SIMON FRASER UNIVERSITY
THINKING OF THE WORLD

ENSC387: Introduction to Electromechanical Sensors and Actuators

LAB 2: ACCELEROMETERS MEASUREMENTS AND APPLICATIONS

DATE DUE: 23:59:59 20 Feb 2016

Please remember that you are operating delicate and very expensive equipment.

In order to allow other students to learn and enjoy this lab, please be careful and follow the instructions provided.

DO NOT OVERTIGHTEN THE ACCELEROMETER TO THE BEAM

DO NOT DISCONNECT THE WHITE CABLE FROM THE ACCELEROMETER

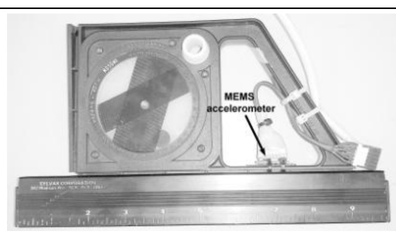
1 Objective

Through this lab you will become familiar with both piezoelectric and capacitive accelerometers. You will observe properties of both accelerometer types measuring AC and DC signals.

You will also explore the different setups required to operate the two accelerometers.

Finally, you will observe and compensate for mechanical loading imposed by the accelerometer on the measured structure.

2 Required Materials

Description	Photo	Description	Photo
Piezoelectric accelerometer		BNC to BNC cable	
Piezoelectric accelerometer cable		ICP amplifier	
ICP amplifier power cable		Ruler	
Beam with capacitive accelerometer		Aluminium basket	
Inclinometer with capacitive accelerometer		Set of weights	

3 Introduction

Accelerometers are useful and popular sensing devices and can be used to implement a wide range of measurement applications. Some common use of accelerometers include inertial measurement of velocity (acceleration single integrated) and distance (double integrated), vibration detection for monitoring and predicting the health and condition of rotating machinery, motion and shock detection, measurement of gravity to determine tilt and inclination, etc. Indeed, the device is so versatile that its range of engineering applications is only limited by your imagination.

There are several approaches in the design of an accelerometer device with each approach offering its own tradeoffs in price, performance and application limitations. For the purpose of this lab, we will focus our attention on the two most common types of accelerometers, namely, the piezoelectric type and the MEMS (micro electro-mechanical system) capacitive type.

3.1 Piezoelectric accelerometer

As discussed in class, the piezoelectric accelerometer (schematically shown in Figure 1) consists of a piezoelectric element (such as treated Lead Zirconate Titanate) being held in place within the device's housing with a compression spring and with an inertia mass attached.

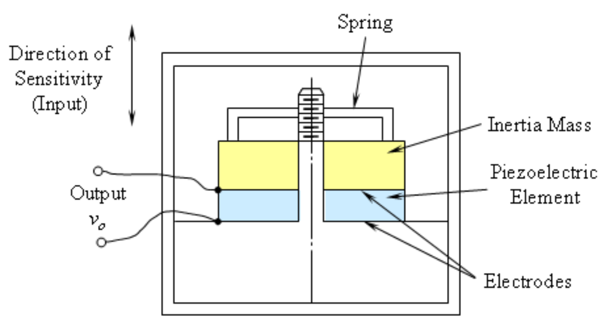


Figure 1: Compression-type piezoelectric accelerometer.

An acceleration a experienced by the inertia mass M causes an inertia force F to be produced and exerted onto the piezoelectric element, leading to generation of charge by the device, proportional to the force F. Due to the high output impedance of the device (particularly at low frequency), a charge amplifier is necessary to perform the charge to voltage conversion and impedance matching. As the charge amplifier's output approaches zero at DC, we conclude that a piezoelectric accelerometer (or any piezoelectric type of device for that matter) cannot be used for making static measurements.

In spite of the abovementioned shortcoming, the piezoelectric accelerometers are widely used for absolute vibration measurements and have the following advantages over the other accelerometer types:

- Very wide dynamic range, almost free of noise – suitable for shock measurement
- Excellent linearity
- Wide frequency range
- No moving parts – long life
- Self-generating – no external power required
- Great variety of models available for nearly any purpose

3.2 MEMS accelerometer

The second type of accelerometer which we will be experimenting with is based on the implantation of a surface Micromachined Mechanical structure including a combination of springs, masses, motion sensing and actuation cells onto a chip using integrated circuit fabrication techniques. A simplified schematic diagram of a MEMS-based accelerometer is shown in Figure 2. The fixed outer plate in conjunction with the movable middle plates, form a measurement capacitor operating in a differential configuration. The movable plate is linked to a proof mass (beam) with each of its two ends tied to a tether. With the movable structure at rest, the middle plate is equidistant from the two fixed plates and therefore the differential output capacitance equals to zero (Figure 2, left). When subject to acceleration or gravity, the proof mass, and therefore the center plate, deflects from its neutral position, thereby creating a non zero differential capacitance (with CS2 > CS1 for the direction of applied acceleration shown in Figure 2, right).

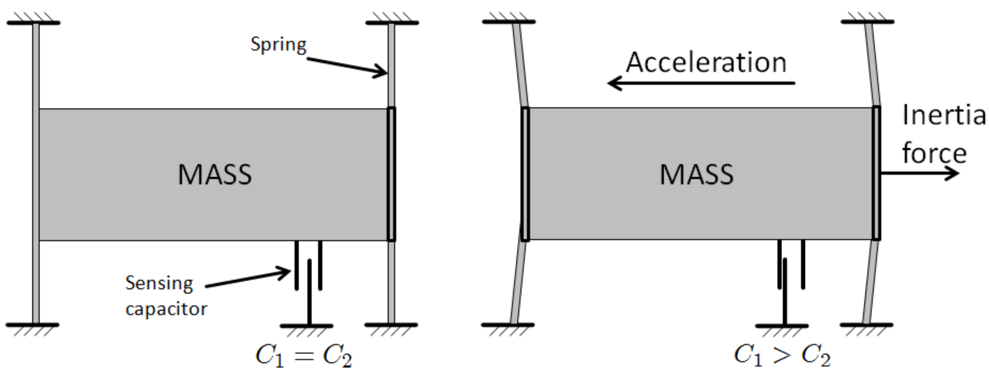


Figure 2 Top view of a Micromachined Mechanical structure at rest (left) and subject to acceleration (right).

It should be noted that the MEMS type of accelerometer described above behaves like a mechanical mass-damper-spring system with the residual gas sealed inside the chip providing a damping action. Support circuitry such as oscillators, amplifiers, demodulators, and filters, etc. are also integrated onboard such that the output voltage generated by the chip can be used to directly interpret its differential output capacitance and therefore the acceleration that is applied to it. While this type of device is low cost and can be used to measure signals with a bandwidth from DC up to several kHz, one should carefully consider the need for compensation of DC offset and thermal drift plus a possible calibration of this type of device in an application.

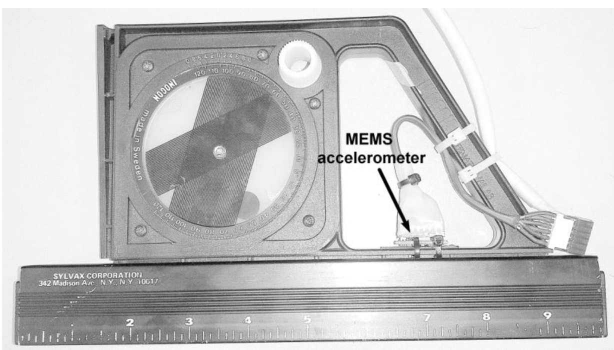
In this experiment, the Analog Devices ADXL330 MEMS accelerometer is available for your exploration. The ADXL330 is a complete 3-axis acceleration measurement system on a single monolithic IC with a ±3 g minimum range. It contains a polysilicon surface micromachined structure built on top of a silicon wafer for sensing the X, Y, and Z axes. Polysilicon springs suspend the structure over the surface of the wafer and provide a resistance against acceleration forces. Deflection of the structure is measured using a differential capacitor that consists of independent fixed plates and plates attached to the moving mass. The fixed plates are driven by 180° out-of-phase square waves. Acceleration deflects the moving mass and unbalances the differential capacitor resulting in a sensor output whose amplitude is proportional to acceleration. Phase-sensitive demodulation techniques are then used to determine the magnitude and direction of the acceleration. The demodulator output is amplified and brought off-chip through a 32 kΩ resistor. The user then sets the signal bandwidth of the device by adding a capacitor. This filtering improves measurement resolution and helps prevent aliasing. The output signals are analog voltages that are proportional to acceleration. The accelerometer can measure the static acceleration of gravity in tilt sensing applications as well as dynamic acceleration resulting from motion, shock, or vibration[1].

The ADXL330 is a 16-pin IC chip incorporating 3 individual accelerometers for measuring acceleration in the X, Y and Z direction with a ±3g range. The chip is packaged in form of a tiny circuit board and its pinout and other technical specifications are described in the DE_ACCM3D.pdf document. We will power the board using an external **5V** power supply and operate the device with a **3.3V** power sourced by the onboard voltage regulator. At this operating voltage, the sensitivity of the device is 330 mV/g.

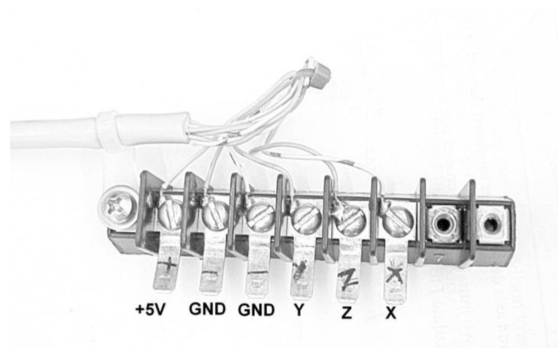
4 Experimental procedure

4.1 Tilt and angle measurement with ADXL330

The ADXL330 accelerometer is mounted on an inclinometer with the *Y* axis of the device oriented perpendicular to earth's gravity. The accelerometer mounted on inclinometer is shown in Figure 3a. The connections are indicated in Figure 3b.



(a)



(b)

Figure 3: Inclinometer with mounted MEMS accelerometer (a); and MEMS accelerometer connections (b).

At zero degree of inclination, the *Y* axis transducer generates an output bias voltage V_{bias} of approximately 1.66V that corresponds to zero gravity. Assuming the transducer generates an output voltage of V_o at an inclination of x degrees, then the angle of inclination can be computed with the following simple procedure:

- The output voltage of the accelerometer with reference to zero gravity $V_{out} = V_o - V_{bias}$
- At device sensitivity of $330mV/g$, the above quantity represents an acceleration $a = V_{out}/(330mV/g)$.
- As indicated in Figure 4, the accelerometer readout will depend on the inclination angle α following the formula: $sin\alpha = a_y / g$, where a_y is the projection of the gravity on the accelerometer measurement axis (the measured acceleration).
- Therefore, the inclination angle $\alpha = arcsin((\mathbf{V_o} - 1.66\ V) / 0.33\ V/g)$.

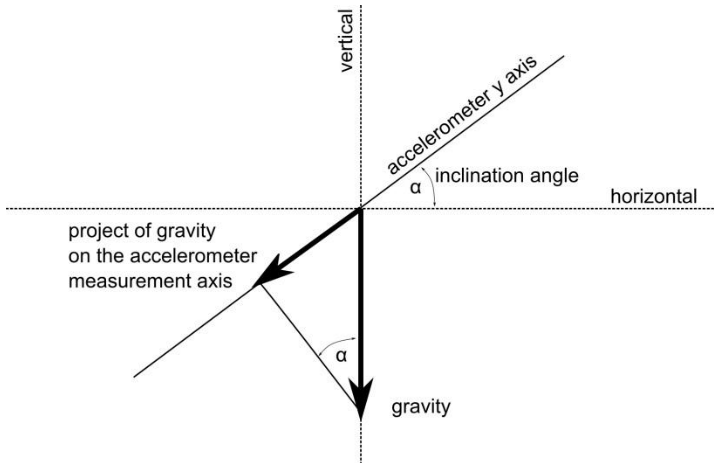


Figure 4: Projection of gravity on the accelerometer measurement axis.

Calibration

Position the inclinometer at zero inclination angle and note the output voltage. This will be the V_{bias} used in the subsequent calculations.

Angle measurement

Use the procedure outlined above to plot a graph for a slope from -90° to +90° (10° step) for the calculated inclination angle versus the output voltage. Try to take as many data points as you can around the 0° slope as this is the region where you will need accurate readings for the next part of the experiment. For each measurement taken, calculate the nonlinearity error.

4.2 Vibration frequency measurements

In large mechanical machinery, the vibrations caused by normal performance can often be used as a reference for detecting improper operation. As the machine ages and wears, the vibration signature (as detected by an accelerometer) could indicate a declining health of the piece of equipment that might require some maintenance work in order to avoid a catastrophic failure. For example, by comparing the current vibration pattern of a power generator against the signature recorded when the machine was new, we are able to detect possible bearing wear and small imbalances in the dynamics of the machine long before it completely fails causing serious consequences. In this part of the experiment, we will use a PCB piezoelectric accelerometer with its ICP signal conditioner and power supply to measure the resonance frequency of an aluminum cantilever beam.

4.2.1 Natural Frequency of a Cantilever

As you would expect, the resonant frequency of a cantilever beam depends on its length, mass and of course its stiffness. As you pluck the cantilever, the potential energy stored in the "spring" gets converted into kinetic energy in the moving mass and then as the mass reaches the peak of the oscillation, the energy is again stored as potential energy in the spring (now in the opposite direction). The end of the cantilever bounces up and down until the energy is dissipated and the cantilever comes to a rest.

To determine the natural frequency of the cantilever, we are going to simplify the problem by considering the cantilever to be a solid, slender bar that is restrained by a spring at the pivot point. Note that the calculations are done considering that the slender bar is vertical. Refer to Figure 5 for the following discussions.

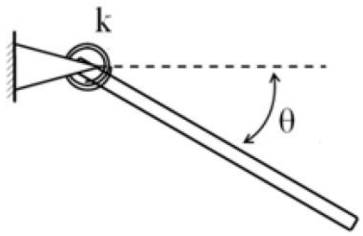


Figure 5. A cantilever with a spring constant k.

For a small value of θ, we can write the cantilever equation of motion as:

$$-k\theta = J\ddot{\theta} \tag{2.1}$$

Where from now on:

- J moment of inertia of the beam (kg.m^2)
- m mass of the beam (kg)
- l length of the beam (m)
- θ deflection angle (Radian)
- k spring constant of the beam (N.m)

The natural frequency of the beam can be found as follows:

$$\omega_n = \sqrt{\frac{k}{J}} \tag{2.2}$$

$$J = \frac{ml^2}{3} \rightarrow \omega_n = \sqrt{\frac{3k}{ml^2}} \tag{2.3}$$

Adding the accelerometer mass on to the beam (for making the actual measurement) change the moment of inertia by a factor of:

$$J_0 = m_{acc}l_{acc}^2 + \frac{ml^2}{3} \tag{2.4}$$

Where l_acc and m_{acc} are the location and the mass of accelerometer, respectively (l_acc should be measured from the clamping edge).

Thus, the compensated natural frequency of the cantilever system becomes:

$$\omega_n = \sqrt{\frac{k}{J_0}} = \sqrt{\frac{3k}{3m_{acc}l_{acc}^2 + ml^2}} \tag{2.5}$$

4.2.2 Experimental procedures for measurement of the natural frequency

In order to measure the natural frequency of the cantilever, we will mount a piezoelectric accelerometer on the cantilever and observe its output on an oscilloscope. Four different mounting locations for the accelerometer have been provided on the cantilever. You will take measurements of the vibration frequency from all the 4 locations and explain any differences you find. Figure 6 shows a picture of the aluminum bar whose vibration frequencies you need to measure in this experiment.

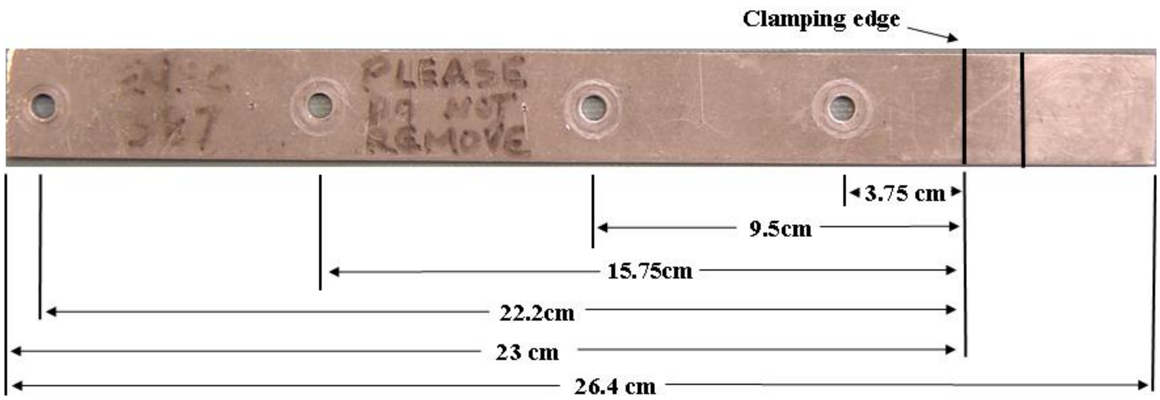


Figure 6: Aluminum bar used for vibration frequency measurement.

Additional specifications for the bars are as follows:

- Bar width = 25.22 mm
- Bar thickness = 3.28 mm
- Bar weight = 56 g

You will notice that there are 4 holes in the aluminum bar for mounting of the accelerometer. At one end, there is a line scored across the bar to indicate the clamping position – the beam should be inserted as much as possible into the clamp without extending beyond the clamp. A box of weights is available to "load" the beam and calculate its spring constant $\boldsymbol{k}$ based on the formula

$$k = \frac{Fl}{\Delta\theta} \tag{2.7}$$

Where F is the force exerted on the end of the beam (weighing mass * 9.81ms^{-2}), l is the length of the cantilever and $\Delta\theta$ is the corresponding angle of deflection (in radians).

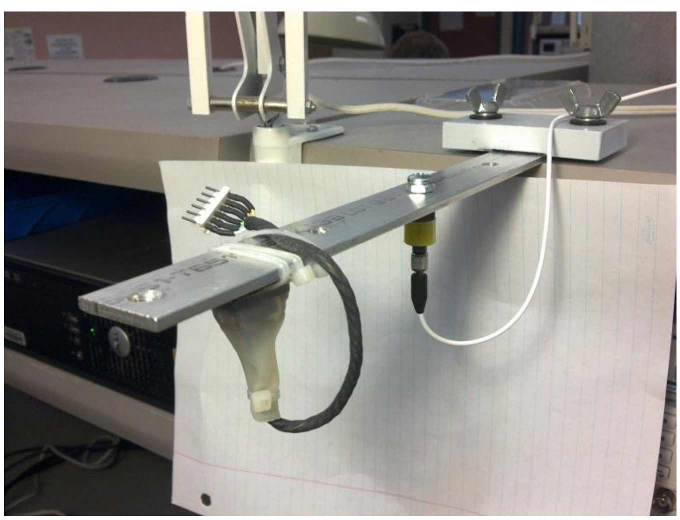


Figure 7: Beam clamping and accelerometer mounting.

1. Mount the beam onto the clamp following Figure 7.

2. Hang the aluminum basket (weight = 22.8g) provided to the end hole of the beam and use a mass of 200g, 500g, 1kg, and 2kg as the load and measure the corresponding amount of deflection for each of these four cases. Use the ADXL330 accelerometer which is mounted on the underside of the beam and the calibration data which you obtained in part 4.1 for your beam deflection measurements. Calculate the average value of k using equation (2.7) based on the above conditions and use this average value to carry out any further computations.
3. Assemble the piezoelectric accelerometer setup using the ICP amplifier, following Figure 8. The white cable has been preassembled for you. No not disconnect the white cable from the accelerometer.

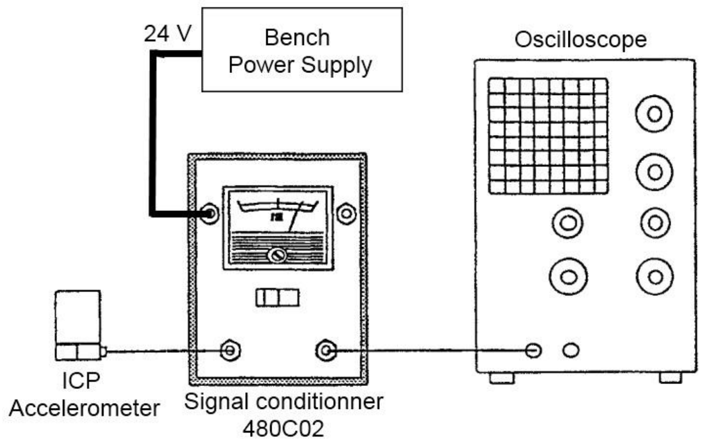


Figure 8: Accelerometer connection scheme

4. After having determined the spring constant, mount the piezoelectric accelerometer onto the end hole of the beam (Figure 7, use your fingers only to secure the accelerometer and DO NOT OVERTIGHTEN THE SCREW). Please observe, the accelerometer is mounted on the underside of the beam to prevent loading the cable. Also, the cable is secured behind the nut to avoid mechanical loading on the vibrating structure. Measure the location of the accelerometer on the beam using the provided ruler.
5. Pluck the beam at its end and observe the accelerometer output on the scope. Use the Tektronix digital scope to make frequency measurements. Repeat the measurements with the accelerometer mounted in each of the 3 other holes. Tabulate the data you have collected to show all of your calculated and experimental results for the various positions of the accelerometer on the beam.
6. Show all measurements and calculations associated with determining the spring constant, $\boldsymbol{k}$.
7. Calculate both the approximate cantilever frequency using equation (2.4) and its corresponding compensated version (2.6) for each of the four accelerometer mounting positions. Note the mass of the accelerometer $\boldsymbol{m_{acc}}$ is 12 g.
8. Show your observed frequencies. Record all four waveforms and include these plots in your report.

9. Compare your theoretical calculations to the experimentally observed values and explain any discrepancies.