Op Amp Noise Figure: Don't Be Mislead

INTRODUCTION

Op amp noise is generally specified in terms of input current and voltage noise, as previously discussed in MT-047, MT-048, MT-049, MT-050, and MT-051. In communications systems, however, noise is often specified in terms of *noise figure* (NF)—see Figure 1 below. This can lead to confusion, especially when op amps are used as gain blocks, and the noise figure of the op amp is not specified for the specific circuit conditions. In order to understand how to apply noise figure to op amps, we will first review the basic theory behind noise figure.

◆ **NF is usually specified for matched input/output conditions, but this is not always a system requirement**

◆ **Noise Figure is a popular figure of merit in RF applications: LNAs, Mixers, etc.**

◆ **Difficulties arise when applying NF to op amps. NF is dependent on**
- ● **Impedance levels**
- ● **Feedback network**
- ● **Closed loop gain**

◆ **Other difficulties arise due to different definitions of NF as found in various textbooks**

◆ **We will start with the basics and work up to the op amp issues**

Figure 1: Noise Figure (NF) in Communications Applications

AVAILABLE NOISE POWER

The first concept is that of *available power* from a source. The available power of a source is the maximum power that can be drawn from the source. Figure 2 below shows a resistor of value R as the noise source. The thermal noise of this source is $\sqrt{(4kTBR)}$. The maximum noise that can be transferred to an ideal noiseless load occurs when the load resistance is also equal to R.

Under these conditions, the maximum available noise power from the source reduces to kTB, where k is Boltzmann's constant, T is the absolute temperature, and B is the noise bandwidth. Note that this power is independent of the value of the source resistance, R.

The *available power*, P_a, of a source is the maximum power that can be drawn from the source. This occurs when the load resistance is equal to the source resistance.

$$P_a = \frac{v_n^2}{4R} = kTB$$

$v_n = \sqrt{4kTRB}$
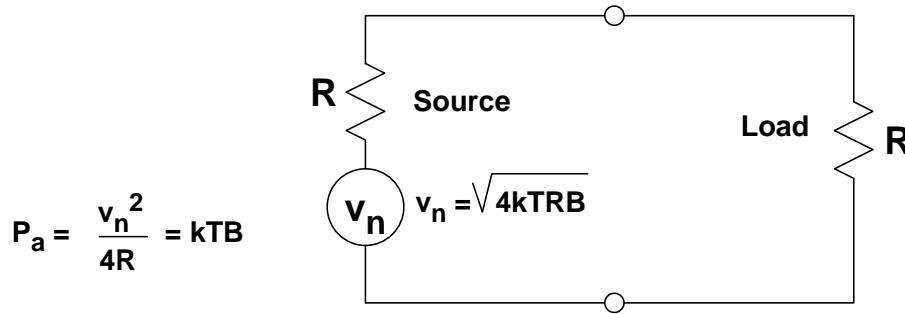
k = 1.38 × 10^{-23} Joules / K (Boltzman's Constant)
T = Temperature (assume 300K, room temperature)
B = Noise bandwidth (Hz)

$$P_{a\,(dBm)} = -174dBm + 10 \log B$$

Figure 2: Available Noise Power from a Source

AVAILABLE POWER GAIN

The next important concept is that of *available power gain* of a two-port network, as shown in Figure 3 below. The two-port network is driven from a signal source having an impedance R_S. The equations show the available signal power from the source and the available signal power from the output of the network. The available power gain is simply the ratio of the available output power to the available power from the source.

$V_O = AV_1$
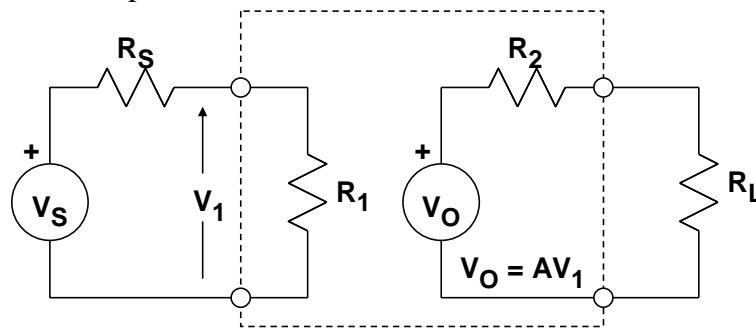
■ Available signal power from source $= P_{as} = \dfrac{V_S^2}{4R_S}$

■ Available signal power at output $= P_{ao} = \dfrac{V_o^2}{4R_2}$

■ Available power gain $= G_a = \dfrac{P_{ao}}{P_{as}} = \dfrac{V_O^2 R_S}{V_S^2 R_2}$

Figure 3: Available Power Gain of a Two-Port Network

DEFINITION OF NOISE FACTOR AND NOISE FIGURE

The gain and the noise of a two-port network can now be defined in terms of the available power gain, G, and the noise factor, F, as shown below in Figure 4. The noise factor, F, is defined as the ratio of the total available output noise power to the available output noise power due to the source only. For a resistive source, the available noise power from the source is simply kTB, and the output noise power due to the source only is G·kTB.
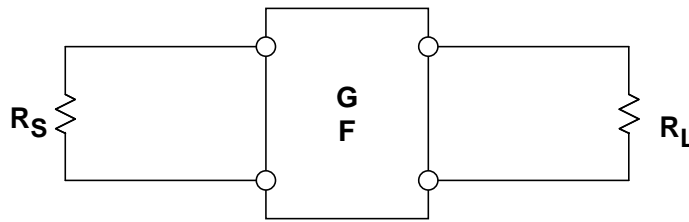
G = Available Power Gain of Network

$$F = \text{Noise Factor} = \frac{\text{Total Available Output Noise Power}}{\text{Available Output Noise Power Due to Source Only}}$$

$$= \frac{\text{Total Available Output Noise Power}}{G \bullet kTB}$$

$$NF = \text{Noise Figure} = 10 \log_{10} F$$

Figure 4: Definition of Noise Factor and Noise Figure
for a Two-Port Noisy Network.

Note that the noise factor, F, is expressed as a ratio, and the noise figure, NF, is simply the ratio F expressed in dB. An ideal noiseless two-port network therefore has noise factor F = 1, and a noise figure NF = 0 dB. We can use these same definitions to calculate the NF of an op amp circuit, however it is much easier to work in terms of the square of voltage noise spectral density and current noise spectral density, rather than power or power spectral density (see Figure 5 below). Also, unmatched conditions are easier to deal with using this approach.

The noise factor F for an op amp is simply the ratio of the square of the total output noise spectral density to the square of the output noise spectral density due to the source only. The noise figure NF = 10·logF.
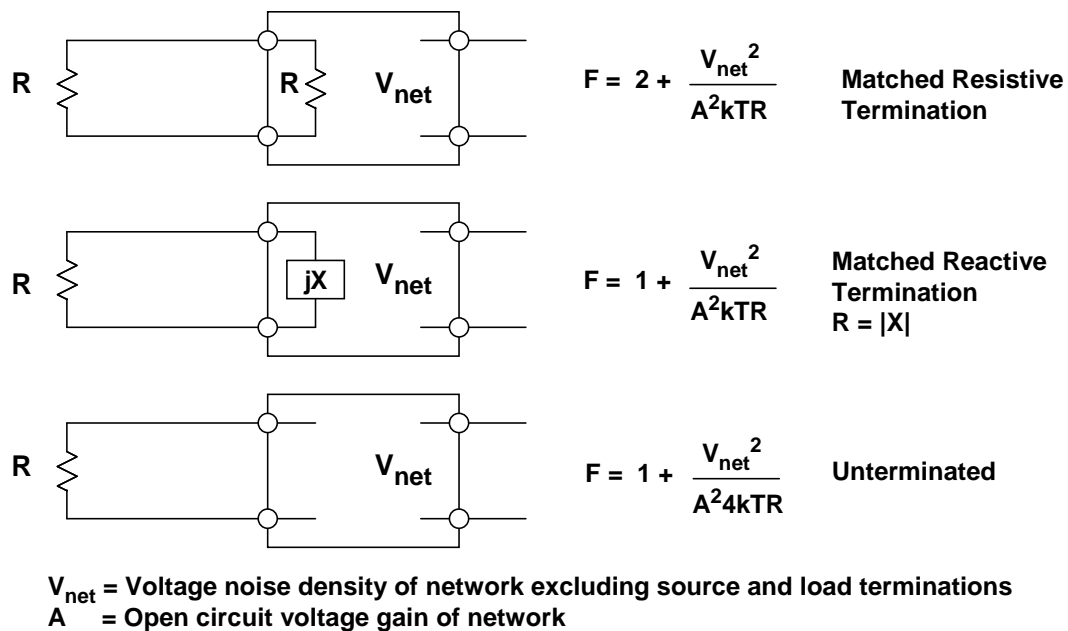
- ◆ **With op amps, it is easier to work with voltage and current noise spectral density, rather than power or power spectral density.**
- ◆ **Unmatched conditions are more easily dealt with using voltage noise spectral density analysis.**
- ◆ **Voltage noise spectral densities add using root-sum-squares (RSS).**
- ◆ **A 1000Ω resistor has a voltage noise spectral density of 4nV/√Hz @ 25°C (300K). (This is good to remember!)**
- ◆ **The basic definition of Noise Factor and Noise Figure in terms of voltage noise spectral density becomes:**

$$\text{Noise Factor} = F = \frac{(\text{Total Output Voltage Noise Spectral Density})^2}{(\text{Output Voltage Noise Spectral Density Due to Source Only})^2}$$

$$\text{Noise Figure} = NF = 10 \log_{10} F$$

Figure 5: Noise Figure for Op Amps

In RF or IF gain blocks, the input impedance is defined. However, when using an op amp in the non-inverting mode as a gain block, the input impedance is high (relative to transmission line impedances), and there are several options regarding the input termination which affect the noise figure. These options have been generalized to cover any two-port network with optional input terminations in Figure 6 below.

$$F = 2 + \frac{V_{net}^2}{A^2 kTR} \quad \text{Matched Resistive Termination}$$

$$F = 1 + \frac{V_{net}^2}{A^2 kTR} \quad \text{Matched Reactive Termination } R = |X|$$

$$F = 1 + \frac{V_{net}^2}{A^2 4kTR} \quad \text{Unterminated}$$

V_{net} = Voltage noise density of network excluding source and load terminations
A = Open circuit voltage gain of network

Figure 6: Noise Factor for Resistive, Reactive, and Unterminated Conditions

Assume that the open circuit voltage gain of the network is A and that the total output noise spectral density (excluding that due to the source resistance and the input termination) is equal to V_{net}.

The top diagram of Figure 6 shows the traditional matched case where the input is resistively terminated to match the source impedance. In this case, the input termination resistor not only attenuates the voltage noise of the source by a factor of 2 but also contributes noise due to its own thermal resistance.

The middle diagram of Figure 6 shows the case of a reactively matched termination. Reactive terminations are often used where the bandwidth is limited but centered on a high frequency carrier. In this case, the source voltage noise is attenuated by a factor of 2, but the reactive termination adds no additional noise of its own to the total output noise.

The bottom diagram in Figure 6 shows the case of an unmatched, unterminated input. In this case, the voltage noise of the source is not attenuated, and there is obviously no additional noise due to the input termination because there is no input termination! Although this situation is not likely in a system using RF/IF gain blocks which generally require impedance matching at all interfaces, it is a possibility when using an op amp as the gain block, since the non-inverting configuration input impedance is relatively high.

If we assume that the noise of the network, V_{net}, is very small relative to the source noise, then it is obvious that the input termination resistor adds 3 dB to the overall noise figure as well as reduces the overall voltage gain by a factor of 2. This is compared to the lowest noise case where there is no input termination. In fact, the lowest possible noise figure for a noiseless network with only an input resistive matched termination is 3 dB. Lower noise figures can be obtained only by using matched reactive terminations.

On the other hand, if the noise of the network, V_{net}, is very large with respect to the source noise, then adding the resistive termination increases the overall noise figure by 6 dB compared to the unmatched unterminated case.

Summarizing, it is interesting to note that using large source resistances will decrease the noise figure but increase overall circuit noise. This illustrates the important fact that *noise figures can be compared only if they are specified at the same impedance level*. In Figure 7 below these effects of amplifier input terminations on overall circuit noise and noise figure are summarized.

◆ **For a low noise network, adding the matching input termination resistor makes the noise figure 3dB worse. The voltage gain is also reduced by a factor of 2.**

◆ **For a high noise network, adding the matching termination resistor makes the noise figure 6dB worse.**

◆ **Reactive matched terminations are often used at fixed IF/RF frequencies in LNAs, mixers, etc.**

◆ **Using large source and termination resistors decreases noise figure but increases overall circuit noise.**

◆ **Noise figures should only be compared at the same impedance level.**

Figure 7: Effects of Input Termination on Noise Figure

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.

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