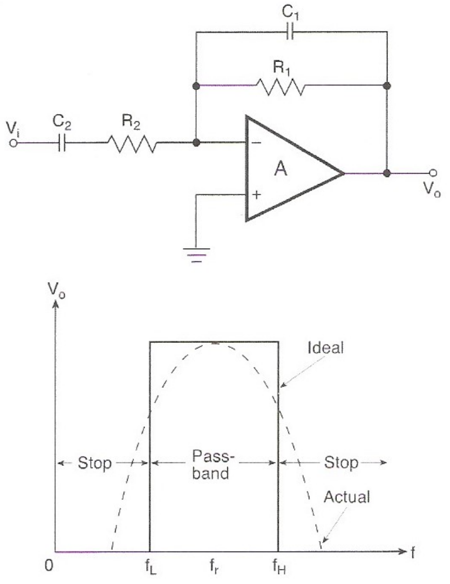

Figure 18: active passband(source:Data Acquisition Handbook,MC measurement computing)