Chapter 1

Operational Amplifiers

1.1 Operational Amplifier Dynamic Characteristics

The gain of an op amp is not the same at all frequencies. The **open loop gain**, which is the gain without feedback, is constant at low frequencies, but then starts to decrease at higher frequencies. This **rolloff** can be seen in Figure 1.1.

The **Bode plot** is logarithmic in both frequency and gain, and so the straight line indicates that gain is inversely proportional to frequency

$$A \propto \frac{1}{f}$$

Gain is often expressed in **decibels**, rather than simply as a ratio of output to input so that

$$G_{db} = 20 \log \left(\frac{V_o}{V_i} \right)$$

and so a change by a factor of 10 in $\left(\frac{V_o}{V_i} \right)$ is a change of 20 db. A **decade** is a factor of 10, so rolloff of 20 db/decade represents a *decrease* in $\left(\frac{V_o}{V_i} \right)$ of a factor of 10 as the frequency *increases* by a factor of 10.

This inverse relationship between frequency and gain is expressed in various ways; the **gain-bandwidth product** (GBW) is

$$GBW = Af$$

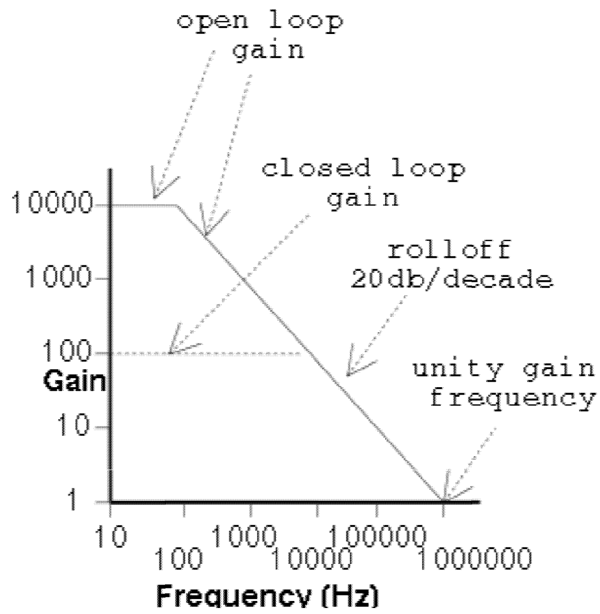

Figure 1.1: Op Amp Dynamic Characteristics

and the **unity-gain frequency** is the frequency at which $\left(\frac{V_o}{V_i}\right)$ is 1.

(I will use the term A to refer to $\left(\frac{V_o}{V_i}\right)$ and G to denote the gain in decibels, as described above. This convention is common, but not universal, so when consulting information on the subject be sure to pay attention to how gain is expressed.)

When negative feedback is employed in an op amp circuit, the **closed-loop gain** is decreased. As frequency increases, and the open-loop gain decreases due to rolloff, the values of open-loop and closed-loop gain eventually coincide. From this point on, the closed loop gain also begins to experience rolloff at the same rate. *Thus the unity-gain frequency for an op amp circuit is the same, regardless of the mid-band gain.*

1.2 Active Filters

One of the uses of op amps is to produce circuits which are used to amplify or attenuate a certain range of frequencies. These are called **active filters**.

1.2.1 Low Pass Filters

A **low pass filter** allows frequencies below a certain **corner frequency** f_c to pass, and attenuates those above. Note that the corner frequency is not an absolute limit; it is the point at which attenuation begins.[1] A low pass filter is shown in Figure 1.2 and its Bode plot is shown in Figure 1.3. (Note: there are numerous designs for filters; the ones shown here are simple to analyze.)

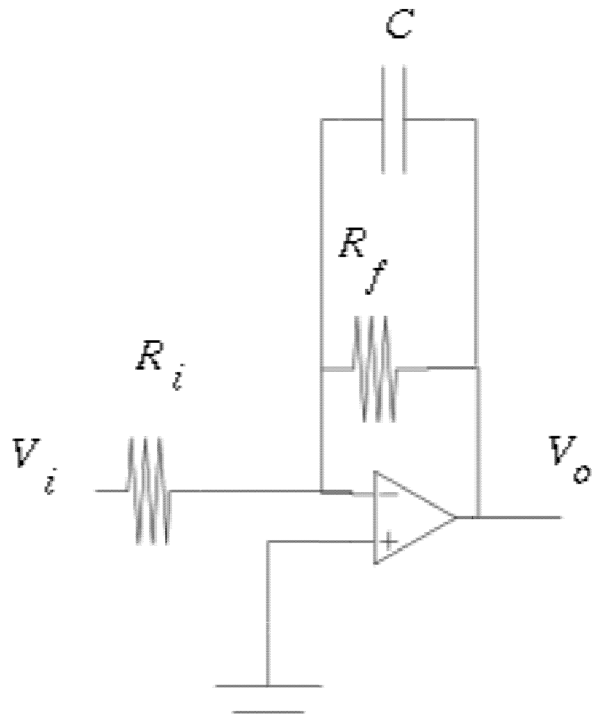

Figure 1.2: Simple Low Pass Filter

1.2.2 High Pass Filters

A **high pass filter** allows frequencies *above* a certain corner frequency, f_c to pass, and attenuates those *below*. As for the low pass filter, the corner frequency is not an absolute limit; it is the point at which amplification

[1] Actually it's the "3 db point" at which the gain differs from the mid-band gain by 3db. Expressing gain without using decibels, it's the point at which the gain is the mid-band gain divided by $\sqrt{2}$.

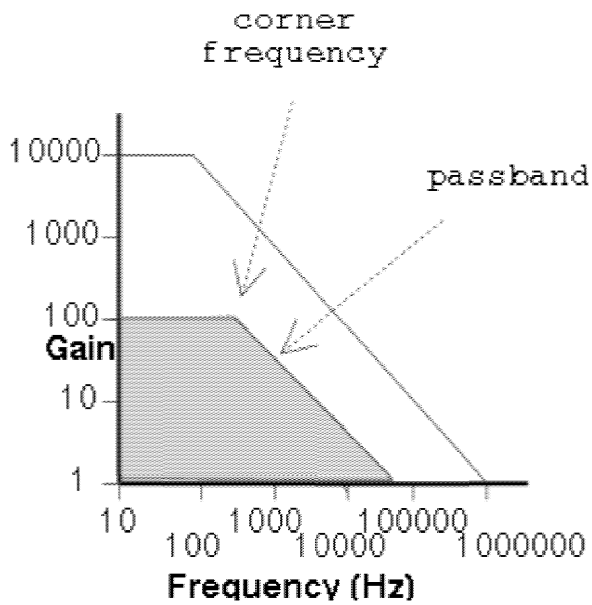

Figure 1.3: Bode Plot for Simple Low Pass Filter

begins. The high pass filter has a limitation due to the rolloff of the op amp. As with any amplifier circuit, it is never possible to have gain above the open loop gain of the op amp, so any high pass filter is actually a **band pass filter**, which will be discussed below. A high pass filter is shown in Figure 1.4 and its Bode plot is shown in Figure 1.5.

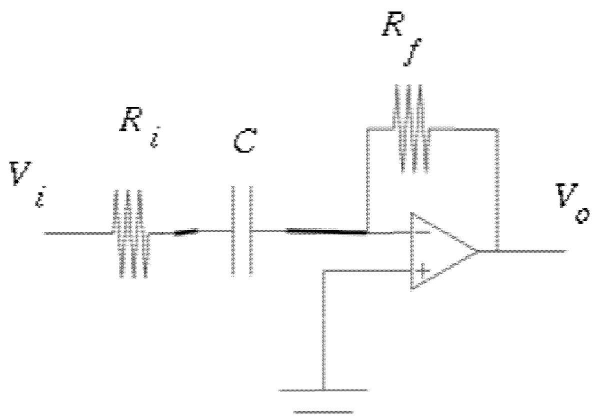

Figure 1.4: Simple High Pass Filter

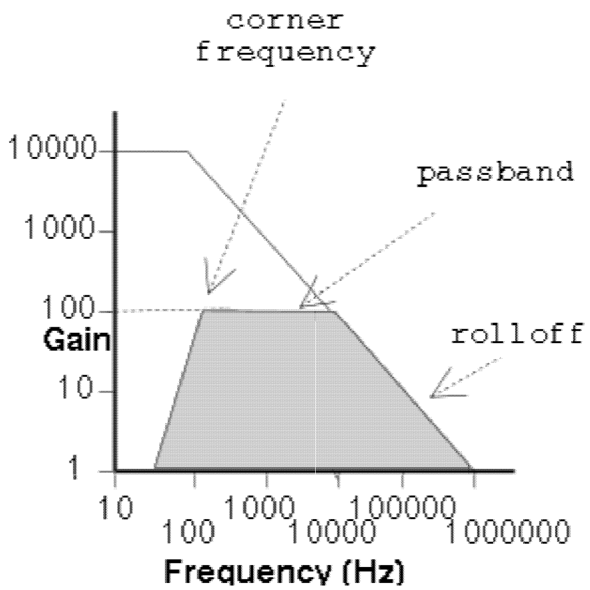

Figure 1.5: Bode Plot for Simple High Pass Filter

1.2.3 Band Pass Filters

A **band pass filter** combines a low pass and a high pass filter to allows frequencies *between* two corner frequencies, f_{c1} and f_{c2} to pass, and attenuates those *outside* that range. Figure 1.6 shows the Bode plot for a band pass filter.

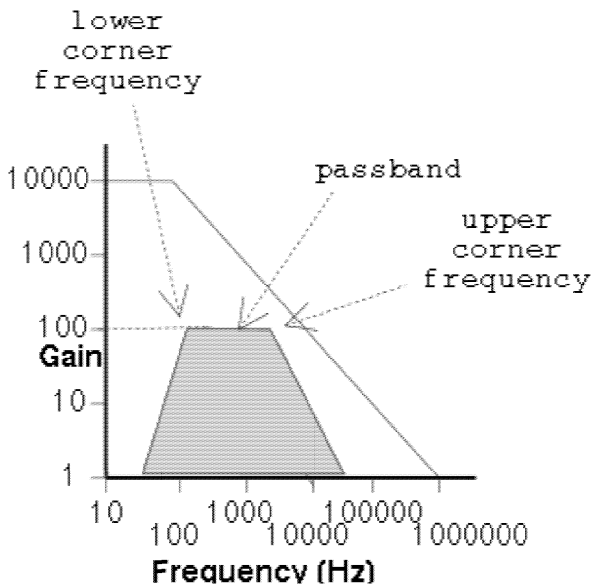

Figure 1.6: Bode Plot for Band Pass Filter