Guest Lectures for Dr. MacFarlane's EE3350

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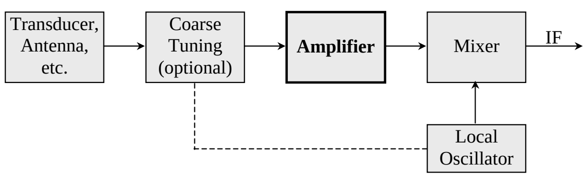
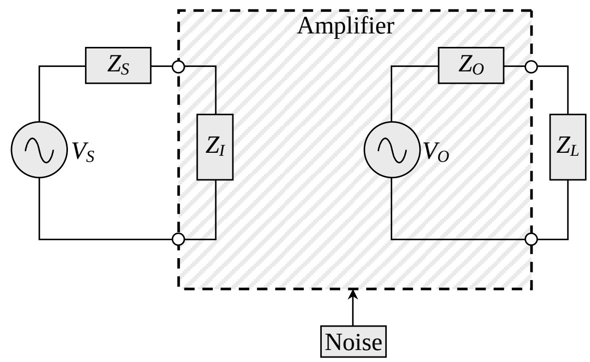
Sat., 11-08-2008

Write name in corner.

1. Problem Statement





- Formulas simplified, not applicable at RF
- *Noise Factor* given by:

$$F_0 = \frac{\text{(noise total @ output)}}{\text{(noise from src @ output)}} = 1 + \frac{\text{(noise from amp @ output)}}{\text{(noise from src @ output)}}$$

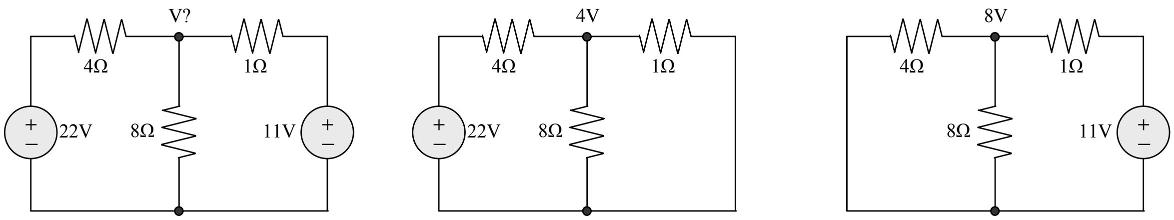
- Can be rewritten as:

$$F_0 = \frac{\text{(noise tot @ out)}}{\text{(gain)(src noise @ inp)}} = \frac{\text{(noise tot @ out)}}{\text{(gain)(src noise @ inp)}} \frac{\text{(sig @ inp)}}{\text{(sig @ out)}} = \frac{(\text{SNR})_{\text{in}}}{(\text{SNR})_{\text{out}}} > 1$$

- Will use previous formula here, but latter formula useful for nonlinear systems
- Measures noisiness of amp, *relative* to source noise
- *Noise Figure* — $NF = 10 \log_{10} F_0 > 0$ (dB)

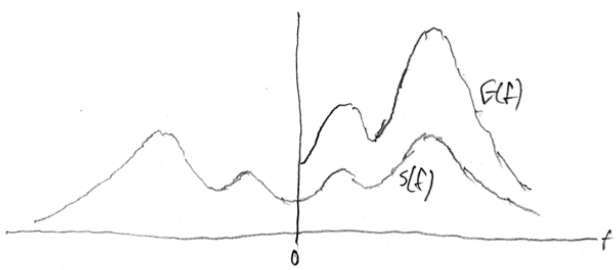
2. Superposition Review

- Short voltage, Open current



- We'll add RMS^2 output noise voltages

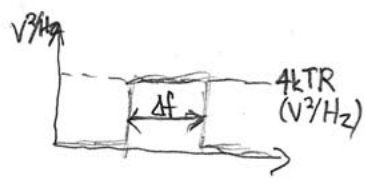
3. PSD Primer

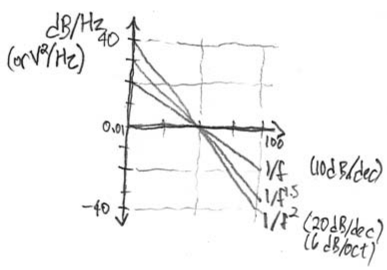


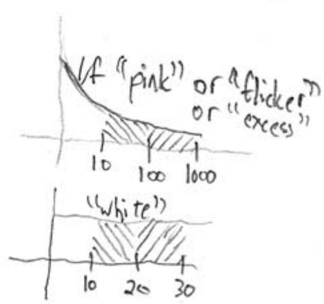
Bendat and Piersol p. 131

$$S_{xx}(f) = \int_{-\infty}^{\infty} R_{xx}(\tau) e^{-j2\pi f \tau}\, d\tau \qquad G_{xx}(f) = 2S_{xx}(f)$$

- FT of autocorrelation; used for random signals, while FT of signal itself used for deterministic signals
- We will use one-sided PSD here, as that is more common; 2-sided is half as large







$20\log_{10}\frac{V}{V_0} = 10\log_{10}\frac{V^2}{V_0^2}$

area $= 4kTR\,\Delta f\ \left(V^2\right)$

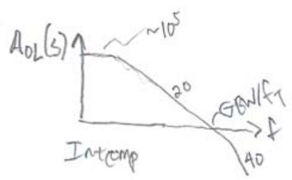
$V_{RMS} = \sqrt{\text{area}} = \sqrt{4kTR\,\Delta f}$

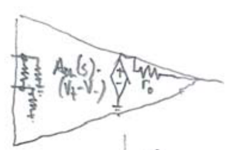
area $= {}^{4kT\,\Delta f}/_{R}\ \left(A^2\right)$

- talk ${}^{dB}/_{dec}$

- talk equal power per linear range or per decade/octave
- Johnson noise (WGN), $k \approx 1.38 \times 10^{-23}$ J/K, $k \approx 4 \times 10^{-21}$ J @289.9 K or 62.2 °F
- $^1/_f$ and $|H(\omega)|^2$ (Bode/Controls), origin annoyance, just use it
- Shot noise from discrete events (photons/electrons), rain on tin roof, white, area = $2qI\Delta f$ $\left(\mathrm{A}^2\right)$
- Reduced by metal film resistors and some types of feedback, not covered
- $q \approx 1.602 \times 10^{-19}$ C, shot: 1 mA$_{DC}$ $\Rightarrow$ 17.90 pA/$\sqrt{\text{Hz}}$, Johnson: 62.5 Ω @289.9 K $\Rightarrow$ 1 nV/$\sqrt{\text{Hz}}$
- Hit flicker, popcorn, avalanche

4. Nonideal Op Amp Primer





- Harry Black, 1927 negative feedback amp, 1934 paper, 1937 patent, permitted operational amplifiers, used in analog computers
- Talk input Z, gain, dominant pole, second pole, output resistance, internal compensation

- Talk about $^1/_f$, white, averaging operation to get effective noise
- Mention stability and second pole
- Mention ideal op-amp problem (equal V, 0 I), and the fact that another problem will come up
- Draw (not shown separately here) noisy ideal opamp, talk noise src dominance

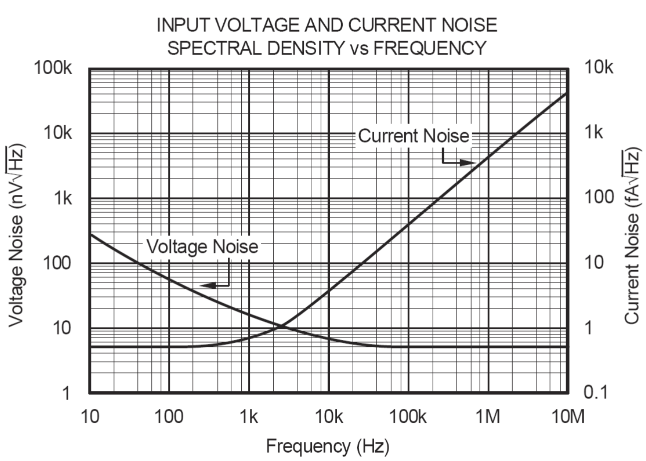
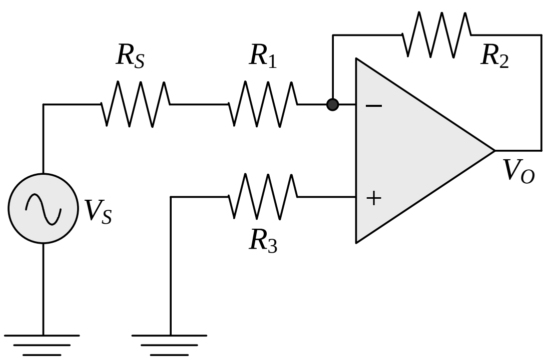


Figure 4.1: Noise in TI/BB OPA2350

- Good GP op-amp, chose arbitrary BW of 180 kHz to 220 kHz, meaning $\Delta f = 40000\,\text{Hz}$
- $e_n = 5\,{}^{\text{nV}}/\sqrt{\text{Hz}}$ or $e_{n'} = 1\,\mu\text{V}_{\text{RMS}}$
- Fit from 10k to 10MHz gives $i_n(f) \approx {}^{f}/_{2500}\,{}^{\text{fA}}/\sqrt{\text{Hz}}$

$$i_n \to \sqrt{\frac{1}{40000}\int_{180000}^{220000} \frac{f^2}{2500^2}\,\mathrm{d}f} \approx 80\,{}^{\text{fA}}/\sqrt{\text{Hz}} \text{ or } i_{n'} = 16\,\text{pA}_{\text{RMS}}$$

5. Inverting Operational Amplifier



- Define $R_1' = R_1 + R_S$. Choice of R_3 as either R_2 in parallel with R_1' or as zero. Talk bias I.
- $R_S = 75\,\text{k}$, $R_1 = 75\,\text{k}$, $R_2 = 300\,\text{k}$, $R_3 = 100\,\text{k}$, $R_1' = 150\,\text{k}$
- V_S, e_{RS}, and e_{R1} all see the same gain; e_{R3}, e_n, and $i_{np}R_3$ all see the same gain.

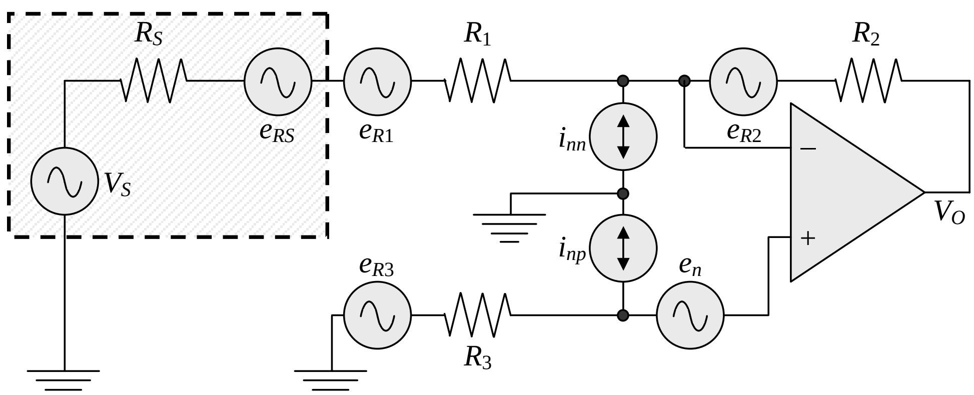


Figure 5.1: Noise Sources in Inverting Operational Amplifier

Source	Node Voltage	RMS	Noise $\left(\mu V^2\right)$
R_S		$e_{rs}R_2/R_1'$	192
R_1		$e_{r1}R_2/R_1'$	192
R_2		e_{r2}	192
R_3	$\frac{e_{r3}}{R_1'} = \frac{v_O - e_{r3}}{R_2}$	$e_{r3}\left(1 + R_2/R_1'\right)$	576
$e_{n'}$		$e_{n'}\left(1 + R_2/R_1'\right)$	9
i_{nn}	$i_{nn} + \frac{0 - v_O}{R_2} = 0$	$i_{nn}R_2$	23.04
i_{np}		$i_{np}R_3\left(1 + R_2/R_1'\right) = i_{np}R_2$	23.04

- Noise from amp at output:

$$\frac{1}{R_1'^2}\left[e_{r1}^2 R_2^2 + e_{r2}^2 R_1'^2 + e_{r3}^2\left(R_1' + R_2\right)^2 + e_{n'}^2\left(R_1' + R_2\right)^2 + i_{nn}^2 R_2^2 R_1'^2 + i_{np}^2 R_2^2 R_1'^2\right]$$
$$= \frac{1}{R_1'^2}\left[4kT\,\Delta f\left(R_1 R_2^2 + R_2 R_1'^2 + R_1' R_2\left(R_1' + R_2\right)\right) + e_{n'}^2\left(R_1' + R_2\right)^2 + i_{nn}^2 R_2^2 R_1'^2 + i_{np}^2 R_2^2 R_1'^2\right]$$

- Noise from src at output:

$$\frac{1}{R_1'^2}\left[4kT\,\Delta f\, R_S R_2^2\right]$$

- Johnson noise from amp is $960\,\mu V^2$ at output
- Other noise from amp is $55.08\,\mu V^2$ at output
- Johnson noise from src is $192\,\mu V^2$ at output
- $F_0 = 1 + 5 + \frac{459}{1600} \approx 6.3$ or $NF \approx 10\log_{10} 6.3 \approx 8.0\,\text{dB}$

6. Instrumentation Amplifier

- Talk CMRR (50-60 dB @ 200kHz) and high input Z ($10\,T\Omega$)

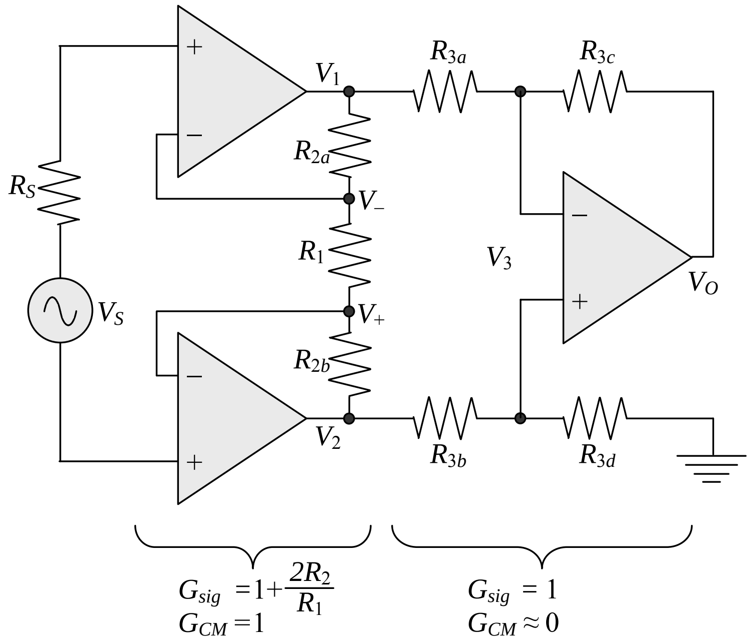


Figure 6.1: Noiseless Instrumentation Amplifier

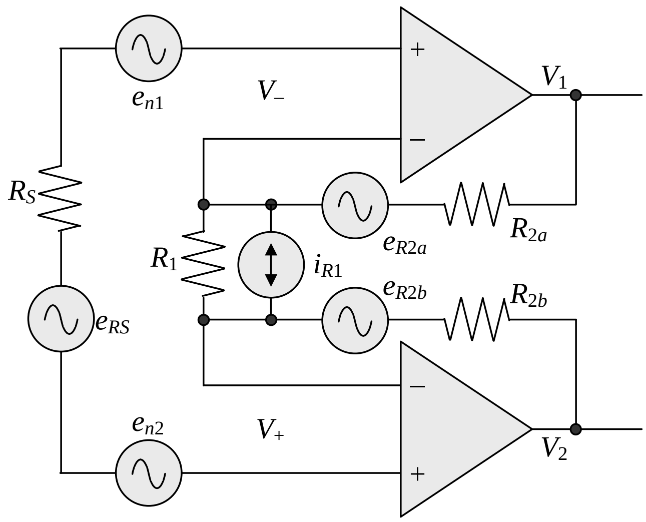
- $v_O - v_3 = v_3 - v_1$ and $-v_3 = v_3 - v_2$ give $v_O = v_2 - v_1$, so the difference propagates with unity gain through the final stage and the common mode signal is greatly attenuated.
- In the first stage:

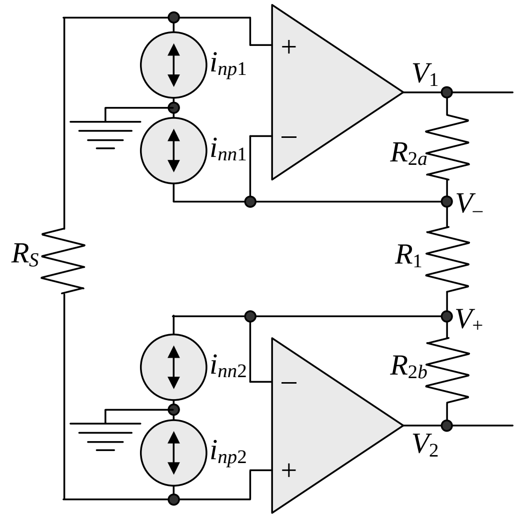
$$\frac{v_1 - v_-}{R_2} = \frac{v_- - v_+}{R_1} = \frac{v_+ - v_2}{R_2}$$

- Solving:

$$v_1 = \frac{(R_1 + R_2)\, v_- - R_2 v_+}{R_1}, \qquad v_2 = \frac{(R_1 + R_2)\, v_+ - R_2 v_-}{R_1}, \qquad v_2 - v_1 = (v_+ - v_-)\left(1 + \frac{2R_2}{R_1}\right)$$

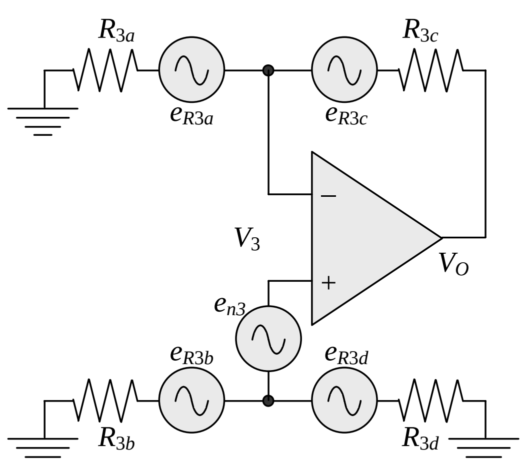
- Take $R_1 = 13\,\text{k}$, $R_2 = 91\,\text{k}$, $R_S = 10\,\text{M}$, $R_3 = 10\,\text{k}$.

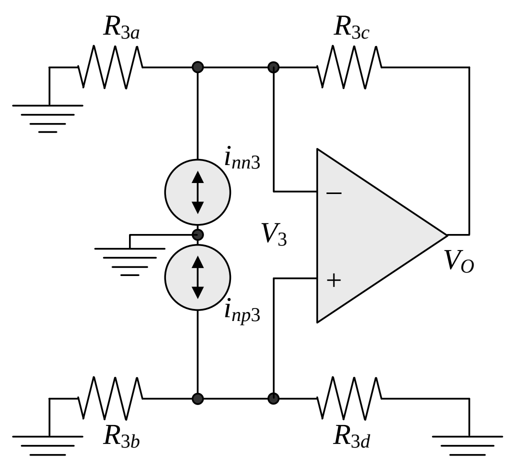




- e_{n1}, e_{n2} and e_{RS} all see the same gain; e_{R2a} and e_{R2b} see the same gain; i_{np1} and i_{np2} see the same gain; i_{nn1} and i_{nn2} see the same gain

Source	Node Voltage	RMS	Noise $\left(\mu V^2\right)$
R_S		$e_{RS}G$	1 440 000
e_{n1}		$e_{n'}G$	225
R_1	$\frac{v_1}{R_2} = i_{R1} = \frac{-v_2}{R_2}$	$2i_{R1}R_2 = e_{R1}(G-1)$	1631
R_{2a}	$\frac{v_1 - e_{R2a}}{R_2} = 0 = \frac{-v_2}{R_2}$	e_{R2a}	58.24
i_{nn1}	$i_{nn1} - \frac{v_1}{R_2} = 0 = \frac{v_2}{R_2}$	$i_{nn}R_2$	2.120
i_{np1}	$i_{np1} = \frac{v_+ - v_-}{R_S}$	$i_{np}R_SG$	5 760 000





- R_{3b} and R_{3d} see the same gain.

Source	Node Voltage	RMS	Noise $\left(\mu\text{V}^2\right)$
R_{3a}	$\frac{e_{R3a}}{R_3} = \frac{-v_O}{R_3}$	e_{R3a}	6.4
R_{3b}	$\frac{e_{R3b}/2}{R_3} = \frac{v_O - e_{R3b}/2}{R_3}$	e_{R3b}	6.4
R_{3c}	$\frac{v_O - e_{R3c}}{R_3} = 0$	e_{R3c}	6.4
e_{n3}	$\frac{e_{n3}}{R_3} = \frac{v_O - e_{n3}}{R_3}$	$2e_{n'}$	4
i_{nn3}	$i_{nn3} + \frac{-v_O}{R_3} = 0$	$i_{nn}R_3$	0.0256
i_{np3}	$\frac{i_{np3}R_3/2}{R_3} = \frac{v_O - i_{np3}R_3/2}{R_3}$	$i_{np}R_3$	0.0256

- Johnson noise due to source is $1\,440\,000\,\mu\text{V}^2$
- Johnson noise due to first stage of amp is $1747\,\mu\text{V}^2$
- Opamp noise in first stage is $11\,520\,500\,\mu\text{V}^2$
- Johnson noise due to second stage of amp is $25.6\,\mu\text{V}^2$
- Opamp noise in second stage is $4.05\,\mu\text{V}^2$
- Noise Factor, with current noise on first stage broken off separately:

$$F_0 \approx 1 + 0.001549 + 8 = 9.001549\,, \qquad NF \approx 10\log_{10} 9.001549 \approx 9.54\,\text{dB}$$

- At very high source impedances, opamp current noise “dominates”.

7. Loose Ends

- Draw a string of single-wire amps with G,F written in. Friis:

$$F_{1,2} = F_1 + \frac{F_2 - 1}{G_1}$$
$$F_{1,2,3} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2}$$
$$\ldots$$

References:

- `SLOD006B` Op Amps for Everyone
- `SLVA043B` Noise Analysis in Operational Amplifier Circuits
- Bendat and Piersol — Random Data: Analysis and Measurement Procedures
- Davenport and Root — An Introduction to the Theory of Random Signals and Noise
- Horowitz and Hill — The Art of Electronics
- Bob Pease — Troubleshooting Analog Circuits