23 A Short Introduction to the Bandwidth of Op-Amp Amplifiers

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Prerequisite knowledge required: Op-amp circuits, Decibels, Bandwidths and Bode Plots

23.1 Introduction

Whenever an amplifier is designed, it's important to know the range of frequencies that are required to be amplified (for example, the frequencies from 20 Hz to 20 kHz might be required for an audio amplifier). While "ideal" op-amps have in theory an infinite bandwidth, real op-amps have a gain that decreases with increasing frequency, and at one frequency (known as the *unity-gain frequency*) the op-amp doesn't have any gain at all: the output has the same amplitude as the difference in voltage between the two inputs[1]. The practical result is that any amplifier built using op-amps has a gain which tends to decrease with frequency.

Knowing how to predict the bandwidth of an op-amp amplifier is essential for anyone designing an amplifier. This chapter is about why the gain of op-amps decreases at higher frequency and how to estimate the bandwidth of both inverting and non-inverting op-amp amplifier circuits.

23.2 What is the bandwidth of an amplifier?

First, I need to define some terms. The *bandwidth* of an amplifier is the range of frequencies over which the gain of the amplifier is within a certain proportion of its maximum value.

Conventionally, the "certain proportion" will be a factor of two in terms of the power gain (in other words 3 dB, or a factor of the square-root of two in terms of the voltage gain) unless noted otherwise[2].

23.3 What happens to the gain of an op-amp as the frequency increases?

Good question. The design of most op-amps follows a single-pole response curve up to just about any frequency of interest[3]. That means that the open-loop gain[4] (in terms of the ratio of the phasor representations of the output and input) can be given to a good approximation by:

$$A(\omega) = \frac{A_{DC}}{1 + j\dfrac{\omega}{\omega_d}} \qquad (23.1)$$

[1] Notice I don't say "the output is equal to the difference in voltage between the two inputs". It isn't: there is a phase difference (usually around 90 degrees) between the input and the output at high frequencies.

[2] This is more formally known as the "3-dB bandwidth" of the amplifier. Unless otherwise stated, that's what I'll mean when I write "bandwidth".

[3] This is a technique known as *dominant-pole compensation*. It's designed to help stop amplifiers oscillating. It's beyond the syllabus for this module, but you'll probably come across it again later in the degree programme.

[4] Reminder: the open-loop gain is the gain of the op-amp itself: the op-amp's output divided by the difference between the non-inverting and the inverting op-amp inputs. This is usually much greater than the closed-loop gain (the output of the whole amplifier circuit divided by the input to the whole amplifier circuit).

where A_{DC} is the gain at DC, and ω_d is the break frequency of a pole known as the *dominant pole*[5]. We could equally-well write this in terms of frequency in Hertz:

$$A(f) = \frac{A_{DC}}{1 + j\frac{f}{f_d}} \tag{23.2}$$

where f_d is the dominant pole's break frequency in Hz.

To determine the gain of any op-amp amplifier circuit as a function of frequency, all you have to do is use equation (23.2) rather than just a constant gain A in the derivation of the gain of the amplifiers. For example:

23.4 Calculating the bandwidth of a non-inverting amplifier

Consider the basic non-inverting amplifier shown in the figure below. To determine the gain of this amplifier as a function of frequency, we can follow the same approach as when we calculated the gain of an ideal non-inverting amplifier, but this time use the frequency-dependent form of the open-loop gain.

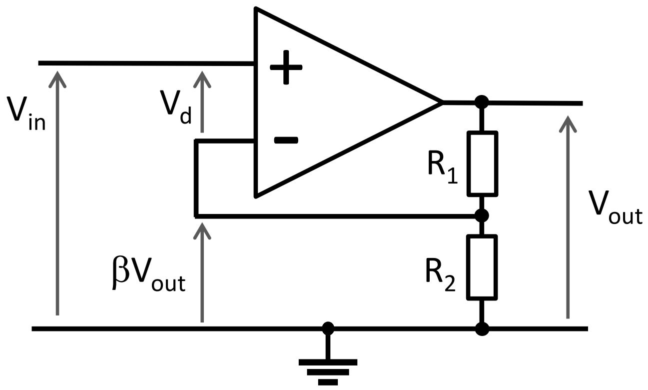

Figure 23.1 A basic non-inverting amplifier

Following this approach, just like when we derived the gain of this circuit before, we can note that the phasor representing the output voltage is the difference between the phasor representations of the input voltages multiplied by the open-loop gain, which in this case gives:

$$\mathbf{V_{out}} = A(f)(\mathbf{V_d}) = \frac{A_{DC}}{1 + j\frac{f}{f_d}}(\mathbf{V_{in}} - \mathbf{V_-}) \tag{23.3}$$

and that the phasor representing the input voltage **V_** is given by the standard potential divider equation:

$$\mathbf{V_-} = \mathbf{V_{out}}\frac{R_2}{R_1 + R_2} \tag{23.4}$$

[5] There are other poles in the frequency response, but they are at such high frequencies that they have a negligible effect at most frequencies of interest, as the gain has dropped so much by then due to the effects of this much lower-frequency pole. That's why this pole is called the *dominant pole*.

Substituting and re-arranging gives:

$$\mathbf{V}_{\mathbf{out}}\left(1+\frac{A_{DC}}{1+j\dfrac{f}{f_d}}\frac{R_2}{R_1+R_2}\right)=\mathbf{V}_{\mathbf{in}}\frac{A_{DC}}{1+j\dfrac{f}{f_d}} \tag{23.5}$$

A bit more algebra reveals that the gain is:

$$G_V\left(f\right)=\frac{\mathbf{V}_{\mathbf{out}}}{\mathbf{V}_{\mathbf{in}}}=\frac{\dfrac{A_{DC}}{1+A_{DC}\left(\dfrac{R_2}{R_1+R_2}\right)}}{1+j\dfrac{f}{f_d\left(1+A_{DC}\left(\dfrac{R_2}{R_1+R_2}\right)\right)}} \tag{23.6}$$

At this point it's helpful to note that the open-loop gain at DC is a very large number, and therefore in almost all practical cases:

$$A_{DC}\left(\frac{R_2}{R_1+R_2}\right)\gg 1 \tag{23.7}$$

so we can approximate:

$$G_V\left(f\right)=\frac{\dfrac{R_1+R_2}{R_2}}{1+j\dfrac{f\left(\dfrac{R_1+R_2}{R_2}\right)}{f_d A_{DC}}} \tag{23.8}$$

Now when $f = 0$, this gives for the gain at DC (G_{DC}):

$$G_{DC}=\frac{R_1+R_2}{R_2} \tag{23.9}$$

which is the formula we've derived before for a non-inverting amplifier, and substituting G_{DC} into equation (23.8), we can write the final result as:

$$G_V\left(f\right)=\frac{G_{DC}}{1+j\dfrac{f\,G_{DC}}{f_d\,A_{DC}}} \tag{23.10}$$

I've written the result in this way so that it's in the general form of a first-order response:

$$G_V\left(f\right)=\frac{G_{DC}}{\left(1+j\dfrac{f}{-p}\right)} \tag{23.11}$$

where G_{DC} is the low-frequency gain and p is the pole in the frequency response, so it's more obvious that the break frequency for this amplifier is:

$$|p| = \left| -\frac{f_d A_{DC}}{G_{DC}} \right| = \frac{f_d A_{DC}}{G_{DC}} \tag{23.12}$$

which suggests that:

$$f_p G_{DC} = f_d A_{DC} \tag{23.13}$$

or in words: the product of the 3-dB bandwidth of the amplifier and the gain at DC is equal to the product of the open-loop gain of the op-amp at DC and the break frequency of the op-amp's dominant pole.

This is quite interesting, and turns out to be very useful…

23.5 The gain-bandwidth product

The dominant pole's break frequency f_d and the open-loop gain A_{DC} are functions of the particular op-amp that is being used. Different op-amps have different values for these parameters (for example a typical TL071 has a dominant pole break frequency of 15 Hz and an open-loop gain of 200,000), but the point is that they are characteristics of the op-amp itself, rather than the circuit the op-amp is used in.

For any given op-amp then, the product f_d x A_{DC} is a constant, known as the *gain-bandwidth product* of the op-amp. Why the *gain-bandwidth product*? Because it's equal to f_p x G_{DC}, and that's the product of the gain at DC and the 3-dB bandwidth of any non-inverting amplifier built with this op-amp.

This allows the 3-dB bandwidth of non-inverting amplifiers to be accurately estimated from just knowing the gain-bandwidth product (GPB) and the DC gain of the amplifier:

$$\text{3-dB bandwidth} = \frac{\text{GBP}}{G_{DC}} \tag{23.14}$$

At the risk of over-emphasising the point: the product of the 3-dB bandwidth and the DC voltage gain of any non-inverting amplifier built using any particular op-amp is always the same (at least to a good approximation).

23.5.1 The unity-gain bandwidth

Sometimes in op-amp data sheets you don't find the gain-bandwidth product specified; you find the unity-gain bandwidth specified instead. For all practical purposes they are equal.

One way to see this is to consider that the unity-gain bandwidth is the frequency at which the open-loop voltage gain has a magnitude of unity (one), and therefore for the op-amp:

$$\left| A\left(f_{ug}\right) \right| = \frac{A_{DC}}{\left| 1 + j\dfrac{f_{ug}}{f_d} \right|} = 1 \tag{23.15}$$

$$\left|1+j\frac{f_{ug}}{f_d}\right|=A_{DC} \tag{23.16}$$

Multiplying both sides by their complex conjugate reveals:

$$1+\frac{f_{ug}^{\ 2}}{f_d^{\ 2}}=A_{DC}^{\ 2} \tag{23.17}$$

$$f_{ug}^{\ 2}=f_d^{\ 2}\left(A_{DC}^{\ 2}-1\right) \tag{23.18}$$

Once again we use the approximation that the open-loop gain of the op-amp is much greater than one, so we can approximate $A_{DC}^{\ 2}-1\approx A_{DC}^{\ 2}$, and therefore:

$$f_{ug}=f_d A_{DC} \tag{23.19}$$

which is just the gain-bandwidth product again.

23.5.2 A quick aside: what about the phase?

I've been careful so far to express the open-loop gain of the op-amp in terms of the magnitude of the output voltage and the magnitude of the difference between the voltages on the inputs, rather than their actual values. The reason I've done this is that the output voltage of an op-amp is in general not in phase with the voltage difference between inputs.

Consider the open-loop gain of an op-amp, expressed in terms of the dominant pole's break frequency f_d and the DC open-loop gain A_{DC}:

$$A(f)=\frac{A_{DC}}{1+j\dfrac{f}{f_d}} \tag{23.20}$$

At very low frequencies (a long way below f_d), we can assume that f/f_d is much less than 1, and therefore we can approximate:

$$A(f)\approx A_{DC} \tag{23.21}$$

So the gain is purely real, which implies that the output will be in phase with the input. However at frequencies much higher than the dominant pole's break frequency, we can assume that f/f_d is much greater than 1, and therefore:

$$A(f)=\frac{A_{DC}}{j\dfrac{f}{f_d}}=-j\frac{A_{DC}\,f_d}{f} \tag{23.22}$$

and this indicates that the output will be lagging the input by 90 degrees[6].

[6] A gain of –j indicates can be written as exp(-jπ/2), which is a phase angle of -90 degrees.

Now as noted above, for most op-amps the dominant pole's break frequency f_d is at a very low frequency (15 Hz in the case of the TL071), so that for many applications (e.g. audio) the op-amp is working entirely at frequencies a long way above the dominant pole's break frequency, and the phase difference between the input and the output will be around 90 degrees.

However, it's important to note that this is the phase difference between the output of the op-amp and the difference in voltages between the non-inverting and inverting inputs to the op-amp. The phase difference between the output and input of an op-amp amplifier circuit (e.g. a non-inverting amplifier) will usually be much less than this.

23.6 Calculating the bandwidth of an inverting amplifier

What about inverting amplifiers (as shown below)? Is the 3-dB bandwidth of an inverting amplifier given by the same simple formula?

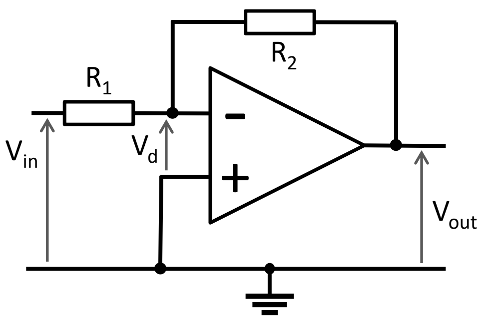

Figure 23.2 A basic inverting amplifier

Sadly, not quite. We can derive the answer in the same way as before: just consider that the open loop gain of the op-amp is:

$$A(f) = \frac{A_{DC}}{1 + j\dfrac{f}{f_d}} \tag{23.23}$$

and include this in the derivation of the gain of this circuit. If this op-amp is ideal except for the limited bandwidth then there is no current flowing into the op-amp's input terminals, and therefore:

$$\frac{\mathbf{V_{in}} - \mathbf{V_d}}{R_1} = \frac{\mathbf{V_d} - \mathbf{V_{out}}}{R_2} \tag{23.24}$$

and for the op-amp:

$$\mathbf{V_{out}} = A(f)(\mathbf{V_+} - \mathbf{V_-}) = -A(f)\mathbf{V_d} \tag{23.25}$$

eliminate $\mathbf{V_d}$ between these two equations, and re-arrange, and we get:

$$\frac{\mathbf{V_{in}}}{R_1} = -\mathbf{V_{out}}\left(\frac{1}{R_2 A(f)} + \frac{1}{R_2} + \frac{1}{R_1 A(f)}\right) \tag{23.26}$$

and expressing this in terms of the gain reveals:

$$G_V(f) = \frac{\mathbf{V_{out}}}{\mathbf{V_{in}}} = \frac{-R_2}{R_1 + \frac{R_1 + R_2}{A(f)}} = \frac{-R_2}{R_1 + \left(1 + j\frac{f}{f_d}\right)\frac{R_1 + R_2}{A_{DC}}} \tag{23.27}$$

Finally, manipulating this into the standard form for a first-order response gives:

$$G_V(f) = \frac{-R_2 / \left(R_1 + \frac{R_1 + R_2}{A_{DC}}\right)}{1 + j\frac{f}{f_d}\frac{R_1 + R_2}{A_{DC}R_1 + R_1 + R_2}} \tag{23.28}$$

and making the usual (and usually very safe) assumption that the low-frequency open-loop gain A_{DC} is much, much greater than one, we can approximate this as:

$$G_V(f) = \frac{-R_2 / R_1}{1 + j\frac{f}{f_d}\frac{(R_1 + R_2)}{A_{DC}R_1}} \tag{23.29}$$

As before, consider the gain at DC where $f = 0$:

$$G_{DC} = -\frac{R_2}{R_1} \tag{23.30}$$

which is as expected, and substituting this back into equation (23.29) gives:

$$G_V(f) = \frac{G_{DC}}{1 + j\frac{f}{f_d A_{DC}}\left(1 + |G_{DC}|\right)} \tag{23.31}$$

Comparing this to the standard form of a first-order response we can deduce that the pole is now at:

$$p = -f_d \frac{A_{DC}}{1 + |G_{DC}|} \tag{23.32}$$

and therefore the break frequency (which is approximately equal to the 3-dB bandwidth) is:

$$f_p = f_d \frac{A_{DC}}{\left(1 + |G_{DC}|\right)} \tag{23.33}$$

In terms of the op-amp's gain-bandwidth product, this gives:

$$f_p = \frac{f_d A_{DC}}{\left(1 + |G_{DC}|\right)} = \frac{GBP}{\left(1 + |G_{DC}|\right)} \tag{23.34}$$

where *GBP* is the gain-bandwidth product of the op-amp.

Note that unlike the non-inverting amplifier, in this case the 3-dB bandwidth times the low-frequency gain G_{DC} is not equal to the gain-bandwidth product of the op-amp. However, we can write that:

$$f_p\left(1+\left|G_{DC}\right|\right)=f_d A_{DC}=GBP \tag{23.35}$$

For inverting amplifiers it's the 3-dB bandwidth of the amplifier multiplied by one plus the modulus of the low-frequency gain which gives the op-amp's gain-bandwidth product.

23.7 A couple of examples

Consider an op-amp with a gain-bandwidth product of 1 MHz. What would the 3-dB bandwidth be of a non-inverting amplifier with a gain of 10? And of an inverting amplifier with a gain of -4?

For the non-inverting amplifier with a gain of 10, the bandwidth would be:

$$f_p=\frac{f_d A_{DC}}{G_{DC}}=\frac{GBP}{G_{DC}}=\frac{1\text{ MHz}}{10}=100\text{ kHz} \tag{23.36}$$

and for the inverting amplifier with a gain of -4, the bandwidth would be:

$$f_p=\frac{f_d A_{DC}}{1+\left|G_{DC}\right|}=\frac{GBP}{1+\left|-4\right|}=\frac{1\text{ MHz}}{5}=200\text{ kHz} \tag{23.37}$$

23.8 The bandwidth of summing amplifiers

What about summing amplifiers? Consider the general summing amplifier as shown below:

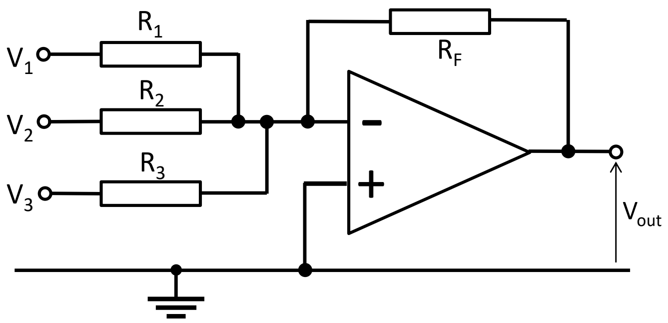

Figure 23.3 Summing amplifier with three inputs

Perhaps surprisingly, it turns out that the bandwidth of the amplifier is the same for all of the inputs, even if the different inputs have different gains.

The analysis in this case is similar to the inverting amplifier. First consider just one input, and connect the other two inputs to ground. This results in the equivalent circuit shown below:

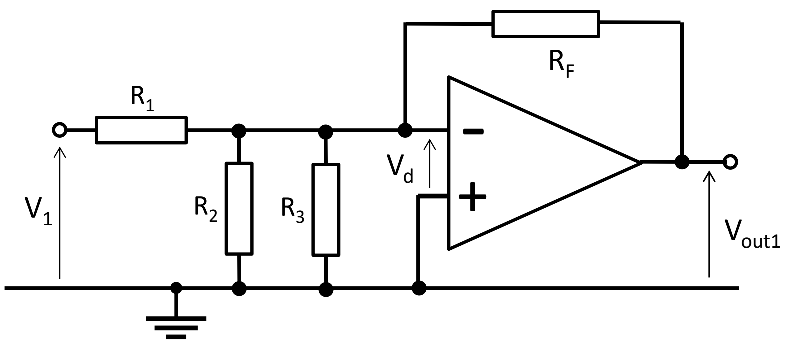

Figure 23.4 Summing amplifier equivalent circuit considering only one input

This modifies the derivation of the gain of the inverting amplifier above, as now not all the current flowing in from the input through R_1 has to go through R_F: some of it can go to ground via R_2 and R_3. So we have to write:

$$\frac{\mathbf{V_{in}} - \mathbf{V_d}}{R_1} = \frac{\mathbf{V_d}}{R_2} + \frac{\mathbf{V_d}}{R_3} + \frac{\mathbf{V_d} - \mathbf{V_{out}}}{R_F} \tag{23.38}$$

and following through in exactly the same way as before eventually leads to:

$$G_V(f) = \frac{-R_F / R_1}{1 + j\dfrac{f}{f_d}\dfrac{R_F}{A_{DC}}\left(\dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} + \dfrac{1}{R_F}\right)} \tag{23.39}$$

from which we can see that the gain at low frequencies (where $f << f_d$) is as expected:

$$G_V(f) = -\frac{R_F}{R_1} \tag{23.40}$$

but the break frequency is:

$$f_p = f_d \frac{A_{DC}}{R_F}\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_F}\right)^{-1} \tag{23.41}$$

which is interesting, since this is a function of all of the input resistors R_1, R_2 and R_3 in parallel, and this will be the same for all of the inputs. Since the gain from each input is $-R_F/R_1$, $-R_F/R_2$ and $-R_F/R_3$ respectively, we can write this as:

$$f_p = f_d A_{DC}\left(\frac{R_F}{R_1} + \frac{R_F}{R_2} + \frac{R_F}{R_3} + 1\right)^{-1} = \frac{f_d A_{DC}}{1 + |G_1| + |G_2| + |G_3|} = \frac{f_d A_{DC}}{1 + \sum |G_i|} = \frac{GBP}{1 + \sum |G_i|} \tag{23.42}$$

In words: the 3-dB bandwidth of the gain from every input into a summing amplifier is given by the gain-bandwidth product of the op-amp divided by one plus the sum of the modulus of all the gains from all the inputs.

23.9 The bandwidth of differential amplifiers

Finally: differential amplifiers, which turn out to be interesting as well. The job of a differential amplifier is to provide an output which is related to the difference between two inputs. You can consider this to be a combination of an inverting amplifier with an input V_{in1}, and a non-inverting amplifier with an input from V_{in2}.

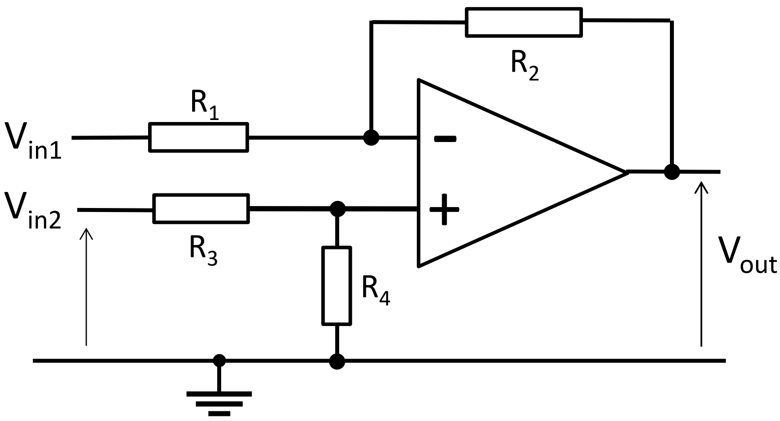

Figure 23.5 Differential amplifier

To work as a differential amplifier, the gain from the inverting amplifier must be minus one times the gain from the non-inverting amplifier, so that:

$$V_{out} = G_{DC} V_{in2} - G_{DC} V_{in1} = G_{DC} \left(V_{in2} - V_{in1} \right) \tag{23.43}$$

The same op-amp is used, so the gain-bandwidth product must be the same for the non-inverting and the inverting amplifiers. However, we've just worked out that for a non-inverting amplifier, the gain as a function of frequency is:

$$G_V(f) = \frac{G_{DC}}{1 + j\dfrac{f\, G_{DC}}{f_d\, A_{DC}}} \tag{23.44}$$

whereas for an inverting amplifier, it's:

$$G_V(f) = \frac{G_{DC}}{1 + j\dfrac{f}{f_d\, A_{DC}}\left(1 + \left|G_{DC}\right|\right)} \tag{23.45}$$

But for the differential amplifier to work, the modulus of the gains at low-frequencies (G_{DC}) must be the same for both amplifiers. Does this mean that the bandwidth of the inverting input and the bandwidth of the non-inverting input must be different, and therefore at higher frequencies this amplifier stops being a differential amplifier?

Well, no. It doesn't. Why? Because the gain of the inverting op-amp amplifier formed by putting V_{in2} to ground really is:

$$G_V(f) = \frac{-R_2 / R_1}{1 + j\dfrac{f}{f_d\, A_{DC}}\left(1 + \left|-\dfrac{R_2}{R_1}\right|\right)} \tag{23.46}$$

since the gain of this inverting amplifier is $-R_2 / R_1$. However the gain of the non-inverting amplifier formed by putting V_{in1} to ground is actually:

$$G_V = 1 + \frac{R_2}{R_1} \tag{23.47}$$

so the gain of the non-inverting amplifier is:

$$G_V(f) = \frac{1 + \frac{R_2}{R_1}}{1 + j\frac{f}{f_d A_{DC}}\left(1 + \frac{R_2}{R_1}\right)} \tag{23.48}$$

which has a pole with exactly the same break frequency as for the inverting amplifier. It's true that it has a larger gain, but in the circuit the input to the differential amplifier comes from the output of the potential divider formed by R_3 and R_4, so all that's required to make sure the gains match at all frequencies is to make:

$$V_+ = \frac{R_4}{R_3 + R_4} = 1 + \frac{R_4}{R_3} = 1 + \frac{R_2}{R_1} \tag{23.49}$$

which is most conveniently done by putting $R_4 = R_2$ and $R_3 = R_1$.

23.10 All single-pole frequency responses, so they have the same shape?

Yes, they do. You might have noticed that in every case above, the gain of the circuit can be expressed in the general form for a first-order response:

$$G(f) = \frac{G_{DC}}{1 + j\frac{f}{f_p}} \tag{23.50}$$

where f_p is the 3-dB frequency of the amplifier (otherwise known as the break or break frequency in the frequency response). Knowing the shape is useful, since it allows us to determine the gain of the amplifier at any frequency quite simply, just by knowing the 3-dB bandwidth.

This is useful, because quite often it's not the 3 dB bandwidth we are most interested in. The specification for audio amplifiers, for example, is often given in terms of a ±0.5 dB gain range over a certain range of frequencies. This suggests that we need to know how to relate the gain-bandwidth product to the gain and various different definitions of bandwidth, so we can calculate at what frequency the gain has reduced by 0.5 dB.

This isn't difficult, you just have to go back to the formula:

$$\left|G(f)\right| = \frac{G_{DC}}{\left|1 + j\frac{f}{f_{3dB}}\right|} \tag{23.51}$$

and use a different value (something other than 1/2) for the difference between the two gains $G(f)$ and G_{DC}.

In general, suppose we are interested in the frequency at which the gain drops by a factor of *X* dB; this would mean that the voltage gain (the square-root of the power gain) would have changed by a factor of $10^{-X/20}$. So:

$$\frac{|G(f)|}{G_{DC}} = 10^{\frac{-X}{20}} = \frac{1}{\left|1 + j\frac{f_{XdB}}{f_{3dB}}\right|} \tag{23.52}$$

and multiplying both sides by their complex conjugates (to determine the amplitudes of the expressions only) gives:

$$10^{\frac{-X}{10}} = \frac{1}{\left(1 + j\frac{f_{XdB}}{f_{3dB}}\right)\left(1 - j\frac{f_{XdB}}{f_{3dB}}\right)} = \frac{1}{1 + \frac{f_{XdB}{}^2}{f_{3dB}{}^2}} \tag{23.53}$$

After a bit of fairly straightforward algebra we get:

$$f_{XBw} = f_{3dB}\sqrt{\left(10^{X/10} - 1\right)} \tag{23.54}$$

which is a factor of $\sqrt{10^{X/10} - 1}$ greater than the 3dB bandwidth of the same amplifier.

For example, if we wanted to know the frequency at which an amplifier's gain drops by 10 dB relative to its value at low frequencies, we'd have to work out:

$$\sqrt{10^{X/10} - 1} = \sqrt{10^{10/10} - 1} = \sqrt{10^1 - 1} = \sqrt{9} = 3 \tag{23.55}$$

which indicates that the 10-dB bandwidth is three times greater than the 3-dB bandwidth, and if we were interested in the frequency at which the gain drops by 0.5 dB relative to its value at low frequencies, we'd have to work out:

$$\sqrt{10^{X/10} - 1} = \sqrt{10^{0.5/10} - 1} = \sqrt{10^{0.05} - 1} = \sqrt{1.122 - 1} = 0.349... \tag{23.56}$$

which indicates that the 0.5-dB bandwidth is a little over one-third of the 3-dB bandwidth.

To save some time, some other example results are given below:

Gain relative to low-frequency value ($1/\beta$)	Bandwidth relative to the half-power bandwidth at the same gain
0.1 dB	0.153
0.2 dB	0.217
0.25 dB	0.243
0.3 dB	0.267
0.5 dB	0.349
1.0 dB	0.509
1.5 dB	0.642
2.0 dB	0.765
3.0 dB	0.998[7]
5.0 dB	1.471
10.0 dB	3.000
20.0 dB	9.950

Another example: if you calculated the 3-dB bandwidth of a circuit to be 80 kHz, then the same circuit will be within 10 dB of its low-frequency (dc) gain up to a frequency of 80 * 3 = 240 kHz, and within 1 dB of its low-frequency (dc) gain up to 80 * 0.509 = 20.36 kHz, as illustrated below.

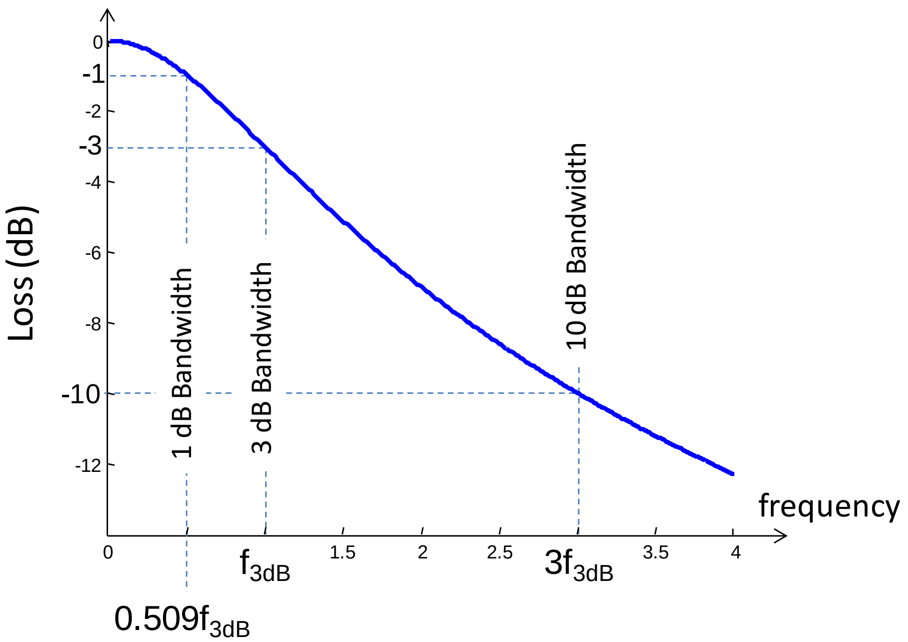

Figure 23.6 Showing the shape of the bandwidth vs frequency curve for simple op-amp circuits

All the basic op-amp amplifier configurations share this single-pole response shape, and therefore the same formula applies: the frequency at which the gain is 1 dB below its low-frequency value is 0.509 of the half-power bandwidth, and frequency at which the gain is 0.1 dB below its low-frequency value is 0.153 of the half-power bandwidth, and so on.

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[7] If you're wondering why this value isn't exactly one, it's because 3 dB isn't exactly a factor of two. However, it's very close, and the difference is not usually significant so we often ignore it, and use the terms half-power bandwidth and 3-dB bandwidth interchangeably.

23.11 Summary: the most important things to know

- The bandwidth of op-amp amplifiers can be calculated from their gain-bandwidth product and their gain.
- For non-inverting amplifiers the 3-dB bandwidth is the gain-bandwidth product divided by the gain at low frequencies.
- For inverting amplifiers the 3-dB bandwidth is the gain-bandwidth product divided by one plus the modules of the gain at low frequencies.
- The X-dB bandwidth can be calculated from the 3-dB bandwidth using the formula $f_{XBw} = f_{3dB}\sqrt{\left(10^{X/10} - 1\right)}$