Op Amp Bandwidth and Bandwidth Flatness

BANDWIDTH OF VOLTAGE FEEDBACK OP AMPS

The open-loop frequency response of a voltage feedback op amp is shown in Figure 1 below. There are two possibilities: Fig. 1A shows the most common, where a high dc gain drops at 6 dB/octave from quite a low frequency down to unity gain. This is a classic single pole response. By contrast, the amplifier in Fig. 1B has two poles in its response—gain drops at 6 dB/octave for a while, and then drops at 12 dB/octave. The amplifier in Fig. 1A is known as an *unconditionally stable* or *fully compensated* type and may be used with a noise gain of unity. This type of amplifier is stable with 100% feedback (including capacitance) from output to inverting input.

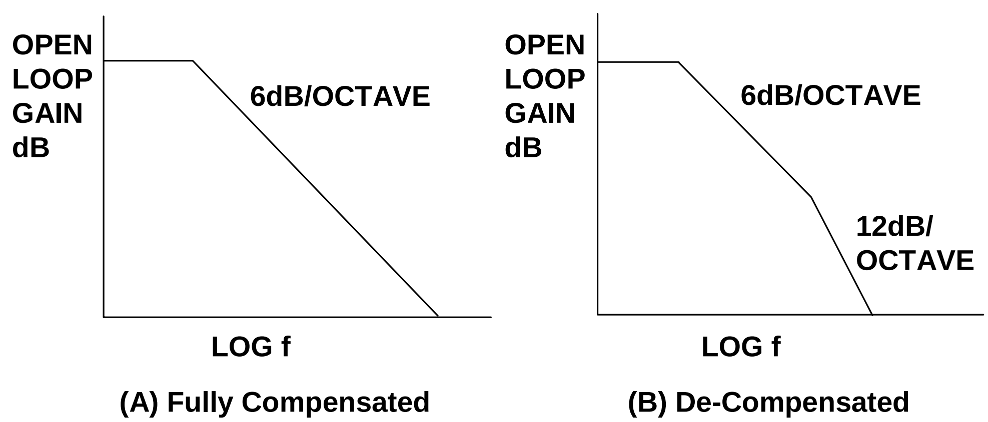


Figure 1: Frequency Response of Voltage Feedback Op Amps

Compare this to the amplifier in Fig 1B. If this op amp is used with a noise gain that is lower than the gain at which the slope of the response increases from 6 to 12 dB/octave, the phase shift in the feedback will be too great, and it will oscillate. Amplifiers of this type are characterized as "stable at gains ≥ X" where X is the gain at the frequency where the 6 dB/12 dB transition occurs. Note that here it is, of course, the *noise gain* that is being referenced. The gain level for stability might be between 2 and 25, typically quoted behavior might be "gain-of-five-stable**,"** etc. These *decompensated* op amps do have higher gain-bandwidth products than fully compensated amplifiers, all other things being equal. So, they are useful, despite the slightly greater complication of designing with them. But, unlike their fully compensated op amp relatives, a decompensated op amp can never be used with direct capacitive feedback from output to inverting input.

The 6 dB/octave slope of the response of both types means that over the range of frequencies where this slope occurs, *the product of the closed-loop gain and the 3 dB closed-loop bandwidth at that gain is a constant* —this is known as the *gain-bandwidth product* (GBW) and is a figure of merit for an amplifier. For example, if an op amp has a GBW product of X MHz, then its closed-loop bandwidth at a noise gain of 1 will be X MHz, at a noise gain of 2 it will be X/2 MHz, and at a noise gain of Y it will be X/Y MHz (see Figure 2 below). Notice that the *closed-loop* bandwidth is the frequency at which the noise gain plateau intersects the open-loop gain.

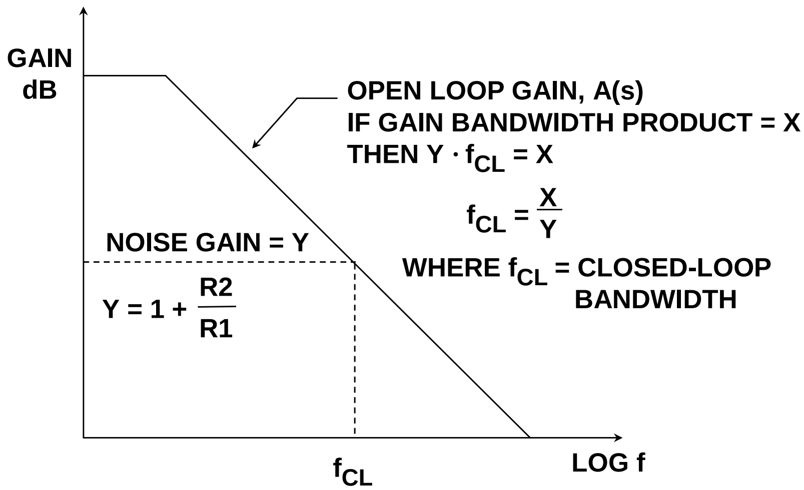


Figure 2: Gain-Bandwidth Product for Voltage Feedback Op Amps

In the above example, it was assumed that the feedback elements were resistive. This is not usually the case, especially when the op amp requires a feedback capacitor for stability.

Figure 3 below shows a typical example where there is capacitance, C1, on the inverting input of the op amp. This capacitance is the sum of the op amp internal capacitance, plus any external capacitance that may exist. This always-present capacitance introduces a pole in the noise gain transfer function.

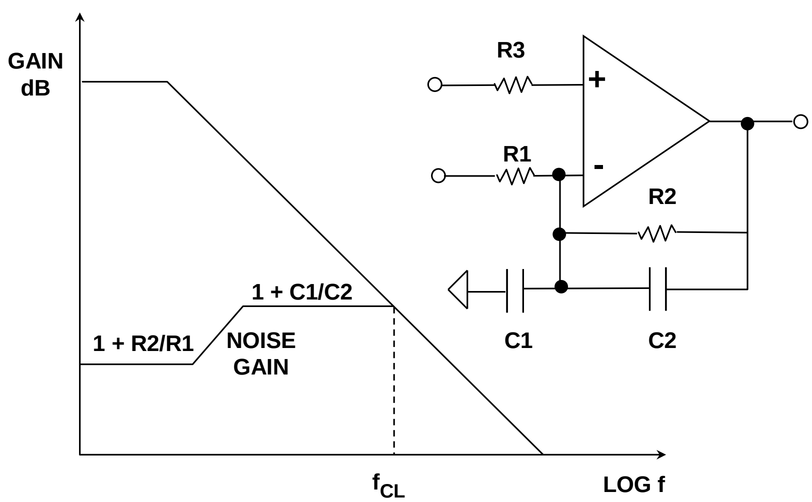


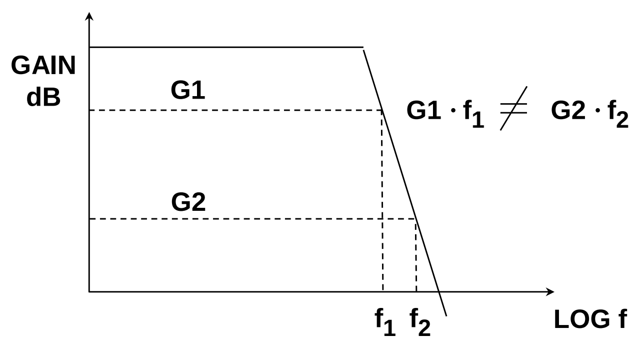
Figure 3: Bode Plot Showing Noise Gain for Voltage Feedback Op Amp with Resistive and Reactive Feedback Elements

The net slope of the noise gain curve and the open-loop gain curve, *at the point of intersection*, determines system stability. For unconditional stability, the noise gain must intersect the open-loop gain with a net slope of less than 12 dB/octave (20 dB per decade). Adding the feedback capacitor, C2, introduces a zero in the noise gain transfer function, which stabilizes the circuit. Notice that in Fig. 3 the closed-loop bandwidth, f_{cl}, is the frequency at which the noise gain intersects the open-loop gain.

The Bode plot of the noise gain is a very useful tool in analyzing op amp stability. Constructing the Bode plot is a relatively simple matter. Although it is outside the scope of this section to carry the discussion of noise gain and stability further, the reader is referred to Reference 1 for an excellent treatment of constructing and analyzing Bode plots.

BANDWIDTH OF CURRENT FEEDBACK OP AMPS

Current feedback op amps do not behave in the same way as voltage feedback types. They are not stable with capacitive feedback, nor are they so with a short circuit from output to inverting input. With a CFB op amp, *there is generally an optimum feedback resistance for maximum bandwidth.* Note that the value of this resistance may vary with supply voltage—consult the device data sheet. If the feedback resistance is increased, the bandwidth is reduced. Conversely, if it is reduced, bandwidth increases, and the amplifier may become unstable.



- **Feedback resistor fixed for optimum performance. Larger values reduce bandwidth, smaller values may cause instability.**
- **For fixed feedback resistor, changing gain has little effect on bandwidth.**
- **Current feedback op amps do not have a fixed gain-bandwidth product.**

Figure 4: Frequency Response for Current Feedback Op Amps

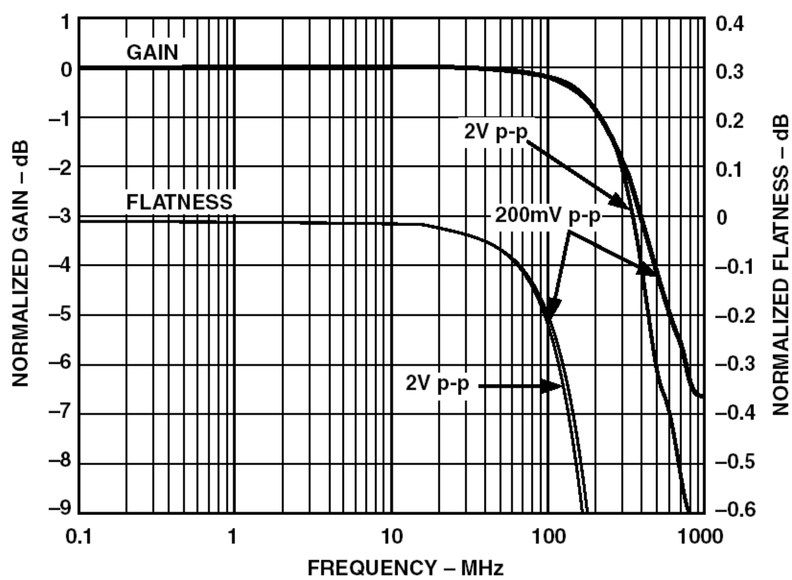
In a CFB op amp, for a given value of feedback resistance (R2), *the closed-loop bandwidth is largely unaffected by the noise gain*, as shown in Figure 4 above. Thus it is not correct to refer to gain-bandwidth product, for a CFB amplifier, because of the fact that it is not constant. Gain is manipulated in a CFB op amp application by choosing the correct feedback resistor for the device (R2), and then selecting the bottom resistor (R1) to yield the desired closed loop gain. The gain relationship of R2 and R1 is identical to the case of a VFB op amp.

Typically, CFB op amp data sheets will provide a table of recommended resistor values, which provide maximum bandwidth for the device, over a range of both gain and supply voltage. It simplifies the design process considerably to use these tables.

BANDWIDTH FLATNESS

In demanding applications such as professional video, it is desirable to maintain a relatively flat bandwidth and linear phase up to some maximum specified frequency, and simply specifying the 3 dB bandwidth isn't enough. In particular, it is customary to specify the *0.1 dB bandwidth*, or *0.1 dB bandwidth flatness*. This means there is no more than 0.1 dB ripple up to a specified 0.1 dB bandwidth frequency.

Video buffer amplifiers generally have both the 3 dB and the 0.1 dB bandwidth specified. Figure 5 below shows the frequency response of the AD8075 triple video buffer.



3dB BANDWIDTH ≈ 400MHz, 0.1dB BANDWIDTH ≈ 65MHz

Figure 5: 3dB and 0.1dB Bandwidth for the AD8075, G = 2, Triple Video Buffer, R_L = 150Ω

Note that the 3 dB bandwidth is approximately 400 MHz. This can be determined from the response labeled "GAIN" in the graph, and the corresponding gain scale is shown on the left-hand vertical axis (at a scaling of 1 dB/division).

The response scale for "FLATNESS" is on the right-hand vertical axis, at a scaling of 0.1 dB/division in this case. This allows the 0.1 dB bandwidth to be determined, which is about 65 MHz in this case. There is the general point to be noted here, and that is the major difference in the applicable bandwidth between the 3 dB and 0.1 dB criteria. It requires a 400 MHz bandwidth amplifier (as conventionally measured) to provide the 65 MHz 0.1 dB flatness rating.

It should be noted that these specifications hold true when driving a 75 Ω source and load terminated cable, which represents a resistive load of 150 Ω. Any capacitive loading at the amplifier output will cause peaking in the frequency response, and must be avoided.

SLEW RATE AND FULL-POWER BANDWIDTH

The slew rate (SR) of an amplifier is the maximum rate of change of voltage at its output. It is expressed in V/s (or, more probably, V/µs). We have mentioned earlier why op amps might have different slew rates during positive and negative going transitions, but for this analysis we shall assume that good fast op amps have reasonably symmetrical slew rates.

If we consider a sine wave signal with a peak-to-peak amplitude of $2V_p$ and of a frequency f, the expression for the output voltage is:

$$V(t) = V_p \sin 2\pi f t. \qquad \text{Eq. 1}$$

This sine wave signal has a maximum rate-of-change (slope) at the zero crossing. This maximum rate-of-change is:

$$\left.\frac{dv}{dt}\right|_{max} = 2\pi f\, V_p\,. \qquad \text{Eq. 2}$$

To reproduce this signal without distortion, an amplifier must be able to respond in terms of its output voltage at this rate (or faster). When an amplifier reaches its maximum output rate-of-change, or *slew rate*, it is said to be *slew limiting* (sometimes also called rate limiting). So, we can see that the maximum signal frequency at which slew limiting *does not* occur is directly proportional to the signal slope, and inversely proportional to the amplitude of the signal. This allows us to define the *full-power bandwidth* (FPBW) of an op amp, which is the maximum frequency at which slew limiting doesn't occur for rated voltage output. It is calculated by letting $2V_p$ in Eq. 2 equal the maximum peak-to-peak swing of the amplifier, dV/dt equal the amplifier slew rate, and solving for f:

$$\text{FPBW} = \text{Slew Rate}/2\pi V_p \qquad \text{Eq. 3}$$

It is important to realize that both slew rate and full-power bandwidth can also depend somewhat on the power supply voltage being used, and the load the amplifier is driving (particularly if it is capacitive). The key issues regarding slew rate and full-power bandwidth are summarized in Figure 6 below. As a point of reference, an op amp with a 1 V peak output swing reproducing a 1 MHz sine wave must have a minimum SR of 6.28 V/µs.

- **Slew Rate = Maximum rate at which the output voltage of an op amp can change**
- **Ranges: A few volts/μs to several thousand volts/μs**
- **For a sinewave, $V_{out} = V_p \sin 2\pi ft$**

$$dV/dt = 2\pi f V_p \cos 2\pi ft$$

$$(dV/dt)_{max} = 2\pi f V_p$$

- **If $2V_p$ = full output span of op amp, then**

$$\text{Slew Rate} = (dV/dt)_{max} = 2\pi \cdot \text{FPBW} \cdot V_p$$

$$\text{FPBW} = \text{Slew Rate} / 2\pi V_p$$

Figure 6: Slew Rate and Full-Power Bandwidth

Realistically, for a practical circuit the designer would choose an op amp with a SR in excess of this figure, since real op amps show increasing distortion prior to reaching the slew limit point.

REFERENCES

1. James L. Melsa and Donald G. Schultz, *Linear Control Systems*, McGraw-Hill, 1969, pp. 196-220, ISBN: 0-07-041481-5

2. Hank Zumbahlen, *Basic Linear Design*, Analog Devices, 2006, ISBN: 0-915550-28-1. Also available as *Linear Circuit Design Handbook*, Elsevier-Newnes, 2008, ISBN-10: 0750687037, ISBN-13: 978-0750687034. Chapter 12

3. Walter G. Jung, *Op Amp Applications*, Analog Devices, 2002, ISBN 0-916550-26-5, Also available as *Op Amp Applications Handbook*, Elsevier/Newnes, 2005, ISBN 0-7506-7844-5. Chapter 2.