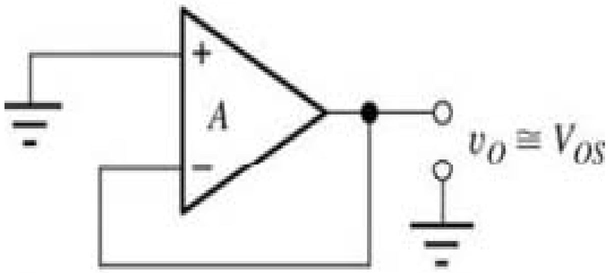
ESc201, Lecture 24: Operational Amplifier (LIMITATIONS) Input Offset Voltage.

(MOS input OpAmps have high R_i but also higher V_{OS} than BJT input)

With inputs being zero, the amplifier output rests at some dc voltage level instead of zero. The equivalent dc input offset voltage is: $V_{OS}=V_o/A$ (1-10 mV).

The amplifier is connected as voltage-follower to give output voltage equal to offset voltage.

To include effect of offset voltage, $v_o = A\left(v_{id} + \frac{v_{ic}}{CMRR} + V_{OS}\right)$



If v_{id} =0,

$$v_o = A\left(\frac{v_{ic}}{CMRR} + V_{OS}\right) = A(v_{OS}) \quad \therefore CMRR = \frac{v_{ic}}{v_{OS}}\ \mu V/V$$

Limitations : Bandwidth (Unity Gain Cut-off) f_T:

OpAmps are compensated for stability to suppress unwanted oscillations, which introduces a pole in the frequency response characteristic, typically ~ 5-10Hz.

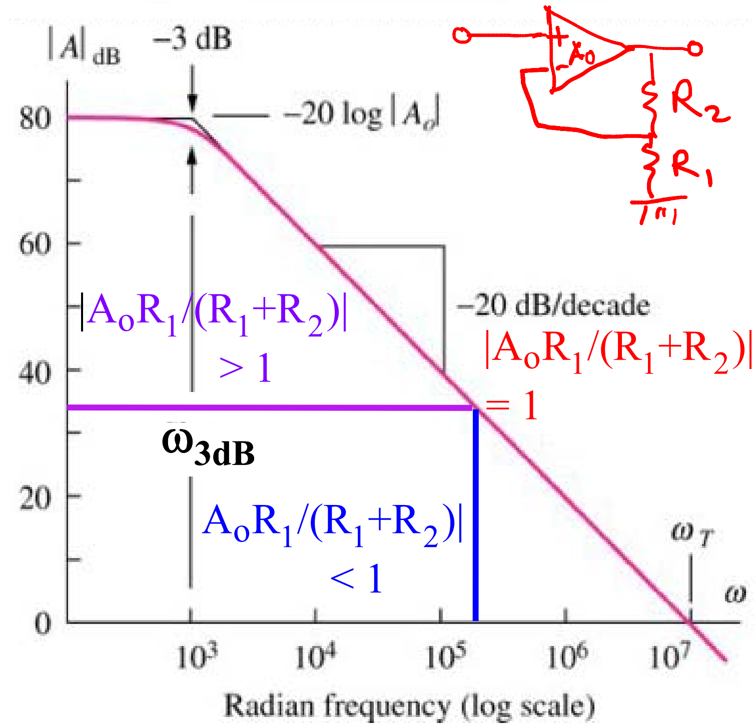
After that, the gain rolls off at -20dB/decade. The frequency at which the magnitude of this gain becomes unity (i.e., 0 dB) is known as the unity gain cut-off frequency (f_T). Where :

$$A_{v\,op.\,loop}\, x f_{op.\,loop} = Af_{op.\,loop} = f_T = A_{v\,feedback}\, x f_{3dB}$$

For a closed-loop feedback amplifier:

$$A_V(s) = \frac{A_o/\{1+A_oR_1/(R_1+R_1)\}}{1+s/\{[1+A_oR_1/(R_1+R_1)]\omega_{3dB}\}} = \frac{A_v(0)}{1+s/\omega_H}$$

$$\omega_H = [1+A_oR_1/(R_1+R_1)]\omega_{3dB} = \frac{\omega_T}{A_v(0)}$$



ESc201, Lecture 25: Operational Amplifier (NON_IDEAL)

Practical OpAmps have limited output voltage and current ranges.

1. **Voltage: Limited to several volts less than power supply span.**
2. **Current: Limited by additional circuits (to limit power dissipation or protect against accidental short circuits).**
3. **Current limit specified as minimum load resistance that the amplifier can drive with a given voltage swing. Eg: $i_o = V_{max}/R_L$.**

Large Signal Limitations: Slew Rate and Full-Power Bandwidth

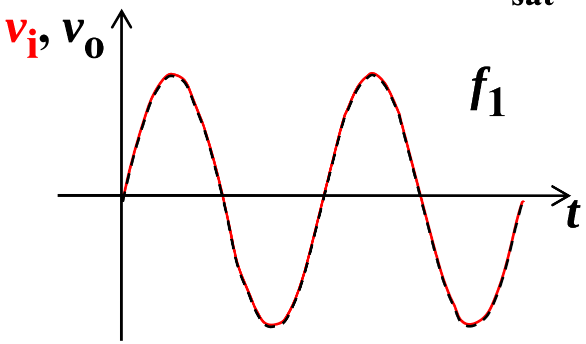
$$v_o = V_M \sin\omega t \quad \text{or} \quad \left.\frac{dv_o}{dt}\right|_{max} = V_M \cos\omega t\Big|_{max} = V_M \cos\omega\Delta t\Big|_{\Delta t \to 0} = V_M\omega$$

For no signal distortion, $V_M\omega \le SR \quad \therefore V_M \le \frac{SR}{\omega}$

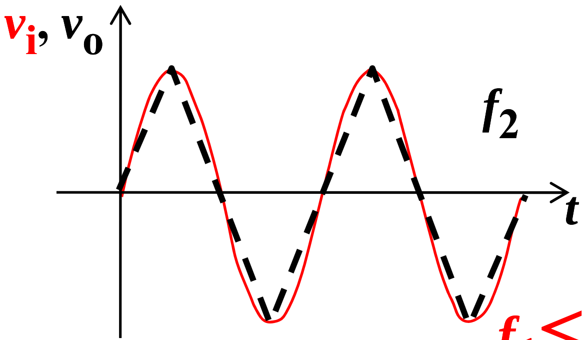
Full-power bandwidth is highest frequency at which a full-scale signal can be developed. $f_M \le \frac{SR}{2\pi V_{FS}}$

Effect of SR Limitation

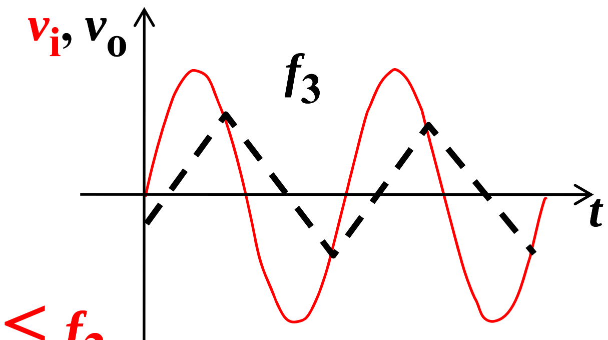
No SR Limitation within V_{sat}



Moderate SR Limitation within V_{sat}

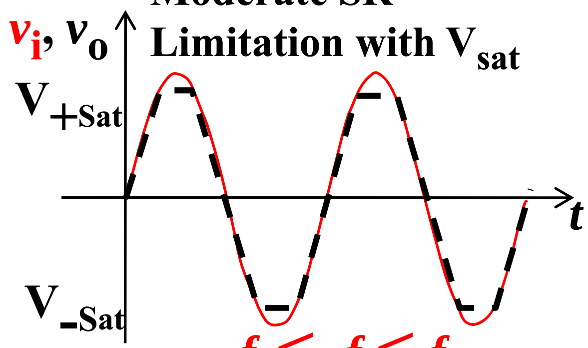


Severe SR Limitation within V_{sat}



$f_1 < f_2 < f_3$

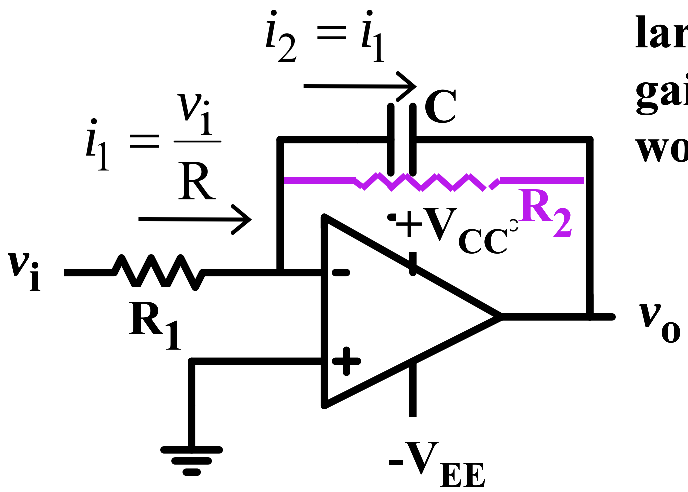
Moderate SR Limitation with V_{sat}



$f_1 < f < f_2$

OpAmp Filters: Passive Filters (High Pass, Low Pass, and Band Pass that you have studied) does not have any gain and hence the signal can be degraded after a few operations. Filters using OpAmps (Known as Active Filters) help in providing gain also.

Low Pass Filter



v_- is at virtual ground. At low frequency $X_C \to \infty$. Hence gain is very large, $v_o \to$ large. But at high frequency $X_C \to 0$. Hence gain is low, $v_o \to 0$. That's a Low Pass characteristic. Cutoff would be given by R_1C.

But in the pass band $v_o \to$ large, can be accepted for the Pass Band as the out would be saturated, but this filter would not work as even outside the pass band the output is large enough to saturate the output.

Remedy : Add a Resistor R_2 in parallel to the capacitor. Where $K = -R_2/R_1$ and $\omega_c = 1/(R_2C)$.

$$\frac{v_O}{v_i} = -\frac{Z}{R_1} = \frac{R_2 \parallel \frac{1}{j\omega C}}{R_1} = \frac{R_2 / R_1}{1 + j\omega C R_2} = \frac{K}{1 + j\frac{\omega}{\omega_C}}$$

Other complicated versions also exist where instead of adding R_2 in parallel to C, a R_2-C_2 combination is used at the v_- node.

Also works as an Integrator

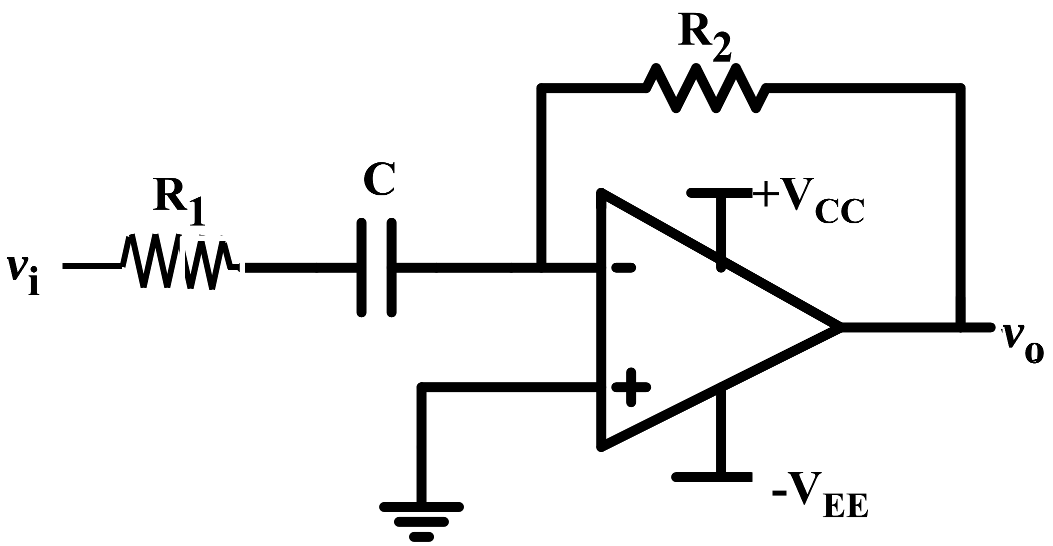
$$\frac{v_i}{R_1} = -C\frac{dv_O}{dt} \quad \text{or} \quad v_O(t) = -\frac{1}{R_1C}\int v_i dt + V_o$$

$\tau = R_1C$ = integration time constant .

Practical integrators would have R_2 to avoid saturation, but design becomes tricky as R_2C should in no way affect τ . Also, the capacitor needs to be discharged periodically to prevent any undesirable accumulation of charges in it. That's why not much used.

High Pass Filter

$$i_1 = \frac{v_i}{R_1 + \frac{1}{j\omega C}} = i_2 = -\frac{v_o}{R_2}$$



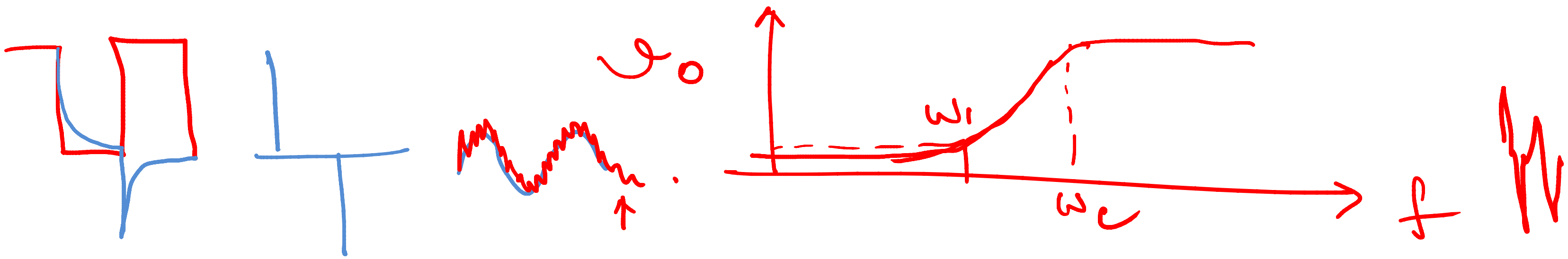
$$\text{or } \frac{v_o}{v_i} = -\frac{j\omega R_2 C}{1 + j\omega R_1 C} = \frac{j\frac{\omega}{\omega_1}}{1 + j\frac{\omega}{\omega_c}}$$

$\omega_1=1/(R_2C)$ is the lower zero crossing frequency, & $\omega_c=1/(R_1C)$ is the lower cutoff frequency. Hence $\omega_1 \ll \omega_c$ is required. Here |Pass Band Gain| = $\omega_c/\omega_1 = R_2/R_1$.

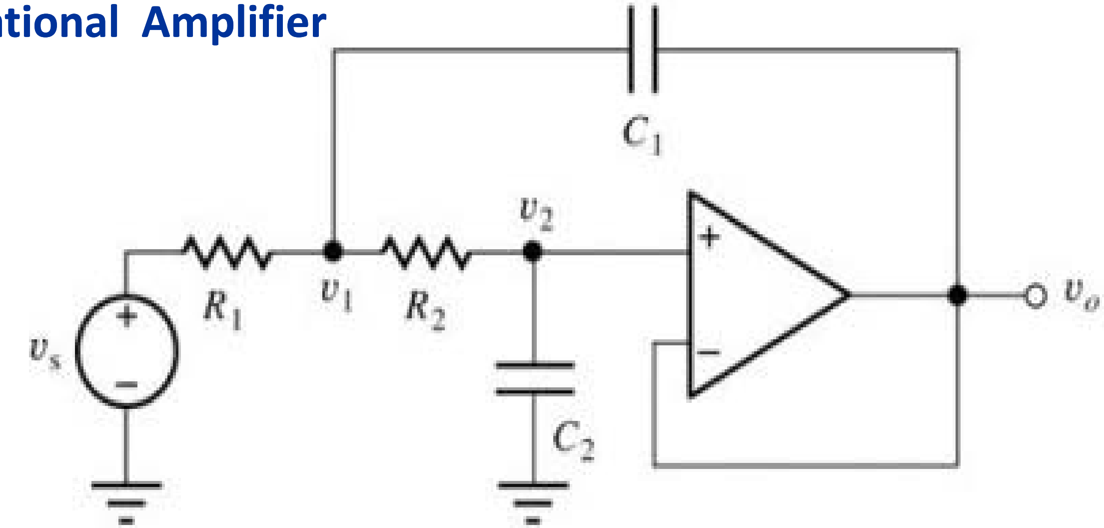
Also works as a Differentiator by removing R_1.

$$i_1 = C\frac{dv_i}{dt} = i_2 = -\frac{v_o}{R_2} \text{ or } v_o = -R_2 C\frac{dv_i}{dt} = -\tau\frac{dv_i}{dt}$$

The circuit tends to amplify the noise present at the input (the derivative of a noise spike can be dangerously large !) Therefore Occasionally used for waveshaping only.



Low Pass filter Example



- **Design second-order low-pass filter with maximally flat response.**
- **Given data: $f_H = 5$ kHZ**
- **Analysis: $C_1 = 2C_2 = 2C$ and $R_1 = R_2 = R$.**

$$R=\frac{1}{\sqrt{2}\omega_o C} \qquad Q=\frac{1}{\sqrt{2}}$$

$$A_{LP}(s)=\frac{s^2}{s^2+s\frac{\omega_o}{Q}+\omega_o^2} \qquad \omega_o=\frac{1}{\sqrt{R_1R_2C_1C_2}}$$

$$A_{LP}(s)=\frac{V_o(s)}{V_s(s)}=\frac{\frac{G_1G_2}{C_1C_2}}{s^2+s\frac{G_1+G_2}{C_1}+\frac{G_1G_2}{C_1C_2}} \qquad Q=\sqrt{\frac{C_1}{C_2}}\frac{\sqrt{R_1R_2}}{R_1+R_2}$$

Often, circuits are designed with $C_1 = C_2 = C$.

$1/(\omega_o C)$ is the reactance of C at ω_o, R is 30% smaller than this value. Thus impedance level of filter is set by C. If impedance level is too low, op amp will not be able to supply current required to drive feedback network.

At 5 kHz, for a 0.01 μF capacitor, $\frac{1}{\omega_o C}=\frac{1}{10^4\pi(10^{-8})}=3180\Omega, \quad R=\frac{3180\Omega}{\sqrt{2}}=2250\Omega$

Final values: = $R_1 = R_2 = 2.25$kW, $C_1 = 0.02$ μF, $C_2 = 0.01$ μF