Lecture 11/19/24

Inertial Sensors (MEMS Gyroscopes)

1) Error sources in vibrational MEMS gyroscopes

From last time, we derived this simplified equation to model the operation of our MEMS gyroscope:

$$V_{OUT} = \frac{4nn_x\beta bmt\varepsilon_o^2\varepsilon_r^2V_D^2V_bV_xR_b}{c^2x_od}\Omega$$

Which can be reduced to:

$$V_{OUT} = K\Omega$$

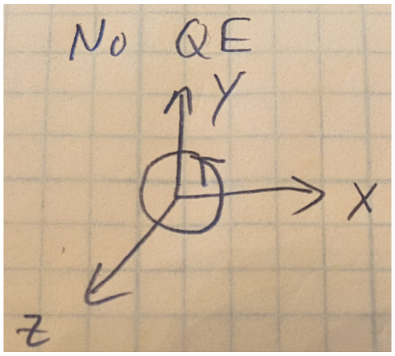
Where V_{OUT} is a DC voltage proportional to **Ω**, and K is a "constant":

$$K = \frac{4nn_x\beta bmt\varepsilon_o^2\varepsilon_r^2V_D^2V_bV_xR_b}{c^2x_od}$$

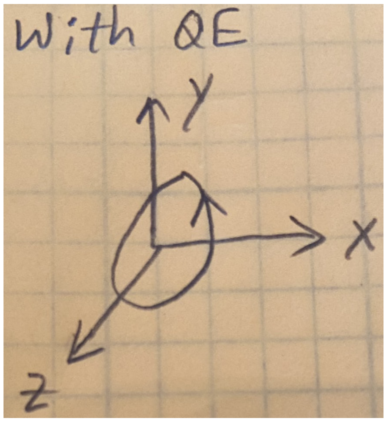
a. Fabrication and component tolerances

Many of the terms in K are design, fabrication, and component terms, which only approximate actual values. Actual values for fabrication dependent terms can lead to Quadrature Error (QE) where small imbalances in k_x, k_y, and m_x, and m_y values lead to non-ideal movement of the proof mass:

When the system is balanced (i.e. no QE), if the proof mass is equally perturbed in both the x and y directions, it's resulting motion should be circular (until coming to rest):



However, if the k and c terms are unbalanced ($k_x \neq k_y$, $c_x \neq c_y$), and the proof mass is perturbed equally in the x and y directions and released, the resulting proof mass motion will be non-circular:



Therefore, the resulting V_{OUT} signal will have some inaccuracies due to this effect. This is not due to design errors, but rather to the tolerances achievable in microfabrication.

b. Translational acceleration

The gyroscope's proof mass will experience inertial forces when the gyroscope is translationally accelerated, and it will respond like an accelerometer's proof mass.

This can result in a translational acceleration dependent bias shift in V_{OUT}.

One way to mitigate this effect is to fabricate two “identical” gyroscopes on the same chip, where they operate 180$^{\text{o}}$ out of phase with respect to each other. This results in each V_{OUT} signal having the same magnitude but opposite sign. However, a translational acceleration will add the same bias to each output signal, and can therefore be corrected for (one V_{OUT} increases while the other V_{OUT} decreases). One bonus, though, is that the system can also detect translational acceleration, although determining its direction could be challenging.

c. Temperature

Most MEMS gyroscopes are strongly affected by temperature. It has been said that MEMS gyroscopes are better at measuring temperature than angular rate…

Therefore, a temperature sensor is often integrated into a MEMS gyroscope so that temperature can be measured and its effects compensated for.

d. Mechanical shock

Large mechanical shock events can cause the proof mass to impact surrounding structures on the chip (frame, springs, etc.).

This can temporarily or even permanently affect gyroscope performance.

e. Vibration and acoustic signals

Most MEMS gyroscopes have: 3 kHz < f_n < 20 kHz.

This frequency range is also the audio frequency range, and the mechanical vibration frequency range for some mechanical systems.

Environmental "vibroacoustic" components at f_n can couple into the high Q MEMS gyroscope and interfere with proof mass motion, resulting in a corrupted gyroscope output signal.

f. Noise sources

Noise sources are present in the MEMS gyroscope's mechanical and electrical systems:

(1) Thermal noise, shot noise, and 1/f noise in electrical/electronic components

(2) Thermal noise in the mechanical portion: all energy dissipative systems experience thermal noise (electrical systems → in resistances, mechanical systems → in damping mechanisms)

This will make the gyroscope's output signal noisy.

g. Misalignment

The gyroscope measures rotation rate about one axis (the z-axis as we have defined its operation).

If the gyroscope is mounted so that it is not exactly aligned with respect to the desired z-axis (the desired axis for angular rate measurement), then the sensor's output will not exactly be Ω_z.

h. Intermode coupling

If two or more high Q MEMS gyroscopes with the same or close f_n's are placed in close proximity, they can interfere with each other through mutual mechanical excitation (i.e. they vibrate each other). This will lead to error in their measurements.

Proper chip level packaging can mitigate this problem.

i. Simplification assumptions

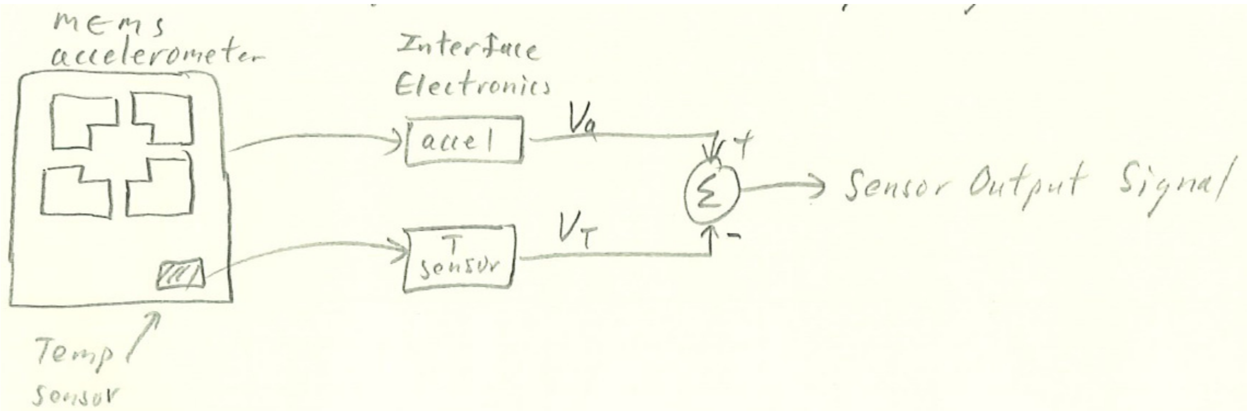
The higher level effects we ignored are there and will have real effects on gyroscope performance.

Temperature Sensors

2) Background

Many microdevices (MEMS and electronics) are highly sensitive to temperature (internal and external).

Therefore, it is often desirable to measure temperature and compensate for the effects of temperature change on an output signal.



However, this approach requires knowledge of how the sensor's output varies with temperature.

3) Types of temperature sensors

a. Temperature dependent resistors

We discussed these earlier in the semester:

$\rho(T) = \rho_o(1 + \alpha_T T + \beta_T T^2) \approx \rho_o(1 + \alpha_T T)$ → for metals

ρ_o → resistivity at a reference temperature, T_o.

Example: for some ρ_o → $R_o = 100\ \Omega$ at 0°C

α_T → linear temperature coefficient of resistivity.

Example: platinum: $\alpha_T = 3.9\text{x}10^{-4}\ /^{o}\text{C}$

Platinum 100 (Pt100): a commonly used temperature measurement resistor (100 Ω at 0°C).

However, platinum is not a commonly used microfabrication material.

b. Thermistors

The thermoresistive characteristics of semiconductor materials often have the following relationship:

$$\rho(T) = \rho_{ref} e^{\left[B\left({}^{1}/_{T} - {}^{1}/_{T_{ref}}\right)\right]}$$

T_{ref} is often 25°C. However, the T and T_{ref} values in the equation are usually in the units of Kelvin.

B is the "B value", and is defined as $B_{T1/T2}$ where T1 and T2 define the temperature range over which the equation with this B value is valid. For example, $B_{25/100}$ defines a thermistor that is defined for temperatures between 25°C and 100°C. Typical B values might be between 3000 and 5000 over this temperature range.

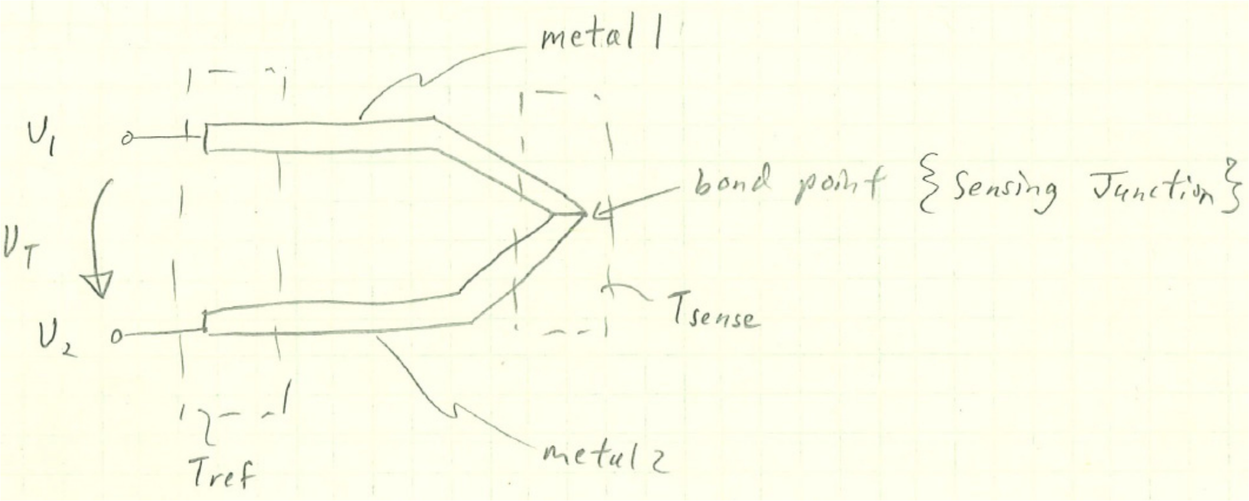
ρ(T) has a large change over a small temperature range, but the effect is nonlinear.

Thermistors can be very low cost and can be made out of semiconductor-based metal oxides. They are often used in electronic medical thermometers (very small temperature range).
A variety of common metal oxides are actually semiconductors.
Examples:

Zinc oxide (ZnO) – used in sunscreen
Titanium dioxide ($TiO2$) – used as white food coloring
Indium tin oxide (ITO) – transparent conductor

c. Thermocouples (thermopiles)

We already discussed thermocouples earlier in the semester (9/26/24). They are based on the Seebeck effect with two dissimilar metals bonded at a sensing junction:



T_{sense} is the temperature being sensed, and T_{ref} is a reference temperature.

V_T is the open circuit voltage appearing on the left end.

$$V_T = V_2 - V_1 = (P_2 - P_1)\left(T_{sense} - T_{ref}\right) = (P_2 - P_1)\Delta T$$

P_1 and P_2 are the Seebeck coefficients for the two metals. This is a thermocouple.

The theromocouple only produces a small current before the output voltage drops: it has a large output impedance. So, a high (very high) impedance voltage meter (amplifier) is needed to accurately read it.

Thermocouples can be made in macroscale or in microscale (on chip) technologies.