Op Amp Total Output Noise Calculations for Second-Order System

The total output noise for a single-pole system was analyzed in Tutorial MT-049. The circuit shown in Figure 1 below represents a second-order system, where capacitor C1 represents the source capacitance, stray capacitance on the inverting input, the input capacitance of the op amp, or any combination of these. C1 causes a breakpoint in the noise gain, and C2 is the capacitor that must be added to obtain stability.
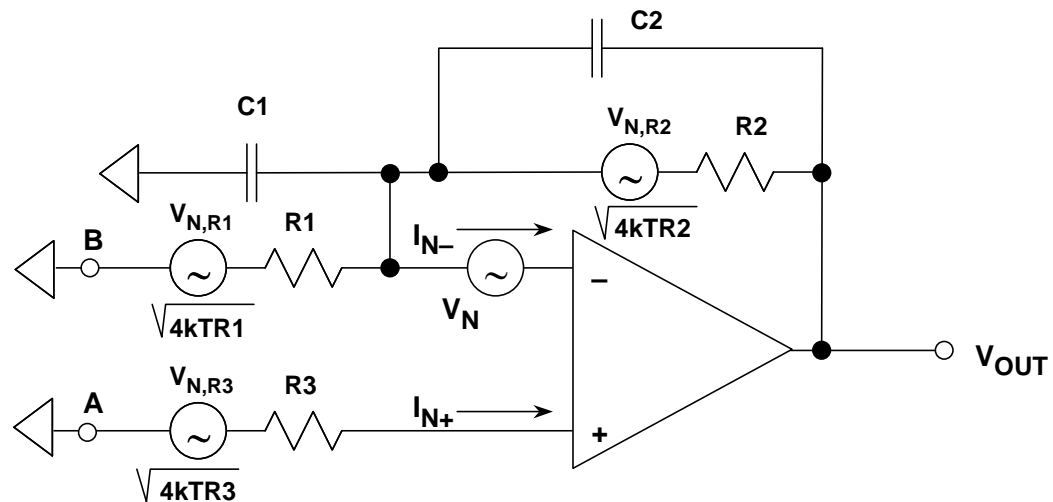

Figure 1: Op Amp Noise Model with Reactive Elements (Second-Order System)

Because of C1 and C2, the noise gain is a function of frequency, and has peaking at the higher frequencies (assuming C2 is selected to make the second-order system critically damped). A flat noise gain can be achieved if one simply makes R1×C1 = R2×C2.

But in the case of current-to-voltage converters, however, R1 is typically a high impedance, and the method doesn't work. Maximizing the signal bandwidth in these situations is somewhat complex and is treated in detail in Tutorial MT-059.

A dc signal applied to input A (B being grounded) sees a gain of $1 + R2/R1$, the low frequency noise gain. At higher frequencies, the gain from input A to the output becomes $1 + C1/C2$ (the high frequency noise gain).

The closed-loop bandwidth f_{cl} is the point at which the noise gain intersects the open-loop gain. A dc signal applied to B (A being grounded) sees a gain of $-R2/R1$, with a high frequency cutoff determined by R2-C2. Bandwidth from B to the output is $1/2\pi R2C2$.

The current noise of the non-inverting input, I_{N+}, flows in R3 and gives rise to a noise voltage of $I_{N+}R3$, which is amplified by the frequency-dependent noise gain, as are the op amp noise voltage, V_N, and the Johnson noise of R3, which is $\sqrt{(4kTR3)}$. The Johnson noise of R1 is amplified by $-R2/R1$ over a bandwidth of $1/2\pi R2C2$, and the Johnson noise of R2 is not amplified at all but is connected directly to the output over a bandwidth of $1/2\pi R2C2$. The current noise of the inverting input, I_{N-}, flows in R2 only, resulting in a voltage at the amplifier output of $I_{N-}R2$ over a bandwidth of $1/2\pi R2C2$.

If we consider these six noise contributions, we see that if R1, R2, and R3 are low, then the effect of current noise and Johnson noise will be minimized, and the dominant noise will be the op amp's voltage noise. As we increase resistance, both Johnson noise and the voltage noise produced by noise currents will rise.

If noise currents are low, then Johnson noise will take over from voltage noise as the dominant contributor. Johnson noise, however, rises with the square root of the resistance, while the current noise voltage rises linearly with resistance, so ultimately, as the resistance continues to rise, the voltage due to noise currents will become dominant.

These noise contributions we have analyzed are not affected by whether the input is connected to node A or node B (the other being grounded or connected to some other low-impedance voltage source), which is why the non-inverting gain $(1 + Z2/Z1)$, which is seen by the voltage noise of the op amp, V_N, is known as the "noise gain".

Calculating the total output rms noise of the second-order op amp system requires multiplying each of the six noise voltages by the appropriate gain and integrating over the appropriate frequency as shown in Figure 2 (below).

NOISE SOURCE EXPRESSED AS A VOLTAGE	MULTIPLY BY THIS FACTOR TO REFER TO OUTPUT	INTEGRATION BANDWIDTH
Johnson noise in R3: $\sqrt{(4kTR3)}$	**Noise Gain as a function of frequency**	**Closed-Loop BW**
Non-inverting input current noise flowing in R3: $I_{N+}R3$	**Noise Gain as a function of frequency**	**Closed-Loop BW**
Input voltage noise: V_N	**Noise Gain as a function of frequency**	**Closed-Loop BW**
Johnson noise in R1: $\sqrt{(4kTR1)}$	**−R2/R1 (Gain from B to output)**	**$1/2\pi R2C2$**
Johnson noise in R2: $\sqrt{(4kTR2)}$	**1**	**$1/2\pi R2C2$**
Inverting input current noise flowing in R2: $I_{N-}R2$	**1**	**$1/2\pi R2C2$**

Figure 2: Noise Sources Referred to the Output for a Second-Order System

The root-sum-square of all the output contributions then represents the total rms output noise. Fortunately, this cumbersome exercise may be greatly simplified in most cases by making the appropriate assumptions and identifying the chief contributors.

The noise gain for a typical second-order system is repeated in Figure 3 below. It is quite easy to perform the voltage noise integration in two steps, but notice that because of peaking, the majority of the output noise due to the input voltage noise will be determined by the high frequency portion where the noise gain is $1 + C1/C2$. This type of response is typical of second-order systems. The noise due to the inverting input current noise, R1, and R2 is only integrated over the bandwidth $1/2\pi R2C2$.

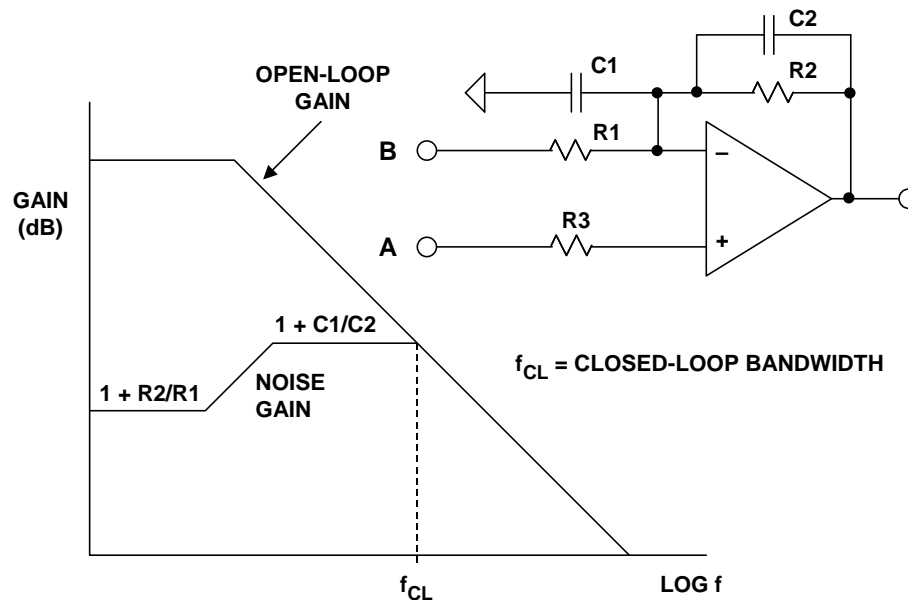**Figure 3: Noise Gain of a Typical Second-Order System**

REFERENCES

1. 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 1.

2. 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 1.