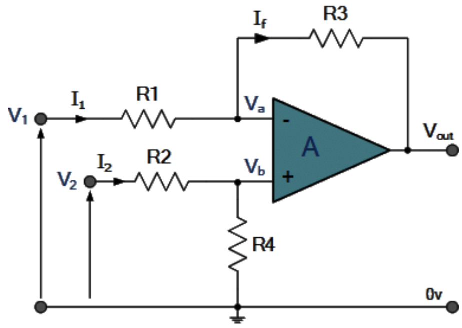
Lecture Six

Amplifiers and signal processing, cont.

The Differential Amplifier

The differential amplifier amplifies the voltage difference present on its inverting and non-inverting inputs. This configuration makes the operational amplifier circuit as a **Subtractor,** unlike a summing amplifier which adds or sums together the input voltages.



When resistors, R1 = R2 and R3 = R4 the above transfer function for the differential amplifier can be simplified to the following expression:

$$V_{OUT} = \frac{R_3}{R_1}\left(V_2 - V_1\right)$$

If all the resistors are all of the same ohmic value, that is: R1 = R2 = R3 = R4 then the circuit will become a **Unity Gain Differential Amplifier** and the voltage gain of the amplifier will be exactly one or unity. Then the output expression would simply be Vout = $V_2 - V_1$.

Also note that if input V1 is higher than input V2 the output voltage sum will be negative, and if V2 is higher than V1, the output voltage sum will be positive.

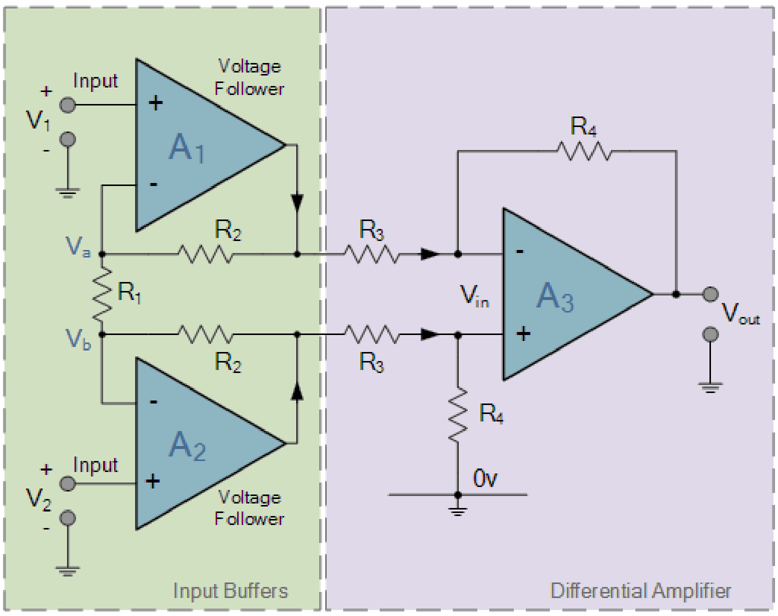
Instrumentation Amplifier

Instrumentation Amplifiers (in-amps) are very high gain differential amplifiers which have a high input impedance and a single ended output. Instrumentation amplifiers are mainly used to amplify very small differential signals from strain gauges, thermocouples or current sensing devices in motor control systems.

Unlike standard operational amplifiers in which their closed-loop gain is determined by an external resistive feedback connected between their output terminal and one input terminal, either positive or negative, "instrumentation amplifiers" have an internal feedback resistor that is effectively isolated from its input terminals as the input signal is applied across two differential inputs, V1 and V2.

The instrumentation amplifier also has a very good common mode rejection ratio, CMRR (zero output when $V_1 = V_2$) well in excess of 100dB at DC. A typical example of a three op-amp instrumentation amplifier with a high input impedance (Zin) is given below:

The two non-inverting amplifiers form a differential input stage acting as buffer amplifiers with a gain of $1 + 2R_2/R_1$ for differential input signals and unity gain for common mode input signals. Since amplifiers A_1 and A_2 are closed loop negative feedback amplifiers, we can expect the voltage at Va to be equal to the input voltage V_1. Likewise, the voltage at Vb to be equal to the value at V_2.



As the op-amps take no current at their input terminals (virtual earth), the same current must flow through the three-resistor network of R_2, R_1 and R_2 connected across the op-amp outputs. This means then that the voltage on the upper end of R_1 will be equal to V_1 and the voltage at the lower end of R_1 to be equal to V_2.

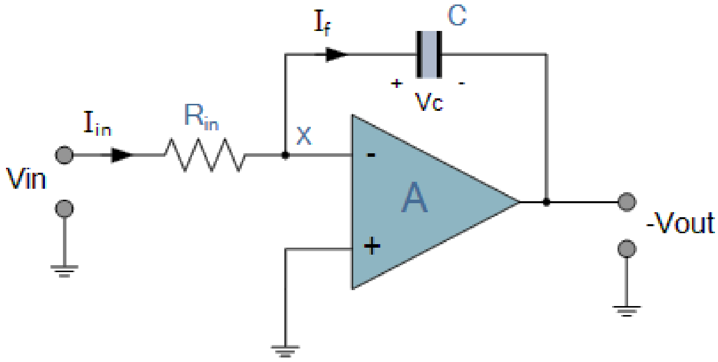
This produces a voltage drop across resistor R_1 which is equal to the voltage difference between inputs V_1 and V_2, the differential input voltage, because the voltage at the summing junction of each amplifier, Va and Vb is equal to the voltage applied to its positive inputs. However, if a common-mode voltage is applied to the amplifier's inputs, the voltages on each side of R_1 will be equal, and no current will flow through this resistor. Since no current flows through R_1 (nor, therefore, through both R_2 resistors), amplifiers A_1 and A_2 will operate as unity-gain followers (buffers). Since the input voltage at the outputs of amplifiers A_1 and A_2 appears differentially across the three-resistor network, the differential gain of the circuit can be varied by just changing the value of R_1.

The voltage output from the differential op-amp A_3 acting as a subtractor, is simply the difference between its two inputs (V2 – V1) and which is amplified by the gain of A_3 which may be one, unity, (assuming that $R_3 = R_4$). Then we have a general expression for overall voltage gain of the instrumentation amplifier circuit as:

$$V_{OUT} = (V_2 - V_1)\left[1 + \frac{2R_2}{R_1}\right]\left(\frac{R_4}{R_3}\right)$$

Integrating Amplifier.

If we changed the purely resistive (R*f*) feedback element of an inverting amplifier with a frequency dependent complex element that has a reactance, (X), such as a Capacitor, C we now have an RC Network connected across the operational amplifiers feedback path producing another type of operational amplifier circuit commonly called an **Op-amp Integrator** circuit as shown.



The **Op-amp Integrator** is an operational amplifier circuit that performs the mathematical operation of **Integration**, where the output to respond to changes in the input voltage over time as the op-amp integrator produces an *output voltage which is proportional to the integral of the input voltage*.

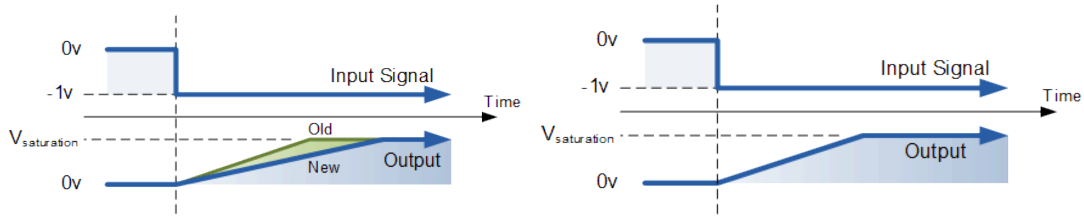
When a step voltage, Vin is firstly applied to the input of an integrating amplifier, the uncharged capacitor C has very little resistance and acts a bit like a short circuit allowing maximum current to flow via the input resistor, Rin as potential difference exists between the two plates. No current flows into the amplifiers input and point X is a virtual earth resulting in zero output. As the impedance of the capacitor at this point is very low, the gain ratio of X_C/R_{IN} is also very small giving an overall voltage gain of less than one, (voltage follower circuit).

As the feedback capacitor, C begins to charge up due to the influence of the input voltage, its impedance Xc slowly increase in proportion to its rate of charge. The capacitor charges up at a rate determined by the RC time constant, (τ) of the series RC network. Negative feedback forces the op-amp to produce an output voltage that maintains a virtual earth at the op-amp's inverting input.

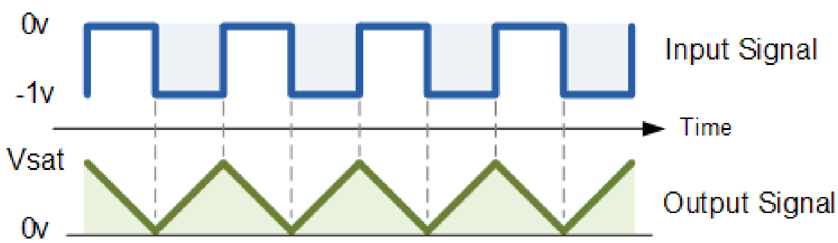
Since the capacitor is connected between the op-amp's inverting input (which is at virtual ground potential) and the op-amp's output (which is now negative), the potential voltage, Vc developed across the capacitor slowly increases causing the charging current to decrease as the impedance of the capacitor increases. This results in the ratio of Xc/Rin increasing producing a linearly increasing ramp output voltage that continues to increase until the capacitor is fully charged.

At this point the capacitor acts as an open circuit, blocking any more flow of DC current. The ratio of feedback capacitor to input resistor (X_C/R_{IN}) is now infinite resulting in infinite gain. The result of this high gain (similar to the op-amps open-loop gain), is that the output of the amplifier goes into saturation as shown below. (Saturation occurs when the output voltage of the amplifier swings heavily to one voltage supply rail or the other with little or no control in between).

The rate at which the output voltage increases (the rate of change) is determined by the value of the resistor and the capacitor, "RC time constant ".



If we apply a constantly changing input signal such as a square wave to the input of an *Integrator Amplifier* then the capacitor will charge and discharge in response to changes in the input signal. This results in the output signal being that of a sawtooth waveform whose output is affected by the RC time constant of the resistor/capacitor combination because at higher frequencies, the capacitor has less time to fully charge. This type of circuit is also known as a ***Ramp Generator*** and the transfer function is given below.



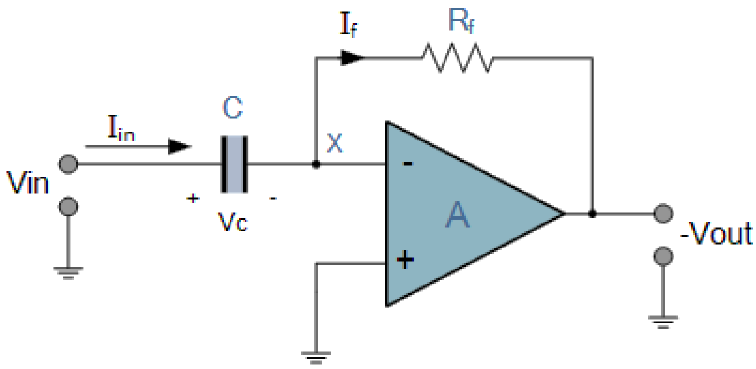
The ideal voltage output for the **Op-amp Integrator** is:

$$V_{out} = -\frac{1}{j\omega RC}V_{in}$$

Where: $\omega = 2\pi f$ and the output voltage Vout is a constant 1/RC times the integral of the input voltage V_{IN} with respect to time. Thus, the circuit has the transfer function of an inverting integrator with the gain constant of -1/RC. The minus sign (-) indicates a 180° phase shift because the input signal is connected directly to the inverting input terminal of the operational amplifier.

Op-amp Differentiator Circuit

The input signal to the differentiator is applied to the capacitor. The capacitor blocks any DC content so there is no current flow to the amplifier summing point, X resulting in zero output voltage. The capacitor only allows AC type input voltage changes to pass through and whose frequency is dependent on the rate of change of the input signal.



At low frequencies the reactance of the capacitor is “High” resulting in a low gain (Rf/Xc) and low output voltage from the op-amp. At higher frequencies the reactance of the capacitor is much lower resulting in a higher gain and higher output voltage from the differentiator amplifier.

However, at high frequencies an op-amp differentiator circuit becomes unstable and will start to oscillate. This is due mainly to the first-order effect, which determines the frequency response of the op-amp circuit causing a secondorder response which, at high frequencies gives an output voltage far higher than what would be expected. To avoid this, the high frequency gain of the circuit needs to be reduced by adding an additional small value capacitor across the feedback resistor R_f.

The ideal voltage output for the op-amp differentiator is given as:

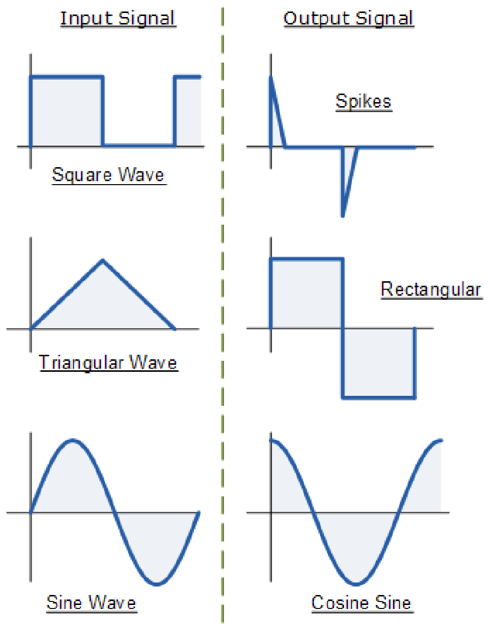
$$V_{OUT} = -R_F C \frac{dV_{IN}}{dt}$$

Therefore, the output voltage Vout is a constant $-R_f * C$ times the derivative of the input voltage Vin with respect to time. The minus sign (-) indicates a 180° phase shift because the input signal is connected to the inverting input terminal of the operational amplifier.

One final point to mention, the **Op-amp Differentiator** circuit in its basic form has two main disadvantages compared to the previous operational amplifier integrator circuit. One is that it suffers from instability at high frequencies, and the other is that the capacitive input makes it very susceptible to random noise signals and any noise or harmonics present in the source circuit will be amplified more than the input signal itself. This is because the output is proportional to the slope of the input voltage so some means of limiting the bandwidth in order to achieve closed-loop stability is required.

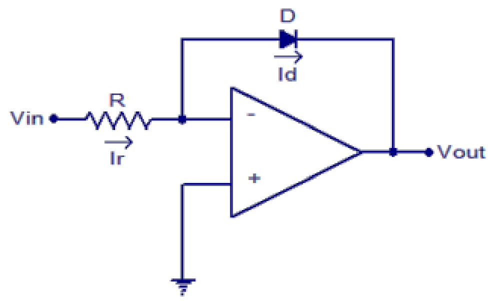
Op-amp Differentiator Waveforms

If we apply a constantly changing signal such as a Square-wave, Triangular or Sine-wave type signal to the input of a differentiator amplifier circuit the resultant output signal will be changed and whose final shape is dependent upon the RC time constant of the Resistor/Capacitor combination.

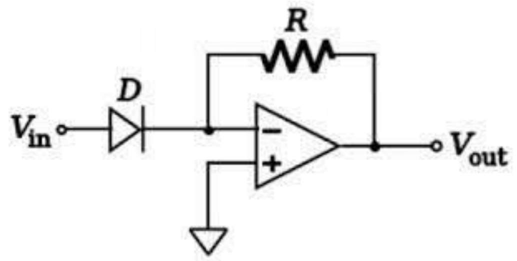


Log and Anti-log amplifiers.

Log amplifier is a linear circuit in which the output voltage will be a constant times the natural logarithm of the input. The basic output equation of a log amplifier is: Vout = Kln(Vin/Vref); where Vref is the constant of normalisation, and K is the scale factor.



Anti-log amplifier is one which provides output proportional to the anti-log, i.e. exponential to the input voltage. If Vin is the input signal applied to an Anti-log amplifier then the output is Vout = Kexp(a*Vin) where K is proportionality constant, a is constant.

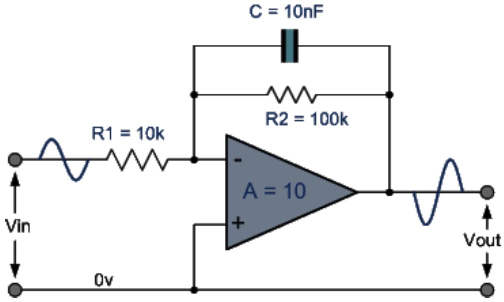


Active Filters

Active Filters contain active components such as operational amplifiers, transistors or FET's within their circuit design. They draw their power from an external power source and use it to boost or amplify the output signal.

Inverting Amplifier Low Pass Filter Circuit

A capacitor has been connected to its feedback circuit in parallel with R2. This parallel combination of C and R2 sets the -3dB point as before, but allows the amplifiers gain to roll-off indefinitely beyond the corner frequency.



$$fc = \frac{1}{2\pi C R_2} \ Hertz$$

At low frequencies the capacitors reactance is much higher than R2, so the dc gain is set by the standard inverting formula of: -R2/R1 = 10, for this example. As the frequency increases the capacitors reactance decreases reducing the impedance of the parallel combination of Xc||R2, until eventually at a high enough frequency, Xc reduces to zero.

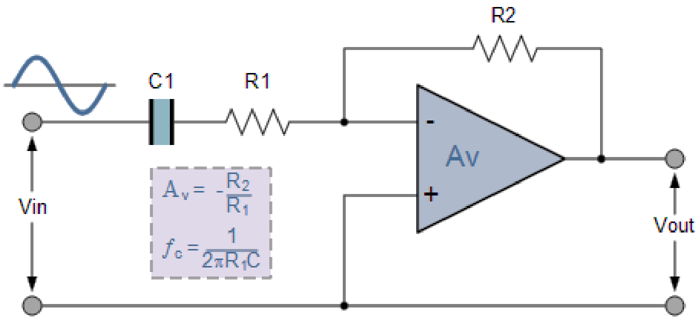
The advantage here is that the circuits input impedance is now just R1 and the output signal is inverted. With the corner frequency determining components in the feedback circuit, the RC set-point is unaffected by variations in source impedance and the dc gain can be adjusted independently of the corner frequency.

Frequency response:

$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{Z_f}{Z_i} = -\frac{\dfrac{R_f / j\omega C_f}{\left[\left(1/j\omega C_f\right) + R_f\right]}}{R_i} = -\frac{R_f}{\left(1 + j\omega R_f C_f\right) R_i} = -\frac{R_f}{R_i}\frac{1}{\left(1 + j\omega\tau\right)}$$

Inverting High Pass Filter Operational Amplifier Circuit

The basic operation of an Active High Pass Filter (HPF) is the same as for its equivalent RC passive high pass filter circuit, except this time the circuit has an operational amplifier or included within its design providing amplification and gain control.

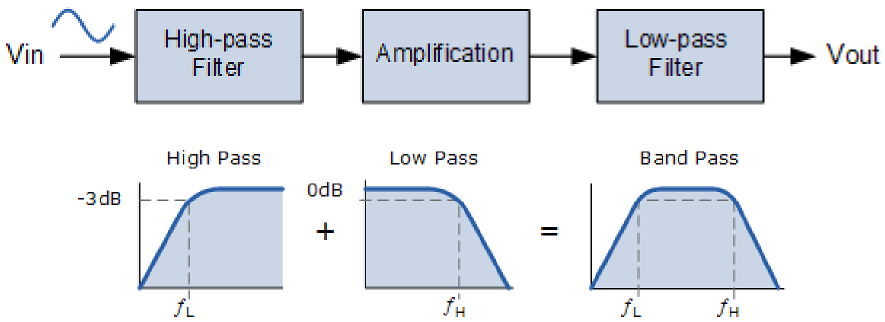


Frequency response:

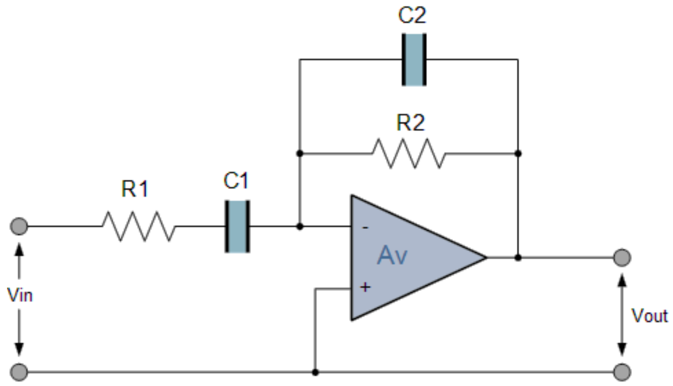
$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{Z_f}{Z_i} = -\frac{R_f}{(1/j\omega C_i) + R_i} = -\frac{j\omega R_f C_i}{1 + j\omega R_i C_i} = -\frac{R_f}{R_i}\frac{j\omega\tau}{1 + j\omega\tau}$$

Active Band Pass Filter

The Active Band Pass Filter is slightly different in that it is a frequency selective filter circuit used in electronic systems to separate a signal at one particular frequency, or a range of signals that lie within a certain “band” of frequencies from signals at all other frequencies. This band or range of frequencies is set between two cut-off or corner frequency points labelled the “lower frequency” (fL) and the “higher frequency” (fH) while attenuating any signals outside of these two points. Simple Active Band Pass Filter can be easily made by cascading together a single Low Pass Filter with a single High Pass Filter as shown.



The cut-off or corner frequency of the low pass filter (LPF) is higher than the cut-off frequency of the high pass filter (HPF) and the difference between the frequencies at the -3dB point will determine the “bandwidth” of the band pass filter while attenuating any signals outside of these points. One way of making a very simple Active Band Pass Filter is to connect the basic passive high and low pass filters we look at previously to an amplifying op-amp circuit as shown:



$$Voltage\ Gain = -\frac{R_2}{R_1}, \quad fc_1 = \frac{1}{2\pi R_1 C_1}, \quad fc_2 = \frac{1}{2\pi R_2 C_2}$$