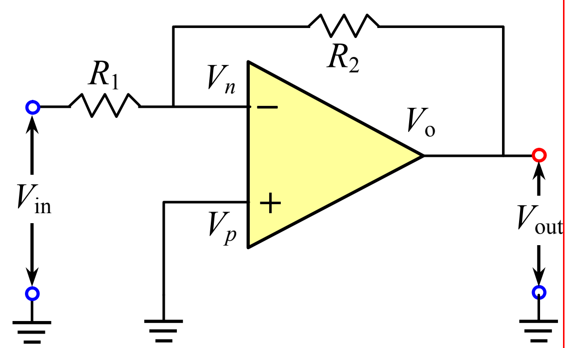
Today, we will:

(Gain Bandwidth Product)

- Do another example problem – op-amps with GBP effects.
- Begin the pdf module: **Stress, Strain, and Strain Gages**, and do some examples.

Example: Op-amp circuit with GBP effects

Given: Ben amplifies the voltage output of a microphone by a factor of 1000 using an inverting amplifier as sketched, with $\boldsymbol{R_1} = \mathbf{1.00\ k\Omega}$ and $\boldsymbol{R_2} = \mathbf{1.00\ M\Omega}$. The quality of the amplified music sounds odd to Ben, particularly at high frequencies, but he is clueless as to why this is happening. His friend Ashley took M E 345 and remembers something about GBP effects with op-amps. She looks up the specs for Ben's op-amp: $\mathbf{GBP_{noninverting} = 0.450\ MHz}$. She explains to Ben that his op-amp is acting like a first-order low-pass filter, and that is why he is losing some of the high frequencies in his music.



$$G_{theory} = -\frac{R_2}{R_1} = \frac{-1000\ k\Omega}{1.00\ k\Omega} = -1000\ ✓$$

To do:

(***a***) Calculate the internal cutoff frequency of this op-amp circuit.

(***b***) Compare the *theoretical* gain and the *actual* gain of this circuit at f = 10,000 Hz.

Solution:

(a) • For an inverting op-amp amplifier we need to convert the GBP manufacturer's spec from noninverting [the spec for GBP is given for noninverting amplifiers]

• From the learning module,

$$\boxed{GBP_{inverting} = -\frac{R_2}{R_1+R_2} GBP_{noninverting}}$$

(notice that $GBP_{inverting}$ is negative)

$$= -\frac{1000\ k\Omega}{(1+1000)\ k\Omega}(0.450\ MHz) = -0.44955\ MHz$$

• The rest of the algebra is pretty much the same as for noninverting amplifiers:

$$f_c = \frac{GBP_{inverting}}{G_{theory}} = \frac{-0.44955\ MHz}{-1000} = \boxed{449.55\ Hz = f_c}$$

[This circuit acts like a low-pass filter with f_{cutoff} = 449.55 Hz !]

This is the "GBP effect"

(b) At f = 10,000 Hz, $G_{actual} = G_{theory}\, G_{GBP,\,inverting} = \left(-\frac{R_2}{R_1}\right)\frac{1}{\sqrt{1+(f/f_c)^2}}$ (G_{theory})

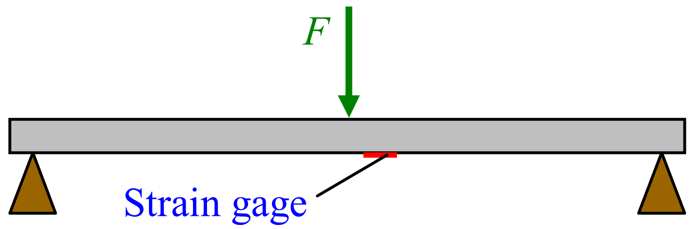
numbers: $\boxed{G_{theory} = -1000}$ but $G_{actual} = -1000\frac{1}{\sqrt{1+(10{,}000/449.55)^2}} = \boxed{-44.9 = G_{actual}}$

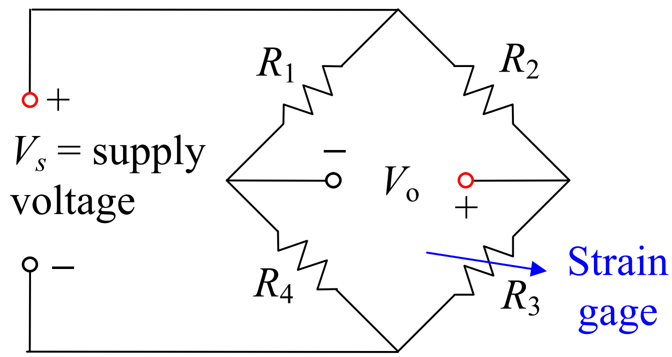
★ Ben should use a 2-stage amplifier !

Smaller by a factor > 20 !

Example: Strain gages

Given: We are measuring the strain on the surface of a beam. The beam's modulus of elasticity is E = 193 GPa. We use one strain gage on the bottom of the beam, as shown; the strain gage factor is S = 2.02. We construct a quarter bridge Wheatstone bridge circuit, with the strain gage on resistor 3, as sketched below. All resistors, including the strain gage itself (when unloaded) are 120 Ω. The supply voltage is 5.00 V DC, and the bridge is initially balanced when there is no load.

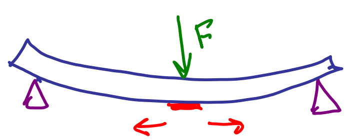




(*a*) To do: Will V_o be positive or negative when a downward load is added?

Solution: When we push down, the strain gage will stretch (positive strain)

(R increases when the strain gage is in tension)



(The strain gage is in tension.)

∴ Therefore, δR_3 is positive when we apply the force.

⊕ for ⊕F

Recall from the pdf notes:
$$\frac{V_o}{V_s} \approx \frac{R_{2,\text{initial}} R_{3,\text{initial}}}{\left(R_{2,\text{initial}} + R_{3,\text{initial}}\right)^2}\left(\cancel{\frac{\delta R_1}{R_{1,\text{initial}}}} - \cancel{\frac{\delta R_2}{R_{2,\text{initial}}}} + \frac{\delta R_3}{R_{3,\text{initial}}} - \cancel{\frac{\delta R_4}{R_{4,\text{initial}}}}\right)$$

δR_1, δR_2, δR_4 all = 0 since these are just fixed resistors in the bridge.

δR_3 is the only non-zero change in resistance, and it is ⊕ when F is ⊕

∴ So,
$$\boxed{V_o \approx V_s \frac{R_{2,\text{initial}} R_{3,\text{initial}}}{\left(R_{2,\text{initial}} + R_{3,\text{initial}}\right)^2} \frac{\delta R_3}{R_{3,\text{initial}}}} \quad (1)$$

Answer: $\boxed{V_o \text{ is positive when F is positive downward}}$

(Always wise to have V_o increase & ⊕ve when F is increasing & ⊕ve)

(b) To do: For a loading in which V_o = 1.25 mV, calculate the strain ε_a in units of microstrain.

Solution: LONG WAY:

• For $V_o = 1.25$ mV, we use the equation for strain vs resistance:

$$\frac{\delta R}{R} = S\varepsilon_a \rightarrow \varepsilon_a = \frac{\delta R}{RS} = \frac{\delta R_3}{R_{3,\text{initial}}} \cdot \frac{1}{S}$$

• But, using Eq. (1) of Part (a), we know that

$$\frac{\delta R_3}{R_{3,\text{initial}}} = \frac{V_o}{V_s}\frac{(R_{2,\text{initial}} + R_{3,\text{initial}})^2}{R_{2,\text{initial}} \cdot R_{3,\text{initial}}}$$

Plug this into here

• Algebra ...

$$\boxed{\varepsilon_a = \frac{1}{S}\frac{V_o}{V_s}\underbrace{\left[\frac{(R_{2,\text{initial}} + R_{3,\text{initial}})^2}{R_{2,\text{initial}} \cdot R_{3,\text{initial}}}\right]}}$$

Note that if $R_{2,\text{initial}} = R_{3,\text{initial}}$, $[\;] = 4$

• Numbers

$$\varepsilon_a = \frac{1}{2.02}\frac{1.25\times10^{-3}\text{ V}}{5.00\text{ V}}\left[\frac{(120\,\Omega + 120\,\Omega)^2}{120\,\Omega \cdot 120\,\Omega}\right] = \underline{\underline{4.950\times10^{-4}}}$$

• In units of microstrain, $\varepsilon_a = 4.950\times10^{-4}\left(\frac{10^6\,\mu\text{strain}}{1}\right) = 495.\,\mu\text{strain}$

unity conversion factor

(to 3 digits)

Answer: $\boxed{\varepsilon_a = 495.\,\mu\text{strain}}$

SHORT WAY:

OR, Use our approximate eq. for a quarter bridge Wheatstone bridge:

$$\boxed{\varepsilon_a = 4\frac{V_o}{V_s}\frac{1}{S}} = 4\frac{1.25\times10^{-3}\text{ V}}{5.00\text{ V}}\frac{1}{2.02}\left(\frac{10^6\,\mu\text{strain}}{1}\right) = \boxed{495.\,\mu\text{strain}}$$

(*c*) To do: If the material is cold work tool steel with modulus of elasticity E = 193 GPa (at room temperature), calculate the axial stress (in MPa) in the beam under this load.

Solution:

$$\boxed{\sigma_a = E \cdot \varepsilon_a}$$

axial strain

axial stress

Young's modulus

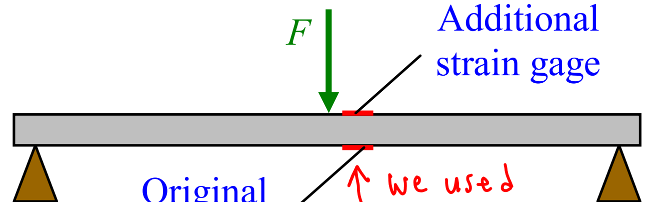
Be careful – power of 10 errors

mega = 10^6
micro = 10^{-6}
giga = 10^9

from Part (b)

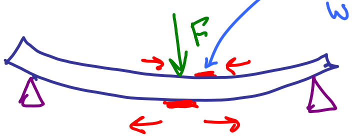
Here, $\sigma_a = \left(193 \times 10^9 \frac{N}{m^2}\right)\left(4.950 \times 10^{-4}\right)\left(\frac{1\ Pa}{N/m^2}\right)\left(\frac{1\ MPa}{10^6\ Pa}\right) = \boxed{95.5\ MPa = \sigma_a}$

(*d*) To do: Suppose we want more sensitivity, so we glue another strain gage on *top* of the beam. Which resistor should we use for this second active strain gage?



we used R_3 for this strain gage

Solution:



The top strain gage will be in compression when F is applied → δR is negative

So, we pick one of the R's in the bridge that has a negative sign:

Again from the pdf notes:
$$\frac{V_o}{V_s} \approx \frac{R_{2,\text{initial}} R_{3,\text{initial}}}{\left(R_{2,\text{initial}} + R_{3,\text{initial}}\right)^2}\left(\frac{\delta R_1}{R_{1,\text{initial}}} - \frac{\delta R_2}{R_{2,\text{initial}}} + \frac{\delta R_3}{R_{3,\text{initial}}} - \frac{\delta R_4}{R_{4,\text{initial}}}\right)$$

(+) (−) (+) (−)

Answer: $\boxed{\text{Pick either } R_2 \text{ or } R_4}$ so that $V_o = -(-\delta R) = (+)$ when F is applied

(*e*) To do: For the setup of Part (d) with the same strain as in Part (b), calculate output voltage V_o.

Solution: · We have doubled the sensitivity of the circuit → it is now a half-bridge circuit. $n = 2$ for a half bridge

· So, the voltage also doubles: $V_o = V_s \varepsilon_a \frac{n}{4} S = (5.00\text{V})(4.95 \times 10^{-4})\frac{2}{4}(2.02) = \boxed{V_o = 2.50\ mV}$