MECH 420 Sensors and Actuators

Laboratory Manual

Fall 2024

The University of British Columbia

Department of Mechanical Engineering

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General Guidelines

1. Preparation and Pre-Labs

Read the lab manual before your lab session. Answer the pre-lab questions and turn your answers in via Canvas **by the submission deadline**.

2. Lab Sessions

We will be having 6 lab sessions.

At the beginning of your lab session, the TA will discuss the lab background.

You can log into the lab PCs using your UBC CWL. Open the LabView VI for your current lab session. The TA will show you the directory in which you can find the VIs. The different LabView VIs are only used to record data, the actuators are all driven directly through power supplies, function generators and amplifiers that are set by the user.

When executing the lab tasks, follow the written instructions and the instructions given by your TA.

Be rigorous in your procedures and be careful during execution not to damage any equipment as this could compromise completion of the laboratory for yourself as well as for others. However, in case equipment is damaged please report this immediately so it can be fixed.

Make sure to take notes during your experimental session in order to record all of the information necessary for your report, such as the data sampling rate.

Verify during the session if you have acquired the data of all the necessary signals. Data might not have been recorded from all devices in case of a bad connection.

Labs 3-6 involve actuator current and voltage measurements. These readings have offsets that need to be accounted for, and the offsets are different for the different stations. Always take a zero reading for current and voltage for the station that you are using.

Some of the data processing schemes (curve fitting Matlab scrips etc.) will be useful again in later labs. Some results from lab exercises will be used again in later labs. Example: You will need calibration results from Lab 3 in Lab 4.

Please bring a USB stick or a different storage device to save the data during your lab session. In case you save the data on the lab computer, for example to email it to you, then please delete these files at the end of your lab session.

3. Lab Reports

3.1 General Lab Report Logistics & Tips

Every student will prepare an individual report. On the first page of your report indicate your name, your lab group, the lab station number of the station at which you did your lab, the date on which you took the lab and the name of the TA supervising your laboratory session.

The report does not need to be a formal lab report. The report can be typed or handwritten.

For each experiment document the experimental setup and experimental conditions such as sampling rates for data acquisition.

Document the **mathematical operations** you have performed on the collected data by providing the corresponding equations in your report as well as the results. **Any person reading your report should understand what you have done.** Always report the **correct units**. Make sure all graphs are **properly labelled**.

The lab report needs to be turned in via Canvas, no later than **1 week after** carrying out your MECH 420 laboratory session.

3.2 Presenting Data

Number figures in consecutive order in which they are mentioned in your report. That implies that each figure should be referred to in the written portion of you report to provide context to the figure.

Each figure should have a descriptive caption. A title is not necessary.

Labels

- Label all data series (include a legend)
- Label all axis
- Include units

Fit lines: fit to expected relationship, not to smoothen data (unphysical – can be misleading), can connect data points with straight line segments

Significant digits: use a reasonable amount – level of confidence

See also: *Theory and design for mechanical measurements, R.S. Figliola, D.E. Beasley, 2006, Chapter 1*

4. Safety

4.1 Safety as a Way of Working

UBC Mechanical Engineering considers safety first, and continuously, in its labs, research, and other activities. Students are expected to engage in safety discussions; to ask questions to ensure they understand safety information; to comply with policies and rules; to maintain a safe workspace; and to report all accidents, incidents, and near misses immediately to their supervisor and to https://cairs.ubc.ca. Students should work with their supervisors to ensure they understand (1) the risks associated with their work and (2) how those risks are controlled.

4.2 Safety Considerations for This Course

Experiments in this course take place in Kaiser 1160, and will be supervised by a Teaching Assistant and/or other UBC staff.

Your TA has been trained in safety and emergency procedures. In the event of an accident, incident, or near miss, alert them immediately. Instructions are also posted on the back of the door of the lab.

A summary of key procedures includes:

- Fire: Leave immediately if there is a fire alarm, which may be either a continuous or intermittent bell. Shut off equipment if it is safe to do so. Your evacuation assembly area is on Main Mall.

- Earthquake: Shut off equipment, duck, cover, and hold on. Count out loud to sixty seconds, then evacuate as if a fire. Take care for broken glass.

- First Aid: Call 9-1-1 for medical emergencies. For first aid, or after you call 9-1-1, call 604-822-2222 for campus first aid.
- Security: Call 604-822-2222 to reach campus security.

PPE required for this course

- Floor-length leg coverings, such as pants or a floor length skirt.
- Closed-toe shoes.
- Long hair tied back.
- Jewelry and watches removed.

Risk Management

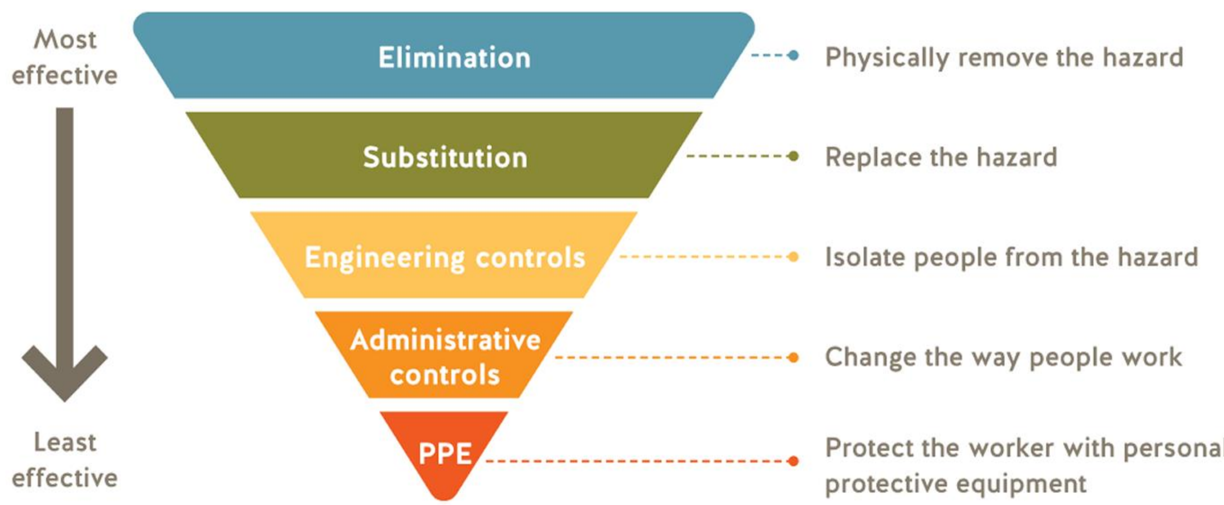


Figure 0.1: Graphic from WorkSafeBC

The instructional team for this course has designed each experiment to eliminate, substitute, and control risks, and to ensure students are protected from hazards, using industry-standard methodology. For each experiment in this course, review the table of risks and how they have been reduced, and what residual risks remain.

Laboratory Exercise #1: Proximity Sensing

Learning Objectives

The main objectives of this laboratory exercise are:

- To understand the principles of the infrared reflective object sensor, the LED position sensor, the eddy current inductive proximity sensor, and the capacitive proximity switch,
- to determine the quasi-static transfer characteristics of the proximity sensors through a calibration procedure,
- to relate information in sensor data sheets to observed device behaviour,
- to recognize the limitations and possible areas of application for these 4 sensor types.

1. Introduction

Background

Proximity sensors are commonly used in industry to detect the presence or the distance of an object without making physical contact. During this laboratory exercise output signals of four different types of proximity sensors will be examined and compared. The sensors operate on different physical principles, making them more or less suitable for certain applications. Sensor calibration is an important process in industry and in research laboratories; the four proximity sensors will be calibrated here to determine their response characteristics with respect to different object materials.

Overview

The setup used in this laboratory exercise shown in Figure 1.1 allows moving different test targets to different distances with respect to the proximity sensors. The proximity sensor signals along with the signal from a reference sensor are fed into a signal conditioning interface. The conditioned voltage signals are read into a PC via A/D conversion through a data acquisition board. Data acquisition occurs using the software package LabVIEW.

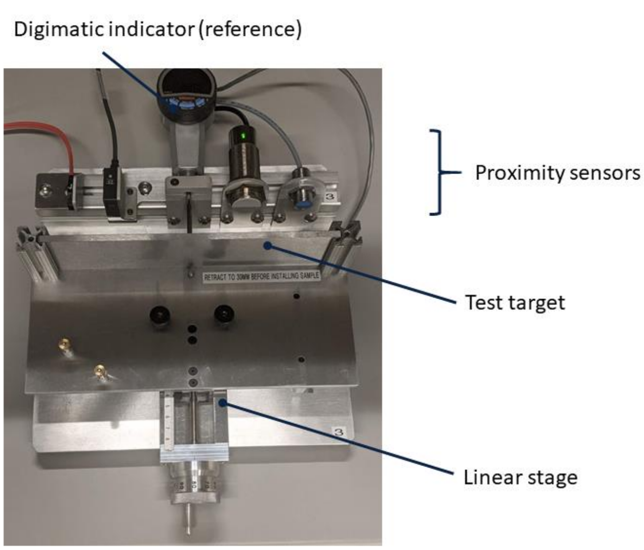


Figure 1.1: The component characterization station, here set up to calibrate the proximity sensors.

2. The Proximity Sensors

The data sheets of the proximity sensors can be found on Canvas.

2.1. Infrared Reflective Object Sensor

Infrared (IR) radiation corresponds to wavelengths in the electromagnetic spectrum that are longer than wavelengths of visible light. IR radiation cannot be seen by eye but it can be detected. Objects that generate heat also generate infrared radiation and those objects include animals and the human body whose radiation is strongest at a wavelength of 9.4 µm. Infrared radiation in this range will not pass through many types of material that are transparent to visible light such as ordinary window glass and transparent plastic. However infrared radiation can pass through, with some attenuation, certain materials that are opaque to visible light such as germanium and silicon. An unprocessed silicon wafer makes a good IR window in a weatherproof enclosure for outdoor use.

The IR sensor used in this exercise (OPB741WZ by Optek Technology, a TT Electronics brand) is made of an infrared emitting diode and a phototransistor. The IR emitting diode gives off IR radiation in the general direction of the target object, and the phototransistor gathers the reflected IR radiation as shown in Figure 1.2.

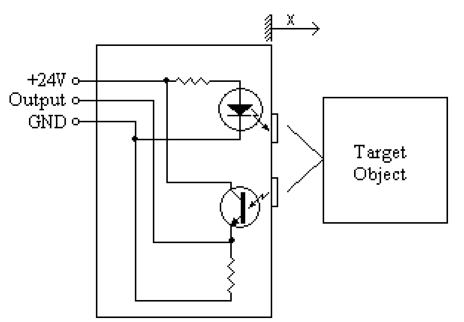


Figure 1.2: A typical configuration of an infrared reflective object sensor.

The intensity of the light received by the photodetector will depend on position x of the target object. In particular, if $x = 0$, the light path between the emitter and the receiver will be completely blocked off and the light intensity at the receiver becomes zero. As x increases, the intensity of the received light will increase, because more and more light will be reflected towards the receiver. The light intensity will reach a peak for some distance x_p, where the light path from the emitter to the receiver via the reflecting surface is mainly unobstructed as shown in Figure 1.3. At larger distances the effect of light distribution over a larger solid angle in space will be predominant; hence, the intensity of the received light will drop as the distance increases. For $x > x_p$ the proximity-intensity ($x - I$) curve for an optical proximity sensor will therefore follow a non-linear relationship similar to

$$I \propto 1/(x^2 + \left(\frac{s}{2}\right)^2) \ ,$$

where s is the distance between the emitter and the receiver. At first approximation we can assume that the amount of current allowed through the collector-emitter circuit is proportional to the light intensity. This current causes a voltage across the emitter-ground resistor, which is used as the sensor signal. The infrared reflective sensor used here is the type OPB741WZ by Optek Technology with approximately $s = 4.5$ mm.

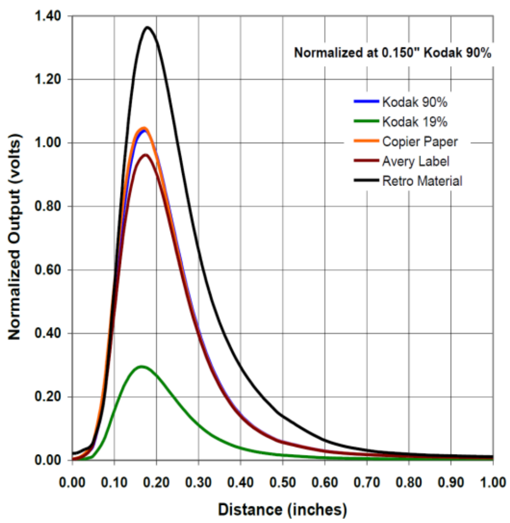


Figure 1.3: Transfer characteristic of the reflective object sensor OPB741WZ by Optek Technology [OPB741WZ data sheet].

2.2. Laser Distance Sensor

The laser distance detector OM20-P0026.HH.YUN by Baumer measures the distance of an object through light reflecting off that object in a different way as the infrared reflective object sensor described above. The pulsed red laser diode of the sensor projects a laser point in the object to be measured. The reflected laser point is mapped on the receiver element by the receiving optics, and the distance to the object to be measured is calculated from the location of the reflected laser point on the receiver element. The sensor output is a voltage between 0 and 10 V corresponding linearly to the object position along the measurement range of 10 mm as shown for the "non-inverted" signal in Figure 1.4.

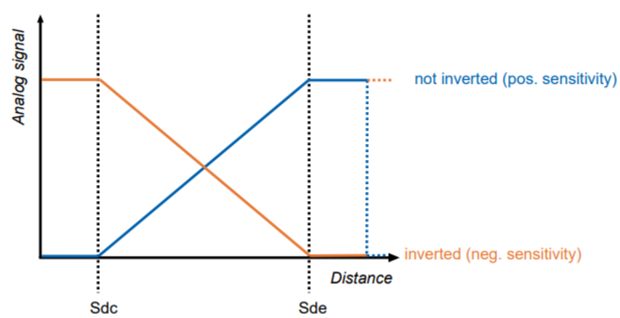


Figure 1.4: Transfer characteristic of the OM20-P0026.HH.YUN distance sensor by Baumer, provided in the data sheet by Baumer.

2.3. Eddy Current Proximity Sensor

If an electrically conductive medium is subjected to a fluctuating magnetic field, eddy currents are generated in the medium. The strength of eddy currents increases with the strength of the magnetic field and the frequency of the magnetic flux. Unlike variable-inductance proximity sensors, the target object of the eddy current sensor does not have to be made of a ferromagnetic material. A conducting target object is needed, but a thin film of conducting material—such as household aluminum foil attached to a nonconducting target object—is sufficient to detect the target. The probe head has two identical coils, which form two arms of an impedance bridge. The coil closer to the probe face is the active coil, the other coil is the compensating coil. When the target object is moved close to the sensor, eddy currents are generated in the conducting medium by the radio-frequency magnetic flux from the active coil. The magnetic field of the eddy currents opposes the primary field, which generates these currents. Hence, the inductance of the active coil increases, creating an imbalance in the bridge. The resulting output from the bridge is an amplitude-modulated signal containing the radio-frequency carrier. This signal is demodulated by removing the carrier. The resulting signal is a measure of the position of the target object. The sensor used in this exercise is the DW-AD-509-M18-320 by Contrinex with an approximately 0 – 10 V output signal over the range of 10 mm.

2.4. Capacitive Proximity Switch

Capacitive proximity sensors use the change in capacitance as an object is being placed in front of the sensor head. They are sensitive to most materials: dielectric materials such as glass, rubber and oil, and conductive materials, such as metals, fluids containing ions and moist wood.

When an object nears the sensing surface it enters the electrostatic field of the electrodes and changes the capacitance in an oscillator circuit. The trigger circuit reads the oscillator’s amplitude and when it reaches a specific level the output state of the capacitive proximity switch changes. Figure 1.5 shows the schematic diagram of such a capacitive proximity switch. Many of such switches provide a screw placed on the backside of the sensor that allows changing the threshold. As the target moves away from the sensor the oscillator’s amplitude decreases, switching the sensor output back to its original state.

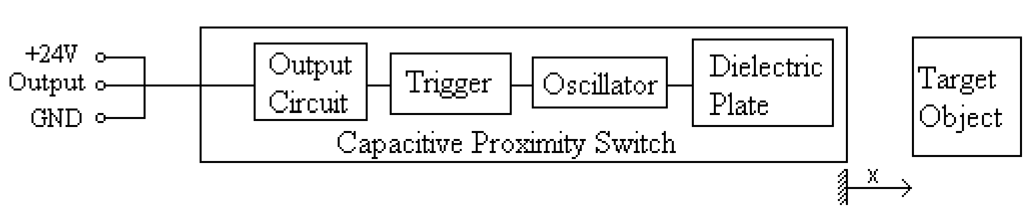


Figure 1.5: Schematic diagram of a capacitive proximity switch.

The sensor used in this exercise is the CT1-AN-1A capacitive switch by Micro Detectors.

3. The Setup and its Components

The proximity sensor characterization apparatus in Figure 1.1 consists of a base, linear crank stage, test target mounting platform, and sensor support structure. Test targets of various materials can be placed on the test target mounting platform that is attached to the moving section of the linear crank stage. As the platform is moved along the crank stage, the distance changes between the test target and the sensor support structure, where a number of proximity sensors and a digital dial indicator are placed. During this procedure, the proximity sensor signals along with the reference signal from the digimatic indicator are recorded by the PC.

Be aware that the digimatic indicator performs an averaging operation on its measurement over approximately 50 ms. This means that the measurement provided by the digimatic indicator represents an average of the measurement of the previous 50 ms, effectively resulting in a signal delay. All other sensors provide the momentary signal. The means that you have to displace the platform sufficiently slowly such that the delay of the digimatic indicator is negligible. A faster displacement would result in an apparent hysteresis in the signal of the other sensors when plotted against the digimatic indicator position.

The Proximity Sensors & Instrumentation

- IR reflective object sensor OPB741WZ by Optek Technology
- Laser distance sensor OM20-P0026.HH.YUN by Baumer

- Eddy current proximity sensor DW-AD-509-M18-320 by Contrinex
- Capacitive proximity switch CT1-AN-1A by Micro Detectors
- Digimatic indicator 543-737b by Mitutoyo
- Data Acquisition interface

The Test Targets

- Aluminum, one side is shiny, one side is sandblasted
- Polished Aluminum
- Steel
- Acrylic

4. Pre-Lab

1) Proximity Sensors
   Consult the data sheets for the 4 proximity sensors on Canvas. Discuss how suitable these 4 sensors are for measuring the position of an object over a range of 10 mm?
2) Curve Fitting
   Apply curve fitting to the data in the file Lab1_prelab_curve_fitting.csv for a fit to the general shape $S(x) = a + be^{cx}$. Copy the code (such as Matlab) you use for this into your pre-lab submission and show a plot of the data including the fit line. Indicate the fit equation and make sure to use correct units.
   For reading Excel data or csv data into MATLAB, you can use the xlsread command as follows, as an example:

   ```
   t = xlsread('Al_shiny.xlsx','Sheet1','A3:A1002');
   ```

   Curve fits in MATLAB such as a least squares curve fit can be achieved though lsqcurvefit().

5. Risks Associated with This Experiment

Category	Task	Hazard / Harm	Controls
Lifting & Handling	Lifting sample plates of up to 860 g mass	Dropping plates on foot	Wear closed-toed shoes
Pinch points and rotating equipment	Moving the linear crank stage	Finger pinch	Only the person handling the crank should touch the setup
Dust, chips, airborne	-	-	-
Electrical	-	-	-
Vibration	-	-	-
Noise	-	-	-
Chemicals	-	-	-
Safe disposal	-	-	-
Slips, trips, falls	-	-	-
Working alone	Various	Working alone	Working alone not permitted
Ergonomics	-	-	-
Other	-	-	-

Residual risk considerations:

The primary risk associated with this lab is to drop sample plates with sharp edges on one's foot. Please be careful when handling these plates. Any injury should be reported to the TA; First Aid should be called and a CAIRS report submitted.

6. Lab Procedure & Analysis

Calibration of the Proximity Sensors

You will now measure the signals of the proximity sensors for the different test targets made from different materials. You will use the measurements to calibrate the sensors. You will also evaluate the limitations of the different sensor types with respect to their applications for object detection.

Experimental Procedure

For all data acquisition experiments inspect your data and make sure you record the signals with sufficient temporal resolution without gathering an unmanageable amount of data; choose an adequate sampling frequency and include it in your report You might want to use Excel for a quick check of the recorded data, while you might use other software such as Matlab to analyze the data for your report.

Be aware that the digimatic indicator performs an averaging operation on its measurement over approximately 50 ms. This means that the measurement provided by the digimatic indicator represents an average of the measurement of the previous 50 ms, effectively resulting in a signal delay. All other sensors provide the momentary signal. The means that you have to displace the platform sufficiently slowly such that the delay of the digimatic indicator is negligible. A faster displacement would result in an apparent hysteresis in the signal of the other sensors when plotted against the digimatic indicator position.

Note: If you like, you can observe this effect by displacing the platform in one direction and then back to its original position while recording the sensor data. Then plot the LED sensor data vs. the signal from the digimatic indicator. The observed apparent hysteresis will widen for a faster displacement of the platform, confirming this is a dynamic effect.

1) Prepare the setup
    1. Move the platform to the end farthest away from the proximity sensors. Mount the aluminum test target on the linear slider with the shiny side facing the sensors. Please make sure not to drop the sample plate onto the digimatic probe so its spindle dos not get bent.

    a) Note that all the sensors are mounted such that their faces are all at the same position as the digimatic indicator when it is fully depressed.
2) Start the LabVIEW VI for Lab 1; use the VI "Lab 1 06-19-2023.vi" and **not** the one called "Lab 1 09-05-2024.vi". Select an adequate sampling rate and run the data collection. This will be helpful initially as you adjust the equipment, but you might not want to save all data sampled.
3) Set the threshold of the capacitive switch
    a) Crank the handle to move the test target towards the sensors.
    b) Adjust the threshold of the capacitive switch by turning the adjustment screw so that the switch changes state approximately at 5 mm. Then push the STOP button in LabView. This will end data

acquisition and automatically open Excel to display the data. Don`t save the collected data. Get the setup ready for data collection by bringing the test target back to its original position.

Alternatively, you can position the test target at around 5 mm and then turn the adjustment screw such that the red indicator on the switch changes state (red light on means the object is near).

4) Collect data for the shiny aluminum test target
   a) Run the VI to start data collection.
   b) Crank the handle to move the test target towards the sensors.
   c) When the test target is closest to the sensors, crank the handle to move the linear slider back to its furthest position away from the sensors while still collecting data. Then stop data collection and save the data file
   d) Always inspect your data to make sure you have all the information you need.
5) Collect data with the remaining test targets including the sandblasted side of the aluminum target
   a) Make sure to retract the linear slide past the 30 mm position to the stop at the 50 mm mark when installing the various different sample material plates as it is possible to damage the digimatic probe spindle. The plates and digimatic indicator interfere when not retracted.
   b) Flip the aluminum test target such that its sandblasted side faces the sensors, then use the polished aluminum, steel, and Acrylic test targets.
   c) Repeat the previous steps (3 & 4) for each of the test targets.

Always save all of your results on a USB stick so that you can finish the report requirements later.

Analysis

It is up to you how you process, analyze and plot the experimental data. In case you are interested in reading the Excel data into MATLAB, you can use the xlsread command as follows:

```
t = xlsread('Al_shiny.xlsx','Sheet1','A3:A1002');
```

This accesses Sheet1 in Excel file Al_shiny and reads the time values in column A from row 3 to 1002 into variable t

1) Prepare one graph for each proximity sensor showing the sensor signal for all test targets as a function of distance between the sensor and the test targets. Use the distance measured by the dial gauge as the reference distance.
2) Compare your observations for all 4 sensors to the specifications in the data sheets and in this lab manual. Comment on range, linearity and hysteresis for each sensor.
3) Determine the calibration equation for both the LED position sensor and the IR reflective object detector for the shiny aluminum test target. For the IR sensor, only fit to the data in the non-linear region at distances greater than the signal peak, for example starting around 5 mm. It might be convenient to perform curve fits in MATLAB such as a simple linear regression using polyfit() or a least squares curve fit lsqcurvefit().
   a) Provide the calibration equations for both sensors.
   b) Provide one plot for each sensor showing the measured data and the fit curve.
4) What type of proximity sensor would you use for the following tasks? Explain.

a) Detecting whether a conductive object is present.

b) Determining the approximate distance of an opaque object.

Laboratory Exercise #2: Displacement Sensing

Learning objectives:
The main objectives of this laboratory exercise are:

- To understand the principles of the potentiometer, the differential variable reluctance transducer (DVRT), and the incremental encoder for measuring linear displacements,
- to determine the quasi-static transfer characteristics of the displacement sensors through a calibration procedure,
- to relate information in sensor data sheets to observed device behaviour,
- to relate the quadrature signal of encoders to the accuracy of the encoder signal, the direction of displacement and velocity.

1. Introduction

Background
Methods to measure position or displacement are essential for most mechatronic systems. While most proximity sensors considered in Laboratory Exercise #1 can be considered displacement sensors, here we will focus on displacement sensors that are connected to both the moving object and the stationary reference; they often apply a mechanical load to the object of which the position or displacement should be determined. As a consequence, these devices are most suitable for tasks that involve low velocities and frequencies. On the other hand, these displacement sensor principles can allow for a much wider operational range compared to the position sensor in Laboratory Exercise #1. During this laboratory exercise three different types of displacement sensors will be characterized, a potentiometer, a differential variable reluctance transducer and an incremental optical encoder. The significant presence of digital systems for information processing and display in measurement and control systems makes digital sensors such as encoders very attractive. Because their output is directly in digital form, they require only very simple signal conditioning and are generally less susceptible to electromagnetic interference than analog sensors.

Overview
The setup used in this laboratory exercise is the same as for Laboratory Exercise #1. Instead of different test targets the displacement sensors will indicate the position of the translation stage. Their signals are fed into a signal conditioning interface. The conditioned voltage signals are read into a PC via A/D conversion through a data acquisition board. Data acquisition occurs again using the software package LabVIEW.

2. The Displacement Sensors

2.1. The Linear Potentiometer
The linear potentiometer provides an absolute reference position of the platform as it is moved by the linear crank stage. A voltage of 10 V is applied across a fixed resistor. This resistor rail has a constant resistance per unit length; as a result, the voltage at any point along its length is proportional to the distance from one end of the rail to that point, and it can be evaluated as for a voltage divider. The moving stage has two brushes attached to it, which are electrically connected, as shown in Figure 2.1. The first brush touches the resistance rail, while the second brush touches a second conducting rail running parallel

such that the signal voltage on the conducting rail is proportional to the stage position. This laboratory Exercise uses the potentiometer model PZ12-A-0050-L by Gefran.

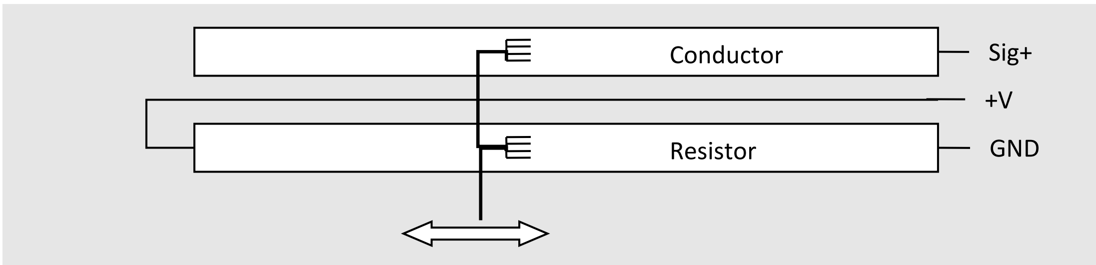


Figure 2.1: Linear potentiometer

2.2. Differential Variable Reluctance Transducer (DVRT)

The differential variable reluctance transducer (DVRT) depicted schematically in Figure 2.2 is an absolute displacement sensor with a much lower mechanical resistance than a potentiometer.

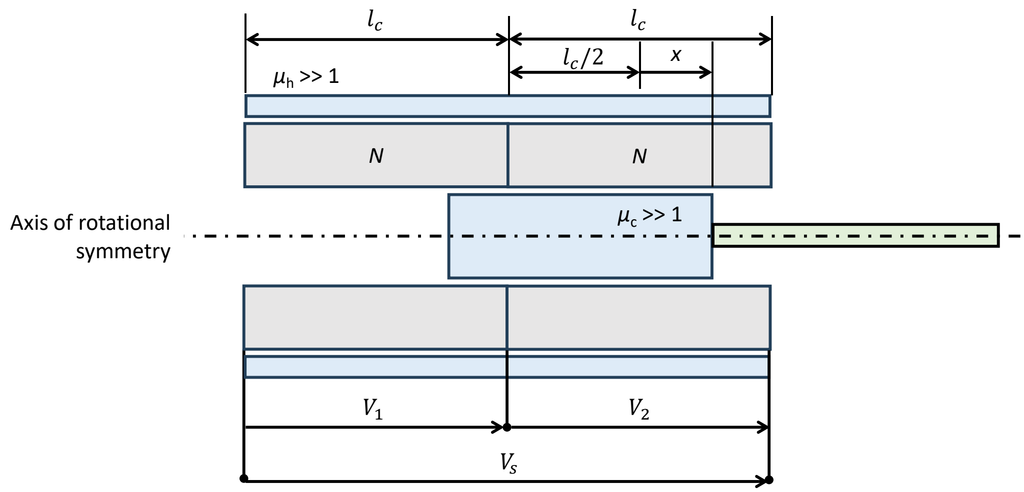


Figure 2.2: Schematic diagram of a DVRT.

The DVRT consists of an insulating, nonmagnetic “form”, which has the two segments of the coil symmetrically wound with a centre-tap. The housing of the DVRT is made from ferromagnetic steel in order to shield the sensor from outside fields. The DVRT has a much larger stroke-to-length ratio than a linear variable differential transformer (LVDT). However, the LVDT shows a higher degree of linearity.

An AC voltage V_s is applied to the extreme ends of the coil. A core made of ferromagnetic material is inserted coaxially through the cylindrical form without actually touching it. The core position is inferred based on the reluctance, or the inductance of each winding. When the core is centered between the two windings the inductance of both windings will be the same. When the core is displaced to the right, the inductance of the right winding will increase, and ideally, the inductance of the left winding decreases by the same amount; when the core displaces to the left, the opposite occurs. The change in inductance is proportional to the change in both the voltage across each respective winding, and the position change of the core, which allows the core position to be determined from the measured voltages.

Arranging the coil in a bridge circuit yields an output voltage

$$V_o = \frac{x}{l_c} V_s$$

that is ideally linearly proportional to the core position x.

The DVRT used in this lab is the LRE19-050R-00-10A by Alliance Sensors Group. Please note that this company refers to their DVRT as a linear-variable inductance transformer (LVIT).

2.3. The Incremental Optical Encoder

Linear and angular position encoders are digital output sensors. An incremental optical position encoder consists of a linear ruler or a low-inertia disk driven by the part whose position is to be determined. That element includes transparent and opaque regions or sectors, and these regions are arranged in a repetitive pattern as in Figure 2.3.

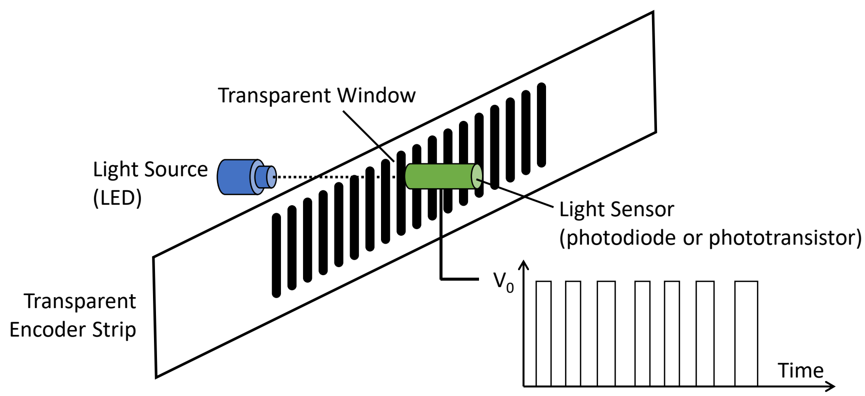


Figure 2.3: Principle of a linear incremental position encoder; optical encoders include windows and an optical reading device.

The incremental optical rotary encoder is the most common type of shaft encoder; they are commercially available together with DC motors, in integrated servomotors. These are feedback-controlled DC motors, which are appropriate for accurate positioning and motion control applications such as robotics and manufacturing.

A linear optical encoder uses a transparent strip with opaque markings (encoder strip), which has one or more linear tracks, with transparent windows (slits) in each track. A parallel beam of light (e.g., from a set of light-emitting diodes, or LEDs) is projected to all tracks from one side of the strip. The transmitted light is picked off using a bank of photosensors on the other side of the strip. The arrangement shown in Figure 2.4 a indicates just one track and one pick-off sensor. The light sensor may be a silicon photodiode or a phototransistor. Since the light from the source is interrupted by the opaque regions of the track, the output signal from the photosensor is a series of voltage pulses. This signal can be interpreted (e.g., through edge detection or level detection) to obtain the increments in the linear position and also linear velocity of the strip.

In motion control applications it is important to measure the direction as well as the magnitude of motion (i.e., velocity rather than speed). In the simplest configuration the strip has only a single track with identical and equally spaced windows, where the width of the opaque area between adjacent windows is identical to the window width. Two photosensors (pick-offs 1 and 2) are positioned facing the track at a quarter-pitch (half the window width) apart as shown in Figure 2.4 a. Figures 2.4 b and c show the output signals (V_1 and V_2) of these photosensors after signal conditioning through pulse-shaping circuitry.

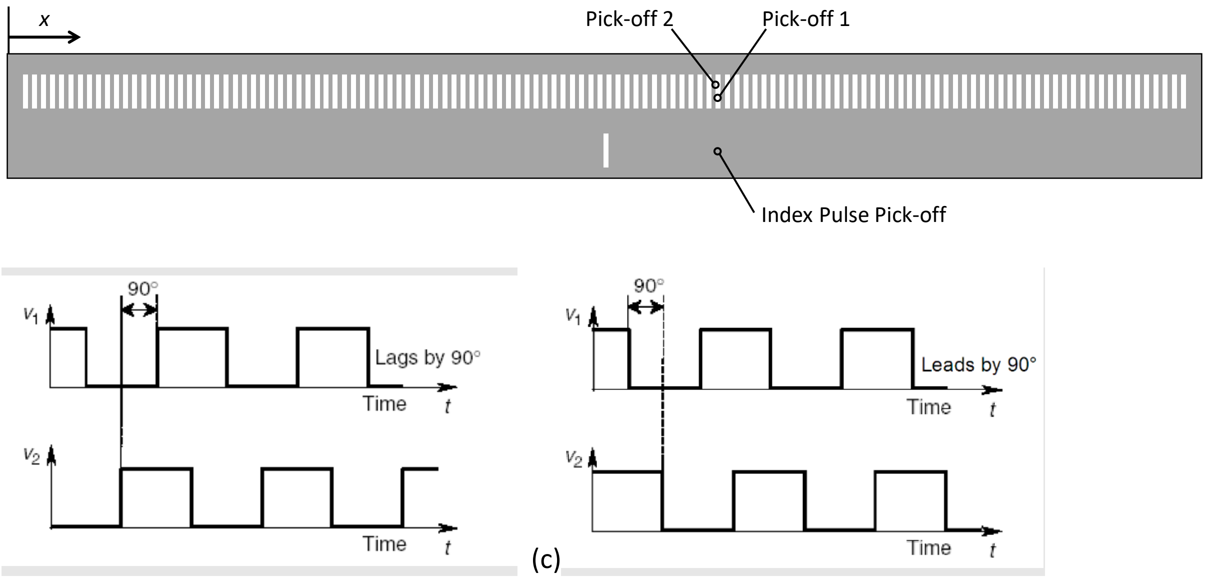


Figure 2.4: Detection of the direction of displacement using an incremental linear encoder; (a) an encoder strip with a single track and two pick-offs, (b) encoder signal for displacement to the right, (c) for displacement to the left.

Figure 2.4 b shows the sensor signals when the strip is displaced to the right and Figure 2.4 c shows the outputs when the strip moves to the left. It follows from the figure that for motion to the right, V_1 lags V_2 by a quarter of a cycle (i.e., a phase lag of 90°), and when moving to the left, V_1 leads V_2 by a quarter of a cycle. Thus, these signals are called “quadrature signals” in view of their 90° phase shift. The direction of displacement is obtained by determining the phase difference of the two output signals, using phase-detecting circuitry. One method of accomplishing this is to time (using clock pulses) the interval from the rising edge of one signal to the next rising edge of this signal and also to the next rising edge of the second signal.

Many incremental encoders have an additional *reference* track, for instance with one single window and associated sensor available as shown in Figure 4.2 a. The strip used in this lab has an index pattern consisting of an opaque region between two narrow windows. The signal generated by this pattern can be used to determine the absolute position of the strip.

Encoder strips with many tracks can directly encode the absolute position either through a natural binary code pattern, or different code patterns such as the Gray code that is more robust to slight misalignments between the individual tracks.

Linear Displacement and Resolution

An incremental encoder measures displacement as a pulse count. We will consider an encoder strip with N windows spanning a length L, where N/L is indicated in lines per inch for the strip used here. A count of n pulses from one pick-off corresponds to a displacement

$$x = \frac{n}{N} L.$$

In addition to the information about the direction of displacement the quadrature signal gives information about the position of the strip. The physical resolution of an encoder with one single encoder track is the increment corresponding to one pulse width for detection of rising or falling edge, or ½ pulse width if opaque and transparent regions of the code disk are distinguished. However, it is possible to use the quadrature signal to increase the resolution of the position measurement. Using the quadrature signal, the physical resolution of displacement measurement

$$\Delta\mathrm{x} = \frac{L}{4N}$$

can be achieved, because each displacement between two corresponding window edges of adjacent windows corresponds to 4 different signal combinations from the two pick-offs.

Linear Velocity Measurement and Resolution

Two methods are available for measuring speed using an incremental encoder:

2. Pulse-counting method
3. Pulse-timing method

In the discussion of these methods we will refer to the signal from a single pick-off generated from either rising or falling edges. In case the quadrature signal is used, the same results are valid for $N_Q = 4N$ increments (transitions) per length L.

In the pulse-counting method, the pulse count n over a fixed time period T yields the velocity U_c. Hence, the average time for one pulse is T/n. The distance moved during one pulse is L/N, yielding a speed

$$\mathrm{U}_c = \frac{Ln}{NT}$$

for a count of n pulses during the time period T. This method provides a low accuracy at low velocities.

In the pulse-timing method, the time for one encoder period is measured using a high-frequency clock signal at frequency f. If m cycles of the clock signal are counted during an encoder period (interval between either the leading or the falling edges of two adjacent windows), the time for that encoder period (i.e., the time to displace by one encoder pitch) is given by m/f. The displacement during this period is L/N as before, yielding a speed

$$\mathrm{U}_t = \frac{Lf}{Nm}.$$

This method is particularly suitable for measuring low speeds.

The velocity resolution is the smallest change in velocity that can be measured. For the pulse counting method, the velocity resolution

$$\Delta\mathrm{U}_c = \frac{L}{NT}$$

is given by the difference in velocity corresponding to a pulse count difference $\Delta n = 1$.

For the pulse timing method, the difference in speed corresponding to a clock count increment of $\Delta m = 1$ yields the speed resolution

$$\Delta\mathrm{U}_\mathrm{t} = \frac{Lf}{Nm(m+1)},$$

which can be approximated by

$$\Delta\mathrm{U}_\mathrm{t} \approx \frac{N\mathrm{U}_t^2}{Lf}$$

for large clock cycle counts m, and is therefore a function of the current velocity U_t.

In this lab, we are using the optical encoder strip LIN-127-4.5-N and the optical encoder module EM1-0-127-N by US Digital.

3. The Setup and its Components

The Component Calibration Station

The apparatus used for proximity sensor characterization will also be used to characterize the displacement sensors. One end of both the potentiometer and the DVRT is attached to the base of the calibration station, while the other end moves with the crank platform. The encoder strip of the incremental linear encoder moves with the platform while the encoder module is fixed to the base of the calibration station. The digimatic indicator serves again as a reference instrument.

Remember that the digimatic indicator performs an averaging operation on its measurement over approximately 50 ms. This means that the measurement provided by the digimatic indicator represents an average of the measurement of the previous 50 ms, effectively resulting in a signal delay. All other sensors provide the momentary signal. The means that you have to displace the platform sufficiently slowly such that the delay of the digimatic indicator is negligible. A faster displacement would result in an apparent hysteresis in the signal of the other sensors when plotted against the digimatic indicator position.

The Displacement Sensors

- Linear potentiometer PZ12-A-0050-L by Gefran
- DVRT (or LVIT) LRE19-050R-00-10A by Alliance Sensors Group
- Optical encoder strip LIN-127-4.5-N and optical encoder module EM1-0-127-N by US Digital.
- Digimatic indicator 543-737b by Mitutoyo

4. Pre-Lab

Consult the data sheets for the 3 displacement sensors on Canvas. What are the range and resolution for each of the sensors?

5. Risks Associated with This Experiment

Category	Task	Hazard / Harm	Controls
Lifting & Handling	-	-	-
Pinch points and rotating equipment	Moving the linear crank stage	Finger pinch	Only the person handling the crank should touch the setup
Dust, chips, airborne	-	-	-
Electrical	-	-	-
Vibration	-	-	-
Noise	-	-	-
Chemicals	-	-	-
Safe disposal	-	-	-
Slips, trips, falls	-	-	-
Working alone	Various	Working alone	Working alone not permitted

Category	Task	Hazard / Harm	Controls
Ergonomics	-	-	-
Other	-	-	-

Residual risk considerations:

The primary risk associate with this lab is to pinch a finger in a location that is difficult to access. Please be careful when operating the crank stage. Any injury should be reported to the TA; First Aid should be called and a CAIRS report submitted.

6. Lab Procedures & Analysis

Part A: Potentiometer and DVRT Calibration

Experimental Procedure

- Open the LabView VI for Lab 2, and the VI takes 10 samples of each sensor reading. Each time when you press the “Take Sample” button, the VI will take another 10 samples. When you are done with collecting data, press the STOP button in LabView. This will end data acquisition and automatically open Excel to display the data that you can then save.
- The linear potentiometer and the DVRT have already been connected to the data acquisition board via the signal conditioning board together with the TA. Verify that the signal conditioning board is connected to its power supplies. Use the digimatic indicator as a reference; zero the digimatic indicator at the forward limit of the platform travel rage ($x = 0$). Then retract the platform to the furthest position. Move the platform to 10 different positions, while acquiring 10 sensor signals for each position. Include the most extreme positions.

Analysis

This should be completed for your report.

1) Calculate the average and standard deviation for the values of each data set and provide these in a table for each sensor. The accuracy of your position readings should correspond to the accuracy of the digimatic indicator.
2) Plot the sensor signals as a function of the linear position. Include error bars indicating a measure of data uncertainty; choose +/- 1 standard deviation for the sensor signals and the estimated accuracy of your position reading for the position values.
3) Determine the equation for the end-points-based linear calibration curve of each sensor signal as a function of position (do not forget to include the correct units). Identify the offset V_0 and the sensitivity B_0.
4) Calculate and plot the absolute non-linearity errors as a function of position. Determine the maximum absolute non-linearity error for each sensor signal and use it to estimate a position error.
5) Compared the errors that you found to the accuracy of your position readings and to the data sheets of both sensors.

Part B: Encoder Operation & Calibration

You will observe the signals from the incremental optical encoder to see how these signals can be used to determine positions and velocities. Make sure to choose an adequate sampling frequency for the different experimental tasks.

For this part, you will have to disconnect the digimatic indicator from the DAQ board and connect the encoder in its place.

Experimental Procedure

Displacement Direction

- Switch to tab B of the LabVIEW VI.
- Rotate the shaft with the crank handle in one direction and record the corresponding encoder signals. Also, make a note of the direction of displacement of the platform.
- Repeat the previous step, displacing the platform in the opposite direction.
- Save both data files so you can analyze the data after the lab.

Characterization of the Encoder Strip

- Turn the crank handle at a slow steady speed and record the data in LabVIEW. Here, you want to resolve the individual encoder windows and measure about 20 of their lengths using the DVRT as a reference.
- Save the data file so you can analyze the data after the lab.

Characterization of Velocity Resolution

- Repeat this procedure for medium steady speed while keeping the same sampling frequency.
- Also save that data file

Analysis

1) Indicate the chosen sampling frequency

Displacement Direction

2) For each direction of displacement of the platform provide one plot with both encoder phases (the two pick-off signals) as a function of time for a few encoder increments.
3) Comment on the measurement of the direction of displacement.

Characterization of the Encoder Strip

4) Convert the DVRT signal to position and plot 20 pulses of one encoder phase against position. Determine the average and standard deviation of the encoder pulses in terms of linear displacement.
5) Compare this with the resolution indicated in the data sheet.

Characterization of Velocity Resolution

6) Calculate the average speed of the platform from one of the encoder phases using the pulse counting method as well as for the pulse timing method for both displacement speeds. Compare this with the average speed from the DVRT signal.

7) Calculate the velocity resolution of the encoder signal for each measurement. For the pulse timing method, determine the exact value of the resolution and also the approximate value (assuming the number of clock pulses m for one encoder increment is large). Compare the different velocity resolution values.

Laboratory Exercise #3: Linear System Component Characterization

Learning objectives:

The main objectives of this laboratory exercise are:

- To characterize the quasi-static transfer characteristics of passive and active elements,
- to characterize springs,
- to characterize a voice coil actuator (VCA),
  - to determine the resistance R, the inductance L, and the force constant Bl,
  - to recognize how the actuator force depends on coil current and position.

1. Introduction

Background

Voice coil actuators (VCAs) are common devices to drive linear and angular motion. VCAs show highly linear characteristics and their small moving mass allows for fast response. VCAs are used in precision positioning tasks such as for read/write heads in CD, DVD, Blu-ray and hard disk drives; they are common in loudspeakers, and they drive shaker tables for applications such as the testing of parts and entire trucks in the automotive industry. Springs are ubiquitous in mechanical systems, and while many springs have a linear force-displacement relationship and are therefore classified as linear springs, some applications benefit from non-linear springs.

Overview

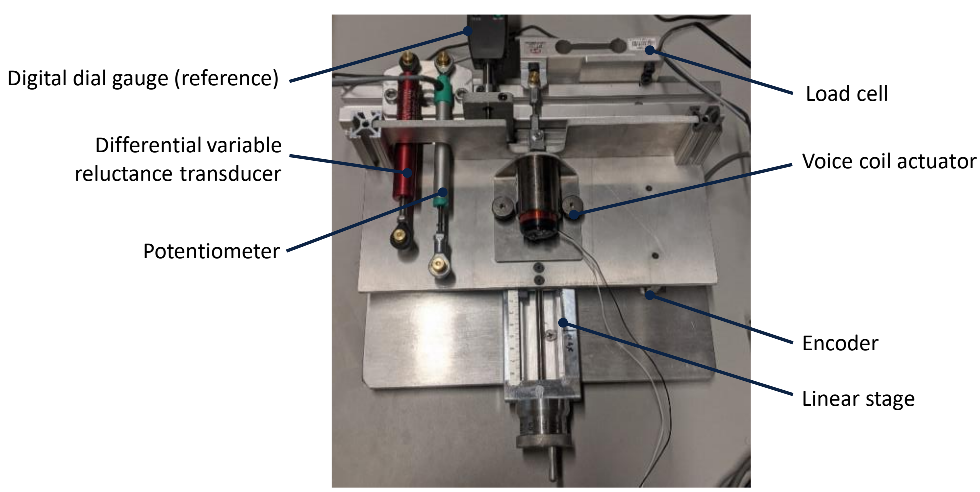


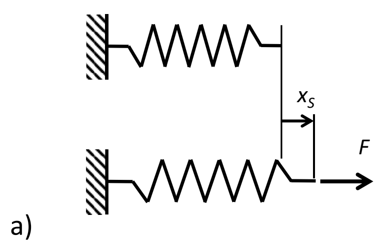
Figure 3.1: The component characterization station, here set up to characterize the VCA.

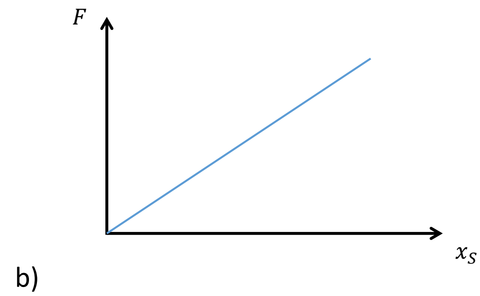
The setup used in this laboratory exercise is the same as for Laboratory Exercises #1 & 2. But for the current exercise, the base of the setup carries a mount with a load cell to which a spring or an actuator such as a VCA can be connected while the other end of the spring or the body of the actuator can be anchored to the moving stage as shown in Figure 3.1. For a spring, displacing the platform allows recording the force-displacement characteristic of that spring. For the VCA, the actuator force and coil voltage can be determined as a function of the coil current and the coil position. Data acquisition occurs again using the software package LabVIEW.

2. The System Components

2.1. The Springs

An external force F acting on a spring with result in the spring elongation x as shown in Figure 3.2a, and for different types of springs, these two quantities are related in different ways. Here, we will consider linear and pre-tensioned springs. For linear springs, we can define a spring stiffness k that relates force and displacement $F_{lin} = k \cdot x_S$ as shown in Figure 3.2b. The pre-tensioned springs require a certain amount of load F_{p0} before they begin to elongate, and that elongation shows a linear relationship between elongation and incremental force $F_p - F_{p0} = k \cdot x_S$ as shown in Figure 3.2c.





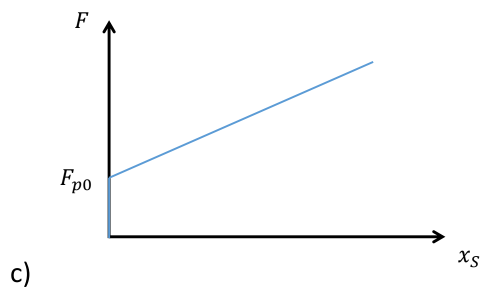


Figure 3.2: Force-displacement relationship for springs; a) an external force F elongates a spring by x_S; b) a linear spring; c) a pre-tensioned spring.

2.2. The Voice Coil Actuator

Figure 3.3 shows the schematic of a voice coil transducer with a cylindrical air gap with a radial magnetic flux density B across an area A. The length of the coil l is exposed to the flux density B, and the coil can be described as an electrical resistor R in series with an inductance L. The coil moves with the output shaft at velocity U_{VCA} with x_{VCA} the axial position of the coil.

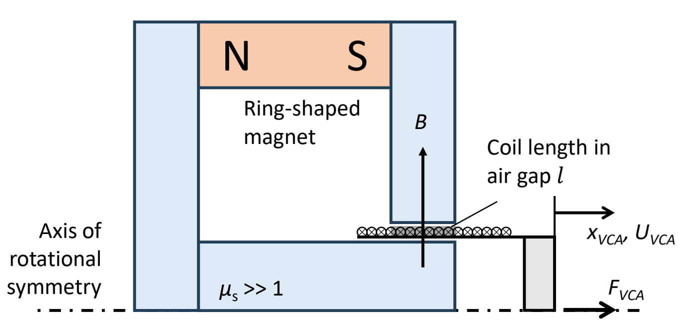


Figure 3.3: Schematic for a cylindrical voice coil transducer.

An electric current *I* through the coil results in the Lorentz force $F_{VCA} = Bl \cdot I$ with the force constant Bl. Simultaneously, according to Faraday's law of induction, moving the coil through the magnetic field in the air gap at a velocity U_{VCA} will induce a voltage $V_i = Bl \cdot U_{VCA}$. The voltage V measured at the coil

$$V = RI + L\dot{I} + Bl \cdot U_{VCA}$$

has contributions from the coil resistance R, the inductance L and from induction. For harmonic (sinusoidal) signals $I(t) = \check{I} \cdot e^{j\omega t}$ in complex notation, time derivatives become products of $j\omega$ yielding

$$V = RI + j\omega LI + j\omega Bl \cdot x_{VCA}.$$

The particular VCA used in this lab is the VCA NCC10-15-023-1PBS by H2W Technologies.

3. The Setup and its Components

The Component Calibration Station

The apparatus used for proximity sensor characterization will also be used to characterize the displacement sensors.

- VCA mount on linear stage
- Spring mount on linear stage
- Load cell mount on base plate

The Sensors & Instrumentation

- Load cell: PTASP6-D (5 kg) by PT
- DVRT LRE19-050R-00-10A by Alliance Sensors Group
- Current & voltage recording for the VCA: The current is sampled using a current sense resistor when using the power supply, and read from the current output of the amplifier when using the amplifier. Voltage readings are taken across the coil for both.

The Springs

- 2 linear springs
- 2 pre-tensioned springs

The Voice Coil Actuator System

- VCA NCC10-15-023-1PBS by H2W Technologies
- The voltage - current converter LCAM 5/15 from H2W Technologies has a gain set to 0.1 A/V. This amplifier runs on a single power supply set to between 25 V and 30 V.
- DC power supply
- Function generator

4. Pre-Lab

1) What is the force constant Bl of the VCA according to its data sheet? You might have to look for it on the product web page of the manufacturer.
2) The VCA should extend a linear spring. Plot both the spring force and the VCA force (for a constant current) as a function of position and identify the force equilibrium.
3) Where does the equilibrium shift if the VCA current is increased or decreased?
4) If the coil of the VCA is held in place find an expression for the electric impedance of the VCA.
5) Using information from the VCA data sheet (or product website), plot the magnitude and the phase of the electric impedance as a function of frequency.

6) Use curve fitting to the voltage and current signal provided in the sample data file on Canvas. Show a curve fit for either signal. For this task, it might be convenient to use a least square curve fit of the voltage and current data in MATLAB (lsqcurvefit) to sin functions; this way you can determine the amplitude and phase for both time series. Make sure you compare the fit results to the original data to ensure it makes sense.
7) Provide the amplitude for either signal and the phase between the signals.

5. Risks Associated with This Experiment

Category	**Task**	**Hazard / Harm**	**Controls**
Lifting & Handling	-	-	-
Pinch points and rotating equipment	Moving the linear crank stage	Finger pinch	Only the person handling the crank should touch the setup
Dust, chips, airborne	-	-	-
Electrical	Applying too much power to the voice coil actuator	The device can overheat (and break) and touching the hot coil can lead to an injury	The lab manual describes how to set the current limit of the power supply
Electrical	-	-	-
Vibration	-	-	-
Noise	-	-	-
Chemicals	-	-	-
Safe disposal	-	-	-
Slips, trips, falls	-	-	-
Working alone	Various	Working alone	Working alone not permitted
Ergonomics	-	-	-

Residual risk considerations:

The primary risks associate with this lab are to pinch a finger in a location that is difficult to access and to overheat the voice coil actuator. Please be careful when operating the crank stage. Please be careful when setting the power supply for the voice coil actuator and make sure to follow the lab manual. Any injury should be reported to the TA; First Aid should be called and a CAIRS report submitted.

6. Lab Procedure & Analysis

Make sure to use the same platform (same station number) you used in lab 2 so you can use your previous DVRT calibration.

Part A: Characterization of the Springs

Experimental Procedure

Be careful not to overstretch the springs; overstretched springs will not return to their initial lengths.

- Connect one of the springs to the calibration setup and record the force signal from the load cell and the position using the DVRT while extending the spring; limit the expansion of the linear springs to 10 mm and the extension of the pretensioned springs to 20 mm.
- Repeat the procedure with the other springs.

Analysis

1) Provide one plot of force vs. displacement per type of spring.
2) Determine $F(x_S)$ for each of the four springs; be careful to include the correct units with the equations.

Part B: Characterization of the VCA

The TA will swap the equipment between Parts A and B of this lab session.

Be aware that several sensor signals show an offset that you need to account for in your data analysis. These signals include the load cell reading and the recorded coil current and voltage signals. You might want to record these signals for zero input to determine the corresponding offsets.

Experimental Procedure

- Prepare the DC power supply for current control operation. Set the voltage to the maximum VCA coil voltage of 7.5 V and dial down the current knob to its lowest setting and increase the current from there for this exercise. If the current is increased such that the voltage limit of 7.5 V is reached, the power supply will not provide any further current – of course, the current will always be zero if nothing is connected to the power supply. Connect the DC power supply to the VCA on the PCB. Connect the VCA to the load cell, set a fixed coil current of 0.3 A and measure the force F, the coil current I_{coil}, the VCA voltage V_{coil}, and the DVRT signal V_{pot} as you displace the coil with the linear stage; keep the VCA's experimental range within 10 mm to 25 mm of the ruler markings. Make sure to record the current and voltage readings at 0 A and 0 V which are offsets that should later be removed from all collected data.
  Make sure you do not force the coil too far into the VCA as this can damage the VCA. Likewise, do not force the setup into the load cell that can sustain irreversible damage as a result. Stop as soon as the load cell reads a negative load.
- Repeat the procedure for two additional fixed current settings below 0.75 A.
- Now swap the power supply for the amplifier:
  - Turn off the power supply. Move the red and black banana cables from the power supply output to the LCAM 5/15 Amplifier output.
  - Move the current sense cable from the coil to the amplifier current output.
  - Set the power supply to 25 V then connect the power cables from the amplifier to the power supply output.
  - Set the function generator to the desired frequency and amplitude and turn the output on. The amplifier is set to output 0.1A/V.

- At a mid-position of the coil, apply a sinusoidal signal to the amplifier over the frequency range f = 1 Hz – 1 kHz with a current amplitude below 0.1 A. Record F, I_{coil} and V_{coil} as a function of time for each frequency.

Analysis

Quasi-static characterization:

1) Find and plot the force $F_{VCA}(x_{VCA})$ as a function of position for the different coil currents I_{coil}.
2) Determine and plot $Bl(x_{VCA})$ for the different coil currents and compare Bl with the “force constant” from the manufacturer.
3) Find and plot $R(x_{VCA})$ for the different I_{coil} and compare with R from the manufacturer.

Dynamic electric characterization:

4) Calculate $\underline{Z}(f)$, and plot $\left|\underline{Z}(f)\right|$ and the phase. This will require curve fitting to the sinusoidal current and voltage signals to find current and voltage amplitude at each frequency as well as the phase between both signals.
5) With R and $\underline{Z}(f)$ or $\left|\underline{Z}(f)\right|$ from above, find L using another curve fitting procedure. Also comment on the fit compared to the data from your measurements.
6) Compare with L from the data sheet.