

A closer look at the slew rate criterion

Hugo Coolens

11th June 2004

Abstract

Even though the slew rate criterion is well known, failing to apply it to a circuit as simple as a standard inverting op-amp amplifier can lead to wrong measurements and false conclusions concerning measured versus theoretically predicted behaviour.

When one has designed a linear op-amp circuit, it is a good idea to check its performance by real measurements. Care should be taken to avoid nonlinear distortion when comparing measured results with design predictions. For an op-amp circuit the most important mechanisms which could cause non linear operation are saturation and slewing.

Consider the simple inverting op-amp amplifier in figure 1. When we try to measure the frequency response of this amplifier, we should apply at the input a sinusoidal signal whose amplitude is large enough, since a large signal to noise ratio will be beneficial for the measurement. However, we should not make the amplitude too large to avoid saturation or slewing of the op-amp.

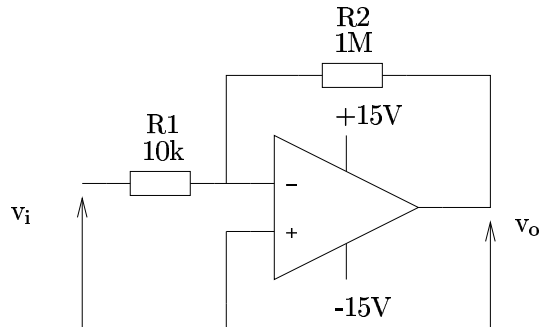


Figure 1: inverting op-amp amplifier

The amplitude of our sinusoidal input signal will be called hereafter $V_{I,P}$ and the maximum value which does not cause nonlinear distortion $V_{I,P,MAX}$. If we assume the saturation voltage of our op-amp 2 volts less than the power supply voltage which we take 15 V, $V_{I,P,MAX} = 130$ mV will not cause saturation. Let us evaluate this value for slewing using inequality (1), the well known slew rate criterion:

$$\omega \cdot V_{O,P} < S_R \quad (1)$$

Let us check for slewing in the passband of our amplifier (e.g. for $f = 100$ Hz) : $2\pi \cdot 100$ Hz $\cdot 13$ V = 8168 V/s < 500000 V/s. This result is satisfactory. For typical parameters ¹ of a 741, the circuit has a DC-gain $A_{CL,0} = 100$ and a closed loop bandwidth $BW_{CL} = 9901$ Hz ². As we want to measure the frequency response also in the roll off region of the amplifier, let us check it there too e.g. for $f = 100$ kHz. At this frequency $A_{CL} = 9.85$, thus the left hand side of inequality (1) becomes $2\pi \cdot 100$ kHz $\cdot 1.28$ V = 804000 V/s. In this case, the slew rate criterion is clearly not met. Thus we should choose a smaller value for $V_{I,P}$. Instead of using a trial and error method, we can

¹unity gain frequency = 1MHz and $S_R = 0.5$ V/ μ s

² $(1 + A_{CL,0}) \cdot BW_{CL} = A_{OL,0} \cdot BW_{OL}$

rewrite equation (1) which is as such not very useful for our purpose as it applies to the output of the amplifier:

$$2\pi f \cdot V_{I,P} \cdot |\overline{A_{CL}}| < S_R \quad (2)$$

Rearranging inequality (2) and using $\overline{A_{CL}} = -\frac{-A_{CL,0}}{1+jf/BW_{CL}}$ brings the slew rate criterion back to the input of the amplifier:

$$V_{I,P} < \frac{S_R \sqrt{1 + \left(\frac{f}{BW_{CL}}\right)^2}}{2\pi f A_{CL,0}} = V_{I,P,MAX} \quad (3)$$

One could be tempted to try to solve this inequality, which essentially would mean to solve a quadratic inequality. If you look however at the right hand side of it, you can see in figure 2 this function has a horizontal asymptote for $f \rightarrow \infty$. In fact, this result could be expected from inequality (1) too, as the left hand side of it has both a factor which increases linearly with frequency and one which decreases linearly proportional to frequency (assuming first order behaviour).

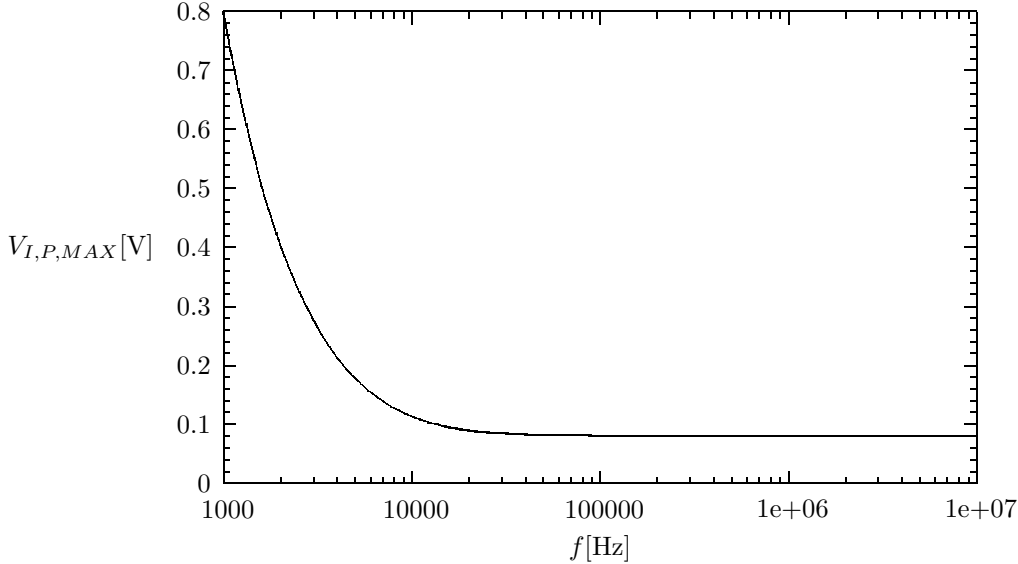


Figure 2: Maximum input amplitude versus frequency to avoid slew rate distortion for figure 1 (R2/R1=100)

Determining the above mentioned asymptote gives:

$$V_{I,P,MAX,\infty} = \frac{S_R}{2\pi A_{CL,0} BW_{CL}} \quad (4)$$

Equation (4) can also be rewritten as:

$$V_{I,P,MAX,\infty} = \frac{S_R}{2\pi |\alpha| A_{OL,0} BW_{OL}} \quad \alpha = -\frac{R2}{R1 + R2} = \frac{-A_{CL,0}}{1 + A_{CL,0}} \quad (5)$$

Equation (5) has the advantage that it uses opamp parameters directly. It can also be used for the standard non-inverting amplifier, in which case $\alpha = 1$.

From equation (5) it is clear that for two op-amps with the same slew rate, the one with the higher bandwidth will yield the worst value for $V_{I,P,MAX,\infty}$.

Equations (4) and (5) show that $V_{I,P,MAX,\infty}$ is dependent on $A_{CL,0}$ for the inverting amplifier, whereas for the non-inverting amplifier it is not. For a unity gain amplifier $V_{I,P,MAX,\infty}$ may be

twice as large for an inverting amplifier than for a non inverting one. Of course, the closed loop bandwidth will also be halved in that case. A more "physical" explanation is that for an inverting amplifier the input signal is attenuated by R1 before reaching the actual input of the op-amp.

Notice also that the graph in figure 2 has a "corner frequency" equal to BW_{CL} . This means you can apply a $V_{I,P,MAX}$ which is $\sqrt{2}$ times $V_{I,P,MAX,\infty}$ at a frequency equal to BW_{CL} without causing slew rate distortion.

Using typical values for a 741, we can conclude from equation (4) that we should limit the amplitude of our sinusoidal input signal to $V_{I,P,MAX} = 80\text{ mV}$ to avoid slew rate distortion for whatever frequency. Using a unity gain frequency of 1.2 MHz and a worst case slew rate of $0.3\text{ V}/\mu\text{s}$, this value is even further reduced to slightly less than 40 mV, which is more than three times less our initial value based on the saturation criterion but will yield an acceptable signal to noise ratio for most measurement setups.

This does not conclude our story yet. Real op-amps are higher order systems. This phenomenon will also be noticeable in the closed loop system response. Calculations for higher order op-amp models may become rather tedious. However, simulation programs like Spice can come in handy for this purpose. When we apply an AC-source of 1 V at the input of our circuit and perform an AC-analysis, we obtain an output voltage $V([OUT])$ which is numerically equal to $|\overline{ACL}|$. Performing some postprocessing on $V([OUT])$ gives us $V_{I,P,MAX} = \frac{S_R}{2\pi fV([OUT])}$. The result is shown in figure 3.

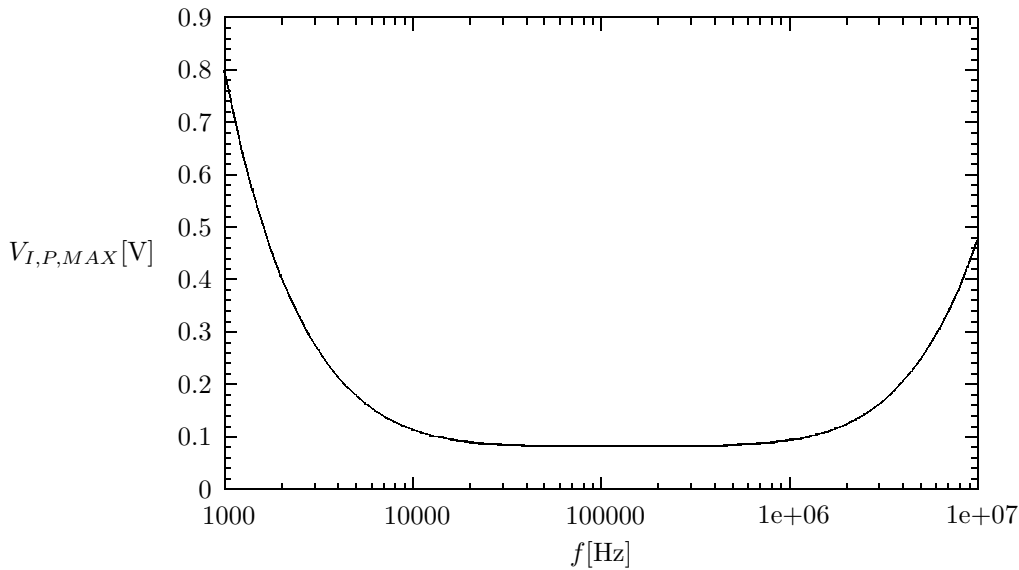


Figure 3: Maximum input amplitude versus frequency to avoid slew rate distortion for higher order op-amp model

We now no longer have a curve with a horizontal asymptote but a U-shaped curve which has a minimum at 126 kHz of 81 mV, pretty close to the value we obtained with our first order approximation.

This method based on the results of an AC-analysis is not restricted to simple circuits as given in the example, but can easily be used for more complex linear opamp-circuits such as filters as well. Of course you should choose an op-amp model which models real frequency domain behaviour closely and preferably not based only on typical but also on worst and best case performance. Keep in mind however that this method does not take into account capacitive loading of an op-amp output which can deteriorate further slew rate performance.

Even though we focussed in this article on the slew rate criterion, don't forget to have a look at the saturation criterion too. In fact you can bring that back to the input of your circuit too in a similar way as was shown for the slew rate criterion: $V_{I,P} < \frac{V_{O,SAT}}{|\overline{ACL}|}$. An AC-analysis with

Spice followed by a little postprocessing is sufficient to calculate $V_{I,P,MAX} = \frac{V_{O,SAT}}{V_{(OUT)}}$. It is not always obvious which of the two criteria will be the dominant one, therefore you should plot both graphs to determine the maximum amplitude which you can apply to your circuit without causing slew rate distortion or saturation. An example of such graphs is shown in figure 4 for the op-amp band pass filter shown in figure 5. It is clear that in this case the saturation criterion is the dominant one.

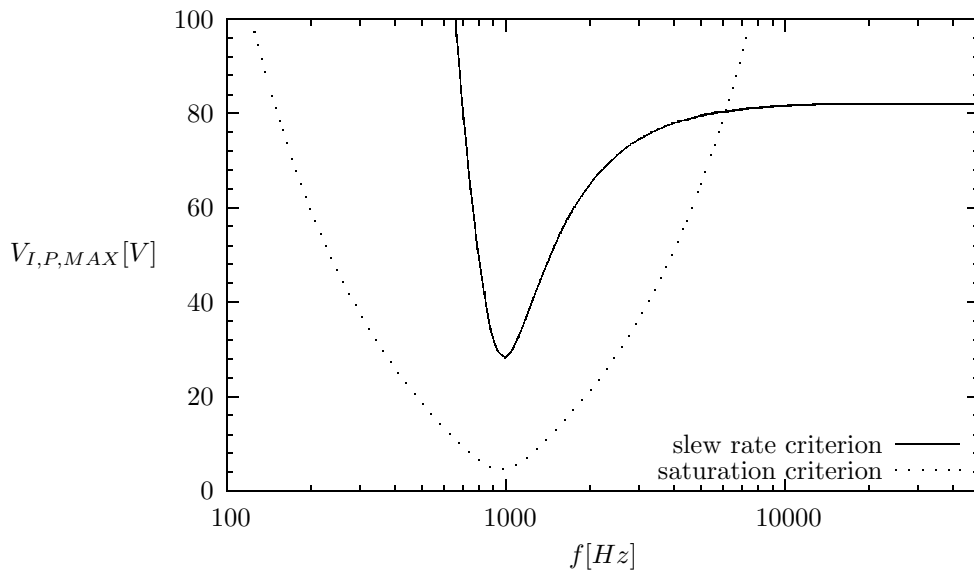


Figure 4: Maximum input amplitude versus frequency to avoid slew rate distortion and saturation for band pass filter

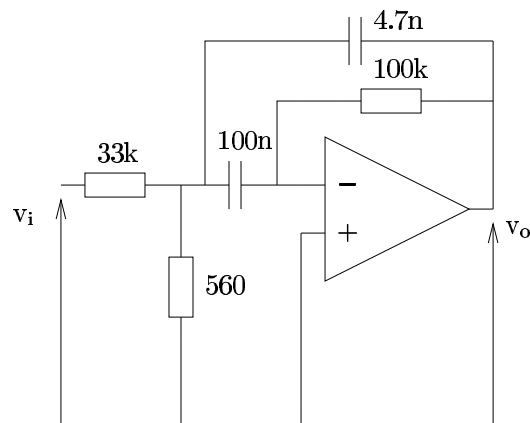


Figure 5: op-amp band pass filter

I hope this article shows that there is more behind the standard slew rate criterion than inequality (1) or what standard handbooks of electronics usually tell.