OPERATIONAL AMPLIFIER NOISE MEASUREMENTS

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ABSTRACT

Noise behavior is an important characteristic of analog circuits, as it usually determines the fundamental limit of the performance of analog circuits. Noise is a signal with random amplitude versus time. This paper presents a quick view of electrical noise types, which is a significant problem for electrical engineers designing sensitive circuit, and uses the standard circuit theory and noise models to calculate noise in op-amp circuits.

1 INTRODUCTION

An amplifier is made with active and passive components. All these components produce noise. To find the noise on the output it should be calculated for every noise source the transfer function to the output. This will end up into a noise signal on the output of the amplifier, which is the statistical sum of all noise sources times their transfer function to the output.

In electrical circuits generally there are 5 common noise sources:

1. Thermal or Johnson noise: is caused by the thermal agitation of charge carriers (electrons or holes) in a conductor. It is white. This noise is present in all passive resistive elements. This kind of noise depends on temperature but not on current flow. The average mean-square value of the voltage noise source is given by:

   $$\overline{dv_R^2} = 4kTR.df$$

   in which k is Boltzmann's constant (1.38×10^{-23} j/K), and T the absolute temperature in Kelvin (K), R is the resistance of the conductor in ohms (Ω) and *df* is differential frequency.

2. Shot noise: this kind of noise does not depend on temperature but it is always associated with current flow. It is also white. Shot noise results whenever charges cross a potential barrier like a pn junction diode.

3. Flicker or 1/f noise: To any of the noise sources described above, a 1/f noise source must be added. It is not white but pink noise. This kind of noise describes the quality of the conductive medium. The more homogeneous the material, the

lower the 1/f noise. Also, the larger the conductive volume, the lower the 1/f noise.

4. Burst or popcorn noise: this noise appears to be related to imperfections in semiconductor material and heavy ion implants. It is an indication of distinct recombination processes in the material, and a sign of bad quality processing. Burst noise for example makes a popping sound at rates below 100 Hz when played through a speaker.
5. Avalanche noise: this noise is created when a pn junction is operated in the reverse breakdown mode; Breakdown itself is a random phenomenon. This type of noise can be avoided by staying away from the breakdown voltage.

In op amp circuits, burst noise and avalanche noise are normally not problems, or they can be eliminated if present. They are mentioned here for completeness, but are not considered in the noise analysis.

2 OP- AMP CIRCUIT NOISE MODEL

The noise specifications refer the measured noise to the input of the op amp. The part of the internally generated noise that can properly be represented by a voltage source is placed in series with the positive input to an otherwise noiseless op amp. The part of the internally generated noise that can properly be represented by current sources is placed between each input and ground in an otherwise noiseless op amp. Figure 1 shows the resulting noise model for a typical op amp.

To perform a noise analysis, the previous noise models are added to the circuit schematic and the input signal sources are shorted to ground. When this is done to either an inverting or a noninverting op amp circuit, the same circuit results, as shown in Figure 1. This circuit is used for the following noise analysis.

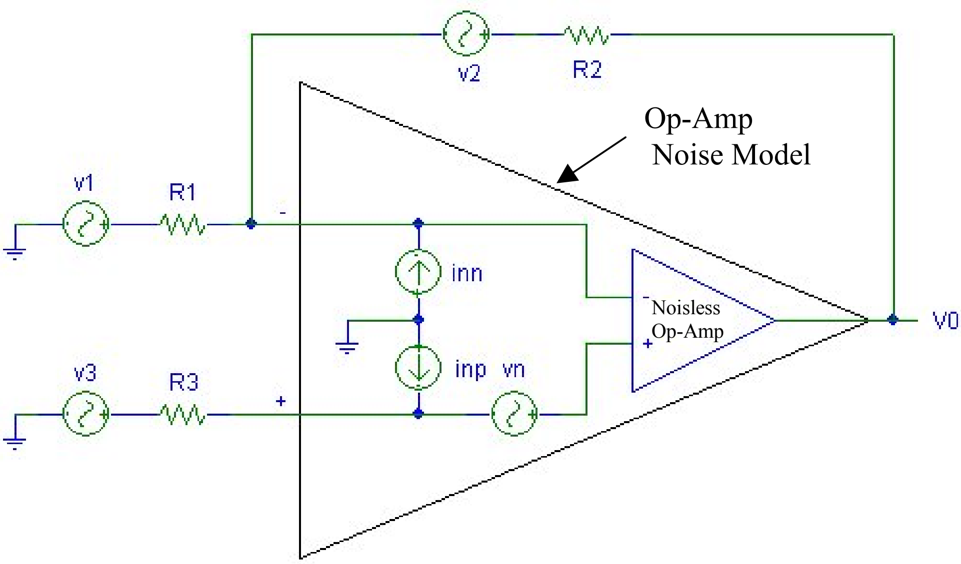

Fig. 1: *Inverting and Non-Inverting Noise Analysis Circuit.*

At first, this analysis can be deciphered piece by piece. Using the principles of superposition, each of the noise sources is isolated, and everything else is assumed to be noiseless. Then the results can be added according to the rules for adding independent noise sources. An ideal op amp is assumed for the noiseless op amp.

Lets first consider that all the elements are noiseless accept the R1, the result of this noise element appear at the output of the model, in this case:

$$\overline{V_1} = \overline{v_1}\frac{R_2}{R_1} \Rightarrow \overline{V_1^2} = \overline{v_1^2}\left(\frac{R_2}{R_1}\right)^2$$

And $\overline{v_1^2} = \int 4kTR_1 df$

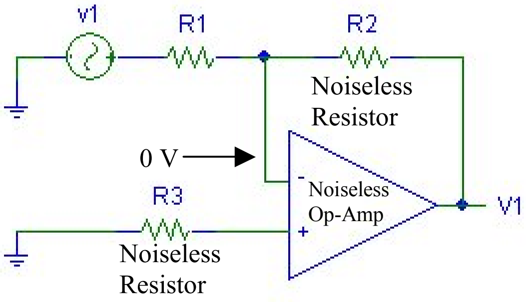

Fig. 2: *V1*

Now lets make the entire element noiseless, except the R2 as the previous calculation the output noise V2 is given by:

$$\overline{V_2} = \overline{v_2} \Rightarrow \overline{V_2^2} = \overline{v_2^2} \text{ And}$$
$$\overline{v_2^2} = \int 4kTR_2 df$$

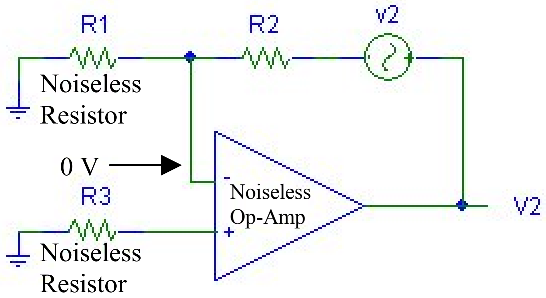

Fig. 3: V_2

By the same way it can be calculated the noise causes by the noise element R3 and assuming the other element to be a noiseless, V3 is given by:

$$\overline{V_3} = \overline{v_3}\left(\frac{R_1 + R_2}{R_1}\right) \Rightarrow \overline{V_3^2} = \overline{v_3^2}\left(\frac{R_1 + R_2}{R_1}\right)^2$$

And $\overline{v_3^2} = \int 4kTR_3 df$

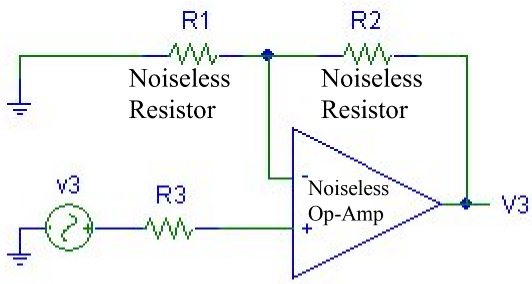

Fig. 4: V_3

Combining to arrive at the solution for the circuit's output rms noise voltage, V_{Rrms}, due to the thermal noise of the resistors in the circuit:

$$V_{Rrms} = \sqrt{V_1^2 + V_2^2 + V_3^2}$$

$$V_{Rrms} = \sqrt{\int\left[4kTR_1\left(\frac{R_2}{R_1}\right)^2 + 4kTR_2 + 4kTR_3\left(\frac{R_1+R_2}{R_1}\right)^2\right]df}$$

If it is desired to know the resistor noise referenced to the input, V_{iRrms}, the output noise is divided by the noise gain A_n of the circuit:

$$A_n = \left(\frac{R_1+R_2}{R_1}\right)$$

$$V_{iRrms}^2 = \left(\frac{V_{Rrms}}{A_n}\right)^2 = \int\frac{\left[4kTR_1\left(\frac{R_2}{R_1}\right)^2 + 4kTR_2 + 4kTR_3\left(\frac{R_1+R_2}{R_1}\right)^2\right]df}{\left(\frac{R_1+R_2}{R_1}\right)^2} = \int 4kT\left[\left(\frac{R_1R_2}{R_1+R_2}\right) + R_3\right]df$$

Now consider the noise sources associated with the op amp itself. The analysis proceeds as before, first to calculate the voltage noise source v_n all the resistors consider being a noiseless, and the current noise sources have been removed. The V_n is given by:

$$\overline{V_n^2} = \int\left[(v_n)\left(\frac{R_1+R_2}{R_1}\right)\right]^2 df$$

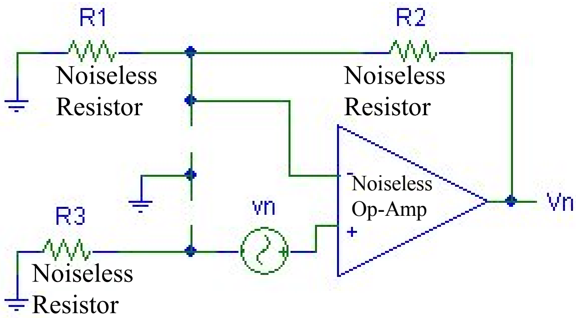

Fig. 5: *Vn*

The two following equation gives the value of the current noise source i_{nn} and i_{np} under condition that ale the other noise sources are negligible or the other elements are noiseless.

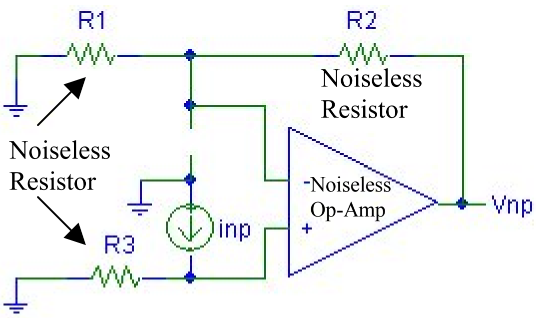

Fig. 6: *Vnp*

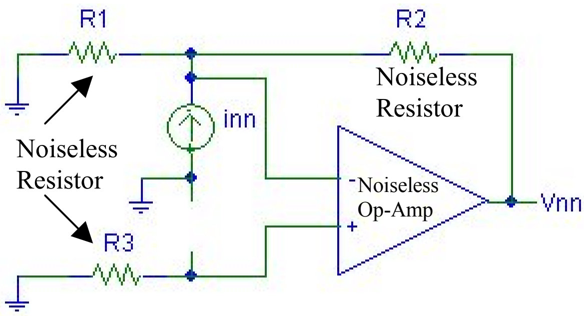

Fig. 7: *Vnn*

$$\overline{V_{nn}^2} = \int[(i_{nn})(R_2)]^2 df$$

$$\overline{V_{np}^2} = \int \left[(i_{np})(R_3)\left(\frac{R_1 + R_2}{R_1} \right) \right]^2 df$$

Combining to arrive at the solution for the circuit's output rms noise voltage, V_{oarms}, due to the input referred op amp noise in the circuit:

$$V_{oarms} = \sqrt{\overline{V_n^2 + V_{nn}^2 + V_{np}^2}} = \sqrt{\int \left[\left[v_n \left(\frac{R_1 + R_2}{R_1} \right) \right]^2 + \left(i_{nn}(R_2) \right)^2 + \left((i_{np}) R_3 \left(\frac{R_1 + R_2}{R_1} \right) \right)^2 \right] df}$$

Now combining the resistor noise and the op amp noise to get the total output rms noise voltage, V_{Trms}.

$$V_{Trms} = \sqrt{\int \left[4kTR_2 \left(\frac{R_1 + R_2}{R_1} \right) + 4kTR_3 \left(\frac{R_1 + R_2}{R_1} \right)^2 \right] df} +$$

$$\sqrt{\int \left[\left[v_n \left(\frac{R_1 + R_2}{R_1} \right) \right]^2 + \left(i_{nn}(R_2) \right)^2 + \left((i_{np}) R_3 \left(\frac{R_1 + R_2}{R_1} \right) \right)^2 \right] df}$$

The only work left is to evaluate the integral. Most of the terms are constants that can be brought straight out of the integral. The resistors and their associated noise are constant over frequency so that the first two terms are constants. The last three terms contain the input referred noise of the op amp. The voltage and current input referred noise of op amps contains flicker noise, shot noise, and thermal noise. This means that they must be evaluated as a combination of white and 1/f noise. The techniques presented here can be used to perform a noise analysis on any circuit. Superposition was chosen for illustrative purposes, but using other circuit analysis techniques can derive the same solutions.

ACKNOWLEDGMENTS

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