ECEN 5053-003 Homework Assignment

Course Name: Embedding Sensors and Actuators
Corresponding Module: C3M3
Week Number: 11
Module Name: Position Sensors
Student Name: Rushi James Macwan

Note: Correct answer is in Blue Font

Homework is worth 100 points.

Part 1: Each question is worth 8 points.

A. Answer the following questions about capacitive proximity detectors.

A.1 What is the sensing face of a capacitive proximity detector? How does the size of the sensing face affect the sensing distance and why?

Sol.

Sensing face is the side of the capacitive proximity detector that is exposed to the object that is to be detected. This is the side of the capacitive proximity detector that actually responds to a change in the dielectric medium surrounding the active face or otherwise called a sensing face outside the capacitive proximity detector. It can be tuned to sense almost any substance.

The size of the sensing face is defined by the electrodes. The larger the measuring electrode, the larger the electrical field and the greater the sensing distance. Moreover, the greater the size of the sensing face in terms of its diameter, the greater the sensing distance will be for a capacitive proximity detector.

Courtesy: Reference Links: [1] [2] [3]

A.2 How does a capacitive proximity detector manifest temperature drift?

Sol.

Within the specified temperature range, the effective sensing distance S_r can change in relation to the nominal sensing distance Sn by the specified range.

Courtesy: Reference Links: [1]

A.3 How are Baumer capacitive detection sensors protected against users supplying the incorrect input voltage or current?

Sol. The Baumer capacitive detection sensors are protected against users supplying the incorrect input voltage or current using two protection types: short-circuit protection and reverse polarity protection. Using these protection types, the sensors are protected against voltage peaks, short circuits and reverse polarity. Also, a residual ripple VR of max. 10% of the direct current average values is tolerated by the sensor within the input over-shot and under-shot limits.

Courtesy: Reference Links: [1]

A.4 What is a standard target for a capacitive detection sensor?

Sol.

The standard target is a predefined part used for comparative measurement of sensing distances and scanning ranges. The standard target is square, 1 mm thick and made of Fe 360 (ST 37). The side length corresponds to either the diameter of the sensing face or the triple nominal sensing distance Sn, the respectively higher value being definitive. The target must be grounded.

Courtesy: Reference Links: [1]

A.5 What is the difference between the usable sensing distance and effective sensing distance of a capacitive proximity switch?

Sol.

Usable sensing distance S_u is the sensing distance of an individual proximity switch measured over the temperature range and at a supply voltage of 85% and 110% of the rated value. For capacitive proximity switches it must be between 80% and 120% of the effective sensing distance.

Effective sensing distance S_r is the sensing distance of an individual proximity switch which is measured at a defined temperature, voltage and installation conditions. For capacitive proximity switches it must be between 90% and 110% of the nominal sensing distance at 23 ±5 °C

Courtesy: Reference Links: [1]

A.6 What is the difference in a capacitive detection switch between a PNP output and an NPN output?

Sol.

Sensors with a PNP or NPN output have a 3-wire design (+Vs, output and 0 V) and operate with direct current (DC). The load resistance of PNP sensors is between output and 0 V (pull-down resistance), while load resistance of NPN sensors is between +Vs and output (pull-up resistance). As a result, the PNP output is connected to the positive voltage supply during switching (positive switching output), whereas the NPN output is connected to the negative voltage supply during switching (negative switching output).

Courtesy: Reference Links: [1]

A.7 What is the difference between normally open (NO) and normally closed (NC) contacts in a capacitive detection switch?

Sol.

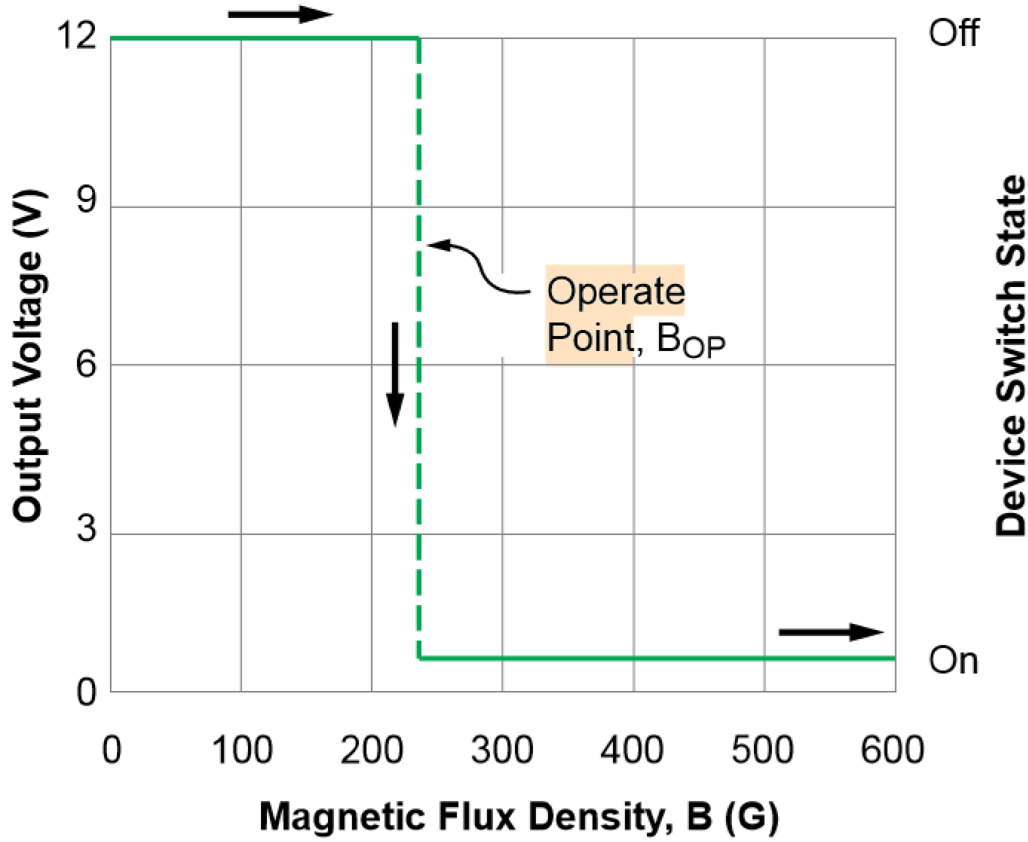
Normally open contacts and/or normally closed contacts define the switching function. Normally open contacts are referred to as normally open (NO), normally closed contacts as normally closed (NC). During damping with an object, sensors with normally open function establish contact connections (Uz = high), while sensors with normally closed function disconnect connections (Uz = low).

Courtesy: Reference Links: [1]

B. Answer the following questions about magnetic position detectors.

B.1 What is the difference between the magnetic operating point and the magnetic release point in a hall effect switch?

Sol.

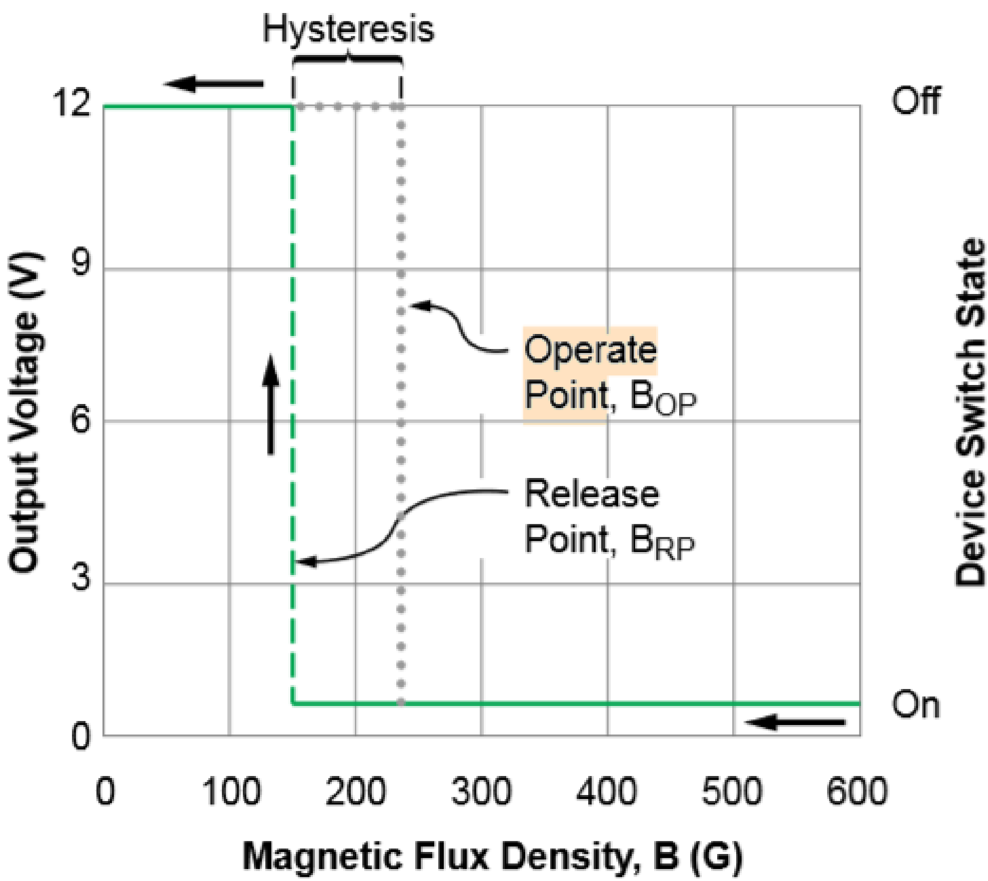


As shown in figure 9, in the absence of an applied magnetic field (0 G), the switch is off, and the output voltage equals the power supply due to the action of an external pull-up resistor. A permanent magnet south pole is then moved perpendicularly toward the active area of the device. As the magnet south-pole approaches the branded face (for a planar Hall device) or the sensitive edge (for a vertical Hall device) of the switch, the Hall element is exposed to increasing positive magnetic flux density.

At some point (240 G in this case), the output transistor turns on, and the output voltage approaches 0 V. That value of flux density is called the operate point, BOP.

Continuing to increase the field strength has no effect; the switch has already turned on, and stays on. There is no upper limit to the magnetic field strength that may be applied to a Hall-effect sensor.

To turn the switch off, the magnetic flux density must fall to a value far lower than the 240 G operate point because of the hysteresis of the device (these types of charts are sometimes referred to as hysteresis charts). For this example, a 90 G hysteresis is used, which means the device turns off when the flux density decreases to 150 G (figure 10). That value of flux density is called the release point, BRP.



To summarize, the operate point is that point at which the hall sensor turns on and remains in the on state until the magnetic flux density falls below a given point when the hall sensor turns off. That tripping point is the release point. Once again, the hall sensor remains off until it reaches the operate point once again.

Thus, the operate point provides a flag that the device is in the ON state and once it falls below the release point it provides a flag that the device is OFF state as long as the operate point is not reached once again.

Courtesy: Handbook of Modern Sensors
Reference Links: [1] [2] [3] [4]

B.2 What is the difference between the output fall time and output rise time in a hall effect switch?

Sol.

Fall time – A measure of the time required for the output voltage of a circuit to change from a high voltage level to a low voltage level, once a level change has started.

Rise time – A measure (10% to 90%) of the time required for the output voltage to rise from a state of low voltage level to a high voltage level, once a level change has been started.

Courtesy: Reference Links: [1] [2]

B.3 What does the term "Single Axis Sensitivity" mean in the context of an LVDT?

Sol.

An LVDT responds to motion of the core along the coil's axis, but is generally insensitive to cross-axis motion of the core or to its radial position. Thus, an LVDT can usually function without adverse effect in applications involving misaligned or floating moving members, and in cases where the core does not travel in a precisely straight line. This means that that the LVDT operates with a sensitivity only in one direction and therefore it is termed as Single Axis Sensitivity.

Courtesy: Reference Links: [1] [2] [3]

B.4 Why is an LVDT an absolute output device? What is the advantage of such a device?

Sol.

An LVDT is an absolute output device, as opposed to an incremental output device. A linear variable differential transformer (LVDT) is an absolute measuring device that converts linear displacement into an electrical signal through the principle of mutual induction. LVDT linear transducers can be up to several inches long, working as an absolute position sensor which is repeatable and reproducible.

This means that in the event of loss of power, the position data being sent from the LVDT will not be lost. When the measuring system is restarted, the LVDT's output value will be the same as it was before the power failure occurred.

Such devices offer a data retention advantage that they do not lose the output in case of a power failure.

Courtesy: Reference Links: [1] [2] [3]

B.5 The LVDT is known as a fast-dynamic response sensor. What are two limiting factors to its speed of response?

Sol.

The absence of friction during ordinary operation permits an LVDT to respond very fast to changes in core position. The dynamic response of an LVDT sensor itself is limited by the inertial effects of the core's slight mass. More often, the response of an LVDT sensing system is limited by the characteristics of the signal conditioner.

Courtesy: Reference Links: [1] [2] [3]

B.6 What does null point repeatability mean? What applications are well suited for an LVDT given its null point repeatability?

Sol.

The series-opposed winding of the secondary coils in an LVDT means that when the core is at the center of the transformer (equidistant between the two secondary coils), the induced voltages have equal amplitude but are out of phase by 180 degrees. Thus, the induced voltages cancel each other, and the output voltage is zero. This is often referred to as the null point. This process repeats itself every cycle continuously for the coils as they voltages are out of phase and is termed as the null point repeatability.

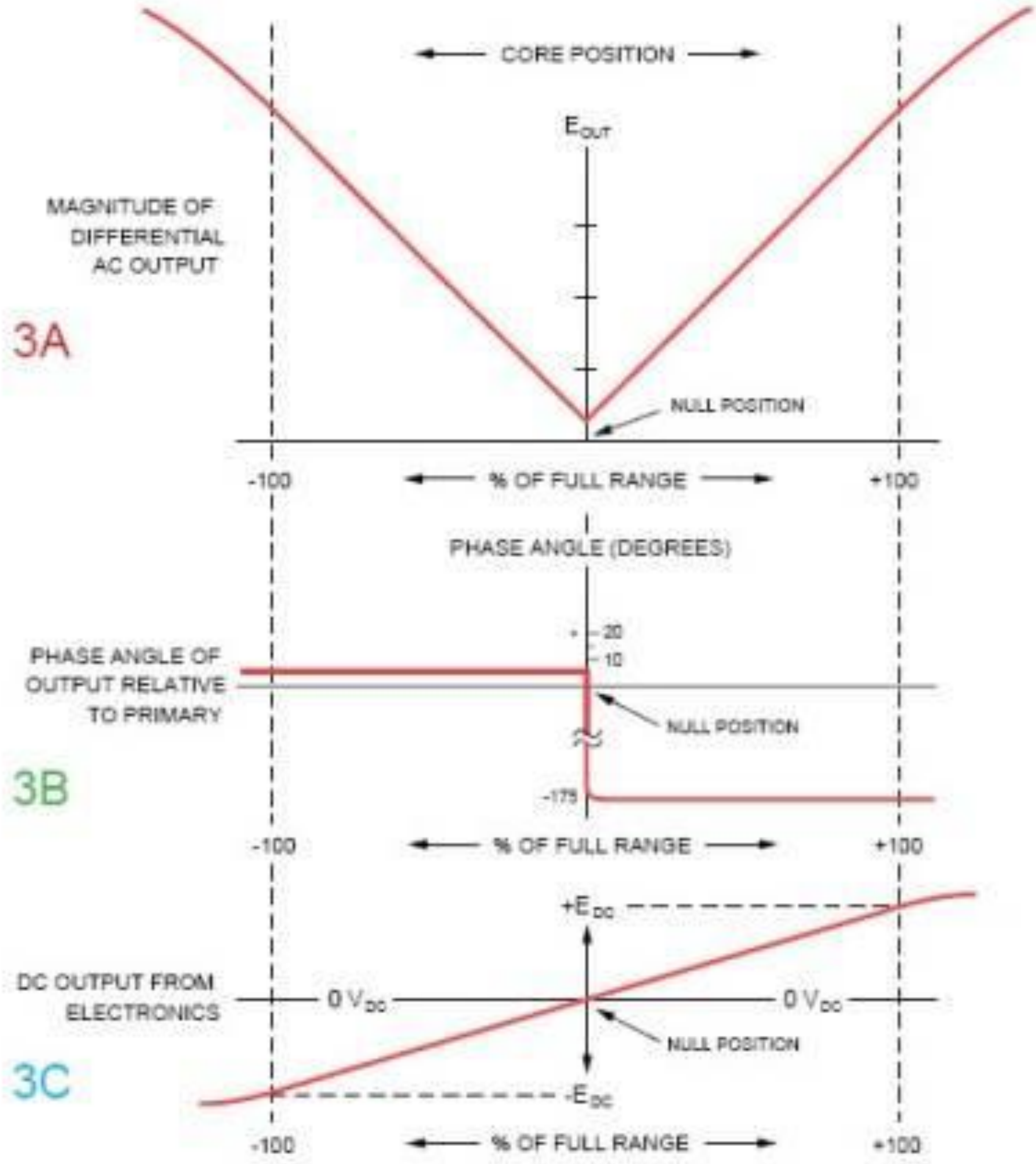
The location of an LVDT's intrinsic null point is extremely stable and repeatable, even over its very wide operating temperature range. This makes an LVDT perform well as a null position sensor in closed-loop control systems and high-performance servo balance instruments.

Courtesy: Reference Links: [1] [2] [3] [4]

B.7 In an LVDT what is the phase angle of the output relative to the primary excitation voltage used for?

Sol.

The phase angle of this AC output voltage, EOUT, referenced to the primary excitation voltage, stays constant until the center of the core passes the null point, where the phase angle changes abruptly by 180 degrees, as shown graphically in Figure 3B.

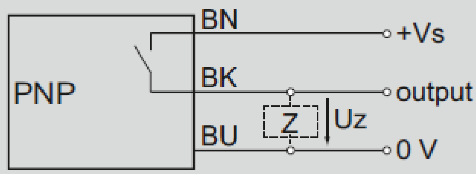


Courtesy: Reference Links: [1] [2] [3]

C. This question refers to the operating states of capacitive detection switches.

C.1 What is the direction of current flow and what is the state of the LED when the switch defined by the diagram below detects an object?

PNP normally open (NO)



State	Uz	LED
undamped	low	off
damped	high	on

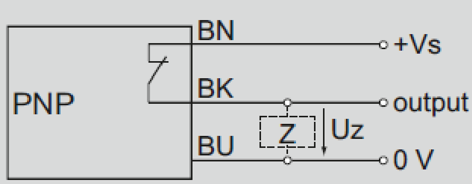
Sol.

Switch	When an object is detected, it will be **in damped state**, it will be then **closed** from the normally open state
Current	Current will flow **from +V_s terminal to GND (0 V) terminal** through the output terminal and the load resistance Z since U_z is high.
LED	**ON**

Courtesy: Reference Link: [1]

C.2 What is the direction of current flow and what is the state of the LED when the switch defined by the diagram below detects an object?

PNP normally closed (NC)



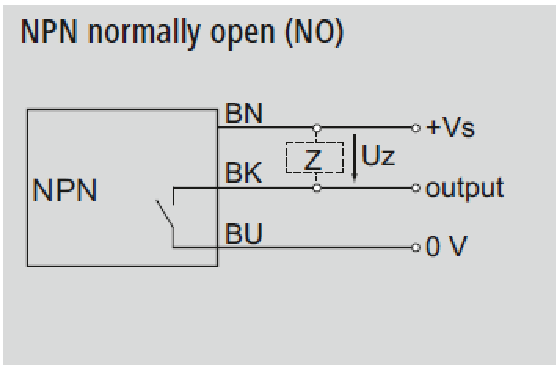
State	Uz	LED
undamped	high	on
damped	low	off

Sol.

Switch	When an object is detected, it will be **in damped state**, it will be then **open** from the normally closed state
Current	Since the output terminal will be disconnected from $+V_s$ terminal, it will be floating and thus U_z will be low and therefore **no current will flow**
LED	**OFF**

Courtesy: Reference Link: [1]

C.3 What is the direction of current flow and what is the state of the LED when the switch defined by the diagram below detects an object?



State	Uz	LED
undamped	low	off
damped	high	on

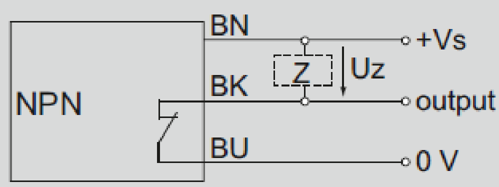
Sol.

Switch	When an object is detected, it will be **in damped state**, it will be then **closed** from the normally open state
Current	Current will flow **from $+V_s$ terminal to GND (0 V) terminal** through the load resistance Z and output terminal since U_z will be high.
LED	**ON**

Courtesy: Reference Link: [1]

C.4 What is the direction of current flow and what is the state of the LED when the switch defined by the diagram below detects an object?

NPN normally closed (NC)



State	Uz	LED
undamped	high	on
damped	low	off

Sol.

Switch	When an object is detected, it will be **in damped state**, it will be then **open** from the normally closed state
Current	Since the output terminal will be disconnected from GND (0 V) terminal, it will be a floating terminal and thus U_z will be low and therefore **no current will flow**
LED	**OFF**

Courtesy: Reference Link: [1]

D. How does the ungrounded capacitive position sensor differ in its method of detecting an object versus the grounded sensor?

Sol.

Ungrounded Capacitive Position Sensors:

In this case, **one electrode of the capacitor is located inside the sensor**, waiting for a conductive object to pass by while a generated AC current of constant frequency flows through the sensor. **The other electrode will be that of a conductive object and AC voltage across the capacitor is detected only for object presence.**

The measuring field and output voltage depends on the area and proximity of the detected object. A sensor without a ground electrode can be effected by minor dirt and moisture, use only in an indoor dry environment

Grounded Capacitive Position Sensors:

Both the measuring and ground electrodes of the capacitor are located inside the sensor while a known measuring field extends into the volume occupied by the non-conductive object. The capacitor senses a dielectric different than air, which leads to a change in capacitance

Courtesy: Class Slides – C3M3V2
Reference Links: [1] [2] [3] [4]

E. A Go to Google Patents (www.patents.google.com) and download US patent 6,777,958. Read the patent, and create a series of bullet points that explain how the sensor in this patent detects capacitance.

Sol.

- As explained in this patent, the sensor incorporates the use of a capacitive stripe which experiences a change in its capacitance with respect to the change in the distance of the object from the sensing face of the sensor.
- The sensor is designed such that this sensing capacitive strip has a constant and fixed capacitance value in the absence of an object in its sensing range.
- This non-zero constant value of the sensing capacitance in the absence of an object in its sensing range can also be called as an "offset" since this is the base capacitance value for the sensor in absence of an object detection.
- To detect these changes in the sensor capacitive strip, the sensor uses a variable radio frequency oscillator.
- The frequency of this radio oscillator is variable and it can be varied using a proper circuit configuration as per the need.
- Moreover, the patent also incorporates the use of other sensing elements as well such as – a local oscillator which has a predefined set frequency value which is preferably set at 925 MHz but can be modified as per the need.
- In addition to the local oscillator, a low pass filter is required to nullify the noise presence in the capacitive sensing process.
- A mixer also plays an essential role in bringing different sensing elements together to form a one cohesive sensor system.
- In the absence of any detectable object in the sensing range of the sensor capacitive strip, a fixed offset capacitance value is observed as a steady-state value.
- This changes with the presence of an object in the vicinity of the sensor under the sensing range.

- Furthermore, the capacitive strip in the sensor is connected to the variable radio frequency oscillator through a series capacitor which helps establish a capacitor divider circuit to lessen the sensitivity of the sensor.
- If this is not the case, the sensor becomes too sensitive to the changes in the capacitive strip and can provide sensing signals even in the absence of an detectable object in its sensing range due to the presence of free charge in the air.
- Thus, the capacitor divider circuit creates a proper stable sensing system.
- In the steady-state situation, the variable radio frequency oscillator is designed to have a frequency that is slightly less than the local oscillator frequency.
- As per the information provided in the patent, the difference is suggested to be about 3 MHz and therefore since the local oscillator frequency is set at 925 MHz, the radio frequency oscillator will be set at around 922 MHz.
- In the presence of an object, the capacitance of the capacitive strip in the sensor increases which in turn leads to a reduced frequency from the variable radio oscillator frequency.
- This modified variable radio oscillator frequency that changes with the change in the capacitance of the capacitive strip in the sensor (which changes in the presence of an object) is further fed to the mixer along with the fixed local oscillator frequency.
- In the next phase, the mixer provides two outputs: one with the sum of the two frequencies and the other one with the difference of two frequencies.
- The low-pass filter will trip off the frequency summation and will only allow the difference of the two frequencies to pass through.
- This is done because the difference of the two frequencies will help us understand the change in the capacitance of the capacitive strip more easily.
- The capacitance of the capacitive strip in the sensor increases (in the presence of an object) and this leads to an increase in the difference of the two frequencies obtained from the LPF.
- Thus, it can be understood, that if the difference of these two frequencies increases, an object is present in the sensing range of the capacitive strip sensor and if that is not the case, the difference would be equal to the offset value of approximately 3 MHz.
- This is the fundamental concept showing the relation between the change in the capacitance which is directly proportional to the change in the frequency difference from the sensor.

F. What is the difference between a unipolar and a bipolar hall effect switch?

Sol.

Unipolar Hall-Effect Switch	Bipolar Hall-Effect Switch
It is activated when external magnetic field exceeds certain threshold value.	Proximity to one magnetic pole will switch this sensor ON.
This hall sensor switches OFF when applied magnetic field diminishes or removed.	Proximity to the opposite pole will switch this sensor OFF.
Unipolar sensors can be activated either by north pole or south pole of the magnet.	The sensor remains in its present state (either ON or OFF) in the absence of magnetic field. It can be activated in the presence/proximity of opposite poles.
These devices can be used while the sensing face of the hall sensor is aligned and oriented toward the south pole (increasing magnetic field pole) of the magnet.	These devices find applications where closely-spaced, alternating north and south poles are used, resulting in minimum required signal amplitude.
The Unipolar Hall switches do not exhibit this behavior.	Bipolar Hall switches take advantage of the extra margin in release-point flux values to achieve lower operate-point flux densities, a definite advantage in ring magnet applications.
The Unipolar Hall switches differ in their operation.	A bipolar switch has consistent hysteresis, but individual units have switch-points that occur in either relatively more positive or more negative ranges.

Courtesy: Reference Links: [1] [2] [3]

G. A unipolar Hall effect switch is sensitive to the presence or absence of the south pole of a permanent magnet.

It has a magnetic operating point B_{OP} of 20 Gauss at -55°C, 55 Gauss at 25°C and 110 Gauss at 125°C.

It has a magnetic release point B_{RP} of 10 Gauss at -55°C, 45 Gauss at 25°C and 90 Gauss at 125°C.

The South pole of a permanent magnet has a magnetic field strength of 15 Gauss at -55°C, 60 Gauss at 25°C and 85 Gauss at 125°C.

You place the south pole of the magnet against the face of the switch at -55°C, and you warm the magnet and switch from -55°C to 125°C in a smooth fashion over a period of 24 hours.

What are the states of your Hall effect switch at -55°C, 25°C and 125°C and why would they be in these states?

Sol.

Here, it is assumed that since initially the south pole of the magnet is placed against face of the switch at -55°C, the sensor will be at or above the operate point and will therefore be in the ON situation.

At -55°C → The hall sensor is ON (gives a logic 1) → This is because the permanent magnet has a field strength of 15 Gauss at -55°C which is greater than the release point (10 Gauss) and lesser than the operate point (20 Gauss), the hall sensor will remain ON → Logic '1' State.

At +25°C → The hall sensor is ON (gives a logic 1) → This is because the permanent magnet has a field strength of 60 Gauss at +25°C which is greater than both the release point (45 Gauss) and the operate point (55 Gauss), the hall sensor will remain ON → Logic '1' State.

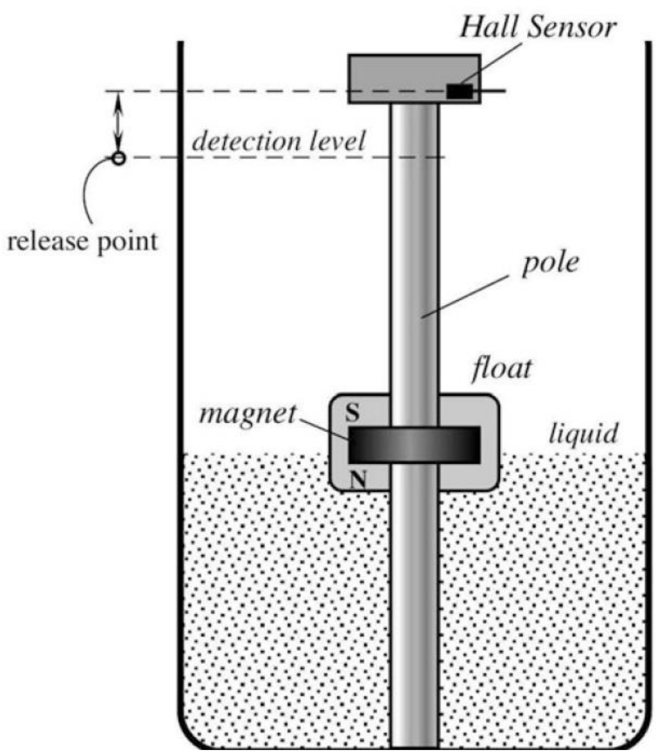
At +125°C → The hall sensor is OFF (gives a logic 0) → This is because the permanent magnet has a field strength of 85 Gauss at +125°C which is lesser than both the operate point (110 Gauss) and release point (90 Gauss), the hall sensor will be turned OFF → Logic '0' State.

In the above cases, the hysteresis has been ignored since it has not been provided in this problem.

H. This excerpt from our textbook "Handbook of Modern Sensors" describes an application for a Hall effect switch.

As a first example of the Hall sensor application, consider a liquid level detector with a float (Fig. 8.24). A permanent magnet is imbedded inside a float having a hole in the center. The float can freely slide up and down over the pole that is positioned inside the tank containing liquid. The float position corresponds to the liquid level. A bilevel Hall sensor is mounted at the top of the pole which should be fabricated on a nonmagnetic material. When the liquid level rises and reaches the detection level (release point), the Hall switch triggers and sends signal to the monitoring device. When the liquid level drops below the release point plus the threshold hysteresis, the output voltage changes indicating that the liquid level dropped. The detection point depends on the key factors—the magnet strength and shape, the Hall sensor's sensitivity, the hysteresis, and presence of ferromagnetic components in the vicinity of the Hall sensor.

Fig. 8.24 Liquid level detector with a Hall sensor



Suppose your liquid is distilled water. The magnet measures 100 gauss at the freezing point of 0°C, and decreases linearly to 90 gauss at 100°C. These measurements assume that the magnet is directly touching a ferritic object. As the distance between the magnet and object increases, the magnetic field sensed by the object drops accordingly.

Specify the proper unipolar switch from the reference "Data sheet for High Reliability Hallogic Hall-effect" by TT Electronics Inc. Given the data you find, what issue in the specs might prevent this device from working properly?

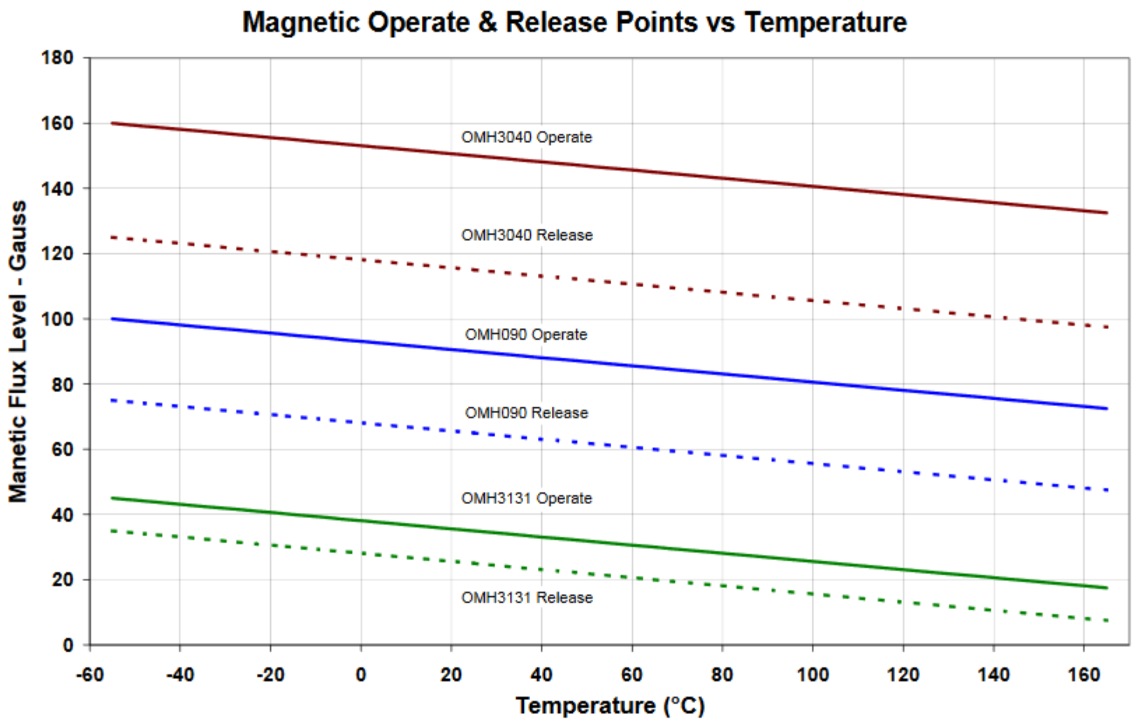
Sol. OMH 090 can be used. Hysteresis level will affect the switching.

Based on the reference document, from the below given screenshots it can be concluded that the unipolar OMH 090 switch is best suitable for this task.

Part Number	Hi-Reliability Hallogic® Sensor	Operate Point Gauss Min / Typ / Max	Release Point Gauss Min / Typ / Max	Hysteresis Gauss Min / Typ / Max	V_{CC} (Volts) Min / Max	Package
OMH090B	Uni-Polar Non-Latching	50/90/180	30 / 65 / 160	10 / 30 / 60	4.5 / 24.0	Through Hole
OMH090S						
OMH3019B		175 / 300 / 500	125 / 235 / 420	30 / 100 / 155		
OMH3019S						
OMH3020B		70 / 220 / 350	50 / 180 / 330	15 / 55 / 200		
OMH3020S						
OMH3040B		70 / 150 / 200	50 / 115 / 180	10 / 35 / 60		
OMH3040S						
OMH3131B		20 / 60 / 95	10 / 45 / 85	5 / 15 / 40		
OMH3131S						
OMH3075B	Bi-Polar Latching	50 / 150 / 250	-250 / -150 / -50	100 / 250 / 500		
OMH3075S						

Electrical Characteristics (V_{CC} = 4.5 V to 24 V, T_A = 25° C unless otherwise noted)
OMH090, OMH090B, OMH090S Uni-Polar

SYMBOL	PARAMETER	MIN	TYP	MAX	UNITS	TEST CONDITIONS
B_{OP}	Magnetic Operate Point[1]	45 50 20	- 90 -	210 180 180	Gauss	-55°C +25°C +125°C
B_{RP}	Magnetic Release Point	25 30 25	- 65 -	150 160 140	Gauss	-55°C +25°C +125°C
B_H	Magnetic Hysteresis	5 10	- 30	95 60	Gauss	-55°C +25°C & +125°C
I_{CC}	Supply Current	- - -	- 5 -	9 11 5	mA	-55°C,V_{CC} = 24 V, Output On, B≥250 Gauss +25° +125°C
V_{OL}	Output Saturation Voltage	- -	- 125	300 400	mV	-55°C,V_{CC} = 4.5 V, I_{OL} = 30 mA,B≥250 Gauss +25°C & +125°C
I_{OH}	Output Leakage Current	- - -	- 0.50 -	10 11 12	µA	-55°C,V_{CC} = 24 V, V_{OUT} =24 V, B≤250 Gauss +25° +125°C
t_r	Output Rise Time	-	0.13	1.00	µs	R_L = 820 Ω, C_L = 20 pF, V_{CC} = 14 V (guaranteed not tested)
t_f	Output Fall Time	-	0.14	1.00	µs	



The reason for the selection of the OMH090 unipolar non-latching switch is due to the fact that its operating point is approximately 95 Gauss at 0°C and 80 Gauss at the 100°C based on the above screenshot. This values are very well suitable for our use since in our case the sensor measures a value of 100 Gauss and 90 Gauss at 0°C and 100°C.

This also means that the OMH090 switch has an operate point that is below the magnetic flux values that the sensor senses as per the data given in the problem for the corresponding temperatures – moreover this is true since it is said that the magnet is touching the ferritic object in both the case.

Therefore, the OMH090 unipolar non-latching switch is best suited for this application.

Secondly, the **magnetic hysteresis** of the switch will actually affect these operate and release point switching since it will come into play. Also, the change in hysteresis will become an issue that may prevent this device from working properly. This is also because the magnetic hysteresis will also vary with temperature and therefore it may happen that the required switching may not happen – **in case if the magnetic touches the ferritic object and still the operate point is not reached in which case the sensor will be locked in the ON mode**.

Courtesy: Reference Links: [1] [2]

I. An eddy current sensor is used to detect the presence of an automobile at a gate. The sensor is pointed towards the front-left side fender of the automobile as it nears the gate.

The frequency of the induced electromagnetic field is 10,000 hz. Assume the electrical conductivity of an automobile can be modelled as that of carbon steel piano wire.

How far into the fender will the eddy currents be induced? Specify a one-decimal point answer in millimeters.

Sol.

Based on the class slides and the information provided in the problem, the following equation will be used to solve this problem:

$\delta = 1 / \sqrt{\pi f \mu \sigma}$
δ = depth of eddy current penetration into object
f = frequency of induced electromagnetic field
μ = magnetic permeability of free space
σ = electrical conductivity of object

In our case, the frequency of the induced electromagnetic field is given as 10 kHz. Thus, f = 10 kHz.

Further, the remaining values are as under with the appropriate reference:

Magnetic permeability of free space = $4\pi\times10^{-7}$ H/m (Reference)
Electrical conductivity of carbon steel = 6.99×10^{6} (S/m) (Reference) (Reference – Piano Wire)

Thus, the depth of the eddy current penetration into the object

= $1 / \text{SQRT}(\pi \times 10^{4} \times 4\pi \times 10^{-7} \times 6.99\times10^{6})$
= 1 / 525.3133
= $\boxed{\textbf{1.9036 mm}}$

J. Answer the following questions about accelerometers.

J.1 What is the resonance frequency of an accelerometer? How does this frequency relate to the highest frequency that the sensor can measure?

Sol.

Resonance is the tendency for a system to oscillate more violently at some frequencies than others. Resonance frequency is the frequency at which the sensor resonates or rings. Frequency measurements want to be well below the resonance frequency of the accelerometer.

For an accelerometer, **the resonance frequency is the point in frequency in the accelerometer's frequency response where the accelerometer outputs maximum sensitivity.** It is specified in units of Hertz. It is as a result of the natural resonance of the mechanical structure of the accelerometer itself.

Thus, the highest frequency that the sensor can measure is given by the resonant frequency. **Below and above the resonant frequency, the sensitivity and thus the highest frequency that the sensor can measure will be lower than at the resonant frequency.**

Courtesy: Reference Links: [1] [2] [3] [4]

J.2 What type of accelerometer is the Analog Devices ADXL1001/1002? (Pick from the technologies described in slide decks C3M3V5, V6, and V7) How do you know this?

Sol. **MEMS Differential Capacitive Accelerometer**

Based on the information provided in the class slides, MEMS Differential Capacitive Accelerometer is the type of the accelerometer that is used in the referenced datasheet.

This is because the accelerometer in the datasheet is said to be operating where the moving component of the sensor is a polysilicon surface-micromachined structure built on top of a silicon wafer. Polysilicon springs suspend the structure over the surface of the wafer and provide a resistance against acceleration forces.

Plus, **it is said that the deflection of the structure is measured using differential capacitors** that consist of independent fixed plates and plates attached to the moving mass. **Acceleration deflects the structure and unbalances the differential capacitor**, resulting in a sensor output with an amplitude proportional to acceleration.

This provides the fact that the accelerometer in the datasheet has been using differential capacitors for its operation and therefore –

MEMS Differential Capacitive Accelerometer would be the type of the accelerometer.

Courtesy: Reference Link: [1]

J.3 Page 7 of the ADXL 1001 sensor spec sheet gives this bar chart below. Based solely on this data, what is an estimate for the sensitivity and worst case tolerance?

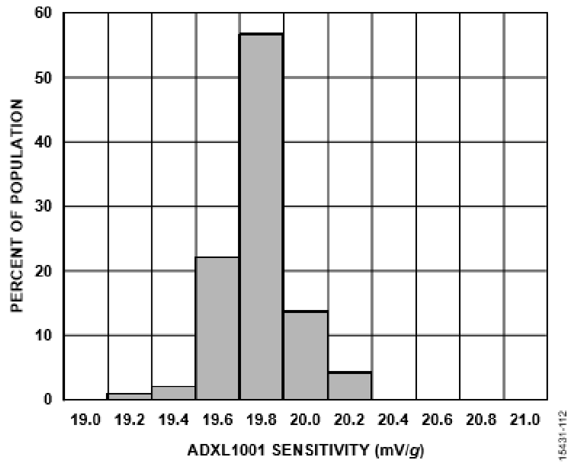


Figure 12. ADXL1001 Sensitivity Histogram at 25°C

Sol.

To solve this problem, first we need to take the weighted average of all the measurements as below based on the given figure:

= [(19.2 x 1) + (19.4 x 2) + (19.6 x 22) + (19.8 x 57) + (20 x 15) + (20.2 x 5)] / (1 + 2 + 22 + 57 + 15 + 5)

= **19.792** (weighted average value in mV/g for the given population spectrum)

Based on the above value, we can find the tolerance by calculating the deviations as under:

$Tolerance_{max}$ = ((19.792 – 19.2) / 19.792) x 100 % = **5.20833**
$Tolerance_{min}$ = ((19.792 – 20.2) / 19.792) x 100 % = **-2.06143**

J.4 How does a piezoelectric accelerometer determine acceleration? What is the most basic equation that governs its operation, and what famous scientist postulated this equation? (Hint: he was also a famous mathematician)

Sol.

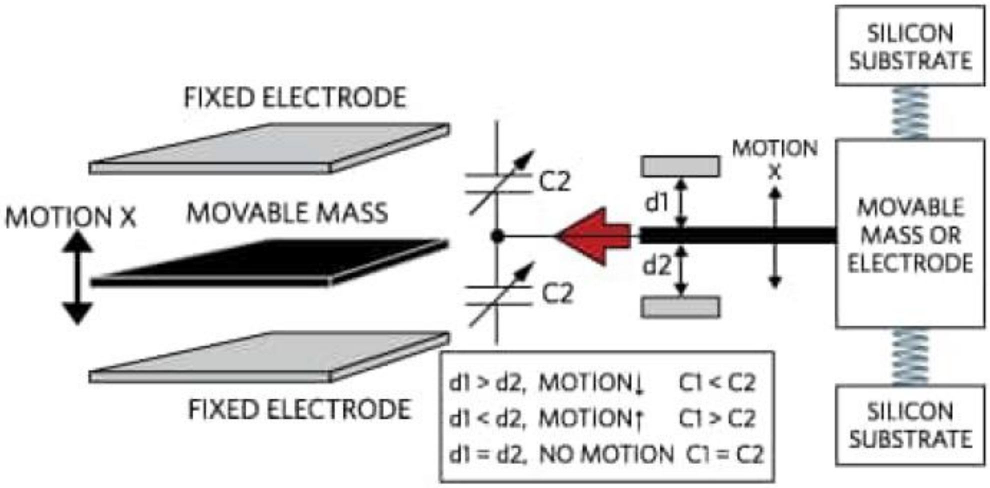
The active element in a piezoelectric accelerometer is a piezoelectric ceramic. One side of the ceramic is rigidly connected to the accelerometer body, the other side has a seismic mass added. When the accelerometer is subjected to vibration, a force is generated which acts on the piezoelectric element and the seismic mass. Due to the piezoelectric effect, a charge output proportional to the applied force is generated from this vibration or shock. Over a wide frequency range the sensor mass and the sensor base have the same acceleration magnitude and therefore the sensor measures the acceleration of the accelerometer body.

To explain it, the force caused by vibration or a change in motion (acceleration) causes the mass to "squeeze" the piezoelectric material which produces an electrical charge that is proportional to the force exerted upon it. Since the charge is proportional to the force, and the mass is a constant, then the charge is also proportional to the acceleration.

To summarize, the equation used to measure the acceleration comes from the basic and most fundamental physics equation: F = m x a; where, F → force observed or applied on a body, m → mass of the body and a → acceleration on the body observed / applied. This equation was presented by **Newton** (also known as **Newton's second law**) which says that force is directly proportional to the mass of the corresponding object and the acceleration produced.

Courtesy: Reference Links: [1] [2] [3] [4]

J.5 What equation is used to determine the magnitude of the displacement in this diagram of a capacitance accelerometer? What is a simple formula you can use to relate the magnitude of the displacement to that of the acceleration?



Sol. $\boxed{\mathbf{a = (k * d) / m}}$

To solve this problem, we can use the capacitance equation and the Hooke's law equation that can help us determine the magnitude of the displacement in the given diagram of a capacitance accelerometer.

The capacitance equation can be given as under:

$$C = \varepsilon_0 \frac{A}{d}$$

(reference)

Here, we have considered the permittivity of free space in the above equation and have assumed for a while that the dielectric medium between the capacitor plates is free space.

Based on the above capacitance equation, it is established that A (the cross-sectional area of the capacitor plates) remains constant and so does the permittivity and therefore the value of the capacitance will be inversely proportional to the distance between the two plates.

Moreover, this distance between the two plates will be dependent on the Hooke's law based on the concept of working of the showcased capacitance accelerometer.

Hooke's law can be given as under:

F = k * d (where k is the spring proportional constant and d is the displacement between the two capacitor plates in our case) (reference)
… [1]

Since, we are talking about accelerometers, we can use the Newton's second law of motion: **F = m * a** (where m is the mass of the object and a is the acceleration of the object). The mass of the object remains constant and therefore the force would proportional to the acceleration applied.
…[2]

To conclude, using the points [1] and [2], it can be claimed that the force would proportional to the distance between the two capacitor plates and it will also be proportional to the acceleration applied. Thus, we can say that the acceleration (a) is directly proportional to the displacement (d).

Therefore, k * d = m * a and so, $\boxed{\mathbf{a = (k * d) / m}}$. This is the relation between the acceleration and the displacement between the capacitance plates.

From the above discussion it can thus be concluded that since the capacitance (C) is inversely proportional to the displacement (d) and since the displacement (d) is directly proportional to the acceleration (a), it can be said that the capacitance (C) will also be inversely proportional to the acceleration observed (a).

Thus, $\boxed{\mathbf{C \propto (1 / a)}}$ would be the final equation in our case.

J.5 What are the advantages and disadvantages of using quartz vs. ceramic for the measuring element in a piezoelectric accelerometer?

Sol.

Quartz:

Naturally piezoelectric, best long term stability. Compared with ceramic, quartz has lower charge output, but higher open circuit voltage sensitivity. Quartz crystals can only be cut certain ways, limiting geometry of the sensor.

Ceramics:

It can be machined or molded into plates, beams or rings, which are polarized to produce the piezo electric effect. Ceramics have high charge output. On the downside, they exhibit the pyroelectric effect and have a limited temperature range.

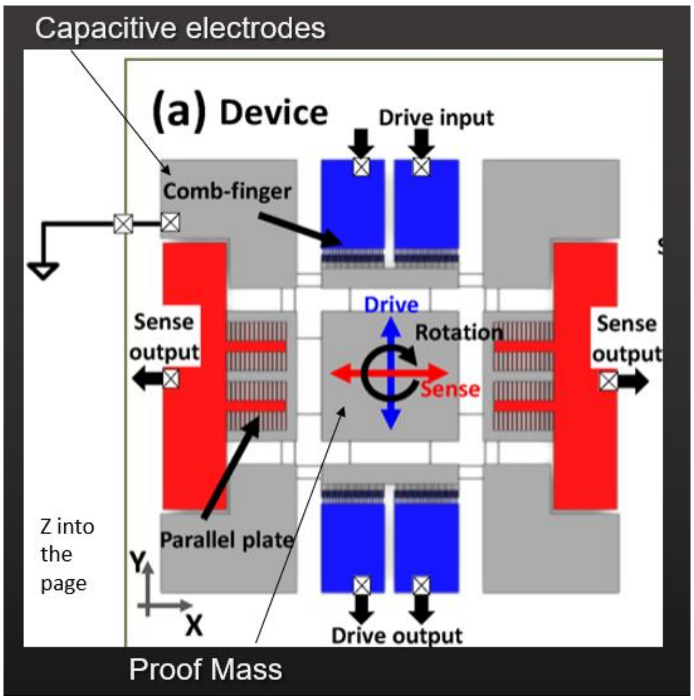
J.6 What are three ceramic materials that are used to create piezoelectric accelerometers? What is their chemical composition?

Sol.

The three ceramic materials that are used to create piezoelectric accelerometers are as under with their chemical composition:

Zinc Oxide	ZnO
Lead Zirconate Titanate	$PbZr_{0.53}Ti_{0.47}O_3$
Sodium Bismuth Titanate	$Bi_{0.5}Na_{0.5}TiO_3$

J.7 The picture below is a diagram of a MEMS gyroscope. What causes the proof mass to vibrate in the x-direction?



Sol.

As it has been mentioned in the class slide (C3M3V8), it is the Coriolis Force F_c causes the sensor (proof mass) to vibrate in the X-direction.

K. An accelerometer is measuring a structure as described below:

Highest frequency measured, f =	2500	hz
Seismic mass, m =	0.005	kg
Accelerometer spring coefficient, k =	100,000	N/m
Accelerometer damping coefficient: c =	28.5	N-sec/m

What is the percentage error in the accelerometer at the highest frequency it can measure? (Type in a two-decimal number)

Sol.

This problem can be solved using the equation provided in the class slide: C3M3V4 as under:

$$X\frac{k}{F_0} = \frac{1}{\sqrt{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta\left(\frac{\omega}{\omega_n}\right)\right]^2}}$$

Based on this equation, we will first calculate the necessary constraints as shown below:

$$\xi = \frac{(c/2)}{\sqrt{k \times m}} = \frac{(28.5/2)}{\sqrt{10^5 \times 0.005}} = 0.637$$

$$\omega_n = \sqrt{\frac{k}{m}} = \sqrt{\frac{10^5}{0.005}} = 4472.135$$

$$\omega = 2 \times \pi \times f = 2 \times \pi \times 2500 = 15.707 \times 10^3$$

Now, using the information obtained above, we will solve for the equation to find the amplification factor which is given as X * (k/F_0).

$$X\frac{k}{F_0} = \frac{1}{\sqrt{\left[1-\left(\frac{15.707\times10^3}{4472.135}\right)^2\right]^2+\left[2\times0.637\left(\frac{15.707\times10^3}{4472.135}\right)\right]^2}}$$

$$= \frac{1}{\sqrt{128.4935 + 20.02145}}$$

$$= 0.08205$$

From the above calculation, the amplification factor obtained is 0.08205 which is 8.205 %.Thus, based on the definition of the amplification factor, only 8.205% of the output signal will be actually available while the rest will be damped.

Thus, the percentage error obtained at the highest frequency can be calculated as shown below:

(1 – amplification factor) x 100 = (1 – 0.08205) x 100 = $\boxed{\textbf{91.795 \%}}$

L. You are using the Analog Devices ADXL1001 accelerometer with the specifications given by this screenshot below. You are using the accelerometer at the nominal ambient temperature of 25°C. Therefore, you can ignore errors due to ambient temperature.

However, you need to calculate the error in g's due to

- Spurious accelerations on the Y and Z axes (i.e. cross axis sensitivity)
- Noise density
- Response error due to frequency

Other data, not on the spec sheet, is given here in this table.

X Axis Acceleration voltage measured, V_x =	900	mV
Y Axis Acceleration, a_y =	5	g's
Z Axis Acceleration voltage, a_z =	3	g's
Acceleration frequency on all 3 axes, f =	3000	hz
Damping Ratio, ζ =	0.65	

What is the total error in g's in your measurement? (Type in a three - decimal number)

Sol.

Based on the information provided in the data sheet, the errors can be calculated as below:

1. Error due to the spurious accelerations on the Y and Z axes (cross axis sensitivity):

   This can be calculated using the cross axis sensitivity which is +/- 1% of the original sensitivity.

   From the datasheet, it can be seen that the original sensitivity is 20 mV/g.

   Thus, the cross axis sensitivity can be given as:
   = +/- 1 % of 20 mV/g
   = +/- 0.2 mV/g

   Therefore, the mV experienced on the Y and Z axes based on the cross axis sensitivity will be:

   g_y = +/- 0.2 x 5 = +/- 1 mV → +/- 5 g's
   g_z = +/- 0.2 x 3 = +/- 0.6 mV → +/- 3 g's

   Furthermore, the g's on the X axes based on the sensitivity provided in the datasheet (20 mV/g) can be given as under:

   g_x = (900 mV) / (20 mV/g) = 45 g's

   From this it can be said that the error due to the spurious accelerations would be approximately **+/- 1.6 mV** or in terms of g's it can be as under:

g_{yz} = (+/- 1.6 mV) / (20 mV/g) = **+/- 0.08 g's**

2. Error due to noise density: (reference)

   From the datasheet, it can be seen that the noise density is given in terms of μg/√Hz.

   The noise density error is: 30 μg/√Hz

   From this, the error in g's can be found by putting the value of the acceleration frequency on all 3 axes as under.

   Error due to noise density
   = Noise density (μg/√Hz) x √Hz
   = 30 x √3000 μg
   = 1.643 mg
   = **0.001643 g's**

3. Response error due to frequency: (based on Problem K)

   Given all the information in the data sheet and the table on the top, we can use the amplification factor formula as under to find the error:

$$X\frac{k}{F_0} = \frac{1}{\sqrt{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta\left(\frac{\omega}{\omega_n}\right)\right]^2}}$$

   Thus, the amplification factor can be calculated as under:

   Resonant frequency → 21 kHz (from data sheet)
   ω_n = 2 x π x 21000 = 131.946 x 10^3 rads^{-1}
   ω = 2 x π x 3000 = 18.849 x 10^3 rads^{-1}
   Damping ratio = 0.65

   Putting these values in the above equation, we get the amplification factor as under:

$$\frac{Xk}{F_o} = \frac{1}{\sqrt{\left[1-\left(\frac{18.849}{131.946}\right)^2\right]^2 + \left[2\times 0.65\left(\frac{18.849}{131.946}\right)\right]^2}}$$

$$= \frac{1}{\sqrt{0.95960 + 0.034488}}$$

$$= 1.002969057$$

Thus, it can be seen from the value of the amplification factor that the error is (amplification factor – 1) = (1 – 1.002969057) = **0.002969057**

Therefore, the error is approximately 0.2969057 % of the total g value.

Thus, the error in g's due to the frequency response is as under:

0.002969057 x 45g = **0.13360 g's**

From parts (1, 2 and 3), the total error in g's for this problem

= 0.08 + 0.001643 + 0.13360 = $\boxed{\textbf{0.215243 g's}}$

SPECIFICATIONS

$T_A = 25°C$, $V_{DD} = 5.0$ V, acceleration = 0 *g*, unless otherwise noted.

Table 1.

Parameter[1]	Test Conditions/ Comments	ADXL1001			ADXL1002			Unit
		Min	Typ	Max	Min	Typ	Max	
SENSOR								
Measurement Range			±100			±50		*g*
Linearity	Percentage of full scale		±0.1			±0.1		%
Cross Axis Sensitivity[2]	ZX cross axis		±1.0			±1.0		%
	YX cross axis		±1.0			±1.0		%
SENSITIVITY (RATIOMETRIC TO V_{DD})								
Sensitivity	DC		20			40		mV/*g*
Sensitivity Change Due to Temperature[3]	T_A = −40°C to +125°C		±5			±5		%
ZERO *g* OFFSET (RATIOMETRIC TO V_{DD})								
0 *g* Output Voltage			$V_{DD}/2$			$V_{DD}/2$		V
0 *g* Output Range over Temperature[4]	−40°C to +125°C		5			5		*g*
NOISE								
Noise Density	100 Hz to 10 kHz		30			25		µ*g*/√Hz
1/f Frequency Corner			0.1			0.1		Hz
FREQUENCY RESPONSE								
Sensor Resonant Frequency			21			21		kHz
5% Bandwidth[5]			4.7			4.7		kHz
3 dB Bandwidth[5]			11			11		kHz
SELF TEST								
Output Change (Ratiometric to V_{DD})	ST low to ST high	235	275		510	545		mV
Input Level								
High, V_{IH}		$V_{DD} \times 0.7$			$V_{DD} \times 0.7$			V
Low, V_{IL}				$V_{DD} \times 0.3$			$V_{DD} \times 0.3$	V
Input Current			25			25		µA
OUTPUT AMPLIFIER								
Short-Circuit Current			3			3		mA
Output Impedance			<0.1			<0.1		Ω
Maximum Resistive Load			20			20		MΩ
Maximum Capacitive Load[6]	No external resistor		100			100		pF
	With external resistor		22			22		nF
POWER SUPPLY (V_{DD})								
Operating Voltage Range		3.3	5.0	5.25	3.3	5.0	5.25	V
Quiescent Supply Current			1.0	1.15		1.0	1.15	mA
Standby Current			225	285		225	285	µA
Standby Recovery Time (Standby to Measure Mode)	Output settled to 1% of final value		<50			<50		µs
Turn On Time[7]			<550			<550		µs
OPERATING TEMPERATURE RANGE		−40		+125	−40		+125	°C

[1] All minimum and maximum specifications are guaranteed. Typical specifications may not be guaranteed.
[2] Cross axis sensitivity is defined as the coupling of excitation along a perpendicular axis onto the measured axis output.
[3] Includes package hysteresis from 25°C.
[4] Difference between maximum and minimum values in temperature range.
[5] Specified as frequency range that is within a deviation range relative to dc sensitivity, range is limited by an increase in response due to response gain at the sensor resonant frequency.
[6] For capacitive loads larger than 100 pF, an external series resistor must be connected (minimum 8 kΩ). The output capacitance must not exceed 22 nF.
[7] Measured time difference from the instant V_{DD} reaches half its value to the instant at which the output settles to 1% of its final value.

M. You are using the Bruel and Kjaer type 4384 piezoelectric accelerometer to measure vibrations in a commercial jet engine. This is a very difficult environment for this accelerometer. The device is subject to the maximum error of the charge sensitivity at the vibrational frequency you are measuring. There is one silver lining. Because your vibrational frequency is so far below the natural frequency of the accelerometer, you can ignore error in the measurement per this equation below:

$$\frac{1}{\sqrt{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2+\left(2\zeta\frac{\omega}{\omega_n}\right)^2}}$$

In addition, your device experiences vibration in the X, Y, an Z direction, even though you are only interested in the vibration in the X direction. Piezoelectric accelerometers are known to be subject to errors due to base strain and operating at elevated temperatures, and that is the case here. There is a magnetic field coming from other instruments nearby, and as always, the accelerometer has its own electrical noise.

Other data, not on the spec sheet, is given here in this table below:

Answer these three questions:

1. What is the total error in g's in your measurement? (Type in a three - decimal number)
2. What is this error expressed as a % of the nominal X-axis acceleration?
3. Which sources of error are your top 3, expressed in order (i.e. first, second third highest sources)

X Axis Acceleration Charge measured, C_x =	2000	pC
Y Axis Acceleration, a_y =	18	g's
Z Axis Acceleration voltage, a_z =	14	g's
Acceleration frequency on all 3 axes, f =	2000	hz
Nominal Calibration Temperature, T_c =	25	°C
Ambient Temperature, T_a =	100	°C
Strain in base of accelerometer, ε =	0.003	
Magnetic field from instruments, B =	1	kgauss

Specifications – Charge Accelerometer Types 4384 and 4384-V

Type No.		4384	4384-V
General			
Weight (excluding cable, wherever applicable)	gram	11	
	oz	0.39	
Charge Sensitivity (at 159.2 Hz)	pC/ms^{-2}	1 ± 2%	1 ± 15%
	pC/*g*	9.8 ± 2%	9.8 ± 15%
Frequency Range (±10% limit)	Hz	0.1 to 12600	
Mounted Resonance Frequency	kHz	42	
Max. Transverse Sensitivity (at 30 Hz, 100 ms^{-2})	%	<4	
Transverse Resonance Frequency	kHz	15	
Max. Operational Continuous Sinusoidal Acceleration (peak)	kms^{-2}	60	
	g	6000	
Electrical			
Residual Noise Level (measured with NEXUS Type 2692-001 in the specified frequency range)	mms^{-2}	2.4	
	m*g*	0.24	
Capacitance (excluding cable)	pF	1100	
Min. Leakage Resistance (at 20 °C)	GΩ	20	
Environmental			
Operating Temperature Range	°C	−74 to +250	
	°F	−101 to +482	
Temperature Coefficient of Sensitivity	%/°C	0.05*	
Temperature Transient Sensitivity (3 Hz Low. Lim. Freq. (–3 dB, 6 dB/octave))	ms^{-2}/°C	0.4	
	g/°F	0.022	
Base Strain Sensitivity (at 250 με in the base plane)	ms^{-2}/με	0.02	
	g/με	0.002	
Magnetic Sensitivity (50 Hz, 0.038 T)	ms^{-2}/T	4	
	g/kGauss	0.04	
Max. Non-destructive Shock (± peak)	kms^{-2}	200	
	g	20000	

Sol.

To solve this problem, we will first calculate the different types of errors in the problem:

1. Error due to charge sensitivity:

   From the data sheet the nominal charge sensitivity is 9.8 pC/g and the new charge sensitivity in pC/g can be given as: 9.8 + 2% (we are considering the increment here to see the highest amount of error involved).

   Thus, new charge sensitivity = 9.8 (1 + 0.02) = 9.8 x 1.02 = 9.996 pC/g

   Now, it is provided that the X-axis acceleration charge measured is 2000 pC.

   Thus, g's due to nominal charge sensitivity → 2000/9.8 = 204.0816 g
   g's due to changed charge sensitivity → 2000/9.996 = 200.0800 g

   Thus, the error in g's here would be 204.08 – 200.08 = **4g's**

2. Error due to the cross axis sensitivity allows a maximum transverse sensitivity of up to 4% based on the datasheet. Considering the maximum transverse sensitivity of 4% for considering the highest amount of error possible, we can calculate the error in charge sensitivity on the Y and Z axes by considering the 9.8 + 2% error rate in charge sensitivity as given in the datasheet.

   Thus,
   Error on Y-axis: (18 g's) x (4%) x (1 + 2%) = 0.72 x 1.02 = 0.7344 g's
   Error on Z-axis: (14 g's) x (4%) x (1 + 2%) = 0.56 x 1.02 = 0.5712 g's

   Based on these values, the error due to the cross axis sensitivity is

   = 0.7344 + 0.5712 = **1.3056 g's**

3. Considering the error due to the strain value in the base of the accelerometer:

   Now, the base strain sensitivity is given as 0.002 g/με.

   The strain in the base of the accelerometer is given as: ε = 0.003

   So, given the base strain sensitivity, we can calculate the error in g's due to this as under:

   Error → $(0.002 \times 10^6\ g/\varepsilon) \times (0.003\ \varepsilon)$ = **6g**

4. Calculating the error in g's due to the elevated temperature:

Now, it has been given in the data sheet that the value of temperature coefficient of sensitivity (%/°C) is given as 0.05.

Here, the ambient temperature is 100°C while the nominal calibration temperature is 25°C which is 75°C lower than the ambient temperature.

Thus, the change in the sensitivity would be at the rate of 0.05 %/°C.

So, the error would be: (0.05 %/°C) x 75°C = 3.75% in the sensitivity.

Therefore, new sensitivity = (9.8 + 3.75% of 9.8) pC/g = 10.1675 pC/g

Based on the value of the new sensitivity, we can calculate the error by finding the values of g's based on the nominal and new sensitivity as under:

Thus,

g's due to nominal charge sensitivity → 2000/9.8 = 204.0816 g
g's due to changed charge sensitivity → 2000/10.1675 = 196.7051 g

Therefore the error in g's = 204.0816 – 196.7051 = **7.3764 g's**

5. Finally, calculating the error due to the magnetic field sensitivity:

   From the datasheet, it is found that the magnetic sensitivity is given as 0.04 g/kGauss. Moreover, in the problem, it is given that the magnetic field from instruments is observed to be 1kGauss.

   Thus, the error in g's due to the magnetic sensitivity would be:

   0.04 g/kGauss x 1 kGauss = **0.04 g's**

Now, the answers to this problem are as under:

A. The total error in g's = 4 + 1.3056 + 6 + 7.3764 + 0.04 = **18.722 g's**

B. To find the error expressed as a % of the nominal X-axis acceleration, we would consider the g's due to the nominal sensitivity on the X-axis which is 204.0816 g and the total error is 18.722 g's.

   Thus, the error in % = (18.722 / 204.0816) x 100 % = **9.1738 %**

C. Finally, it can be observed that the errors in the descending order in terms of g's can be given as under:

   Error due to elevated temperature > Error due to base strain > Error due to charge sensitivity