Predicting Op Amp Slew Rate Limited Response

National Semiconductor
Linear Brief 19

The following analysis of sine and step voltage responses applies to all single dominant pole op amps such as the LM101A, LM107, LM108A, LM112, LM118 and the LM741. Each of these op amps has an open loop response curve with a shape similar to the one shown in *Figure 1*. The distinguishing feature of this curve is the single low frequency turnover from a flat response to a uniform −20 dB per decade of frequency (−6 dB/octave) drop in gain, at least until the curve passes through the 0 dB line. Closing the loop to 40 dB (X100) as shown with a dotted line on *Figure 1* does not change the shape of the curve, but it does move the turnover to a higher frequency. These open loop and closed loop response curves determine the gain applied to small signal inputs. The logical question then arises as to when a signal can no longer be treated as a small signal and the amplifier response begins to deviate from this curve.

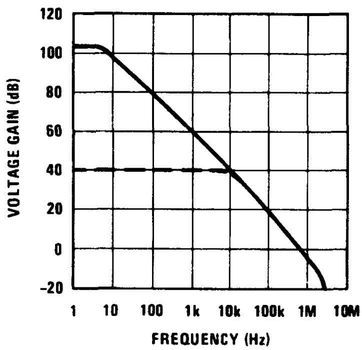

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FIGURE 1. Open and Closed Loop Frequency Response

The answer lies in the slew rate limit of the op amp. The slew rate limit is the maximum rate of change of the amplifier's output voltage and is due to the fact that the compensation capacitor inside the amplifier only has finite currents[1] available for charging and discharging. A sinusoidal output signal will cease being a small signal when its maximum rate of change equals the slew rate limit S_r of the amplifier. The maximum rate of change for a sine wave occurs at the zero crossing and may be derived as follows:

$$v_O = V_P \sin 2\pi ft \qquad (1)$$

$$\frac{dv_O}{dt} = 2\pi f V_P \cos 2\pi ft \qquad (2)$$

$$\left.\frac{dv_O}{dt}\right|_{t=0} = 2\pi f V_P \qquad (3)$$

$$S_r = 2\pi f_{max} V_P \qquad (4)$$

where: v_O = output voltage

V_P = peak output voltage

S_r = maximum $\frac{dv_O}{dt}$

The maximum sine wave frequency an amplifier with a given slew rate will sustain without causing the output to take on a triangular shape is therefore a function of the peak amplitude of the output and is expressed as:

$$f_{max} = \frac{S_r}{2\pi V_P} \qquad (5)$$

Equation 5 demonstrates that the borderline between small signal response and slew rate limited response is not just a function of the peak output signal but that by trading off either frequency or peak amplitude one can continue to have a distortion free output. *Figure 2* shows a quick reference graphical presentation of equation 5 with the area above any V_{PEAK} line representing an undistorted small signal response and the area below a given V_{PEAK} line representing a distorted sine wave response due to slew rate limiting.

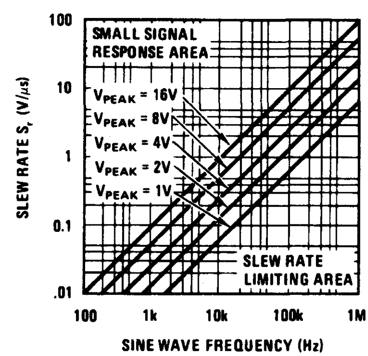

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FIGURE 2. Sine Wave Response

As a matter of convenience, amplifier manufacturers often give a "full-power bandwidth" or "large signal response" on their specification sheets.

This frequency can be derived by inserting the amplifier slew rate and peak rated output voltage into equation 5. The bandwidth from DC to the resulting f_{max} is the full-power bandwidth or "large signal response" of the amplifier. For example the full-power bandwidth of the LM741 with a 0.5V μs S_r is approximately 6 kHz while the full-power bandwidth of the LM118 with an S_r of 70 V/μs is approximately 900 kHz.

The step voltage response at the output of an op amp can also be divided into a small signal response and a slew rate limited response. The signal turnover and uniform −20 dB/decade slope shown in the small signal frequency response curve of *Figure 1* are also characteristic of a low pass filter and one can in fact model an op amp as a low pass RC filter followed by a very wideband amplifier. *Figure 3* shows a model of a X100 circuit with a 3 dB down rolloff frequency of

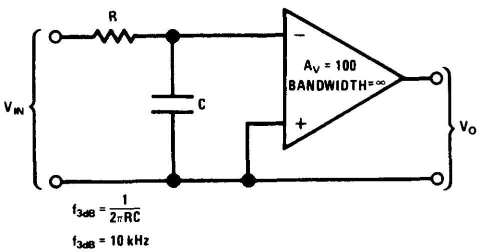

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FIGURE 3. Small Signal Op Amp Model

10 kHz. From basic filter theory[2] the 10% to 90% rise time of single pole low pass filter is:

$$t_r = \frac{0.35}{f_{3dB}} \quad (6)$$

which for this example would be 35 μs. Again this small signal or low pass filter response ceases when the required rate of change of the output voltage exceeds the slew rate limit S_r of the amplifier. Mathematically stated:

$$\frac{V_{STEP}}{t_r} \geq S_r \quad (7)$$

This means that as soon as the amplitude of the output step voltage divided by the rise time of the circuit exceeds the S_r of the amplifier, the amplifier will go into slew rate limiting.

The output will then be a ramp function with a slope of S_r and a rise time equal to:

$$t'_r = \frac{V_{STEP}}{S_r} \quad (8)$$

Subsituting equation 6 into equation 7 gives the critical value of V_{STEP} directly in terms of f_{3dB}:

$$\frac{V_{STEP}\, f_{3db}}{0.35} \geq S_r \quad (9)$$

which can be graphed as shown in *Figure 4*. Any point in the area above a V_{STEP} line represents an undistorted low pass filter type response and any point in the area below a given V_{STEP} line represents a slew rate limited response.

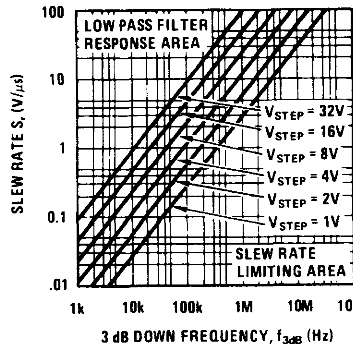

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FIGURE 4. Step Voltage Response

The above equations and graphs should allow one to avoid the pitfalls of slew rate limiting and also provide a means of using engineering tradeoffs to extend the response of the single dominant pole type of ampilfier.

REFERENCES

1. Solomon, J. E.; Davis, W. R.; and Lee, P. L.: *"A Self-Compensated Monolithic Operational Amplifier With Low Input Current and High Slew Rate"*, pp. 14–15, ISSCC Digest Tech. Papers, February 1969.
2. Millman, J. and Hawkias, C. C.: *"Electronic Devices and Circuits"*, pp. 465–466, McGraw-Hill Book Company, New York, 1967.