Outline

• How to find the least noisy amplifier for your application?

SNR, NF, etc.

• What you really want is the best SNR – Signal to noise ratio, or its db version – take the log of the ratio.

• SNR = 10 log_{10}(V_s^2 / V_n^2).
  – Usually, $V_n$ grows as the bandwidth of the amplifier increases, whereas $V_s$ stays the same once the bandwidth covers where the signal is. So it’s crucial that your amplifier covers only minimum necessary frequency band.
  – Bandpass filter gives you this.

• Since this figure cannot be specified for an op-amp (without knowing the signal level, $V_s$), we use NF to specify the inherent capability (figure of merit) of an amp, where the noise of the amp is compared to that of the inherent Johnson noise (at its input):

• NF = 10 log_{10}((V_n^2 + V_J^2) / V_J^2), where $V_n$ is the noise from the amp, and $V_J$ is the Johnson noise, which is an unavoidable noise.

• NF depends on the frequency as well as the source impedance, $R_s$ (only real part counts for noise!)
  – high $R_s$ makes $V_J$ large and masks $V_n$. This is not a real improvement of your circuit even though NF will improve.
  – Note that $V_n$ often depends on $R_s$.

• Usually, since you don’t have control over $R_s$, you should choose the amp with smallest NF for your $R_s$ and signal frequency.
  – Note that you could use a transformer to change $R_s$ if that really improves $V_n$.
  – Adding extra resister in series with the signal source to increase $R_s$, on the other hand, is not a good idea since it increases $V_J$ without increasing $V_s$ (often decrease it).

How can we reduce $V_n$?

• It is customary to specify the noise performance of an amplifier using $e_n$ and $i_n$.

• $e_n$ is the noise voltage which would be added to the signal at the input, whereas

• $i_n$ is the noise current which would flow from (to) the input and the signal source.

• They tell us that when a signal source of output impedance, $R_s$, and signal voltage $v_s$ is connected to this amp, you will find a voltage of $v_{out} = G\{v_s + e_n + (R_s i_n)\}$ at the output.

• In terms of RMS voltage, then the output voltage due to the noise is $v_{out\text{-rms}} = G\sqrt{e_n^2 + (R_s i_n)^2 + 4kTR_s}$.

• SNR = 10 log_{10}(v_s^2 / (e_n^2 + (R_s i_n)^2 + 4kTR_s))

Typical values of $e_n$ and $i_n$
• $e_n$ ranges from 1 nV/$\sqrt{\text{Hz}}$ to close to 1 µV/$\sqrt{\text{Hz}}$.
• $i_n$ ranges from 0.1 fA/$\sqrt{\text{Hz}}$ to close to 10 pA/$\sqrt{\text{Hz}}$.
• If I take LT1028, $e_n = 1$ nV/$\sqrt{\text{Hz}}$ and $i_n = 3$ pA/$\sqrt{\text{Hz}}$
• Since this amp has rather small $e_n$, it will perform well if the signal source has small $R_s$. But if $R_s$ is large, the increase in the noise due to $i_n$ is rapid and will not perform well.
• Instead you would choose something like OP-77 whose $e_n$ is 10 nV/$\sqrt{\text{Hz}}$, 10 times larger than LT1028, but $i_n = 0.1$ pA/$\sqrt{\text{Hz}}$.
• When $R_s$ is small, OP-77 does not perform nearly as well as LT1028 due to its large $e_n$. But for example, if $R_s = 100k\Omega$, OP-77 is better (14 nV/$\sqrt{\text{Hz}}$ vs. 300 nV/$\sqrt{\text{Hz}}$).
• Fig. 7.60 in page 449 of H&H illustrates this point graphically.
• Diagonal line represent the minimum noise (no noise from the amp) due to the Johnson noise of the signal source, $4kT R_s$.
• If $R_s$ is small LT1028 will give you the smallest noise whereas with larger $R_s$, OP27, OP37, LT1007 is better (1 k\$\Omega$) and OP77, LT1001 are better at 100 k\$\Omega$.
• In summary, if your signal source has large $R_s$, you want to choose small $i_n$ (noise current) amplifier. If $R_s$ is small, you should use small $e_n$ amp.

Effect of feedback circuit

• In real life, one almost never uses op-amp without negative feedback (to improve linearity, etc.). How does that affect the noise performance?

\[
V_+ = v_s + e_n + i_n R_s + v_R, \quad \text{where} \quad \langle v_R^2 \rangle = 4kT R_s.
\]
\[
V_- = e_n' + i_n' R_{//} + v_R + V_{\text{out}} *[R_1/(R_1+R_2)], \quad \text{where} \quad R_{//} = R_1//R_2 \quad \text{and} \quad \langle v_{R//}^2 \rangle = 4kT R_{//}.
\]
• Assuming the golden rule of op-amp circuit: $V_+ = V_-,$
• $V_{\text{out}} = [(R_1+R_2)/R_1][ v_s + e_n + i_n R_s + v_R - (e_n' + i_n' R_{//}) + v_R ]$
• Taking $\text{rms}$ noise voltages, $V_n^2 = \langle e_n^2 + (i_n R_s)^2 + v_R^2 + e_n' + (i_n' R_{//})^2 + v_{R//}^2 \rangle$.
• This should match with $V_n^2 = e_A^2 + (i_A R_s)^2 + 4kT R_s$. 

• Therefore, \( i_A^2 = i_n^2 \), and \( e_A^2 = e_n^2 + e_n'^2 + (i_n'R_{\text{r}})^2 + v_{R_{\text{r}}}^2 = 2e_n^2 + (i_n'R_{\text{r}})^2 + v_{R_{\text{r}}}^2 \), where we used that \( \langle e_n^2 \rangle = \langle e_n'^2 \rangle \) (the noise voltages for inverting and non-inverting inputs are the same – and independent).

• In H&H, \( 2e_n^2 \) is redefined as \( e_n^2 \) (“\( e_n \) is the adjusted noise voltage for the differential configuration, i.e. 3 dB larger than for a single-transistor stage.”)