MECH420

Sensors and Actuators

Laboratory Manual for Experiment 3

Fall 2020

The University of British Columbia

Department of Mechanical Engineering

Table of Contents

Laboratory Exercise #3: Dynamic Transducer Transfer Characteristics – Time Domain

Learning Objectives

The main objectives of this laboratory exercise are:

- To understand the principles of operation of some common motion sensors: rotary potentiometer, LVDT, DC tachometer, and capacitive accelerometer
- To become familiar with simple digital data processing for signal integration and differentiation
- To understand the errors associated with these procedures.

Background

Linear and rotary motion sensors are widely used to monitor the transient behavior of a system. While differential and integral quantities can easily be derived from measured quantities, care has to be taken to avoid errors.

1. System Overview

In this system, a "lateral slider" is moved by a PC-controlled DC motor connected to one pulley of a belt-and-pulley (conveyor) system, as shown in Figure 3.1. The position of the lateral slider is measured using a rotary potentiometer attached to the other pulley. The rotational velocity of that pulley (and hence the speed of the slider) is measured using a DC tachometer attached to the pulley. The linear displacement of the slider is determined using a linear variable differential transformer (LVDT) that is directly attached to the slider. An accelerometer is mounted on the lateral slider to determine its acceleration.

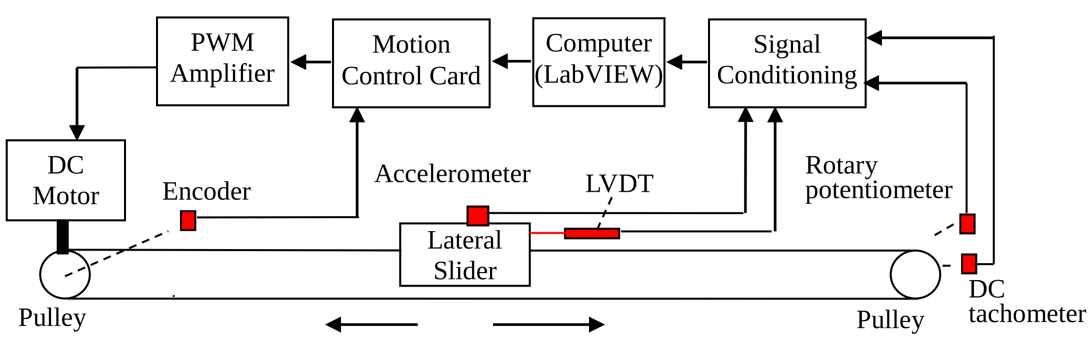

Figure 3.1: The "lateral slider" pulley system with sensors.

2. The Motion Sensors

2.1 The Rotary Potentiometer

Rotary potentiometer or "pot" is an active transducer for measuring angular displacement. A possible configuration of this sensor is shown in Figure 3.2 centre. Helix-type rotary potentiometers are available for measuring absolute angles exceeding 360°, as shown in Figure 3.2 on the right. The resistive element of a pot consists of a coil of wire or a film of high-resistive material—such as carbon, or conductive plastic. Typically, this resistive element has a uniform resistance per unit length. A constant voltage v_{ref} (or e_{ex} in Fig. 3.2) is applied along the coil (or film) using an external dc voltage supply. The transducer output signal v_o (or e_o in Fig. 3.2) is the dc voltage between the movable contact (wiper arm) sliding on the coil and one terminal of the coil, as shown schematically in Figure 3.2. This output voltage,

$$v_0 = k\theta$$

is proportional to the angular position θ of the slider arm.

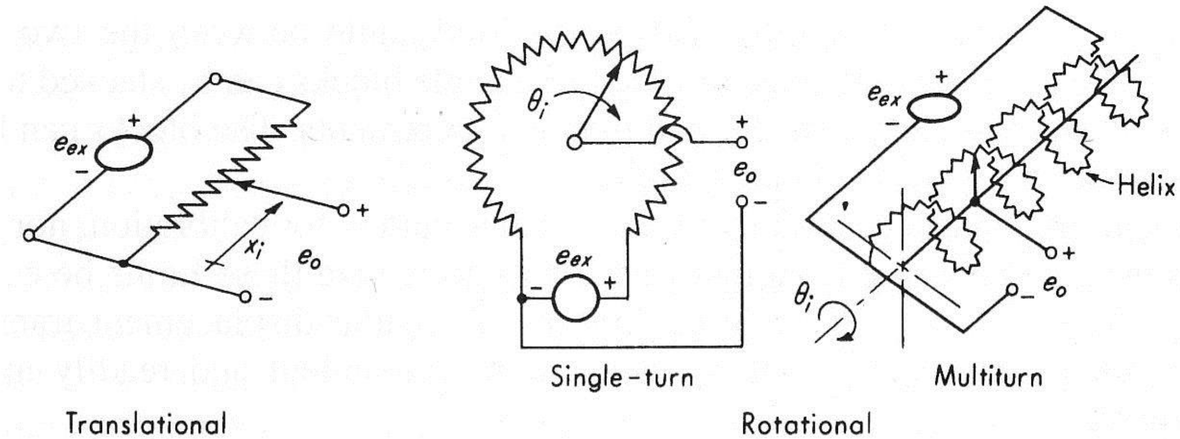

Figure 3.2: Schematic diagrams of potentiometers [3.1].

2.2 Linear Variable Differential Transformer (LVDT)

The Linear-Variable Differential Transformer (LVDT), shown schematically in Figure 3.3, is a displacement sensor with a much lower mechanical resistance than a pot.

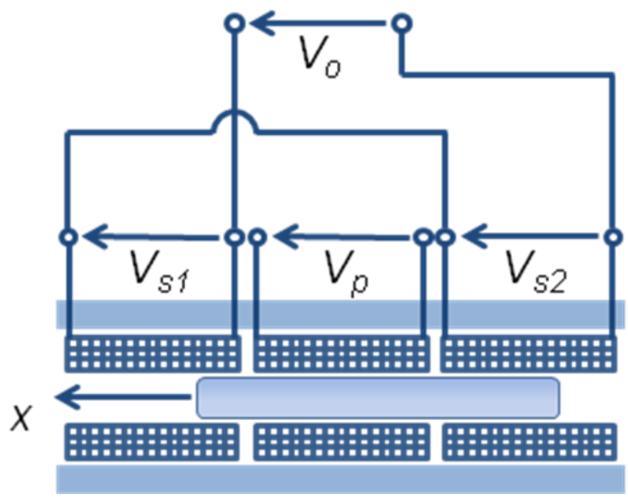

Figure 3.3: Schematic diagram of an LVDT.

The LVDT consists of an insulating, nonmagnetic "form", which has a primary coil in the mid-segment and a secondary coil symmetrically wound in the two end segments. The housing of the LVDT is made from magnetized steel in order to shield the sensor from outside magnetic fields. An ac voltage v_{ref} (or V_p in Fig. 3.3) is applied to the primary coil. This will generate, by mutual induction, an ac voltage of the same frequency in the secondary coil. A core made of ferromagnetic material is inserted coaxially through the cylindrical form without actually touching it. This facilitate the linkage of the magnetic flux between the primary coil and the secondary coil. Specifically, the degree of flux linkage depends on the axial position of the core. As the core moves, the reluctance of the magnetic flux path (and the flux linkage) changes. The two secondary coils are connected in series opposition (as shown in Figure 3.3), so that the potentials induced in the two secondary coil segments oppose each other. Therefore, the net induced voltage is zero when the core is centrally located between the two secondary winding segments. This is known as the *null position*. When the core is displaced from this position, a nonzero induced voltage will be generated. At steady state, the amplitude of this induced voltage V_o is proportional to the core displacement x in the linear (operating) region. Consequently, the amplitude of V_o may be used as a measure of the displacement. Note that because of opposed secondary windings, the LVDT provides the magnitude as well as the direction of displacement [3.2].

2.2.1 LVDT Signal Conditioning

Signal conditioning associated with an LVDT includes filtering and amplification. The output signal from the secondary coil of an LVDT is an amplitude-modulated signal where the signal component at the carrier frequency is modulated by the lower-frequency transient signal produced due to change in the core position x. A demodulator circuit is commonly used to interpret the crude output signal from an LVDT. This signal conditioning circuit is shown in Figure 3.4 [3.2].

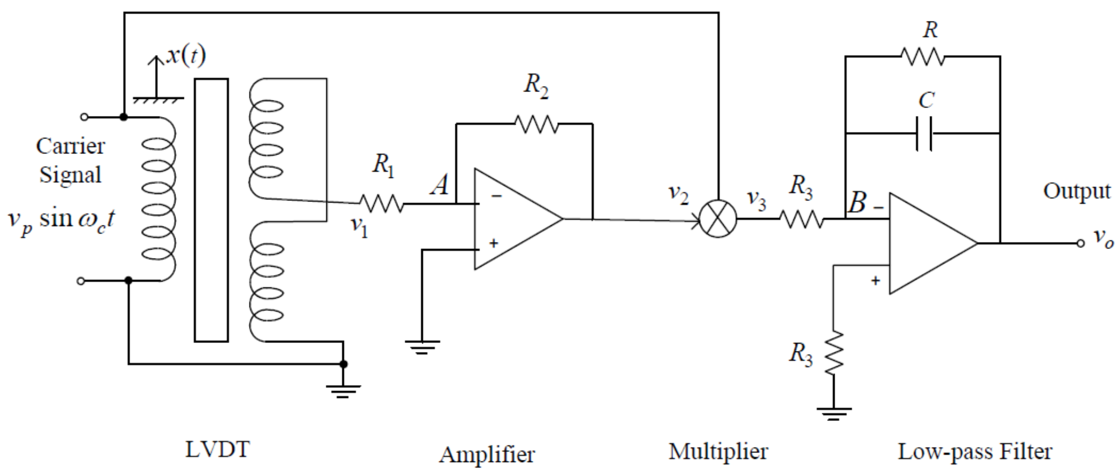

Figure 3.4: A signal conditioning system of the LVDT [3.2].

2.2.2 LVDT Rate Error

In the LVDT, an additional voltage can be induced through the rate of change of the magnetic flux linkage. Therefore, the displacement readings can be distorted by the velocity of the core so that for the same displacement value, the transducer reading can be slightly different depending on the current velocity. This error, known as the rate error, increases with the ratio, $\dfrac{(\text{Velocity of the core})}{(\text{Carrier frequency})/(\text{Stroke of LVDT})}$. It follows that the rate error can be reduced by increasing the carrier frequency.

2.3 DC Tachometer

The DC tachometer is a permanent-magnet dc velocity sensor, which uses the principle of electromagnetic induction between a permanent magnet and a conducting coil. Its configuration is shown in Figure 3.5 [3.2].

Its principle of operation is the same as that for a dc generator. The rotor is directly connected to the rotating object. The output signal that is induced in the rotating coil is picked up as the dc voltage v_0 using a suitable commutator device so as to maintain the direction of the induced voltage the same throughout each revolution. The proportionality between v_0 and ω_c is used to measure the angular speed ω_c.

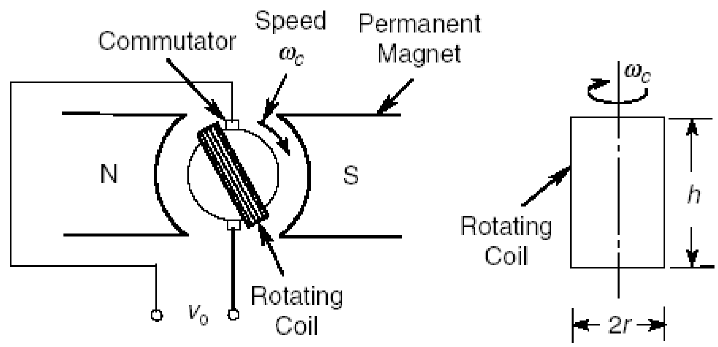

Figure 3.5: The configuration of a DC tachometer [3.2].

The torque required to drive a tachometer is proportional to the generated current. A high tachometer torque acting on the moving object (the mechanical loading), whose speed is measured, is not desirable. Hence, the tachometer current needs to be reduced as much as possible by making the input impedance of the signal-acquisition device (i.e., hardware for voltage reading and interface) as large as possible. Furthermore, distortion in the tachometer output voltage signal can be caused by reactive (inductive and capacitive) loading of the tachometer.

2.4 The Capacitive Accelerometer

Capacitive accelerometers have become very popular because of their low price and high accuracy. Compared to other accelerometer technologies such as piezoelectric devices, capacitive accelerometers operate at very low frequencies down to the steady state.

The principle of operation of capacitive accelerometers is based on a small proof mass that is held by springs. Any acceleration acting on the sensor leads to an inertial force on the proof mass, which consequently moves relative to the sensor housing as much as what is permitted by the spring force. This displacement changes the value of the sensor capacitor, which is acquired through integrated circuitry and converted into a voltage signal (the sensor output).

3. Basic Discrete Data Processing

Capturing a continuous-time signal $s(t)$ with a data acquisition system generates a series of signal samples s_i that are discrete in amplitude as well as in time. In general, these signal samples are captured at constant time intervals Δt, with $t_{i+1} = t_i + \Delta t$. The derivative with respect to time of the original signal can be approximated (computed) as,

$$\frac{d\,s(t)}{d\,t} \approx \frac{s_{i+1} - s_i}{\Delta t} \approx \frac{s_{i+1} - s_{i-1}}{2\,\Delta t},$$

while the time integral can be computed as,

$$\int_0^T s(t)dt \approx \sum_{i=0}^{N} s_i \Delta t \qquad \text{with } \Delta t = T / N,$$

where, the time interval 0 to T corresponds to the data sample range 0 to N.

The quality of the results from these numerical procedures depends strongly on the quality of the discretized signal s_i. One common problem is the high noise content of the recorded signal, which might already have been present in the original analog signal $s(t)$. If the amplitude of the noise signal is comparable to the change in the signal amplitude between two sampling steps $s_{i+1} - s_i$, this will lead to a highly inaccurate discrete derivative of the signal.

The noise content of the sampled signal can be reduced by smoothing of the signal. This can be achieved by calculating a moving average of the sampled signal:

$$\bar{s}_i = \frac{1}{2n+1} \sum_{j=i-n}^{i+n} s_i .$$

Note that this corresponds to low pass filtering of the signal, where a larger n leads to a lower cut-off frequency. This procedure will therefore eliminate all high frequency signal content and should only be employed if no content is expected or desired in the corresponding high frequency range. The smoothened signal can then be used for differentiation with respect to time.

Numerical integration of the signal is also associated with a risk for errors. The captured signal needs to be carefully calibrated before integration. Otherwise, any small offset will be added up during numerical integration (summation) and can lead to a large error accumulation over time; this error accumulation will lead to a linear signal drift.

Note: Typically, noise amplification is greater in numerical differentiation.

4. The Components of the Experimental Setup

4.1 The Lateral Positioning System

The lateral slider shown in Figure 3.6 consists of a horizontal aluminum funnel attached to an aluminum block. The block runs linearly (i.e., in a straight line) on two guide rails using linear bearings, and is driven by a timing belt. The timing belt has a 10 mm tooth pitch, and is mounted on two pulleys with 20 teeth each. The drive pulley is driven directly by the DC motor, with no gear reduction. An LVDT is attached to the slider and the frame in order to measure the position of the slider. In the setup shown in Figure 3.6, the accelerometer is mounted on the slider to capture its acceleration. A DC tachometer and a rotary potentiometer are attached to the axis of the pulley that is not driven by the DC motor, to measure the displacement and the speed of the slider.

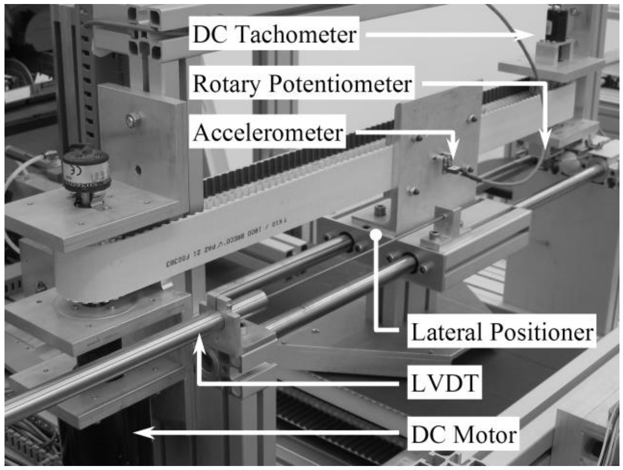

Figure 3.6: The lateral slider including DC motor and motion sensors.

4.2 The Rotary Potentiometer

The Hybritron 3541H-1-502 5K rotary potentiometer can be installed on either the drive or the idle shaft of the lateral slider. External circuitry is required to limit the output of the potentiometer to the +/-10 V analog input voltage range of the available National Instruments DAQ card. This circuitry is shown in Figure 3.7. The 10 kΩ resistor in series with the 5 kΩ potentiometer limits the maximum output of the potentiometer to 8 V for a supply voltage of 24 V (why?). The potentiometer provides a voltage output proportional to the rotation angle of its shaft over its full range of 0 to 10 revolutions corresponding to an output of 0 V to 8 V. The resolution specified in the datasheet is infinitesimal (in theory).

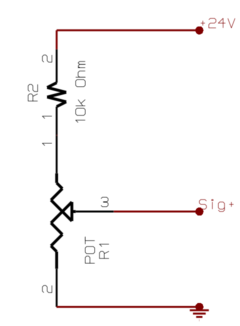

Figure 3.7: Rotary potentiometer interface circuit.

4.3 The LDVT

The Sentech 75S2DC-5000R Linear Variable Displacement Transducer (LVDT) is attached to the lateral slider. It provides a voltage output proportional to the displacement of the core inside the body of the LVDT. The core is attached to the lateral slider, while the body is attached to the stationary table, providing a voltage output proportional to the displacement of the lateral slider from an arbitrary zero point. The linear range of this sensor is 0 mm to 254 mm, corresponding to a voltage output of 1 V to 10 V.

4.4 The DC Tachometer

The SA-740A-2 DC tachometer generator can be installed on the drive shaft or idle shaft of the conveyor belt (hence, the lateral slider). It provides a voltage output proportional to the rotational speed of the shaft, with a sensitivity of 7 V/1000 RPM. The maximum rated speed of the tachometer is 12,000 RPM.

4.5 The Capacitive Accelerometer

The ADXL203 capacitive accelerometer is attached to the lateral slider. It is a single IC with two measurement axes. Each voltage output is proportional to the acceleration of the chip along the corresponding axis. The accelerometer's range is -1.7 g to +1.7 g (with the acceleration due to gravity, g = 9.81 m/s^2). The sensitivity is between 940 mV/g and 1060 mV/g, with a 0 g offset of 2.5 V. The accelerometer is mounted on an ADXL203EB evaluation board, which includes filtering capacitors that limit the bandwidth of the sensor to 50 Hz.

4.6 The DC Motor

A NEMA 34 DC brushed motor is used to drive the lateral slider. Its model is Cleveland Motion Controls Torquemaster 3528. It provides a continuous torque of 1.20 Nm and a peak torque of 10.60 Nm. It has a torque constant K_t of 0.196 Nm/A. The motor is driven by a LOGOSOL LS-5Y-BL PWM amplifier. The amplifier is set up in the current mode and has an adjustable current gain K_a.

4.7 The Encoder

An encoder is used to control the motor operation. For a description of the encoder see the description of the laboratory experiment 2. The encoder provides 1440 counts per revolution (when using quadrature signals).

4.8 The data acquisition system

See the description in the laboratory experiment 1.

5. Experiments

System component list

1. Rotary encoder (1440 counts/rev after using quadrature signals)
2. Rotary potentiometer
3. LVDT sensor
4. DC permanent-magnet tachometer
5. Capacitive accelerometer (50 Hz)
6. DC motor
7. PWM amplifier for the DC motor
8. Motion control card with I/O interface
9. Desk-top computer with LabVIEW
10. Data acquisition board (4 analog input channels, 200 Hz)
11. Pulley system that transforms the motor rotation into the translatory displacement of conveyor belt and slider.

Part A: Calibration of the Rotary Potentiometer and the LVDT

Experimental Procedure

1. We connect all sensors to the following input ports of the signal conditioning interface: AI0 – LVDT, AI1 – rotary potentiometer, AI2 – accelerometer, AI3 – DC tachometer.
1. We open C:\Mech420\Lab3\Lab3.vi in LabVIEW.
2. We select the Part A tab.
3. In the array on the left box, we enter 10 angular positions of the motor within the range [0; 1500 counts]. *Note*: The first value is 0.
4. We run the program.
5. The software drives the motor through 5 cycles during which the lateral positioning system stops at each of the entered positions, 10 times. The software also records the reading of the rotary potentiometer and of the LVDT and saves the results into an MS Excel file (This file is provided to you, for data analysis).

Analysis

1. Calculate the average position signal (in V) for both position sensors, for the actual motor position (in mm) for each of the 10 selected positions. Plot the sensor signals as a function of the linear position using the average values for the sensor readings.
2. Calculate the linear static transfer functions for both sensors using the least-squares fit (linear regression) [3.2] calibration.

Part B: Calibration of the DC Tachometer

Experimental Procedure

1. We select the Part B tab.
2. In the array on the left, we enter 10 angular speeds in the range [35; 80 rpm].
3. We run the program.
4. The software controls the motor speed. The lateral slider is moved at a constant speed along most of its length and back.
5. The software records the velocity readings of the DC tachometer and the position readings of the potentiometer for all 10 speeds. It stores this information in an Excel file. This file is provided to you, to perform the data analysis.

Analysis

1. Calculate the velocity at each point using the data from the potentiometer. You will need to use the potentiometer calibration obtained in Experiment A to convert the potentiometer signal into a position. The data samples were taken at a rate of 200 Hz. Comment on your approach. Plot the velocity as a function of time.

2. Determine the average DC tachometer reading and the average velocity from the potentiometer for each constant linear velocity. Plot the tachometer voltage as a function of linear velocity.
3. Determine the linear (static) transfer function of the tachometer using least squares fit (linear regression) [3.2] calibration. Compare this result to the calibration specified by the tachometer manufacturer.

Part C: Transient Sensor Response

Experimental Procedure

1. We select the Part C tab.
2. We select the correct station on the front panel (station 1 or station 2). This sets the correct control parameters for both stations. This is necessary because the two systems behave differently.
3. We enter 10 acceleration values in the range [1; 16 rps/s].
4. We set a reasonable data sampling rate (it is usually set around 200 Hz).
5. We run the program.
6. The software ramps the motor speed up and down, accordingly.

   The software records the acceleration signals of the capacitive accelerometer, the velocity signal from the tachometer, and the position readings of the rotary potentiometer and the LVDT, for all 10 accelerations. It stores this information in an Excel file. This file is provided to you, to perform the data analysis.

Analysis

1. Convert the tachometer data into velocities using the calibration equation derived in Part B. Find the offset voltage of the accelerometer from the measurements. Use the data sheet of the accelerometer to find its sensitivity and convert the voltage readings into acceleration values. Then numerically integrate the acceleration data from the accelerometer and plot the resulting velocity and the velocity determined with the tachometer over time. How do they compare?
2. Calculate the position at each point using the data from the potentiometer. Numerically integrate the acceleration data a second time (i.e., twice), and also numerically integrate the tachometer data (once). Compare the results with the position measured with the potentiometer. Explain potential sources of discrepancy.

6. Additional Exercises (These should be included at the end of your report)

1. Derive an equation that relates the linear displacement x of the lateral positioner to the count n of the angular encoder.
2. Acquire (on line) the data sheet of the accelerometer. Use it to answer the following questions:

a) What is the output voltage range of the accelerometer?

b) What is the resonant frequency of the accelerometer?

c) Using output capacitors, what range of bandwidths (DC to f_{max}) can you achieve?

d) What is the relationship between f_{max} and the corresponding capacitor C?

3. Search and obtain the data sheets and images of the following items (not those used in the present experiment): 1. A linear DC actuator (motor that moves in a straight line); 2. Drive hardware for the actuator; 3. An LVDT; 4. A microcontroller. Suppose that the LVDT is connected to the actuator, and the microcontroller is programmed to acquire the signals from the LVDT, and based on that information and the required motion profile, a signal is generated and provided to drive the actuator. Give a schematic diagram that contains the images of these components and any other required hardware for this system. In the diagram, show how the components are interconnected, using lines to represent cable strands (signal paths). *Note*: No knowledge on programming the microcontroller, how to properly match the components, and how to operate the system, is needed to be included here. Only the interconnection details of the components should be presented.

References

[3.1] E. O. Doebelin, *Measurement Systems: Application and Design*, 5th edition, McGraw-Hill, New York, NY, U.S.A., 2004.

[3.2] *Sensors and Actuators: Engineering System Instrumentation*, 2nd Edition, C. W. de Silva, CRC Press, Taylor & Francis, Boca Raton, FL, ISBN: 978-1-4665-0681-7, 2016.

Lab 3:

Preparation

- Measurements: Displacement, Velocity, Acceleration
- Read the Lab Manual about: Rotary potentiometer, LVDT, DC tachometer, capacitive accelerometer
- For further information about these sensors, you may read the textbook
- *Note*: Interpret bandwidth as "half-power bandwidth"
- Time constant of accelerometer, $\tau = RC$
- *Note*: Angular frequency $\omega = 2\pi f$
- For numerical processing of data (e.g., averaging, differentiation, integration) use a suitable part of the collected data, not the entire data record. *Note*: You may have to ignore the starting and ending data. Check the recorded data.