Experiment 1

Proximity Sensors

Objectives:

This experiment will allow you to:

- To study and understand different mechanisms and principles of some types of digital proximity sensors.
- To observe the response of some types of digital proximity sensors to different materials.
- To study different types of output circuit of proximity sensors.

Apparatus:

- Proximity sensors (inductive, capacitive, magnetic, optical)
- Relay
- LED
- Digital multimeter (DMM)
- Power supply
- Resistor

Theoretical Background:

Sensors dealing with "discrete position", i.e. sensors which detect whether or not an object is located at a certain position without physically touching them are known as digital proximity sensors. Sensors of this type provide a "Yes" or "No" statement depending on whether or not the position, to be defined, has been taken up by the object. These sensors, which only signal two statuses, are also known as binary sensors or in rare cases as initiators.

With many production systems, "mechanical" position switches are used to acknowledge movements which have been executed. Additional terms are used such as micro switches, limit switches, or limit valves. Because movements are detected by means of contact sensing, relevant constructive requirements must be fulfilled. Also, these components are subject to wear in contrast.

Proximity sensors operate electronically and offer the following **advantages**:

- Precise and automatic sensing of geometric positions.
- Contactless sensing of objects and processes; no contact between sensor and work piece is usually required.

- Fast switching characteristics; because the output signals are generated electronically, the sensors are bounce-free and do not create error pulses.
- Wear-resistant function; electronic sensors do not include moving parts which can wear out.
- Unlimited number of switching cycles.
- Suitable versions are also available for use in hazardous conditions (e.g. Areas with explosion hazard).

Part 1: Proximity Sensor Types

Nowadays, proximity sensors are used in many areas of industry for the reasons mentioned above. They are used for sequence control in technical installations, monitoring, and safe-guarding processes. In this context, sensors are used for early, quick and safe detection of faults in the production process. The prevention of damage to man and machine is another important factor to be considered. A reduction in downtime of machinery can also be achieved by means of sensors, because failure is quickly detected and signaled. In this experiment, four types of these sensors will be studied:

- Inductive proximity sensors.
- Capacitive proximity sensors.
- Magnetic proximity sensors.
- Optical proximity sensors.

Inductive Proximity Sensors

The sensor incorporates an electromagnetic coil which is used to detect the presence of a conductive metal object. The sensor will ignore the presence of an object if it is not metal, Figure 1.1. This type of sensor consists mainly of four elements: coil, oscillator, trigger circuit, and an output, Figure 1.2. Inductive proximity sensors are designed to generate an **electromagnetic field**. When a metal object enters this field, surface currents, known as eddy currents, are induced in the metal object. These eddy currents drain energy from the electromagnetic field (causes a load on the sensor) resulting in a loss of energy in the oscillator circuit and, consequently, a reduction in the amplitude of oscillation. The trigger circuit detects this change and generates a signal to switch the output ON or OFF. When the object leaves the electromagnetic field area, the field regenerates and the sensor returns to its normal state. The oscillator is not affected by moisture and dusty/dirty environments.

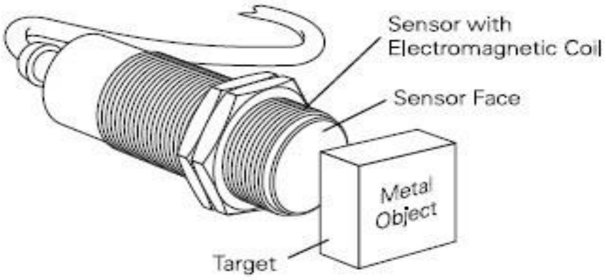


Figure 1.1: Inductive Proximity Sensor

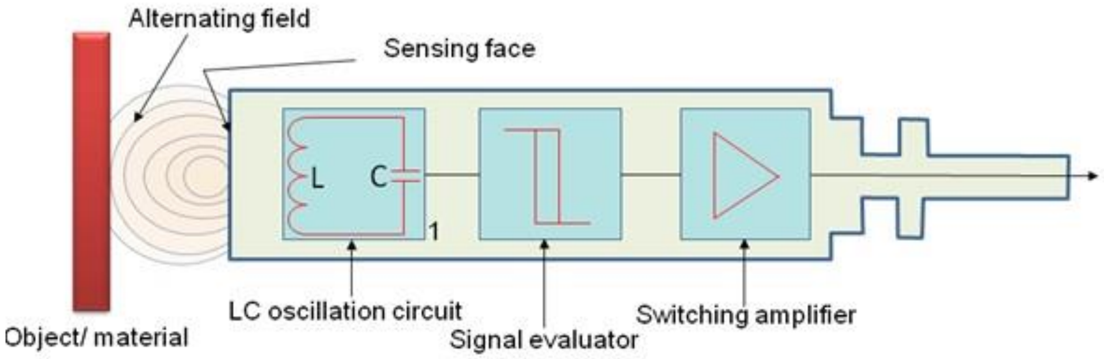


Figure 1.2: Construction of an Inductive Proximity Sensor

The operating distance of an inductive proximity sensor varies for each target and application. The ability of a sensor to detect a target is determined by the material of the **metal target, its size, and its shape**.

The **advantages** of inductive proximity sensors include:

- No moving parts/no mechanical wear.
- Not color dependent.
- Less surface dependent than other sensing technologies.

The **disadvantages** of inductive proximity sensors include:

- Only sense the presence of metal targets.
- Operating range is shorter than ranges available in others sensing technologies.
- Maybe affected by strong electromagnetic fields.

Capacitive Proximity Sensors

Capacitive proximity sensor is a noncontact technology suitable for detecting metals, non- metals such as paper, glass, liquids and cloth, Figure 1.3. However, it is best suited for nonmetallic targets because of its characteristics and cost relative to inductive proximity sensors. In most applications with metallic targets, inductive sensing is preferred because it is both a reliable and a more affordable technology.

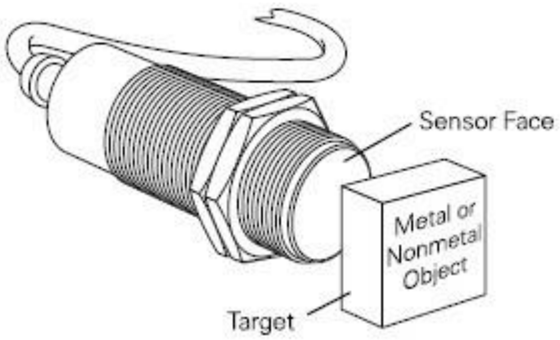


Figure 1.3: Capacitive Proximity Sensor

Capacitive proximity sensors consist of four main components: capacitive probe or plate, oscillator, signal level detector, output switching device, Figure 1.4. These sensors are similar in size, shape, and concept to inductive proximity sensors. However, capacitive proximity sensors react to alterations in an **electrostatic field**. The probe behind the sensor face is a capacitor plate. When power is applied to the sensor, an electrostatic field is generated that reacts to changes in capacitance caused by the presence of a target. When the target is outside the electrostatic field, the oscillator is inactive. As the target approaches, a capacitive coupling develops between the target and the capacitive probe. When the capacitance reaches a specified threshold, the oscillator is activated, triggering the output circuit to switch states between ON or OFF, Figure 1.4.

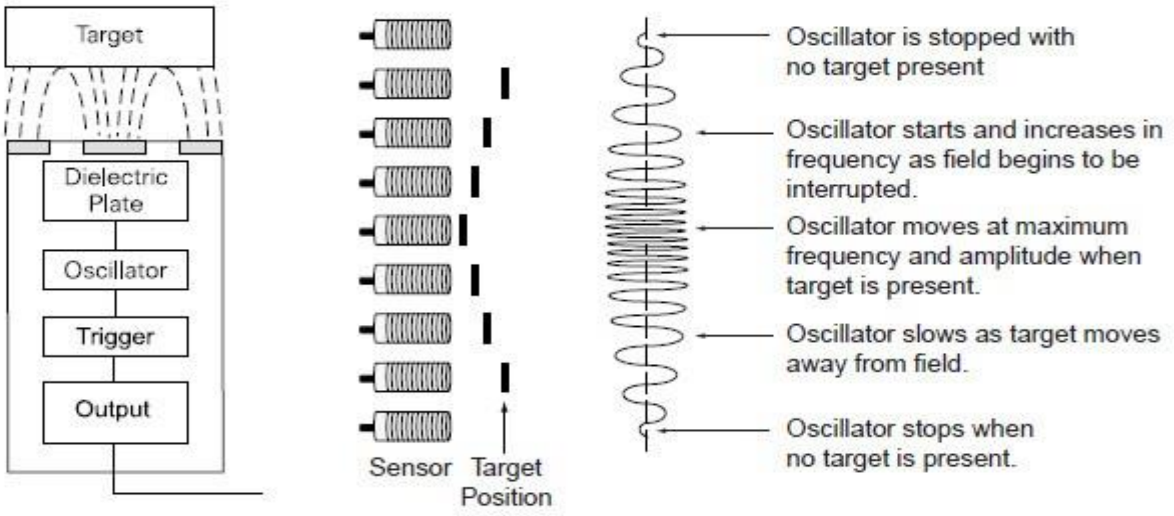


Figure 1.4: Capacitive Proximity Sensor Set-Up and Operation

An important point to be considered while using capacitive proximity sensor is that any material entering the sensor’s electrostatic field can cause an output signal. This includes mist, dirt, dust, or other contaminants on the sensor face.

The **advantages** of capacitive proximity sensors include:

- Detects metal and nonmetal, liquids and solids.
- Can “see through” certain materials (product boxes).
- Solid-state, long life.
- Many mounting configurations.

The **disadvantages** of capacitive proximity sensors include:

- Short (1 inch or less) sensing distance varies widely according to material being sensed.
- Very sensitive to environmental factors (humidity in coastal/water climates can affect sensing output).
- Not at all selective for its target, hence, control of what comes close to the sensor is essential.

One application for capacitive proximity sensors is level detection through a barrier. For example, water has a much higher dielectric than plastic. This gives the sensor the ability to "see through" the plastic and detect the level water, Figure 1.5.

Figure 1.5: Application for Capacitive Proximity Sensors

Magnetic Proximity Sensors

Magnetic proximity sensors are noncontact proximity devices utilize **Hall Effect** principles. Magnetic proximity sensors are characterized by the possibility of large switching distances and availability with small dimensions. They detect magnetic objects (usually permanent magnets), which are used to trigger the switching process.

Magnetic proximity sensors are actuated by the presence of a permanent magnet. Their operating principle is based on the use of **"reed contacts"**, Figure 1.6, which are thin plates hermetically sealed in a glass bulb with inert gas. The presence of a magnetic field forces the thin plates to touch each other causing an electrical contact. The surface of plate has been treated with a special material particularly suitable for low current or high inductive circuits.

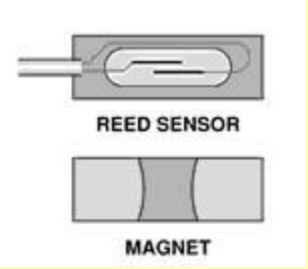


Figure 1.6: Hysteresis in Magnetic Proximity Sensor

The advantages of magnetic sensors compared to traditional mechanical switches are the following:

- Contacts are well protected against dust, oxidization and corrosion due to the hermetic glass bulb and inert gas; contacts are activated by means of a magnetic field rather than mechanical parts.
- Special surface treatment of contacts assures long contact life.
- Maintenance free.
- Easy operation and small size.

Optical Proximity Sensors

In its most basic form, a photoelectric sensor can be thought of as a switch where the mechanical actuator or lever arm function is replaced by a beam of light. By replacing the lever arm with a light beam the device can be used in applications requiring sensing distances from less than 2.54 cm to one hundred meters or more. All photoelectric sensors operate by sensing a change in the amount of light received by a photo detector. The change in light allows the sensor to detect the presence or absence of the object, its size, shape, reflectivity, opacity, translucence, or color. There are a vast number of photoelectric sensors from which to choose. Each offers a unique combination of sensing performance, output characteristics, and mounting options.

A photoelectric sensor consists of five basic components: light source, light detector, lenses, logic circuit, and the output, Figure 1.7. A light source sends light toward the object. A light receiver, pointed toward the same object, detects the presence or absence of direct or reflected light originating from the source. Detection of the light generates an output signal (analog or digital).

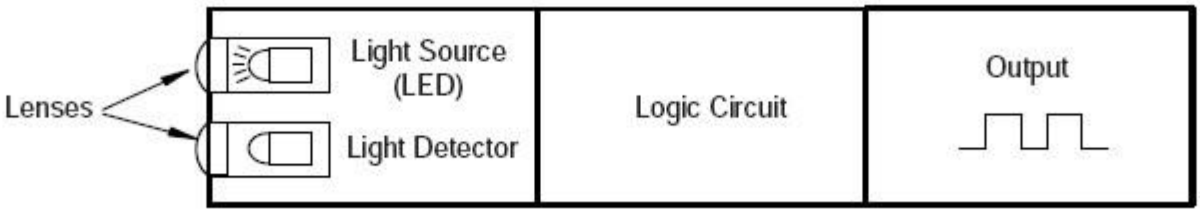


Figure 1.7: Optical Proximity Sensor

Photoelectric sensors can be housed in separate source and receiver packages or as a single unit. An important part of any sensor application involves selecting the best sensing mode for the application. There are three basic types of sensing modes in photoelectric sensors: Transmitted beam, Retroreflective, and Diffuse sensors.

Transmitted Beam Sensors

In this sensing mode, the light source and receiver are contained in separate housings, Figure 1.8.

The two units are positioned opposite each other so the light from the source shines directly on the receiver. The beam between the light source and the receiver must be broken for object detection.

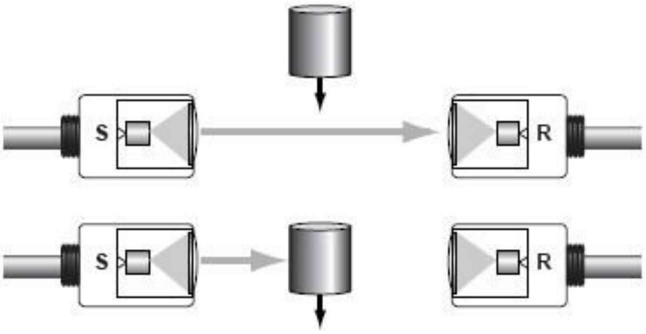


Figure 1.8: Transmitted Beam Sensor

Transmitted beam sensors provide the longest sensing distances and the highest level of operating margin. For this reason, transmitted beam is the best sensing mode for operating in very dusty or dirty industrial environments.

The **advantages** of transmitted beam sensor are the following:

- Because of their well-defined effective beam, transmitted beam sensors are usually the most reliable for accurate parts counting.
- Use of transmitted beam sensors eliminates the variable of surface reflectivity or color.
- Because of their ability to sense through heavy dirt, dust, mist, condensation, oil, and film, transmitted beam sensors allow for the most reliable performance before cleaning is required and, therefore, offer a lower maintenance cost.
- Transmitted beam sensors can sometimes be used to “beam through” thin-walled boxes or containers to detect the presence, absence, or level of the product inside.

On the other hand, it has the following **disadvantages**:

- Very small parts that do not interrupt at least 50% of the effective beam can be difficult to be reliably detected.
- Transmitted beam sensing may not be suitable for detection of translucent or transparent objects. The high margin levels allow the sensor to “see through” these objects.

Retro-reflective Sensors

A retro-reflective sensor contains both the emitter and receiver in the same housing. The light beam from the emitter is bounced off a reflector (or a special reflective material) and detected by the receiver. The object is detected when it breaks this light beam, Figure 1.9.

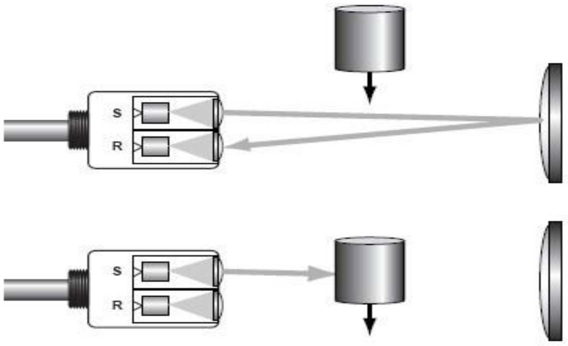


Figure 1.9: Retro-Reflective Sensor

A wide selection of reflectors is available. The maximum available sensing distance of a retro-reflective sensor depends in part upon both the size and the efficiency of the reflector. For the most reliable sensing, it is recommended that the largest reflector available be used. Retro-reflective sensors are easier to install than transmitted beam sensors because only one sensor housing is installed and wired. Retroreflective sensing is less desirable in highly contaminated environments.

The retro-reflective sensor has the following **advantages**:

- Moderate sensing distances.
- Less expensive than transmitted beam because simpler wiring.
- Easy alignment.

On the other hand, it has the following **disadvantages**:

- Shorter sensing distance than transmitted beam.
- Fewer margins than transmitted beam.
- May detect reflections from shiny objects or highly reflective objects.

Diffuse Sensors

Sometimes it is difficult, or even impossible, to obtain access to both sides of an object to install receiver or reflector. In these applications, it is necessary to detect a reflection directly from the object. The surface of object scatters light at all angles; a small portion is reflected toward the receiver. This mode of sensing is called diffuse sensing, Figure 1.10.

Object and background reflectivity can vary widely. Relatively shiny surfaces may reflect most of the light away from the receiver, making detection very difficult. The sensor face must be perpendicular with these types of object surfaces. On the other hand, very dark, matte objects may absorb most of the light and reflect very little for detection. These objects may be hard to detect unless the sensor is positioned very close.

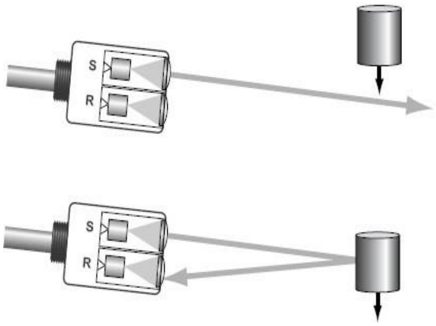


Figure 1.10: Diffuse Sensor

The diffuse sensor has the following **advantages**:

- Applications where the sensor-to-object distance is from a few inches to a few feet and when neither transmitted beam nor retroreflective sensing is practical.
- Applications that require sensitivity to differences in surface reflectivity and monitoring of surface conditions that relate to those differences in reflectivity are important.

On the other hand, it has the following **disadvantages**:

- Reflectivity: the response of a diffuse sensor is dramatically influenced by the surface reflectivity of the object to be sensed.
- Shiny surfaces: Shiny objects that are at a non-perpendicular angle may be difficult to detect.
- Small part detection: Diffuse sensors have less sensing distance when used to sense objects with small reflective area.

- Most diffuse mode sensors are less tolerant to the contamination around them and lose their margin very rapidly as dirt and moisture accumulates on their lenses.

Part 2: Hysteresis in Proximity Sensors

An effect that must considered when using a proximity sensor is the difference between its “operate” and “release” points which is called hysteresis. The amount of target travel required for release after operation must be accounted for when selecting target and sensor locations. Hysteresis is needed to help prevent chattering (turning on and off rapidly) when the sensor and/or target is subjected to shock and vibration. Vibration amplitudes must be smaller than the hysteresis band to avoid chatter. This effect is shown in Figure 1.11.

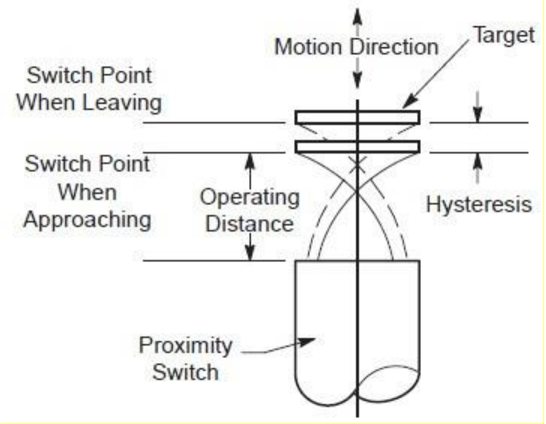


Figure 1.11: Hysteresis Effect in an Inductive Proximity Sensor

Part 3: Proximity Sensors Output Circuit Types (PNP Vs. NPN)

There are two types of output circuit of the proximity sensors; NPN and PNP output circuits. The NPN type is also known as a sinking type sensors where the sensor provides path to GND and sinks the current (current enters the sensor, ammeter is reading negative current). On the other hand, PNP proximity sensors are known as a sourcing output type where the sensor provides the high voltage and current is sourced (exit, ammeter reads positive current) from the sensor. Thus, it is very important to know the output circuit type of the sensor in order

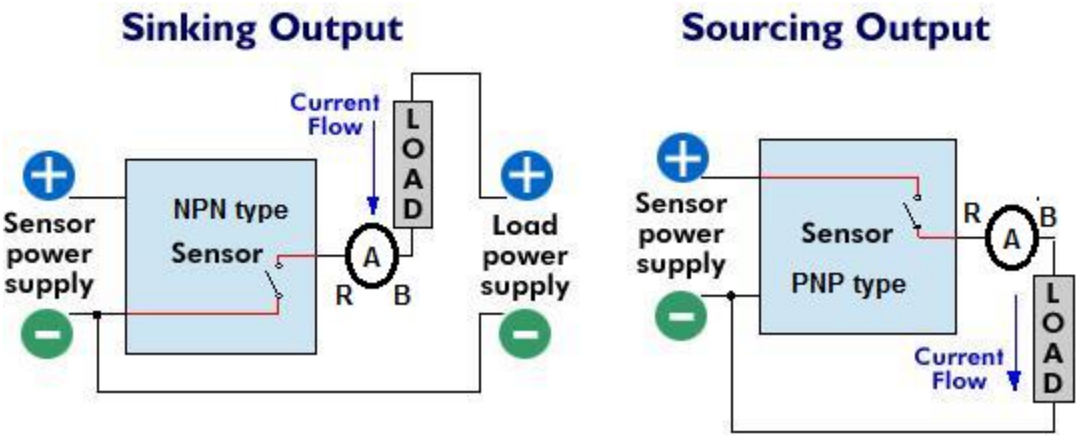


Figure 1.12: Sinking and Sourcing Output Circuits (R: red probe of the DMM, B: black probe of the DMM)

Part 4: Testing the Output Circuit of the Sensor

To determine the type of the output circuit of the proximity sensor, a simple test is done.

1- Connect the circuit in Figure 1.13.

2- With no material in the surrounding of the sensor, measure the output voltage and record it (V1).

3- Approach the sensor with a material that can activate the output circuit of the sensor, then measure the output voltage and record it (V2).

4- If V1 was zero and V2 is a high voltage, this is a PNP sensor. If V1 has a small value and V2 is zero, the sensor has NPN type.

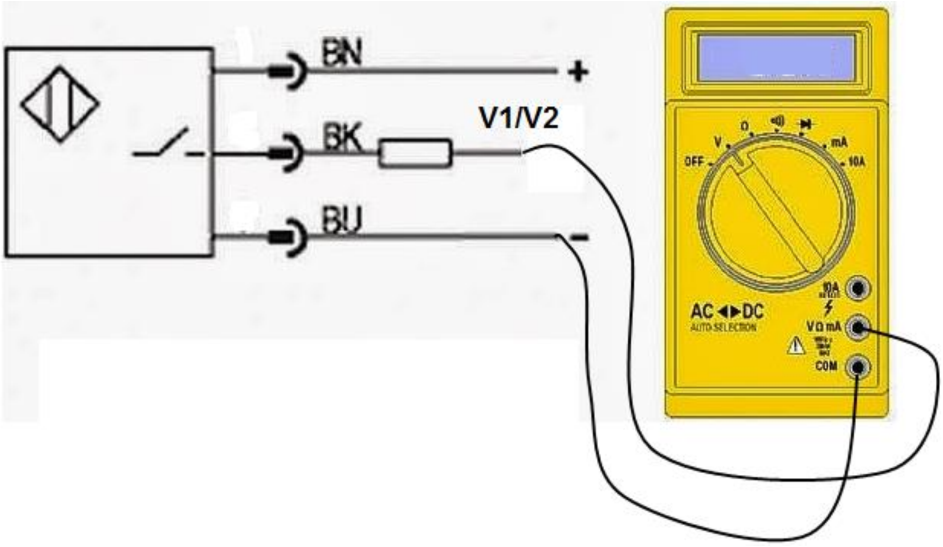


Figure 1.13: Determining the Output Circuit Type of the Proximity Sensor (PNP/NPN)

Part 5: Technical Terms in the Datasheet of a Proximity Sensor

1- Operating Voltage: range of voltage that can be supplied to operate the sensor.

2- No Load Current: current consumed from the power supply in order to activate the circuit of the sensor.

3- Maximum (Rated) Load Current: the maximum current that the senor can supply (pass) to the load without the senor being damaged.

4- Voltage Drop: the drop voltage on the internal circuit (resistance) of the sensor.

5- Switching Hysteresis (Differential Travel): this is given as a percentage of the switching on distance, which means that the turn off distance will equal the switching on distance+ the percentage*switching on distance.

Procedure:

Part 1: Sensor Type

1. Supply power to your sensor; brown is 12V, blue is 0V and black is output.
2. Approach the sensor with the different materials provided by your lab supervisor. Observe the LED on the sensor and determine which of the materials turned the sensor.

   Metal, magnet, plastic

Part 2: Sensor Output Circuit Type Determination (PNP/NPN)

1. Supply power to your sensor; brown is 12V, blue is 0V and black is output.
2. Measure the output voltage once without an object nearby and once with a detectable object.

   V_{out} (without the presence on an object) = --------------------

   V_{out} (with the presence on an object) = --------------------
3. The sensor output circuit is: ---------------------------

Part 3: Hysteresis Phenomenon

1. Connect the proper circuit to your sensor type. Choose between the figures in Figure 1.14.
2. Approach the sensor with a proper material. Note the turn on and off of the LED you connected.
3. Measure and record the turn on/off distance and record them.

   Turn on distance = ---------------------------- (mm)

   Turn off distance = ---------------------------- (mm)

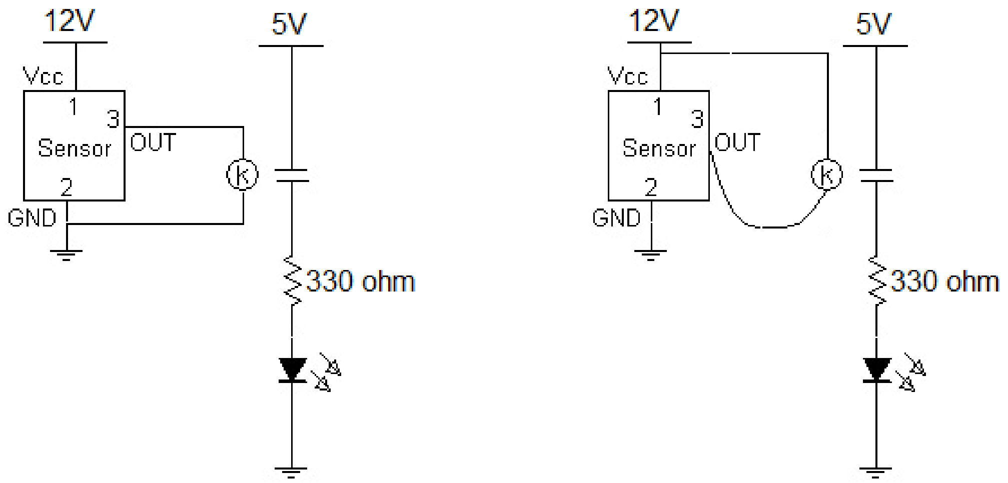


Figure 1.14: Different Connection Based on the Sensor Output Circuit

Discussion and Analysis:

1. What is the type of each of proximity sensor you tested?
2. Is the switching ON distance the same as the switching OFF distance? If it does not, what is the phenomenon causing this? Explain it in your own words? Which sensor has the largest difference between the ON and OFF distances?

Experiment 2

Thermal Sensors: RTD

Objectives:

This experiment aims to:

- Studying the characteristics of resistance temperature detector (RTD).
- Studying the construction, transduction circuit, and application of PT-100.

Apparatus:

- Module KL-64012 on KL-62001
- PT-100 (RTD)
- Digital Multimeter (DMM)
- Thermostatic Container

Theoretical Background:

Surrounding temperature affects the resistance of a conductor. In other words, the variation of the temperature will change the resistance of a conductor. Using this characteristic, we can calculate the resistance from present temperature value.

RTD (resistance temperature detector) is a wire-wound resistor with a positive temperature coefficient of resistance. Metals used as RTD’s generally have a low temperature coefficient of resistance, high stability, and a wide temperature detection range. Platinum is the most common material used for the RTDs. Other materials such as copper and nickel are also suitable for this purpose. The resistance vs. temperature curves of platinum, copper and nickel are shown in Figure 2.1.

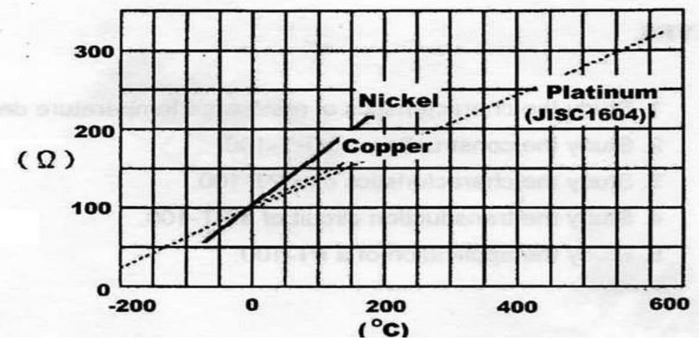


Figure 2.1: Resistance vs. Temperature Curve

The resistance vs. temperature characteristic of RTD can be expressed by:

$$Ro = R\,(1 + \alpha_1 T + \alpha_2 T_2 + \alpha_3 T_3 + ...) \qquad \textbf{(2.1)}$$

Where Ro is resistance at 0C°.while α_1, α_2, α_3 are temperature coefficients of resistance, and T is temperature in degrees Celsius. From Equation 2.1, we can see that sometimes RTDs are nonlinear. However, that approximate relationship for the resistance vs. temperature characteristic of RTD between zero and one hundred degrees Celsius can be expressed by:

$$Ro = R\,(1 + \alpha_1 T) \qquad \textbf{(2.2)}$$

Where for platinum α_1 is 0.00392 /C°. Thus, generally, RTDs are considered linear devices.

The RTD is a wire-wound element with internal configuration of (two-wire, three-wire, and four-wire), which is shown in Figure 2.2.

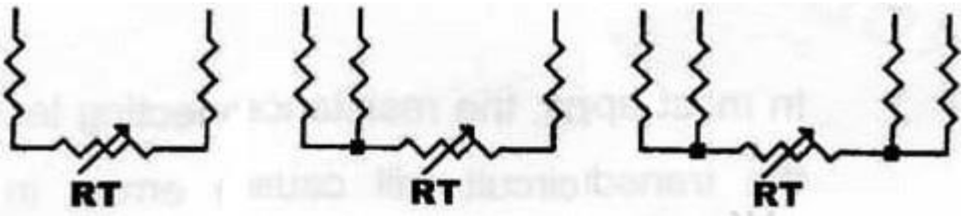


Figure 2.2: Internal Schematic Diagram for RTD

The two-wire RTDs advantage is its low cost, however, the characteristics maybe affected by the resistance changes of connecting leads which affects it's precision. Therefore, the two- wire RTD is commonly used in application where the resistance changes of leads are less than the resistive changes of the RTD.

The three-wire RTD is suitable for industrial applications where a compromise between precision and cost must be reached. The effects of connecting leads can be reduced by using appropriate wiring arrangements.

Figure 2.3 shows an RTD temperature measurement circuit.

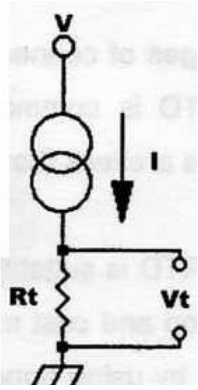


Figure 2.3: RTD Measuring Circuit

When a constant current I is applied to the RTD, the voltage Vt across its two terminals can be measured. Because I is constant, we can use the equation $Rt = Vt/I$ to calculate Rt. Finally, calculate the temperature T using the following equations.

$$V t = I * Rt = I * Ro\,(1 + \alpha T) \tag{2.3}$$

$$T = (V t - I * Ro)/(\alpha * I * Ro) \tag{2.4}$$

Where current I is constant, $Ro = 100\ \Omega$, and $\alpha = 0.00392$ /C°.

In most applications, the resistance of connecting leads between the RTD and the transduction circuit will cause some error in measured temperature. Therefore, how to eliminate the effect of connecting wires is an important consideration in designing a transduction circuit.

Resistive sensors usually require circuitry that converts their resistance changes to voltage changes. A resistive bridge (e.g., Wheatstone bridge) is typical for circuits used in many telemetry systems. The two-wire RTD can be connected to the bridge circuit, as shown in Figure 2.4. The RTD resistance Rt and the connection-lead resistance $RL1$ and $RL2$ combine as a bridge arm. This combination will result errors when the bridge is in balance.

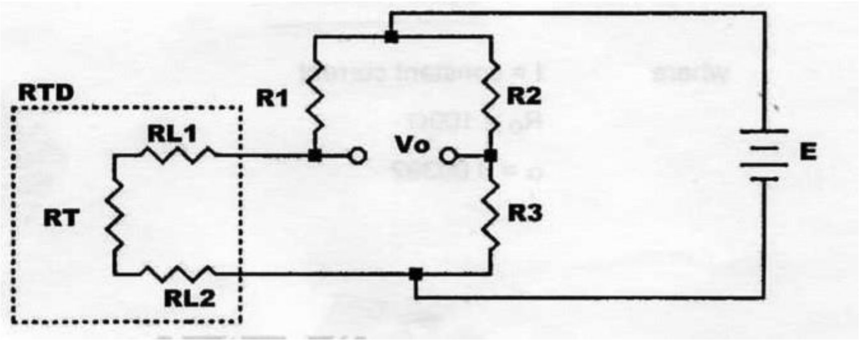


Figure 2.4: Wheatstone Bridge for Two-Wire RTD

Three-wire RTD can also be connected to resistive bridge, as show in Figure 2.5 (a & b), so that changes in connecting leads are compensated for. All the three connecting leads have the same length and resistance ($RL1 = RL2 = RL3$). In Figure 4.5a, lead-resistance changes in the RTD leg of the bridge are compensated for by equal changes in the $R3$ leg when the resistance $R3$ is approximately equal to the resistance of RTD.

In Figure 2.5 (a), when the bridge balance is reached. Assuming $R_1 = R_2$, thus:

$$R_3 + RL2 = R_t + RL1 \tag{2.5}$$

If the connecting leads have the same length and are of the same material RL2 = RL1, the effect of lead-resistance can be neglected when resistance R_3 is equal to the R_t.

$$R_1\,(R_3 + RL2) = R_2\,(R_t + RL1) \tag{2.6}$$

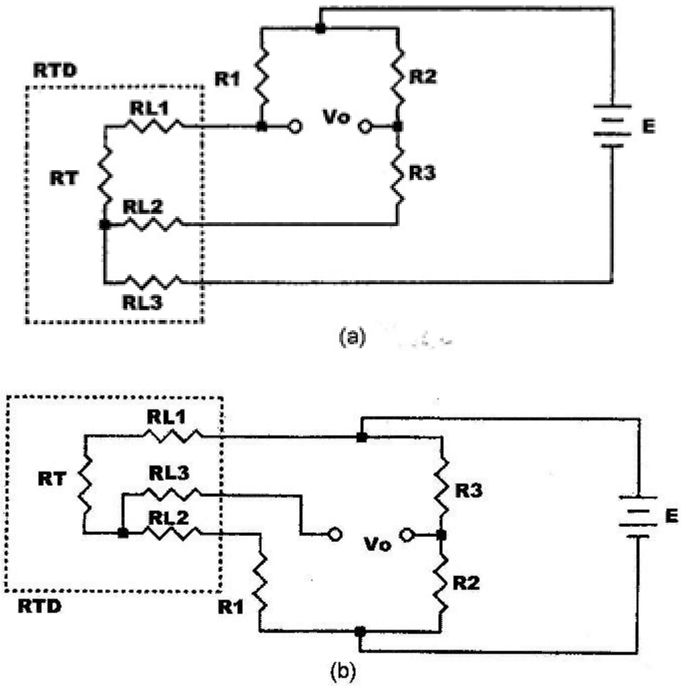


Figure 2.5: Wheatstone Bridge for Three-Wire RTD

In Figure 2.5 (b), when the bridge balance is reached. Assuming $R2 = R3$, thus:

$$R_2\,(R_t + RL1) = R_3\,(R_1 + RL2) \tag{2.7}$$

If the connecting leads have the same length and are of the same material $RL1 = RL2$, the effect of lead-resistance can be neglected when resistance R_1 is equal to the R_t.

$$R_t + RL1 = R_1 + RL_2 \tag{2.8}$$

Therefore, we can conclude that for the three-wire RTD, the connecting leads must have the same length and are of the same material. Otherwise, errors caused by the connecting lead will be unavoidable.

The **four-wire RTD** has high precision over long distances; but unfortunately high cost. Figure 2.6 shows a **wrong connection** for the 4-wire RTD, the forth wire is disconnected from the circuit (useless). Current loop is the **correct configuration** for the 4-wire RTD, Figure 2.7. The current has the same value at every point of the current loop.

PT-100 is one form of the RTD. It is made of the platinum wire and has the resistance of 100 Ω at 0C°. The construction of PT-100 is shown in Figure 2.8. The platinum wire is wounded on a glass or ceramic insulator, which is then installed within a glass or stainless steel protection tube. The gap between the insulator and the protection tube is filled with ceramic or cement. The protection tube is used to protect the sensing element in various measuring environments.

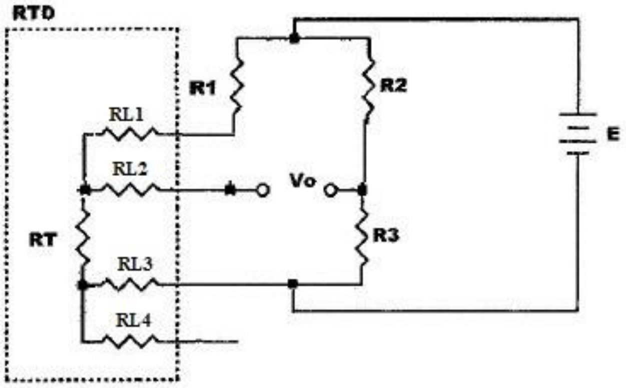


Figure 2.6: Wheatstone Bridge for Four-Wire RTD

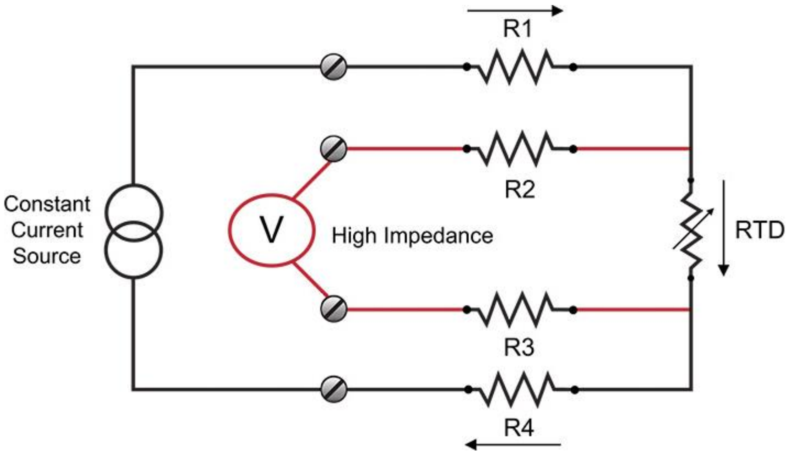
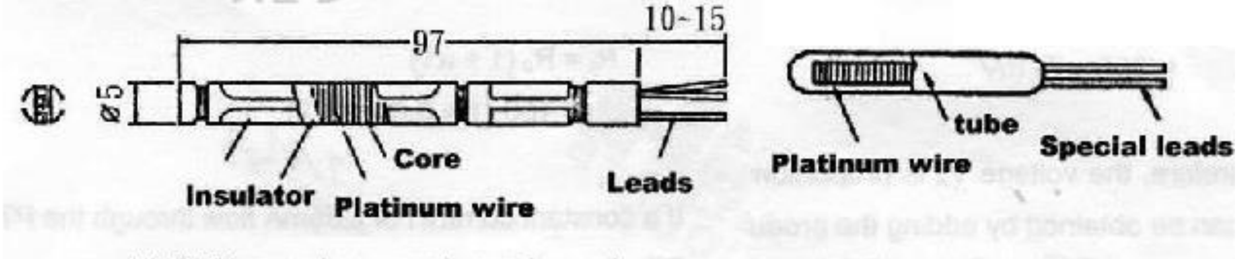
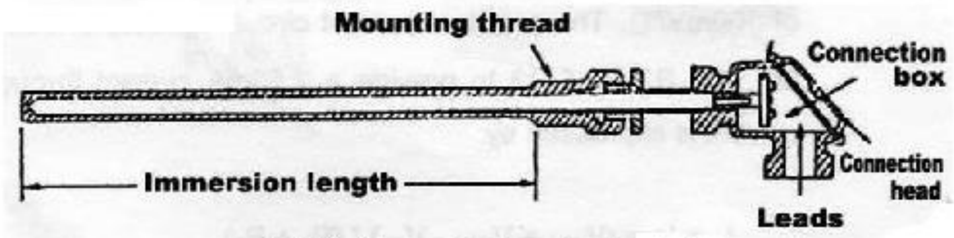


Figure 2.7: Current Loop Measurements for Four-Wire RTD



(a) Platinum wire wound on mica rod

(b) Glass tube package



(c) Stainless-steel protection tube

Figure 2.8: PT 100 Construction

Procedure:

Task 1: R vs. T Characteristic of PT-100

- Using Equation 2.2, calculate the resistance R_t for each 10 C° decrement in temperature starting from 90 C°.

- Insert the PT-100 into Thermostatic container. Measure and record the resistance for each temperature setting.

Task 2: Transduction circuit

- Place module KL-64012 on KL-62001 as shown in Figure 2.9.

- Connect the PT-100 to module KL-64012.

- Connect the DMM to measure the current of PT-100. Turn the power on.

- By adjusting the potentiometer R2 set this current to 2.55 mA.

- Turn the power off and remove the DMM.

- Turn the power on then adjust the output voltage at Vf1 to 2.55V DC by adjusting the potentiometer R14.

- Insert the PT-100 into the Thermostatic container.

- Measure and record the output voltage of PT-100 at Vo27 for each temperature setting.

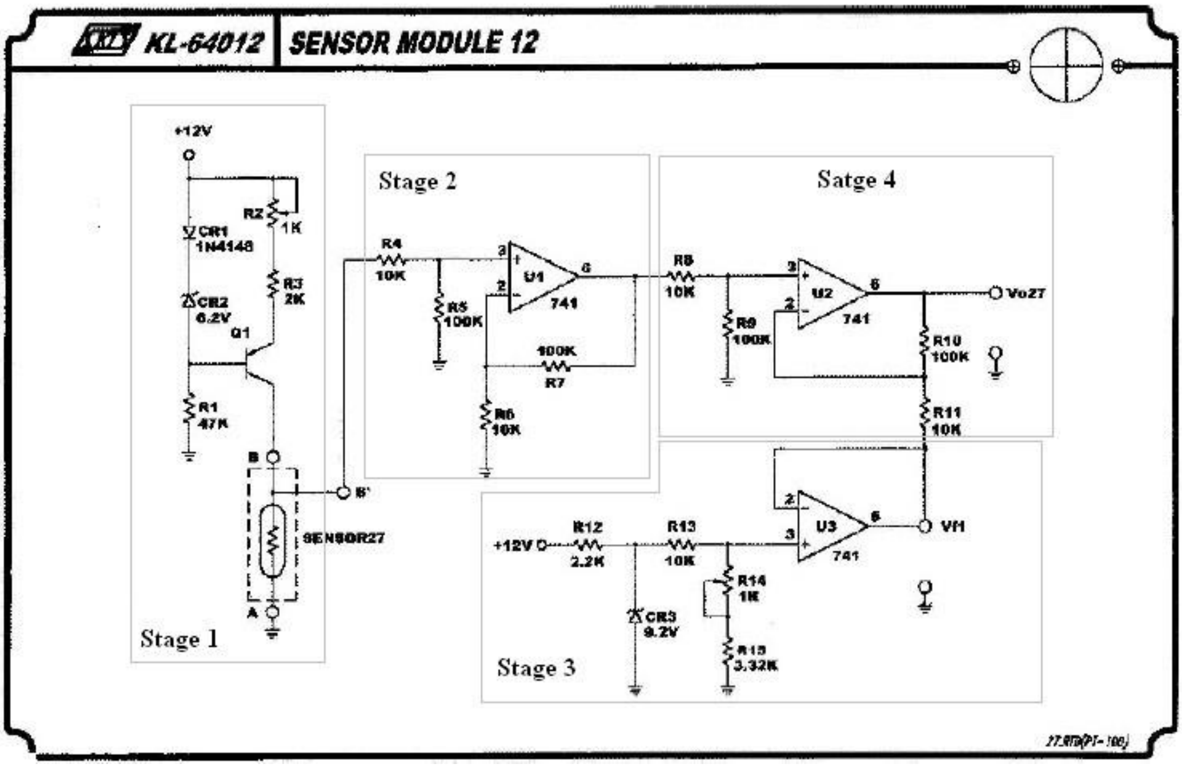


Figure 2.9: PT-100 Transduction Circuit

Discussion and Analysis:

Task 1

1. Describe the structure of PT-100 used in this experiment.
2. Plot the theoretical R vs. T curve

Task 2

1. Plot a voltage versus temperature characteristic curve of the PT-100 transducer.
2. Analyze the circuit shown in Figure 2.9 and derive the relationship between the output voltage Vo27 and the temperature T. Based on this relationship, what is the transduction ratio in mV/C°.

The Hashemite University
Faculty of Engineering

Department of Mechatronics Engineering
Control and Transducers Lab.

Experiment 3

Thermal Sensors: Thermocouple

Objectives:

This experiment will allow you to:

- Be aware of principle, construction, and characteristics of a thermocouple.
- Able to conduct transduction circuit of a thermocouple.

Apparatus:

- Thermocouple
- Copper wires
- Power supply
- Operational amplifier
- Digital Multimeter
- Potentiometer
- Thermometer
- Thermostatic container
- Resistances (1 kΩ, 1MΩ)

Theoretical Background:

In RTD experiment (Experiment # 2), we studied change in material resistance as a function of temperature. Measurement of resistance change, and hence temperature, requires external power sources. However, there are a large percentage of temperature measurement devices that depends on another electrical behavior of materials. This is characterized by a voltage- generating effect in which an electromotive force (emf) is produced that is proportional to temperature. Such an emf is found to be almost linear with temperature and very repeatable for constant materials. This phenomenon is based on thermoelectric properties of materials.

Thermocouples Principles

A thermocouple is a junction formed from two dissimilar metals. A temperature difference will cause a voltage to be induced as shown in Figure 3.1.

Figure 3.1: Induced emf.

Thermocouples are widely used for temperature measurement because they are inexpensive, rugged and reliable, and they can be used over a wide temperature range. In addition, they can be used over a wide temperature range. If we want to measure the output voltage from a thermocouple, every connection of different materials made in the thermocouple loop for measuring devices, extensions leads, and so on will contribute to the total an emf, depending on the difference in materials and various junction temperatures. The problem of the extension leads is shown in Figure 3.2.

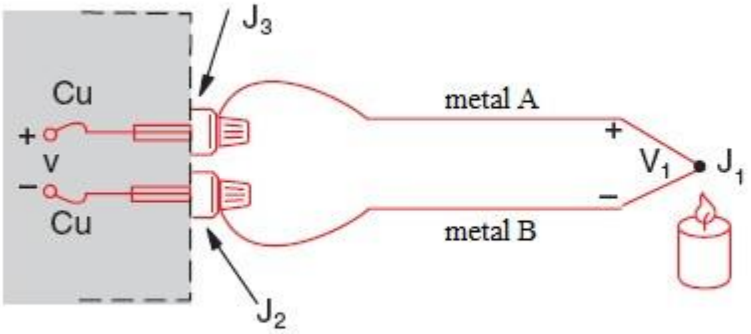


Figure 3.2: Extension Leads of Thermocouples

Figure 3.3 shows an equivalent circuit to the circuit shown in Figure 3.2. From this figure, you can notice the measurement junction J1, which should be the only junction responsible for the emf measured by the voltmeter. But you must also notice two other junctions; J2 and J3. These junctions are created between both of metals A and B and the copper extension wires connected to the measurement device. These additional junctions mean that there is an extra two sources for emf generation. To produce an output that is definite with respect to the temperature to be measured, the extra two junctions must be forced to be at a known common temperature. In this case the junction is known as reference junction.

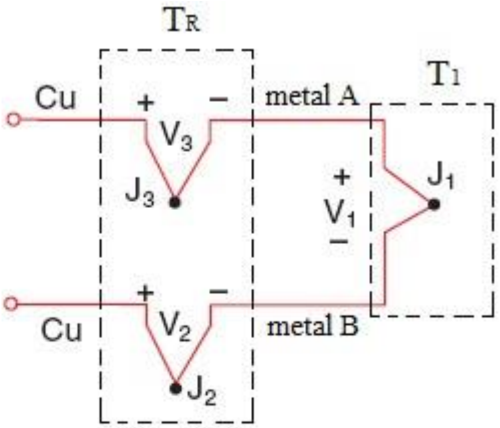


Figure 3.3: Equivalent Circuit of Figure 3.2

For the arrangement in Figure 3.3, the generated emf depends only on the temperature difference (T1-TR) and the type of metals A and B. The voltage produced has a magnitude dependent on the absolute temperature difference between the measurement junction and reference junction. Polarity depends on which junction is a higher temperature and which metal (A or B) is more positive than the other. In Figure 3.4, J2 and J3 are place in ice bath, which means that the reference junctions are at 0C◦.

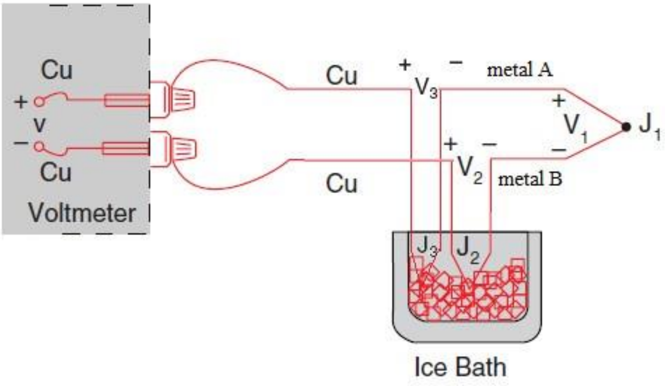


Figure 3.4: Reference Junctions at 0C◦

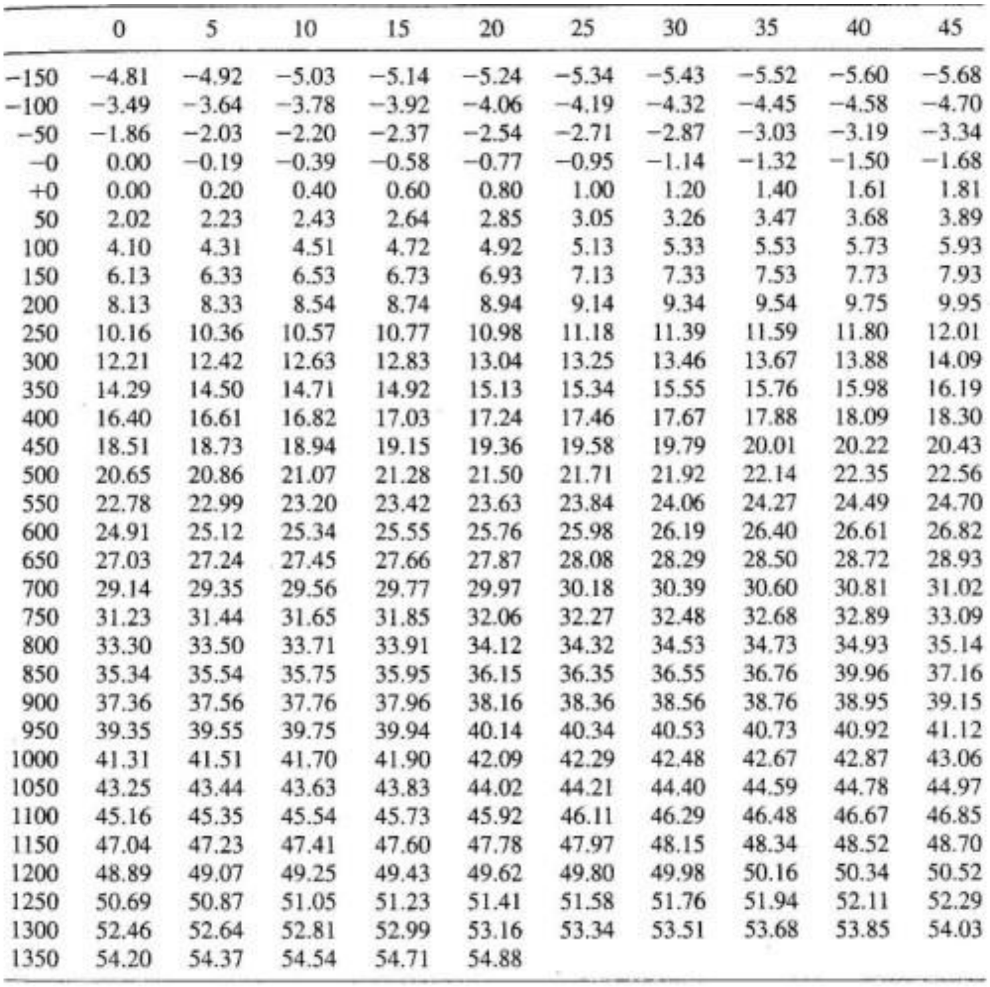
Temperature Interpolation

The TC tables simply give the voltage those results for particular type of TC when the reference junctions are at a particular reference temperature, and the measurement junction is at a temperature of interest. In most cases, the measure voltage does not fail exactly on a table value. When this happens, it is necessary to interpolate between table values that bracket the desired value. In general, the value of temperature can be found using the following interpolation equation:

$$TM = TL + \left(\frac{TH - TL}{VH - VL}\right)(VM - VL) \quad \textbf{(3.1)}$$

Where T_M is the measured temperature (C◦), V_M is the measured voltage (V), V_H is a voltage just higher than V_M and is available in Table 3.1, V_L is a voltage just lower than V_M and is available in Table 3.1, T_H is the corresponding temperature to V_H (C◦), T_L is the corresponding temperature to V_L (C◦).

Table 3.1: K-Type TC Table at T*ref* =0°C (Voltage is In mV)



	0	5	10	15	20	25	30	35	40	45
−150	−4.81	−4.92	−5.03	−5.14	−5.24	−5.34	−5.43	−5.52	−5.60	−5.68
−100	−3.49	−3.64	−3.78	−3.92	−4.06	−4.19	−4.32	−4.45	−4.58	−4.70
−50	−1.86	−2.03	−2.20	−2.37	−2.54	−2.71	−2.87	−3.03	−3.19	−3.34
−0	0.00	−0.19	−0.39	−0.58	−0.77	−0.95	−1.14	−1.32	−1.50	−1.68
+0	0.00	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.61	1.81
50	2.02	2.23	2.43	2.64	2.85	3.05	3.26	3.47	3.68	3.89
100	4.10	4.31	4.51	4.72	4.92	5.13	5.33	5.53	5.73	5.93
150	6.13	6.33	6.53	6.73	6.93	7.13	7.33	7.53	7.73	7.93
200	8.13	8.33	8.54	8.74	8.94	9.14	9.34	9.54	9.75	9.95
250	10.16	10.36	10.57	10.77	10.98	11.18	11.39	11.59	11.80	12.01
300	12.21	12.42	12.63	12.83	13.04	13.25	13.46	13.67	13.88	14.09
350	14.29	14.50	14.71	14.92	15.13	15.34	15.55	15.76	15.98	16.19
400	16.40	16.61	16.82	17.03	17.24	17.46	17.67	17.88	18.09	18.30
450	18.51	18.73	18.94	19.15	19.36	19.58	19.79	20.01	20.22	20.43
500	20.65	20.86	21.07	21.28	21.50	21.71	21.92	22.14	22.35	22.56
550	22.78	22.99	23.20	23.42	23.63	23.84	24.06	24.27	24.49	24.70
600	24.91	25.12	25.34	25.55	25.76	25.98	26.19	26.40	26.61	26.82
650	27.03	27.24	27.45	27.66	27.87	28.08	28.29	28.50	28.72	28.93
700	29.14	29.35	29.56	29.77	29.97	30.18	30.39	30.60	30.81	31.02
750	31.23	31.44	31.65	31.85	32.06	32.27	32.48	32.68	32.89	33.09
800	33.30	33.50	33.71	33.91	34.12	34.32	34.53	34.73	34.93	35.14
850	35.34	35.54	35.75	35.95	36.15	36.35	36.55	36.76	39.96	37.16
900	37.36	37.56	37.76	37.96	38.16	38.36	38.56	38.76	38.95	39.15
950	39.35	39.55	39.75	39.94	40.14	40.34	40.53	40.73	40.92	41.12
1000	41.31	41.51	41.70	41.90	42.09	42.29	42.48	42.67	42.87	43.06
1050	43.25	43.44	43.63	43.83	44.02	44.21	44.40	44.59	44.78	44.97
1100	45.16	45.35	45.54	45.73	45.92	46.11	46.29	46.48	46.67	46.85
1150	47.04	47.23	47.41	47.60	47.78	47.97	48.15	48.34	48.52	48.70
1200	48.89	49.07	49.25	49.43	49.62	49.80	49.98	50.16	50.34	50.52
1250	50.69	50.87	51.05	51.23	51.41	51.58	51.76	51.94	52.11	52.29
1300	52.46	52.64	52.81	52.99	53.16	53.34	53.51	53.68	53.85	54.03
1350	54.20	54.37	54.54	54.71	54.88					

Change of Table Reference

As mentioned before, Table 3.1 is obtained at 0C◦ reference temperature. So if the temperature is to be measured at different temperature like 25C◦, a correction factor has to be subtracted. For example, if the V (210C◦) is to be measured at reference of 25C◦, so from table:

V (210C◦) at 0C◦ = 8.54 mV, and V (25C◦) at 0C◦ = 1 mV.
Then, V (210C◦) at 25C◦ reference = 8.54 - 1 = 7.54 m

Figure 3.6 shows the characteristics of different types of thermocouples.

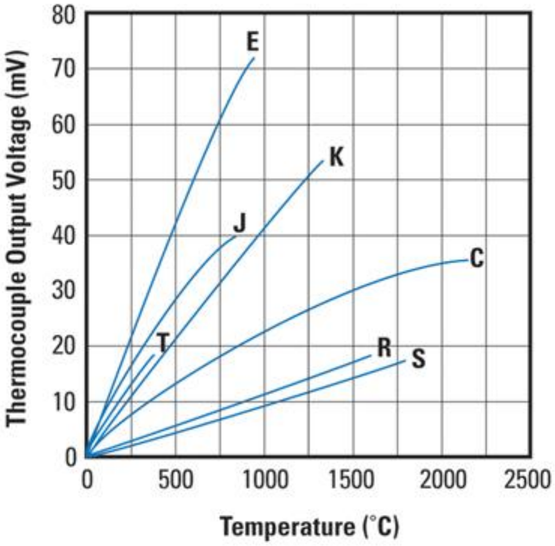


Figure 3.6: Curves of Thermocouple Voltage versus Temperature

Procedure:

1. Connect the circuit shown in Figure 3.7.
2. Set R1 to 1 kΩ and R2 to 1000 kΩ.
3. Null the operational amplifier using the potentiometer R3.
4. Connect the DMM to measure the output voltage.
5. Measure the room temperature and record it.
6. Insert the thermocouple into the Thermostatic container.
7. Measure and record the output voltage for each temperature setting on Table 3.2.
8. Repeat the steps from 3 to 7 for R1=1 kΩ and R2=2000 kΩ. and fill in Table 3.3.

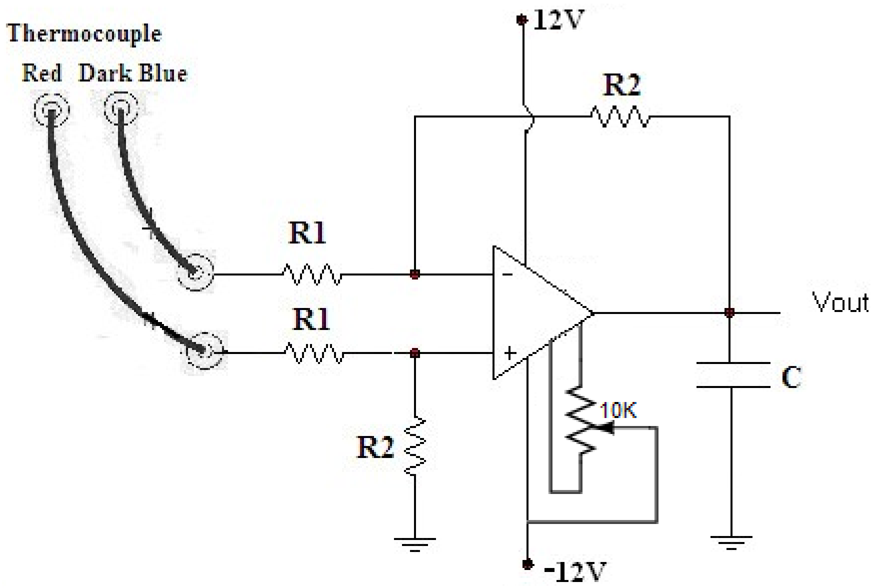


Figure 3.7: TC Interfacing Circuit

Discussion and Analysis:

1. Mention the type of TC we used in this experiment and metals used in building it. Which metal is positive with respect to the other?
2. The junctions between TC wires and the extension leads wires will be at the room temperature. Will this cause a problem that cannot be fixed? If you can fix the problem, how will you accomplish that?
3. Plot the output voltage versus temperature theoretically and experimentally on the same graph.
4. What additions to the circuit in Figure 3.7 do you suggest to improve its result?

Experiment 5

Displacement Sensors: Strain Gauges

Objectives:

This experiment will include:

- Principle, construction, and characteristics of strain gauges.
- Transduction circuit of strain gauges.
- Applications of strain gauges.

Apparatus:

- Module KL-64007 on KL-62001
- Weights (100 gram, 50 gram, 25 gram)
- Digital Multimeter (DMM)

Theoretical Background:

Strain Gauges

Strain is defined as the fractional change in length of a body due to an applied force, Figure 5.1. While there are several methods of measuring strain, the most common is with a strain gauge which is a sensor whose electrical resistance varies in proportion to the amount of strain in the element being deformed.

The conductor in Figure 5.1 has a length *L* and a corresponding resistance *R*. If a compression force is applied to this conductor, then the resistance *R* will be decreased due to a decrease in length and an increase in area. If a tension force is applied to this conductor, then the resistance R will be increased because of an increase in length and a decrease in area. In other words, when an external force is applied, the conductor changes geometric shape (assuming that the resistivity of the conductor is constant).

The intrinsic resistance of a conductor can be given by:

$$Ro = \rho * \frac{Lo}{Ao} \quad \textbf{(5.1)}$$

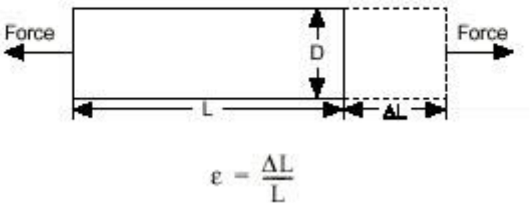


Figure 5.1: Strain in a Conductor

Where *Ro is* the resistance in ohms, ρ is the resistivity in ohms-meter, *Lo* is the length in meter, and *Ao* is the cross sectional area in square meters.

If a force is applied to the conductor, its length will change by ΔL and the new length is $Lo + \Delta L$. Assuming the volume of the conductor is constant, an increment in the length must cause a decrement in area by ΔA. Based on this, the characteristic equation of the strain gauge (in theory) is obtained and is given by:

$$\Delta R = 2Ro\left(\frac{\Delta L}{Lo}\right) \quad \textbf{(5.2)}$$

The metallic strain gauge consists of a very fine wire or, more commonly, metallic foil arranged in a grid pattern and is mounted on a backing material. The grid pattern maximizes the amount of metallic wire or foil subject to strain in the parallel direction as shown in Figure 5.2.

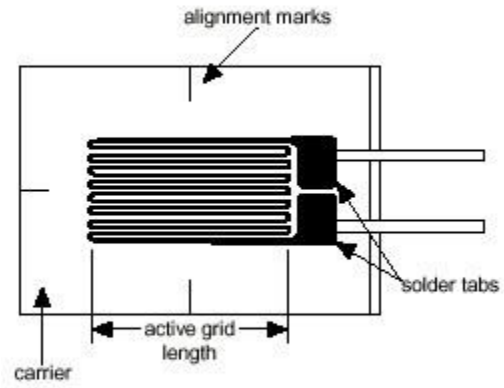


Figure 5.2: Strain Gauge

The strain experienced by the test specimen is transferred directly to the strain gauge, which responds with a linear change in its electrical resistance. Strain gauges are available in a wide choice of shapes and sizes to suit a variety of applications. Commercially, they are available with nominal resistance values from 30 to 3000 **Ω**, with 120, 350, and 1000 **Ω** being the most common values.

A fundamental parameter of the strain gauge is its sensitivity to strain, expressed quantitatively as the gauge factor (*GF)*. Gauge factor is defined as the ratio of fractional change in electrical resistance to the fractional change in length (strain):

$$GF = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R / R}{\mathrm{E}} \qquad \textbf{(5.3)}$$

The gauge factor for metallic strain gauges is typically around 2.

The strain gauge has been in use for many years and is the fundamental sensing element for many types of sensors, including pressure sensors, load cells, torque sensors, position sensors, etc. Strain gauges are frequently used in mechanical engineering research and development to measure the stresses generated by machinery. Aircraft component testing is one area of application, tiny strain-gauge strips glued to structural members, linkages, and any other critical component of an airframe to measure stress.

The changes in strain gauge are typically ***small***. Thus, sensitive interfacing circuits must be used to detect these changes. The most common interfacing circuit with strain gauges is Wheatstone bridge. The strain gauge is connected into a Wheatstone bridge circuit with a combination of four active gauges (full bridge), two gauges (half bridge), or, less commonly, a single gauge (quarter bridge). In the half and quarter circuits, the bridge is completed with precision resistors.

Typically, the rheostat arm of the bridge (R2) is set at a value equal to the strain gauge resistance with no force applied. The two ratio arms of the bridge (R1 and R3) are set equal to each other. Thus, with no force applied to the strain gauge, the bridge will be symmetrically balanced and the voltmeter will indicate zero volts, representing zero force on the strain gauge. As the strain gauge is either compressed or tensed, its resistance will decrease or increase, respectively, thus unbalancing the bridge and producing an indication at the voltmeter. This arrangement, with a single element of the bridge changing resistance in response to the measured variable (mechanical force), is known as a ***quarter-bridge*** circuit, Figure 5.3.

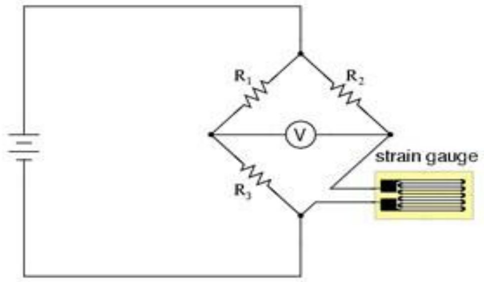


Figure 5.3: Quarter-Bridge Strain Gauge Circuit

As the distance between the strain gauge and the three other resistances in the bridge circuit may be substantial, wire resistance has a significant impact on the operation of the circuit. This effect is shown in Figure 5.4.

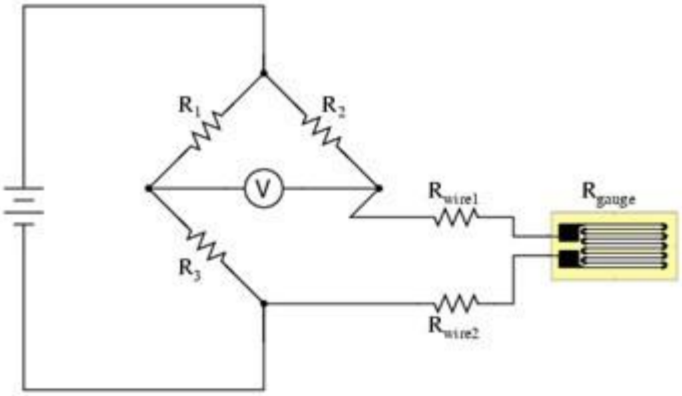


Figure 5.4: Leads Effect on Measurements

The strain gauge's resistance (R_{gauge}) is not the only resistance being measured: the wire resistances R*wire*1 and R*wire*2, being in series with R_{gauge}, also contribute to the resistance of the lower half of the rheostat arm of the bridge, and consequently contribute to the voltmeter's indication. This, of course, will be falsely interpreted by the meter as physical strain on the gauge. While this effect cannot be completely eliminated in this configuration, it can be minimized with the addition of a third wire, connecting the right side of the voltmeter directly to the upper wire of the strain gauge, Figure 5.5.

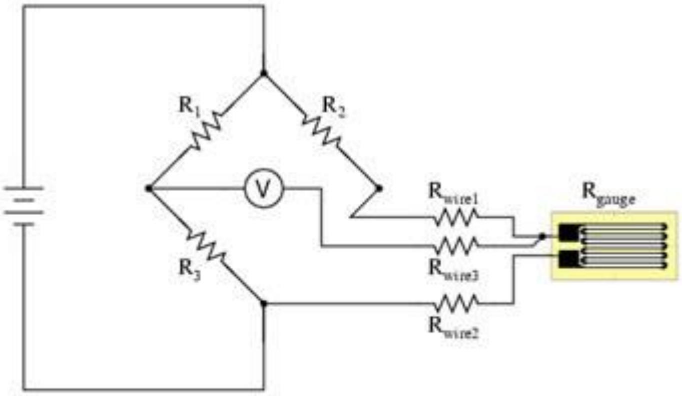


Figure 5.5: Three Wire, Quarter Bridge Strain Gauge Circuit

Because the third wire ***carries practically no current*** (due to the voltmeter's extremely high internal resistance), its resistance will not drop any substantial amount of voltage. Notice how the resistance of the top wire (R*wire*1) has been "bypassed" now that the voltmeter connects directly to the top terminal of the strain gauge, leaving only the lower wire's resistance (R*wire*2) to contribute any stray resistance in series with the gauge. Not a perfect solution, of course, but twice as good as the last circuit. To reduce error of measurement due to temperature, a "dummy" strain gauge in place of R2 is used. So that, both elements of the rheostat arm will change resistance in the same proportion when temperature changes. This will efficiently reduce the effects of temperature change while only the stressed gauge will sense strain. This is shown in Figure 5.6.

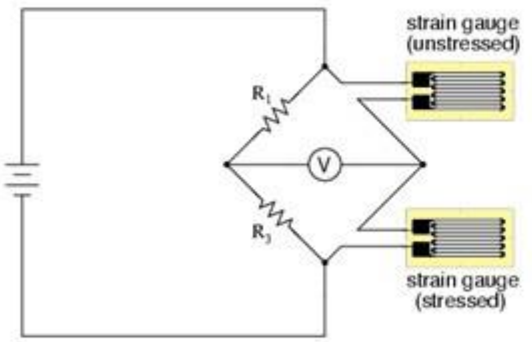


Figure 5.6: Quadratic Bridge Strain Gauge Circuit with Temperature Compensation

Even though there are now two strain gauges in the bridge circuit, only one is responsive to mechanical strain, and thus we would still refer to this arrangement as a quarter-bridge. However, if we were to take the upper strain gauge and position it so that it is exposed to the opposite force as the lower gauge (i.e. when the upper gauge is compressed, the lower gauge will be stretched, and visa-versa), we will have both gauges responding to strain, and the bridge will be more responsive to applied force. This utilization is known as a ***half-bridge***. Since both strain gauges will either increase or decrease resistance by the same proportion in response to changes in temperature, the effects of temperature change remain canceled and the circuit will suffer minimal temperature-induced measurement error. This circuit is shown in Figure 5.7.

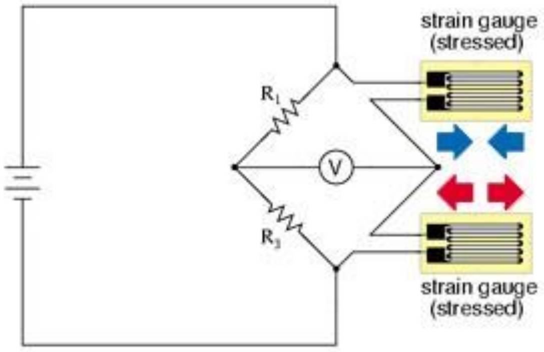


Figure 5.7: Half Bridge Strain Gauge Circuit

An example of how a pair of strain gauges may be bonded to a test specimen so as to yield this effect is illustrated here in Figure 5.8. With no force applied to the test specimen, both strain gauges have equal resistance and the bridge circuit is balanced. However, when a downward force is applied to the free end of the specimen, it will bend downward, stretching gauge #1 and compressing gauge #2 at the same time as shown in Figure 5.9.

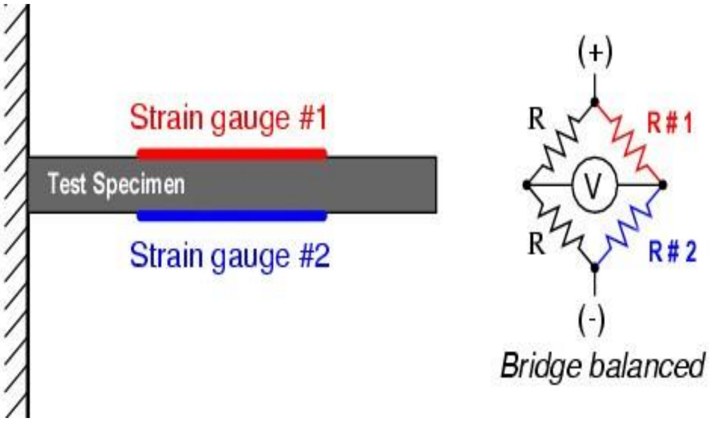


Figure 5.8: Unstrained Test Specimen

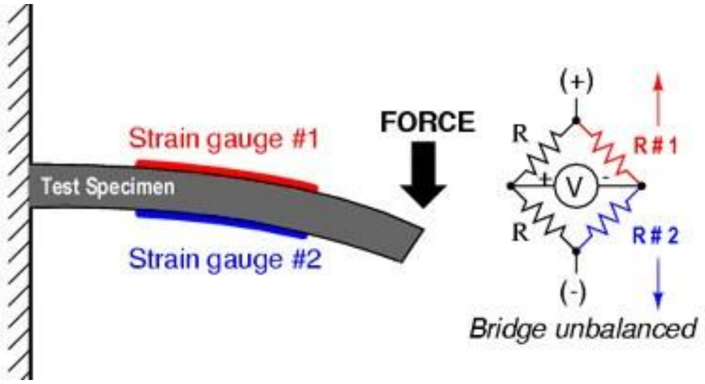


Figure 5.9: Strained Test Specimen

In applications where such complementary pairs of strain gauges can be bonded to the test specimen, it may be advantageous to make all four elements of the bridge "active" for even greater sensitivity. This is called a ***full-bridge*** circuit and is shown in Figure 5.10. Both half-bridge and full-bridge configurations grant greater sensitivity over the quarter-bridge circuit, but often it is not possible to bond complementary pairs of strain gauges to the test specimen. Thus, the quarter-bridge circuit is frequently used in strain measurement systems.

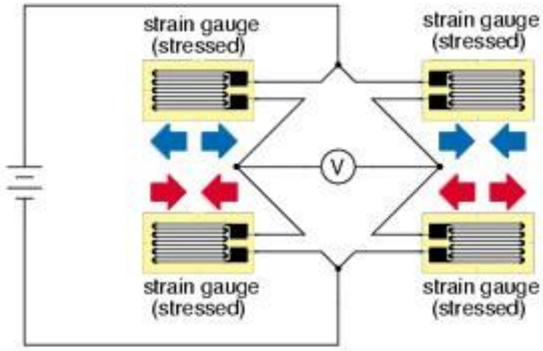


Figure 5.10:Full Bridge Strain Gauge Circuit

When possible, the full-bridge configuration is the best to use. This is true not only because it is more sensitive than the others, but because it is linear while the half bridge is sometimes linear and the quarter bridge is never linear. Linearity, or proportionality, of these bridge circuits is best when the amount of resistance change due to applied force is very small compared to the nominal resistance of the gauge(s). With a full-bridge, however, the output voltage is directly proportional to applied force, with no approximation (provided that the change in resistance caused by the applied force is equal for all four strain gauges).

Hysteresis in Strain Gauges

Strain gauges suffer from hysteresis, Figure 5.11, phenomenon where the resistance has a higher values while unloading than they have while loading.

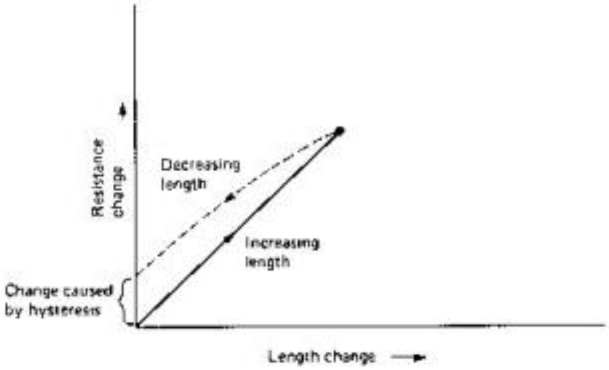


Figure 5.11: **Hysteresis in Strain Gauges**

Differential Amplifier

A differential amplifier is an amplifier that accepts voltage at both of its inputs and has a negative feedback. Figure 5.11 shows a differential amplifier.

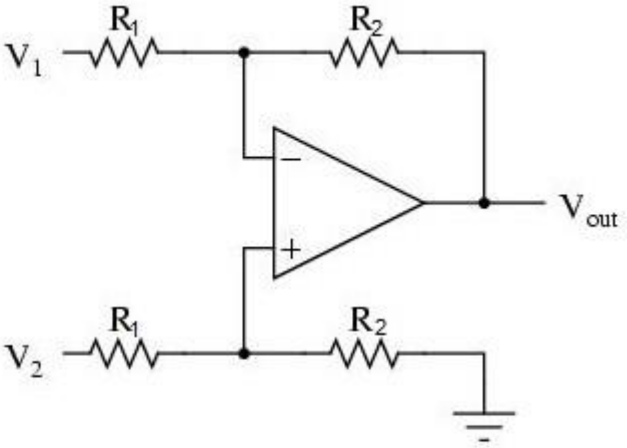


Figure 5.12: **Differential Amplifier**

The following equation represents the relationship between the inputs and the output of the differential amplifier shown in Figure 5.12:

$$Vout = \frac{R2}{R1}(V2 - V1) \tag{5.4}$$

The above equation shows that if a large gain is to be obtained from this kind of amplifier, $R1$ has to be of a small magnitude which means that its input impedances are rather low compared to that of some other op-amp configurations. The solution to this problem, fortunately, is quite simple. All needed to be done is to "buffer" each input voltage signal through a voltage follower as shown in Figure 5.13.

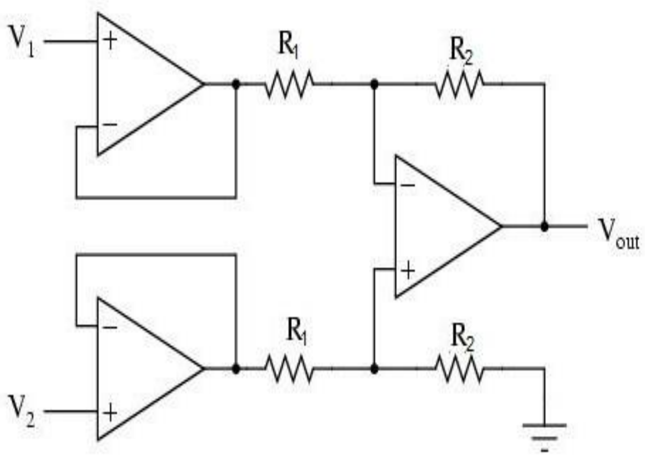


Figure 5.13: Differential Amplifier with Buffered Inputs

Instrumentation Amplifier

The differential amplifier configuration shown in Figure 5.13 is a good configuration. But it will be even greater to be able to adjust the gain of the amplifier circuit without having to change more than one resistor value. The solution to this is quite simple and is called an "instrumentation amplifier", Figure 5.14.

The relationship of the instrumentation amplifier shown in Figure 5.14 to its input voltages is given by the following equation:

$$Vout = \left(1 + \frac{2R}{Rgain}\right)\left(\frac{R2}{R1}\right)(V2 - V1) \tag{5.5}$$

Though it may not be obvious by looking at the schematic, the differential gain of the instrumentation amplifier can simply be changed by changing the value of one resistor; Rgain. But of course, the overall gain could still be changed by changing the values of some of the other resistors, but this would necessitate balanced resistor value changes for the circuit to remain symmetrical. Note that the lowest gain possible with the above circuit is obtained with Rgain completely open (infinite resistance).

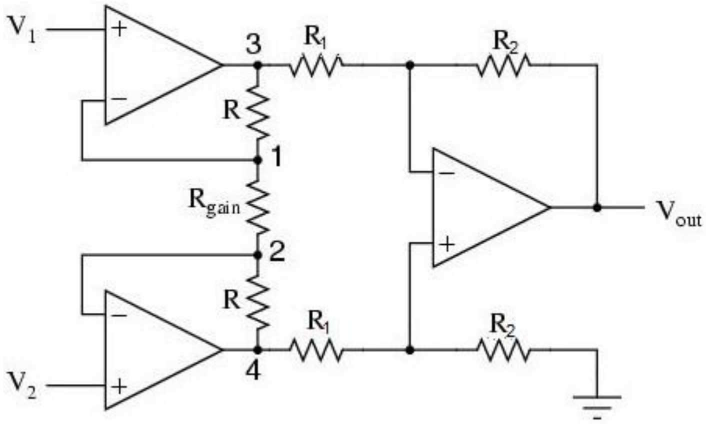


Figure 5.14: Instrumentation Amplifier

Description of Experimental Circuit

Four strain gauges, two on the top side and two on the bottom side of the beam, are used in a Wheatstone bridge with a total gain of 2.7 mV ±10% /kg. The bridge is followed by the instrumentation amplifier shown in Figure 5.14. The recommended excitation voltage to the sensor is ±5V DC. In Figure 5.15, an instrumentation amplifier consists of operational amplifiers U4, U5, and U6, with a total gain of

$$G = \left(1 + \frac{2R15}{R24 + R25}\right) \tag{5.6}$$

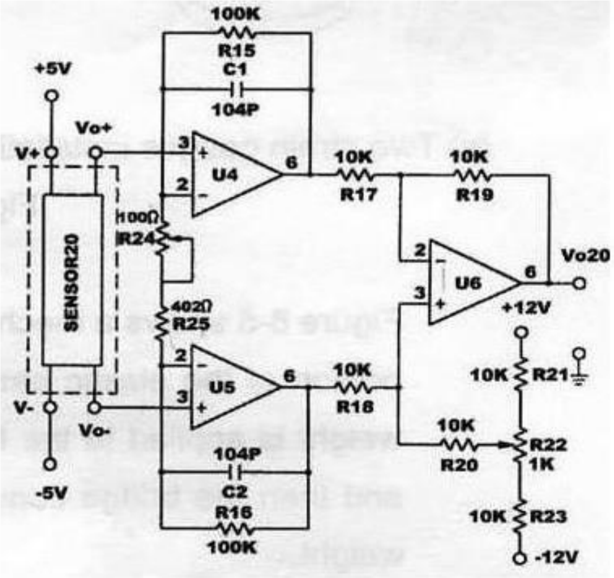


Figure 5.15: Strain Gauge Transducer Circuit

To obtain an output of 1 mV/g, the voltage gain of the instrumentation amplifier must be 250 (4 mV/kg × 250 = 1mV/g). Under a null weight condition, the output voltage of the load cell is not zero. The former can be improved with providing an offset voltage to the input of the instrumentation amplifier, and the later can be improved with adjusting the R24 to increase the voltage gain. The output voltage from the potentiometer may be from +12 to -12 V. By adjusting R22, the transduction output can easily obtain a zero under null weight conditions.

Procedure:

Task 1: Canceling Hysteresis Effect

1. Set the strain gauge transducer module KL-64007 on the trainer KL-62001.
2. Under null weight condition, adjust the potentiometer R22 and measure the output voltage at Vo20 for Vo20 = 0 V.
3. Set the weight of 0.2 kg on the disk and adjust R24 for Vo20 = 0.2 V.
4. Measure and record the output voltage at Vo20 for each weight (Important note: before adding more weights, repeat step #2).

Task 2: **Including Hysteresis Effect**

1. Repeat the first three steps in Task 1.
2. Measure and record the output voltage at Vo20 for each weight (Important note: add weights from minimum to maximum and back to minimum sequentially).

Discussion and Analysis:

1. Derive the transduction ratio in terms of *R*15, *R*16, *R*24, *R*25, *R*19, and *R*17 of the circuit shown in Figure 5.14. Show the steps of the derivation. (You need to apply the superposition theorem - no numerical values are allowed to be used).
2. Plot the voltage vs. weight curve of the system using data.
3. Do you think that the position of the load on the cantilever beam affects the measurements? Explain your answer.
4. What arrangement of the gauges in the bridge do you suggest to achieve the output voltage (before the stage of the instrumentation amplifier) you obtained during the experiment, Draw the circuit indicating the strain gauges positions and condition.

Experiment 6

Displacement Sensors:
Variable Length Transducer (VLT)

Objectives:

This experiment will include:

- Confirming the relationship between length and resistance of a material.
- Observing how the relationship may be used in a variable length transducer.
- Investigating a method of obtaining a direct reading of resistance value.

Apparatus:

- VLT
- Operational amplifier
- Power supply
- Digital Multimeter (DMM)
- Resistances
- Potentiometer

Theoretical Background:

We know that the resistance of an object is directly proportional to its length, given by the formula:

$$Ro = \rho * \frac{Lo}{Ao} \qquad \textbf{(6.1)}$$

Let us investigate the variation of resistance with length using an apparatus which allows *i* to be varied whilst keeping the resistivity and the cross-sectional area of the specimen constant. First, examine the Variable Resistor Sub-unit, TK294K, for use with Linear Transducer Test Rig TK294. You will see that it has three connections. Two of these connections are made directly to the resistive element, one at each end of it; the third connection is made to a sliding contact which may travel up and down the resistive element. The position of this sliding_contact may be varied by pushing or pulling the threaded connecting rod. The schematic symbol of the transducer is as shown in Figure 6.1.

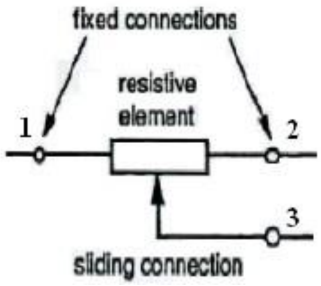


Figure 6.1: Schematic Diagram of a Variable Length Transducer

By using one of the fixed connections and the sliding connection a resistive element may be made its effective length varies with the position of the slider, but whose resistivity and cross-section remain constant. This is the situation that we desire.

For an operational amplifier circuit with resistive feedback, the equation of operation is given by

$$Vout = \left(-Rf \;/\; Rin\right) * Vin \tag{6.2}$$

If *Vin and Rin are* kept constant and *Rf* is then varied, the output voltage will be directly proportional to *Rf* .

Procedure:

1. Measure the full effective length and the VLT resistance at that length. Record the values and calculate the sensors sensitivity.

   Lmax= -------------------------- Rmax= ------------------------------

2. Connect up the circuit of Figure 6.2. *There is no need for the capacitor or the potentiometer* or the (Rf//R). Explain.
3. Start from displacement equal zero. Record the voltage reading
4. Move the slider 5 mm to the left and repeat the readings.
5. Repeat this procedure for positions at 5 mm intervals for the full travel of the transducer and record all readings

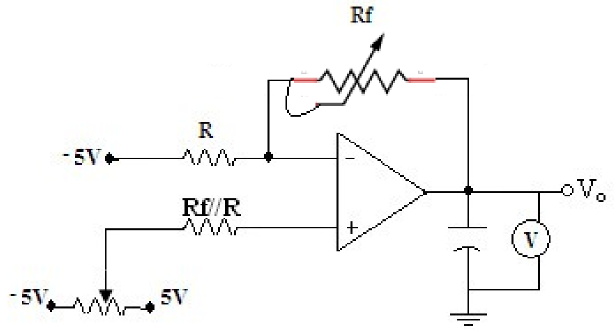


Figure 6.2: A Variable Length Transducer Connected To an Op Amp

Discussion and Analysis:

1. Calculate the resistance value for each value of position.
2. Plot the calculated resistor values against position.
3. What is the advantage of positioning the variable length transducer in the feedback of the amplifier while having fixed input resistance? What is the disadvantage of switching the locations of the transducer and the fixed resistance?

Experiment 8

Servo Motor System

Objectives:

- To understand the main components of the servo motor kit
- To understand the function and principle of operation of each component.
- To be able to integrate the components to build different control configurations of a dc motor.

Apparatus:

1. Operational Amplifier Unit: OA150A
2. Attenuator Unit: AU150B
3. Pre–Amplifier Unit: PA150C
4. Servo Amplifier Unit: SA150D
5. Power Supply: PS15E
6. Motor: DCM150F
7. Input Angular Potentiometer: IP150H
8. Output Angular Potentiometer: OP150K
9. Redction Gear Tacho Unit: GT150X
10. Loading Unit: LU150L
11. Function generator and Oscilloscope (are signals provided and displayed via a DAQ and matlab software)

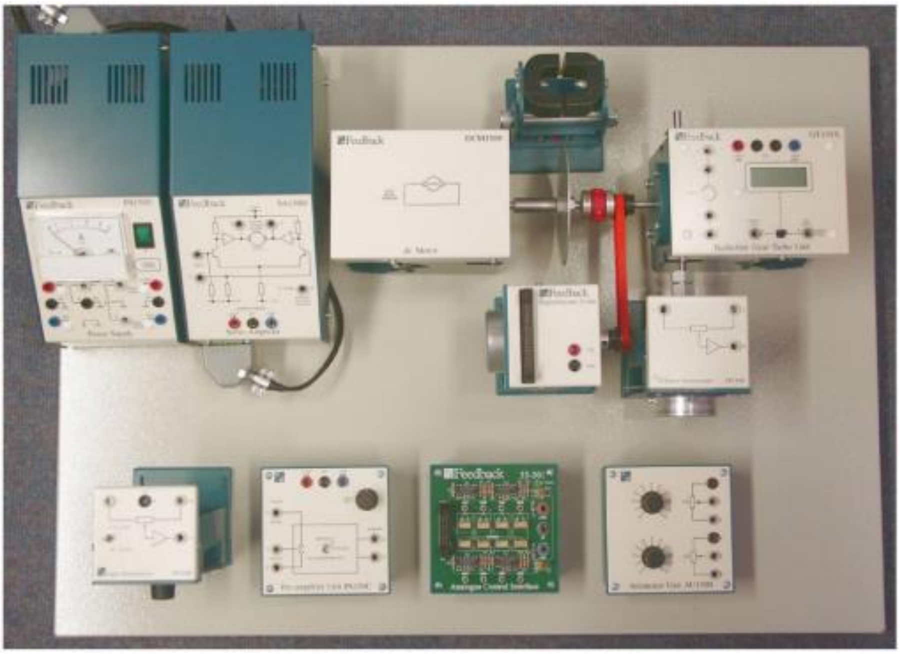


Figure 8. 1 Servo Modular System

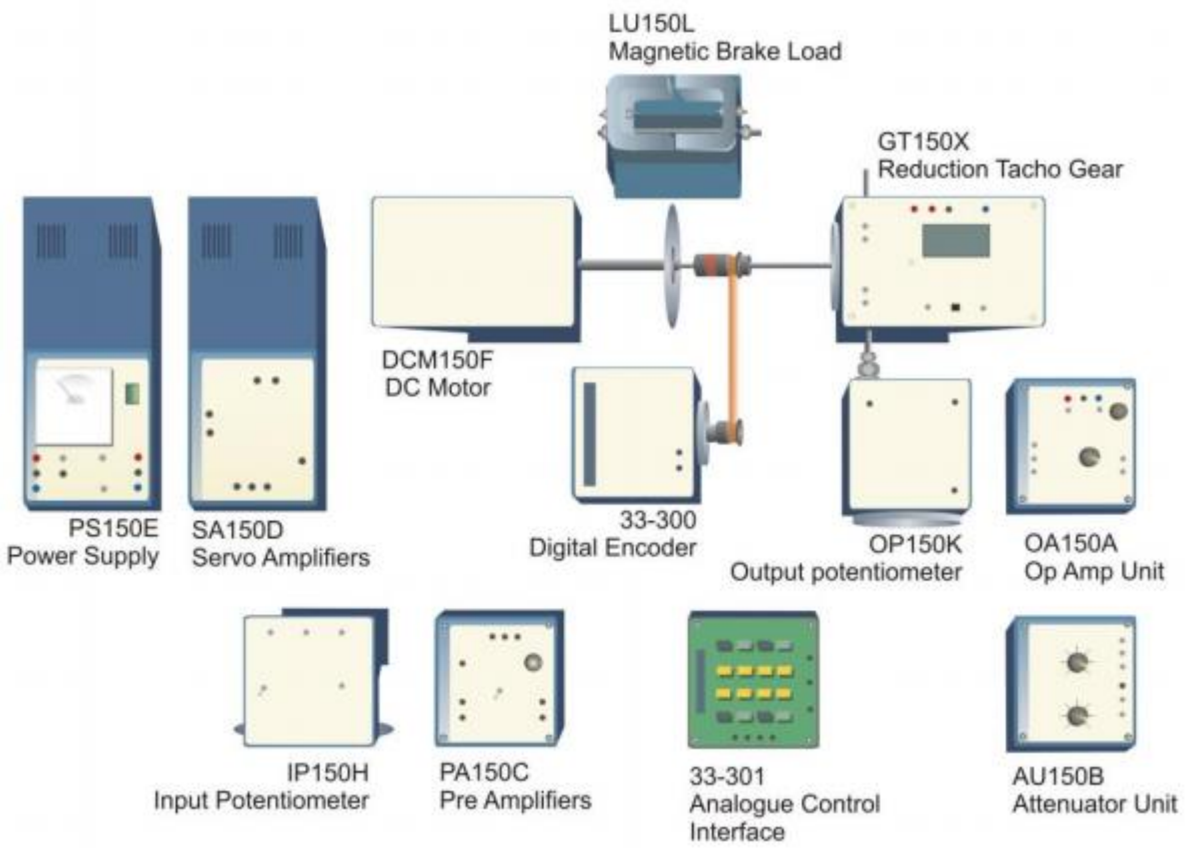


Figure 8. 2: Servo Modular System with Interface

Theoretical Background:

DC motors are used extensively in many control applications. Therefore, it is necessary to establish mathematical models for DC motors. The transfer function of a DC motor can be approximated by a first order model with unknown constants in their speed controlled form. These constants can be identified experimentally.

DC motors in its position controlled form are used in applications - such as robot arm, machine tools, and valves- the position of motor is the output of interest rather than the speed.

1. Motor (DCM150F):

A dc permenat magnet motor which has an extended shaft, and onto which can be fixed the magnetic brake or inertia disk. The motor may aso be attached to the Reduction Gear Tacho Unit GT150X using a hexagonal coupling. Figure 8.3 shows the top view of the motor DCM150F.

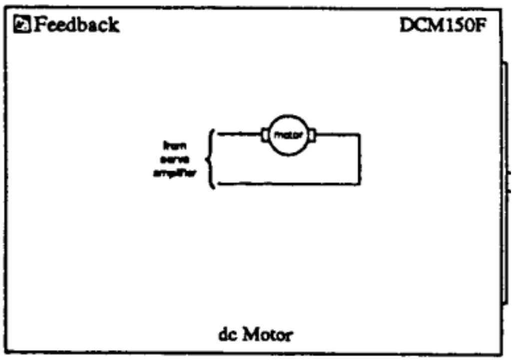


Figure 8. 3 DCM150F Topview

The DC motor produces torque. The mechanical-electrical model of the servo motor is presented in Figure 8.4. The motor used for the experiments is a 24V DC brushed motor with a no-load speed of 4050rpm. Table 8.1 gives the values of the motor parameters supplied by the manufacturer.

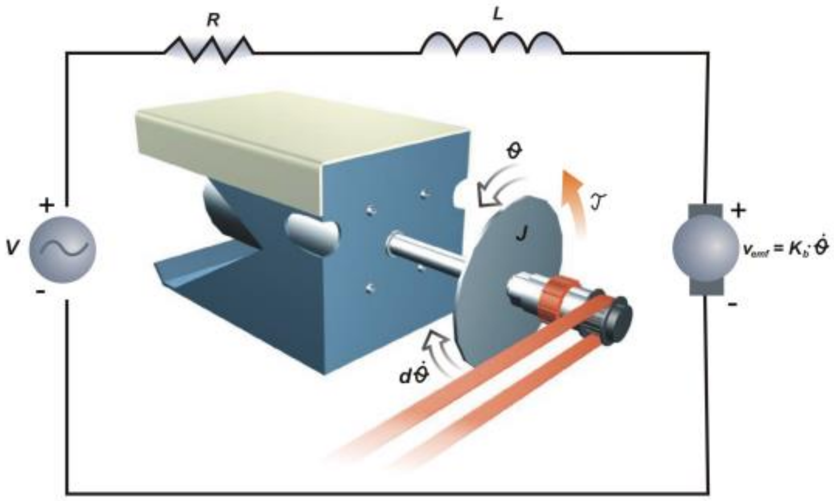
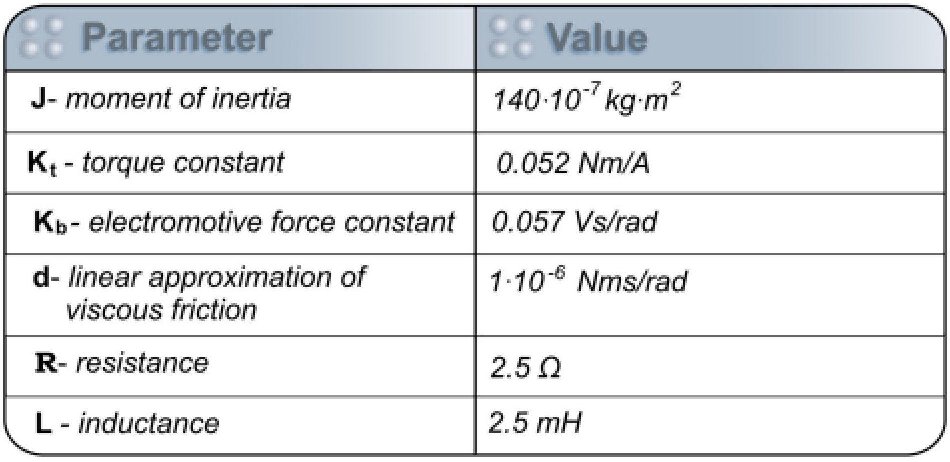


Figure 8. 4 Phenomenological Model

Table 8.1: DC motor Parameters



Parameter	Value
J- *moment of inertia*	$140 \cdot 10^{-7}\ kg \cdot m^2$
K$_t$ - *torque constant*	0.052 Nm/A
K$_b$- *electromotive force constant*	0.057 Vs/rad
d- *linear approximation of viscous friction*	$1 \cdot 10^{-6}$ Nms/rad
R- *resistance*	2.5 Ω
L - *inductance*	2.5 mH

Due to brush friction, a certain minimum input signal is needed to start the motor running.

The transfer function of an *armature speed controlled* dc motor (ignoring the armature inductance) is:

$$\frac{\omega(s)}{E(s)} = \frac{k_m}{\tau_m s + 1} \tag{1}$$

Where:

$\omega(s)$	output speed Laplace transform
$E(s)$	input voltage Laplace transform
k_m	motor torque constant ([rad/sec] / volts)
τ_m	motor time constant (sec)

If the input voltage is a step input of amplitude A, then the output speed time-domain response (with zero initial condition) is:

$$\omega(t) = Ak_m(1 - e^{-t/\tau_m}) \tag{2}$$

2. Servo Amplifier (SA150D):

The top view of the unit is shown in Figure 8.5. As it is clear in the figure, the servo amplifier has two inputs 1 and 2. A high signal to either input activates a transtor causing the motr to rotate in a certain direction. A high signal to the other input activates the scond transistor cuasing the moor to rotate in the oppisite direction. Reversing the direction of current flowing through the motor, reverses the direction of rotation of the motor. Figure 8.6 illustrates the operation of direction reversal. Having low signals at both 1 and 2 terminals will cause the motor not to run. Having high signals at both 1 and 2 terminals causes fast braking of the motor.

The unit provides a current gain via the transistors in order for the current to be enough to drive the motor.

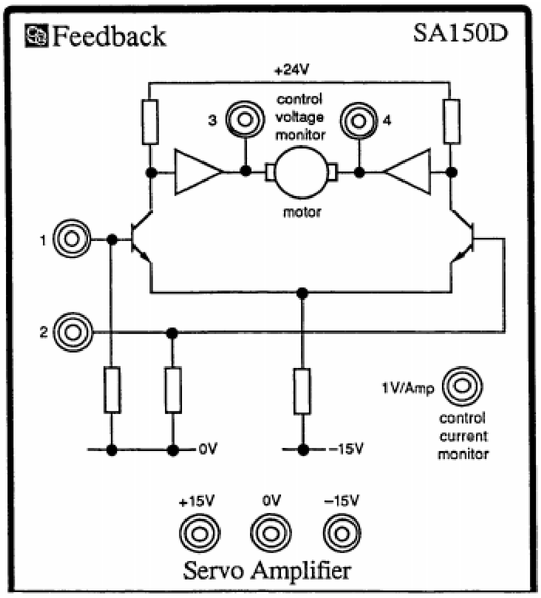


Figure 8. 5: SA150D Topview

3. Power Supply (PS150E):

This unit supplies a 24V d.c 2A unreguated supply to the motor, through a multiway connector to the servo amplifer.

On the front panel, there are two sets of ±15 and 0V, stabillized dc supplies to operate the smaller units and amplifers and provides reference vltages.

An ammeter is also included in the power supply unit in order to monitor the current drawn by the motor.

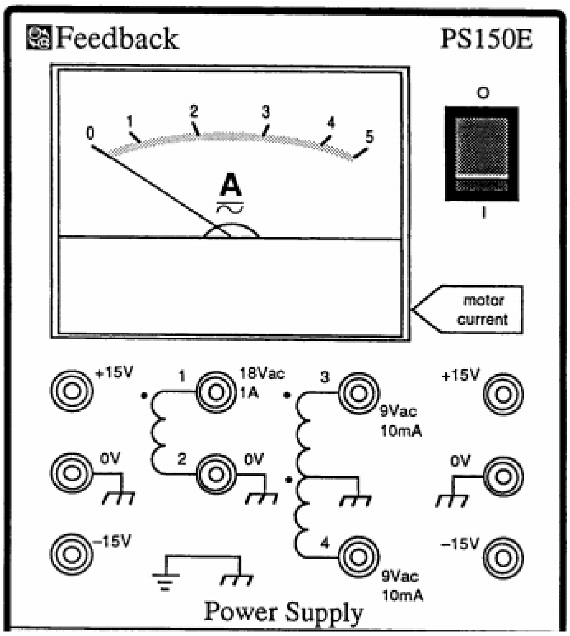


Figure 8. 6: PS150E Topview

4. Attenuator unit (UAU150B):

This unit consists of two separate 10 KΩ potentiometers. Each potentiometer can provide a gain between (0-1) depending on the position of its knob. The unit can either provide a reference voltage when connected to a dc source or be used as a gain controller when connected to the output of an amplifier.

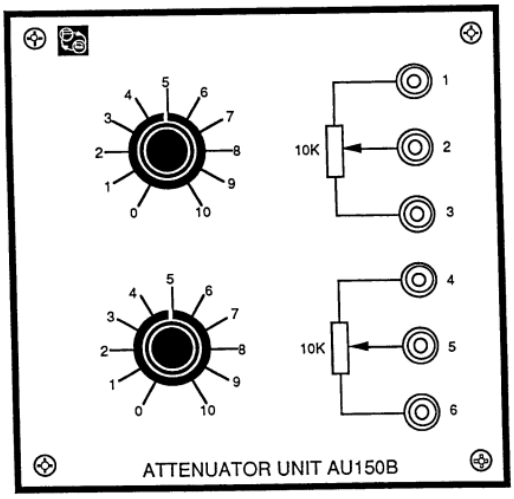


Figure 8. 7: AU150B Topview

5. Op Amp Unit (OA150A):

This unit is an inverting amplifier. A selector switch allows the use of the unit as a summer (a), PI controller (b) or with any external circuit (external feedback between 4 and 5 terminals) in the feedback path. The unit is used to calculate error by finding the difference between the set point and feedback signal and ca also be used as a controller,

Depending on the position of its knob this unit can be modeled as

1. Summation point of unity gain $k_{op}=1$
2. Summation point with transfer function:

$$T_{op}(s) = \frac{1}{1+s}$$

3. Summation point with transfer function depending on an external circuit.

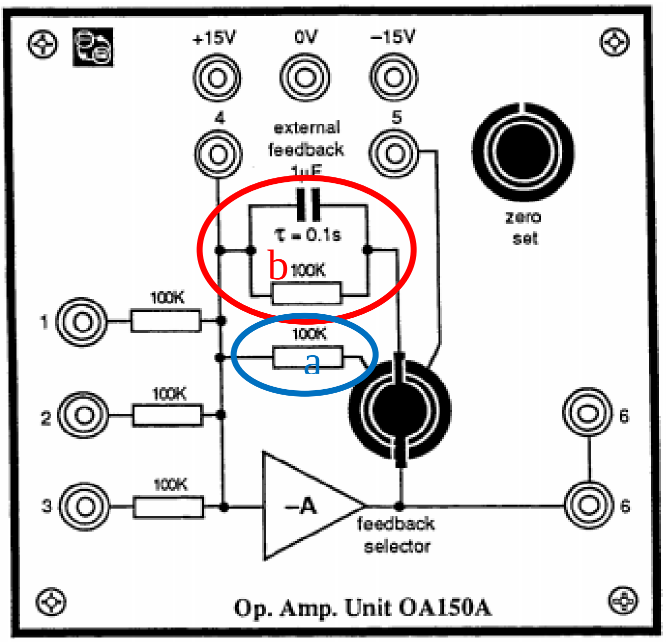


Figure 8. 8: Operational Amplifier OA150A Topview

6. Pre –amplifier unit (PA150C):

This unit provides thecorrect signals to derive the servo amplifer. A positive signal applied to either input causes output (3) to go positive (High) while the other output (4) to stay near zero. On the other hand, a negative signal applied to either input causes output (4) to go positive (High) while the other output (3) to stay near zero. Thus bidirectional motor drive is obtained when these outputs are linked to the SA150D servo amplifer uit inputs.

Using the error signal as an input to the pre-amplifier, with its magnitude used to determine the amount of motor drive and its polarity as to the direction of rotation.

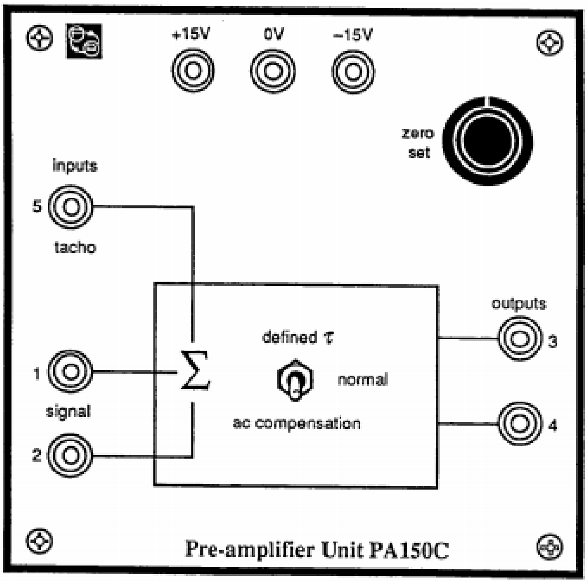


Figure 8. 9: PA150C topview

7. Reduction gear Tacho unit (GT50X):

Tachometers are used in control systems in many ways; they can be used as a speed indicator to provide shaft-speed readout or to provide speed feedback signal in the case of speed control systems.

This unit containes:

A reduction gearbox with a ration of 30/1 from the high speed input shaft to the low speed output shaft. The gear also transmitts the motion 90°.

A d.c tachogenerator driven by the high speed shaft with an output on the top panel which can be used to display the tacho speed directly in r/min or to monitor a d.c voltage on another unit.

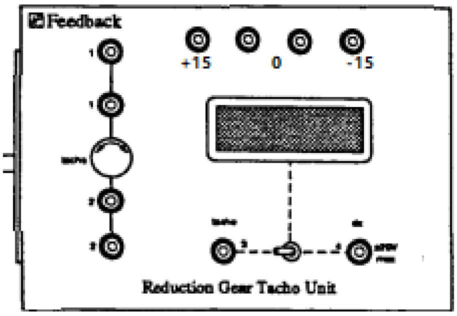


Figure 8. 10: GT150X topview

8. Input and Ouput Potentiometers (IP150H and OP150K):

These are rotary potentiometers. The input potentiometer has ±150° of motion while the ouput potentiometer has no mechanical stops and can't be damaged by continuous rotation.

The input potentiometer is used to set up a reference volatge while the ouput potentiometer is connected to the GT150X low-speed output shaft by using push on coupling as shown by Figure 8.11.

Each unit has a buffer amplifier with a unity gain so that even if the ouput is shorted to the power supply or ground, the potentiometer will not be damaged by overloading. The buffer also ensure that the potentiometer wiper does not have to carry any current load during normal use.

The terminals 1 and 2 of the potentiometers, see Figure 8.12, are connected to +15 and -15. The bufferamps are correctly powered whichever way the terminals 1 and 2 are connected. The important thing is to reverse the polaritys of 1 and 2 on the input and output potentiometers to ensure a negtive feedback when needed. i.e if the terminal 1 at the input potentiometer is connected to +15V, the terminal 1 on the ouput potentiometermust be connected to -15V. Same applies for the terminal 2.

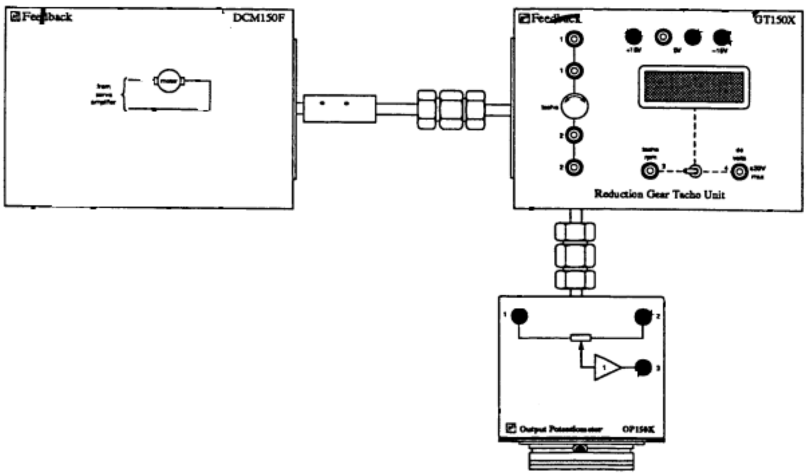


Figure 8. 11: Coupling between GT150X Output Shaft and Output Potentiometer Shaft

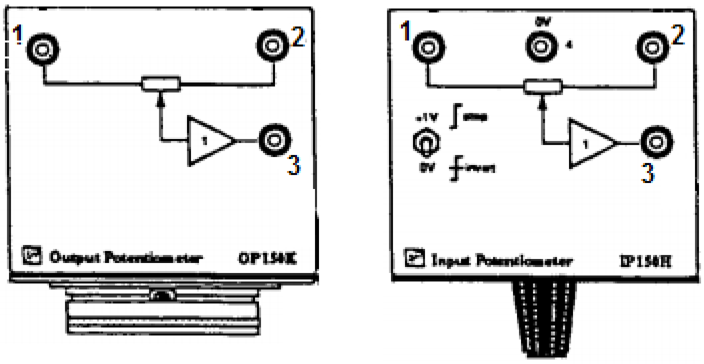


Figure 8. 12: IP150H and OP150K Topviews

9. Loading Unit (magnetic brake) :

This unit represents the load in the system. An eddy current brake consists of a conductive piece of metal, either a straight bar or a disc, which moves through the magnetic field of a magnet, either a permanent magnet or an electromagnet (where the current flowing through the coil creates a magnetic field). When it moves past the stationary magnet, the magnet exerts a drag force on the metal which opposes its motion, due to circular electric currents called **eddy currents** induced in the metal by the magnetic field. It should be noted that the conductive sheet is not made of ferromagnetic metal such as iron or steel; usually copper or aluminum are used, which are not attracted to a magnet. The brake does not work by the simple attraction of a ferromagnetic metal to the magnet. Figure 8.12, illustrates the principle of the electromagnetic barking.

In the lab, an aluminum disc can be mounted on the extended motor shaft and when rotated between the poles of the magnet of the loading unit, the eddy currents generated have the effect of a brake.the strength of the magnetic brake can be controlled by the position of the magnet.

A heavey disc of the same dameter can also be mounted on the shaft instead of aluminim disc to increase the inertia of the motor, Figure 8.14.

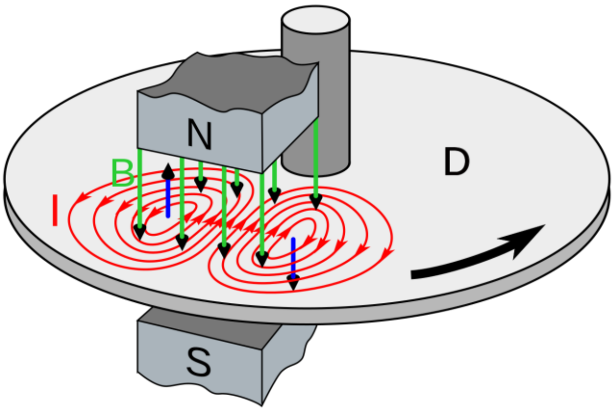


Figure 8. 13: Electromagnetic Brake Operation

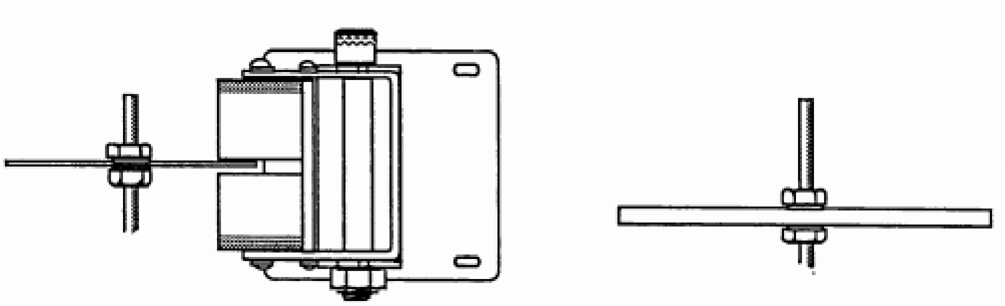


Figure 8. 14: (a) Loading Unit Magnetic Brake Disc   (b) Inertia Disc

10.Digital Encoder

An incremental encoder can be connected to the motor shaft via a belt, shown in Figure 8.15. The encoder is used to measure the position of the shaft as a digital pulses.

Because the encoder measures relative position, every time the simulation is started the modular servo output and input potentiometers should be placed in the zero position to ensure agreement.

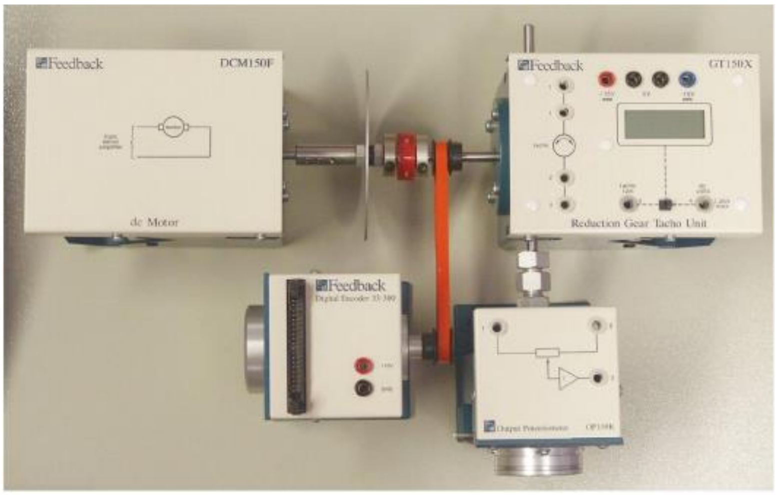


Figure 8. 15: Digital Encoder Connection to The Motor Shaft

Procedure:

1. While the power supply is off, connect the components to create a speed or a position controlled motor.
2. Operate the power supply and test your system.

Discussion and Analysis:

1. For a permanent magnet dc motor, and assuming the armature inductance L_a=0, derive equation (1) where E(s) is the armature input voltage, ω(s) is the motor speed.
2. Use the Laplace inverse to derive equation (2).

Experiment 9

First and Second Order Systems

Objectives:

- To implement open and closed loop speed control systems.
- To implement open and closed loop position control systems.
- To improve the response of a closed loop speed control system.
- To improve the response of a closed loop position control system.
- To analyze the response of speed and position control systems.

Apparatus:

1. Operational Amplifier Unit: OA150A
2. Attenuator Unit: AU150B
3. Pre–Amplifier Unit: PA150C
4. Servo Amplifier Unit: SA150D
5. Power Supply: PS15E
6. Motor: DCM150F
7. Input Angular Potentiometer: IP150H
8. Output Angular Potentiometer: OP150K
9. Redction Gear Tacho Unit: GT150X
10. Loading Unit: LU150L
11. Function generator and Oscilloscope (are signals provided and displayed via a DAQ and matlab software)

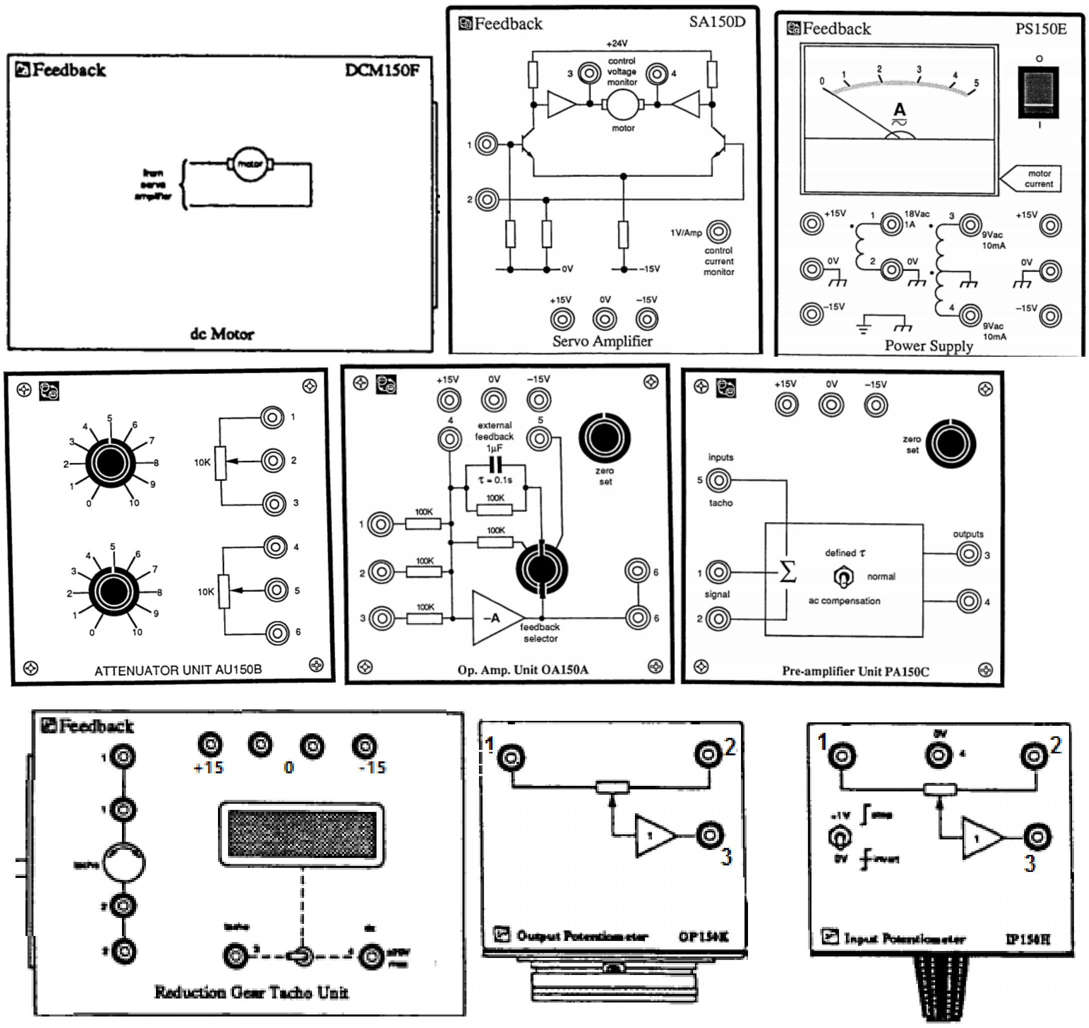


Figure 9.1: Servo Motor System Components

Theoretical Background:

Control systems are inherently dynamic, because of that, their performances are usually described in terms of transient and the steady-state response. The **Transient** response is the response that disappears with time. The **Steady-state** response is the response that exists for a long time after the initiation of an input signal.

1. Dynamic response of first order control systems.

Many systems can be modeled as a first order system by the following general form differential equation:

$$\frac{1}{b}\dot{y}+\frac{a}{b}y=r(t) \tag{9.1}$$

Taking its Laplace transformation, the following transfer function is obtained:

$$\frac{Y(s)}{R(s)} = \frac{b}{s+a} \tag{9.2}$$

The time domain response of system to a **unit step** input is given by Figure 9.1 and equation 9.3.

$$y(t) = \frac{b}{a}(1 - e^{-at}) \tag{9.3}$$

The characteristics of the system can be defined with help of Figure 9.1 by the following parameters:

1. System gain (K): the system gain (K) can be defined as the dc value (steady state value of the output y(t). for a **unit step** input, it can be given by:

$$K = \lim_{s\to 0} sY(s) = \lim_{s\to 0} s(\frac{1}{s}\frac{b}{s+a}) = \lim_{t\to\infty} y(t) = \frac{b}{a} \tag{9.4}$$

or from Figure 9.1,

$$K = \frac{y_{steady-state}}{r_{steady-state}}$$

2. Time constant (τ): the time constant (1/a) is defined as time value when the system reaches 63% of its steady-state value. And can be found by the two methods illustrated by Figure 9.2.

$$\tau = \frac{1}{a} \tag{9.5}$$

3. Rise time (Tr): the rise time (Tr) is defined as the time taken by the system to change from 10% till 90% of its steady-state value.

$$T_r = \frac{2.2}{a} \tag{9.6}$$

4. Settling time (Ts): the rise time (Ts) is defined as the time taken by the system to reach 98% of its steady-state value.

$$T_s = \frac{4}{a} \tag{9.7}$$

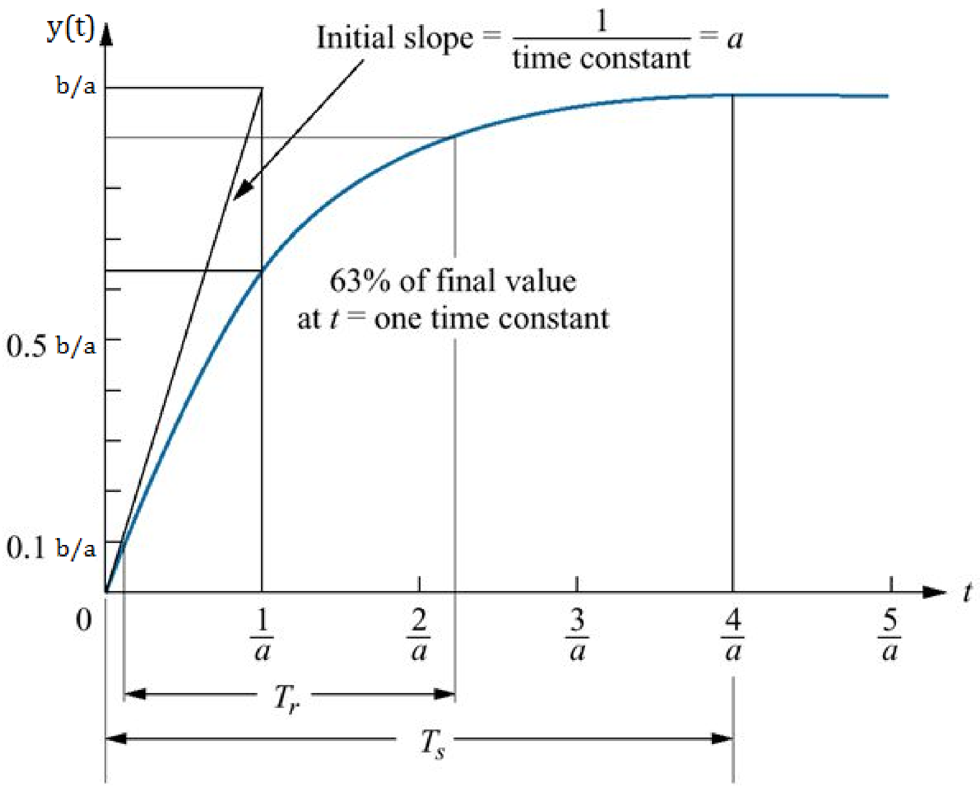


Figure 9.2: Unit Step Response of a First Order System to a Unit Step Input.

2. Dynamic response of Second order control systems.

In a control system the parameters of the system can be adjusted to obtain desired response specifications such as rise time, settling time, peak time, maximum overshoot, and the steady-state error.

The standard form of the transfer function of a closed-loop second order system is given by the following equation

$$T(s) = K\frac{\omega_n^2}{s^2+2\omega_n\zeta s+\omega_n^2} \tag{9.8}$$

Where:

ω_n is the natural frequency

ζ is the damping ratio

K is the Dc-gain

If the input of the system is a **unit step**, then,

$$Y(s) = K\frac{\omega_n^2}{s(s^2+2\omega_n\zeta s+\omega_n^2)} \tag{9.9}$$

The characteristic equation of this system is obtained from equation 9.8 as:

$$s^2 + 2\omega_n\zeta s + \omega_n^2 = 0 \tag{9.10}$$

then;

$$s_{1,2} = -\zeta\omega_n \pm \omega_n\sqrt{\zeta^2 - 1} \tag{9.11}$$

From equation 9.11, the two poles of the system might be

1. Pure complex conjugate: **ζ**=0 (undamped system)
2. Complex conjugate: 0<**ζ**<1 (underdamped system)
3. Real equal: **ζ**=1 (critically damped)
4. Real distinct: **ζ**>1 (overdamped)

Figure 9.3 shows the step response for different values of ζ.

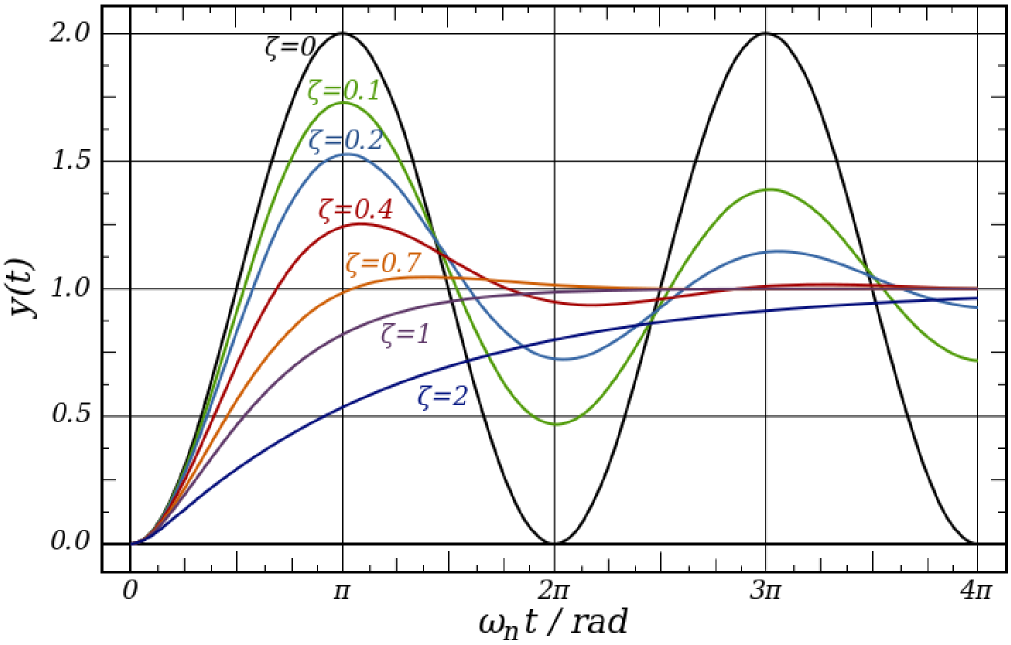


Figure 9.3: Second Order System Responses

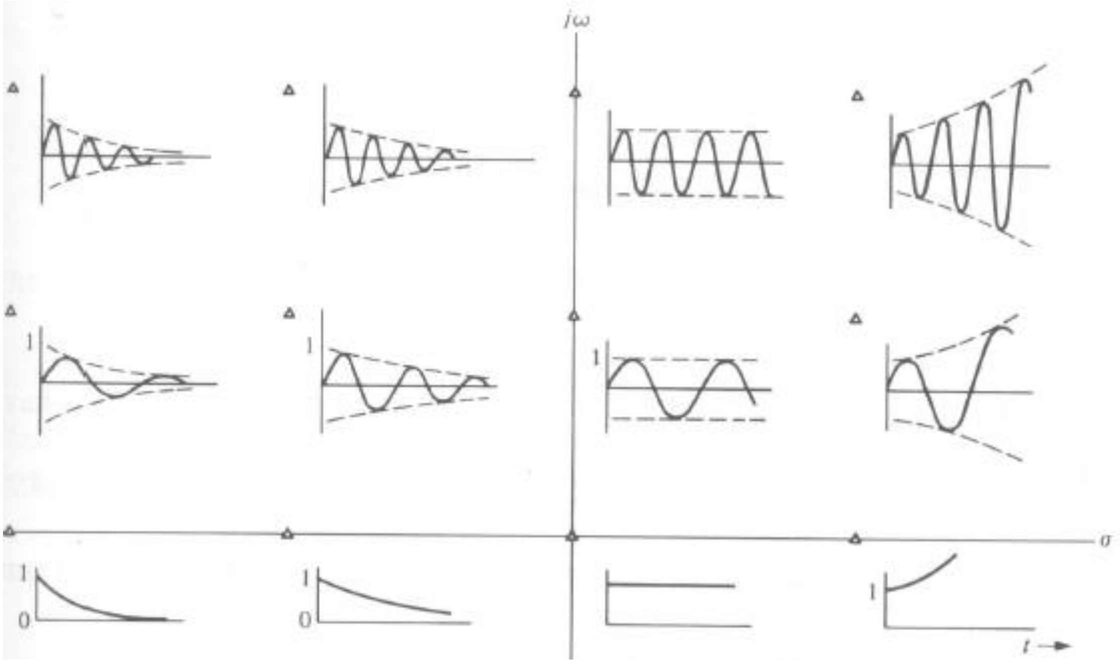


Figure 9.4: Second Order System Responses in Different Areas of the s-plane

Note that the less the damping ratio, the more the system oscillation.

For an under damped system $0 < \xi < 1$

$$s_{1,2} = \underbrace{-\zeta\omega_n}_{\text{Real part}} \pm \underbrace{j\omega_n\sqrt{1-\zeta^2}}_{\text{Imaginary part}} \tag{9.12}$$

Taking the Laplace inverse of equation 9.9 in case ($0 < \xi < 1$)

$$y(t) = 1 - \frac{1}{\sqrt{1-\xi^2}} e^{-\xi w_n t} \sin\left(w_n\sqrt{1-\xi^2} * t + \cos^{-1}\xi\right) \tag{9.13}$$

Figure 9.5 shows the under damped response of the system to a unit step input and some of the performance specifications. These system specification are given by the following equations

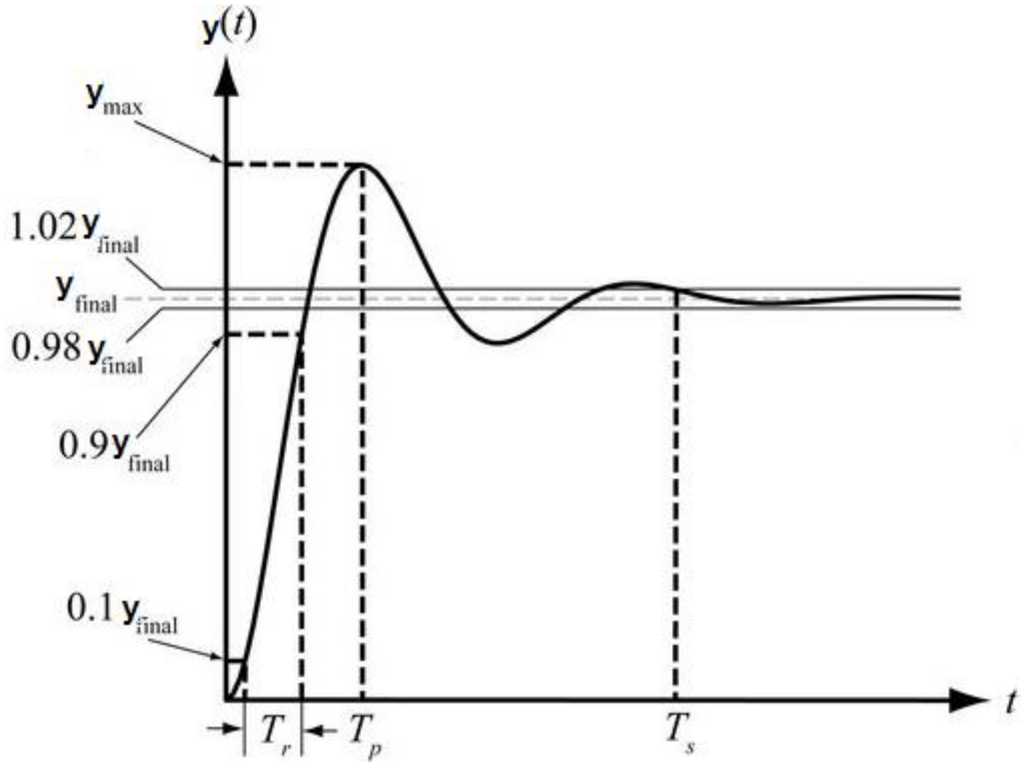


Figure 9.5: Underdamped Second Order System Response

Percent overshoot

$$\text{PO \%} = 100\, e^{-\xi\pi / \sqrt{1-\xi^2}} \tag{9.14}$$

Maximum value (peak value y_{max})

$$M_p = \left(1 + \exp\left(-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}\right)\right) * y_{ss} \tag{9.15}$$

Peak time

$$T_p = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} \tag{9.16}$$

Settling time (2% error; i.e. the time needed for the output to reach 98% or 102% of its steady state value)

$$T_s = \frac{4}{\xi w_n} \tag{9.17}$$

Rise time (time needed for the output to change from 10% to 90% from its steady state value)

$$T_{r1} = \frac{2.16\xi + 0.64}{w_n} \qquad (9.18)$$

$$K = \lim_{s\to 0} sY(s) = \lim_{t\to\infty} y(t) \qquad (9.19)$$

The number of oscillations necessary to reach the setting time can be given by:

$$N = \frac{4\sqrt{1-\zeta^2}}{2\pi\zeta} \qquad (9.20)$$

Note that all system dynamic characteristics are functions of the system natural frequency and damping ratio which are both functions of the physical system parameter such as R, L and C for electrical systems or M, K and B for mechanical systems.

The servomotor system you studied at the previous lab behaves as a first order system when controlled in its speed form and as a second order system when controlled in its position control form.

When the motor is speed controlled, it can be controlled at both open loop and closed loop configurations. When the motor is position controlled, it can be controlled only at closed loop configurations while it will be unstable at its open loop configuration.

Procedure:

The experiment consists of two parts: speed and position control systems.

Part 1: Speed Control System

1. Connect the servomotor in its speed control form. Connect all the needed power.
2. Connect the feedback signal (output of the Tacho. Amplifier unit) to the oscilloscope and monitor the response.

Part 2: Position Control System

1. Zero set the Pre-Amp, (i.e. the input voltage to op-amp must be zero and measure the output Vout, turn the knob until Vout = 0).
2. Connect the servomotor in its position control form. Connect all the needed power.
3. Connect the output of the output-potentiometer to the oscilloscope and monitor the response.
4. Change the gain of the attenuator unit and observe the change in the system response.

Discussion and Analysis:

1. Derive the transfer function of the closed loop speed control system.
2. Based on your answer in 1, what is the effect of increasing the controller gain on both the dc gain and the time constant of the closed loop system?
3. What is the effect of increasing the controller gain on both the dc gain and the time constant of the motor?
4. Derive the transfer function of the closed loop position control system.
5. Based on your answer in 4, what is the effect of increasing the controller gain on the closed loop system:
   a. Dc gain.
   b. Damping ratio.
   c. Natural frequency.

Experiment 10

Characteristics of Open-Loop and Closed Loop Systems

Objectives:

- To investigate the characteristics of an open-loop system. Sensitivity, accuracy, disturbance rejection are considered in this experiment.
- To evaluate the performance of a closed-loop system in comparing with that of the open-loop system. The performance characteristics to be considered include:
  - Disturbance rejection
  - Sensitivity
  - Accuracy
  - Closed-loop system disturbance rejection improvement
  - The extent to which loop gain affects these performance characteristics

Apparatus:

1. Operational Amplifier Unit: OA150A
2. Attenuator Unit: AU150B
3. Pre–Amplifier Unit: PA150C
4. Servo Amplifier Unit: SA150D
5. Power Supply: PS15E
6. Motor: DCM150F
7. Input Angular Potentiometer: IP150H
8. Output Angular Potentiometer: OP150K
9. Redction Gear Tacho Unit: GT150X
10. Loading Unit: LU150L
11. Function generator and Oscilloscope (are signals provided and displayed via a DAQ and matlab software)

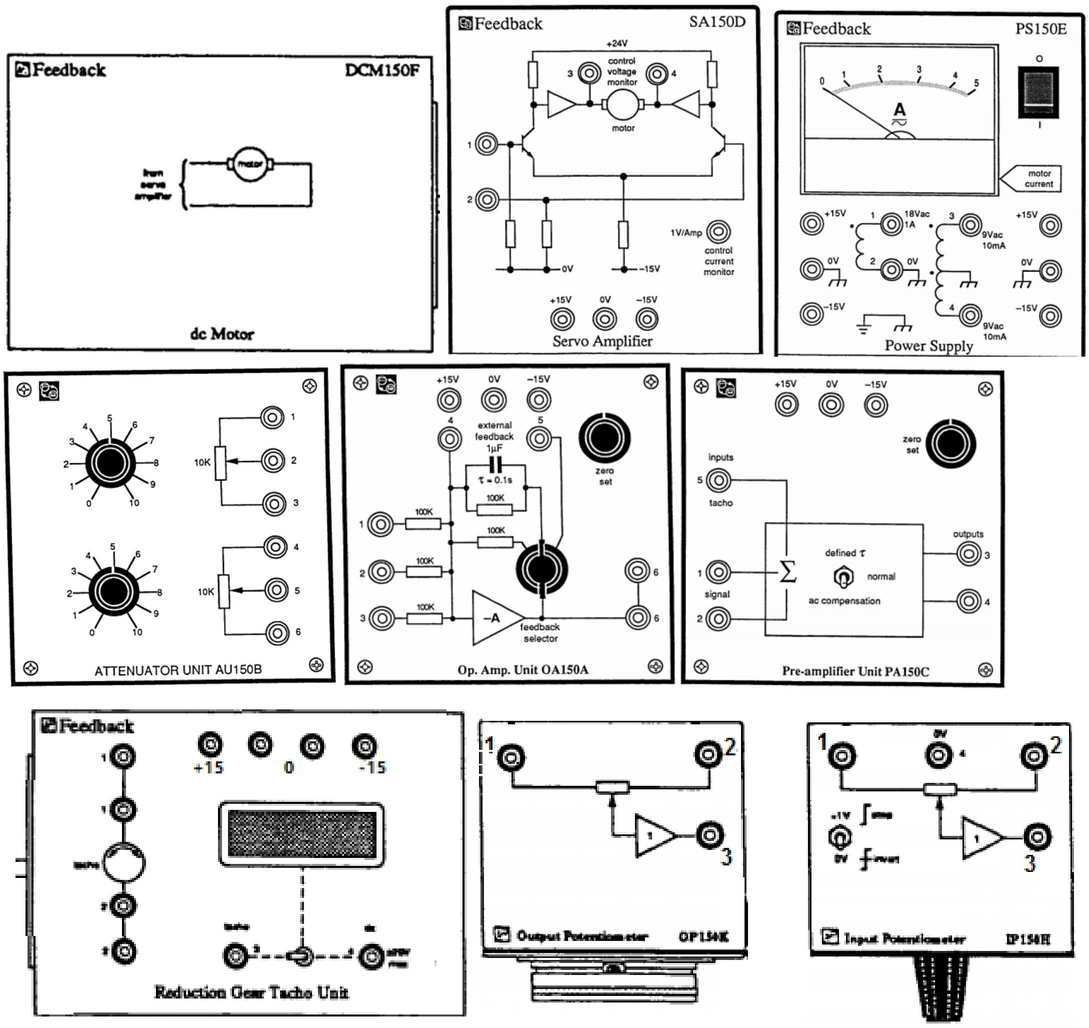


Figure 10.1: Servo Motor System Components

Theoretical Background:

Control systems are inherently dynamic, because of that, their performances are usually described in terms of transient response and the steady-state response. The **Transient** response is the response that disappears with time. The **Steady-state** response is the response that exists for a long time after the initiation of an input. A control system is an interconnection of components forming a system configuration that will provide a desired system response. The basis for analysis of a system is the foundation provided by linear system theory, which assumes a cause effect relationship for the components of a system. Therefore a component or process to be controlled can be represented by a block as shown in Figure 10.2. The input-output relationship represents the cause-and-effect relationship of the process, which in turn represents a processing of the input signal to provide an output signal variable, often with power amplification.

Figure 10.2: Process

An open loop system uses a controller and an actuator to obtain the desired response, and it is a system without feedback as in Figure 10.3.

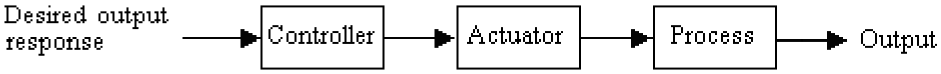


Figure 10.3: Open-loop Control System

In contrast, a closed-loop system utilizes an additional measure of the actual output to compare it with the desired output response. The measure of the output is called feedback signal. A feedback control system is a control system that tends to maintain a prescribed relationship of one system variable to another by comparing functions of these variables and using the difference as a means of control. See Figure 10.4.

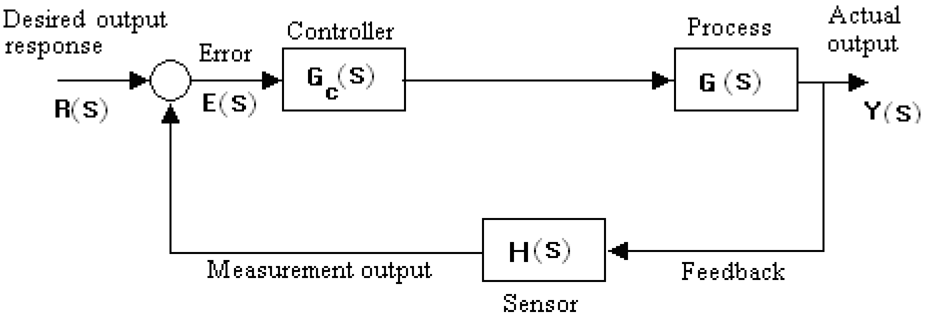


Figure 10.4: Closed-loop Feedback Control System

Control systems performance is judged by several characteristics such as Accuracy, sensitivity and disturbance rejection.

1. Accuracy

The accuracy of a system can be studied by observing the error in the system. From the system block diagram in Figure 10.4, the error is

$$E(s) = R(s) - Y(s)H(s) \tag{10.1}$$

Assuming unity feedback

$$E(s) = R(s) - Y(s) \tag{10.2}$$

Then

$$\mathrm{E(s)} = \frac{1}{1+G_C(s)G(s)}\mathrm{R(s)} \tag{10.3}$$

The smaller the error, the higher the accuracy of the system is. The steady-state error of the system is:

$$e_{ss} = \lim_{t\to\infty} e(t) = \lim_{s\to 0} sE(s) \tag{10.4}$$

2. Sensitivity

Another important characteristic of control systems is system sensitivity. System sensitivity is the ratio of the changes in the system transfer function to a small incremental change of the process transfer function (or parameter).

System transfer function is

$$T(s) = \frac{Y(s)}{R(s)} = \frac{Gc(s)G(s)}{1+Gc(s)G(s)} \tag{10.5}$$

Therefore, the sensitivity is defined as:

$$S_G^T = \frac{\Delta T(s)/T(s)}{\Delta G(s)/G(s)} \tag{10.6}$$

In the limit, for small incremental changes, Equation 10.6 becomes:

$$S_G^T = \frac{\partial T/T}{\partial G/G} = \frac{\partial T}{\partial G}\cdot\frac{G}{T} \tag{10.7}$$

The sensitivity of the open-loop system to changes in the plant G(s) is equal to 1. The sensitivity of the closed loop is readily obtained by using equation 10.7. The sensitivity of the feedback system is:

$$S_G^T = \frac{\partial T}{\partial G}.\frac{G}{T} = \frac{Gc(s)}{(1+Gc(s)G(s))^2}.\frac{G(s)}{G(s)Gc(s)/(1+Gc(s)G(s))} \tag{10.8}$$

Or:

$$S_G^T = \frac{1}{1+Gc(s)G(s)} \tag{10.9}$$

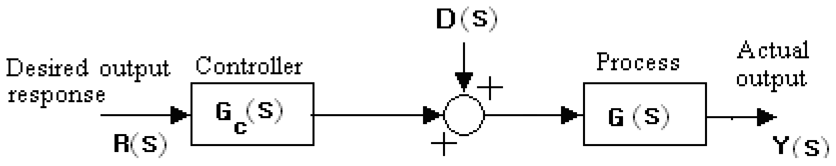
3. Disturbance Rejection

For the open loop in Figure 10.5.a

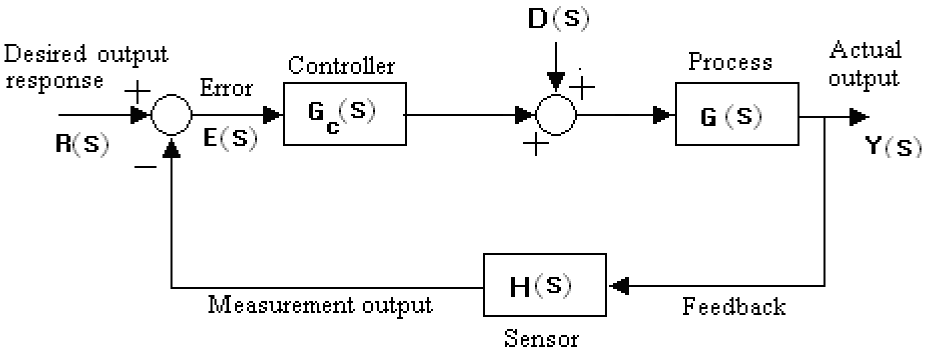
$$\mathrm{Y}(\mathrm{s}) = Gc(s)G(s)R(s) + G(s)D(s) \tag{10.10}$$

$$\mathrm{Y_R}(\mathrm{s}) = Gc(s)G(s)R(s) \tag{10.11}$$

$$\mathrm{Y_D}(\mathrm{s}) = G(s)D(s) \tag{10.12}$$



(a)



(b)

Figure 10.5: (a): Open Loop Control System with Disturbance Signal

(b)Closed-loop Control System with Disturbance Signal

For the closed-loop system in Figure 10.5.b, assuming no input signal (R(s)=0) and unity feedback, then

$$\mathrm{Y_D}(\mathrm{s}) = \frac{\mathrm{G(s)}}{1 + G_C(\mathrm{s})G(\mathrm{s})} D(s) \tag{10.13}$$

Now assuming no input signal (D(s)= 0) then

$$\mathrm{Y_R}(\mathrm{s}) = \frac{Gc(s)G(s)}{1 + Gc(s)G(s)} R(s) \tag{10.14}$$

Then,

$$\mathrm{Y}(\mathrm{s}) = \frac{Gc(s)G(s)}{1 + Gc(s)G(s)} R(s) + \frac{\mathrm{G(s)}}{1 + G_C(\mathrm{s})G(\mathrm{s})} D(s) \tag{10.15}$$

where,

Y_R is the output due to the input signal

Y_D is the output due to the disturbance signal

The ratio $Y_D(s)/Y(s)$ represents the disturbance contribution to the system.

Procedure:

Connect the servomotor system where its input is voltage and its output is speed. Don't forget to connect the necessary power supply.

In case of closed loop system, make sure to choose a suitable feedback gain such that the oscillation resulting from noise would disappear **(even if it doesn't disappear, remember that it is steady state characteristics that is important in this experiment, thus the transient part of the response can be ignored).**

Part 1: Steady state error.

1. Set the reference voltage using the attenuator to avoid saturation.
2. While the system is in its open loop configuration and the magnetic break is removed, observe the speed of the motor and monitor the output voltage on the oscilloscope.
3. Change the gain of the controller (attenuator). Observe the change in motor speed (increased slightly, increased noticeably, decreased slightly or decreased noticeably) and monitor the output voltage on the oscilloscope.
4. For the same above settings, make the system closed loop, observe the speed of the motor and monitor the output voltage on the oscilloscope.
5. Change the gain of the controller. Observe the change in motor speed (increased slightly, increased noticeably, decreased slightly or decreased noticeably) and monitor the output voltage on the oscilloscope.

Part 2: Sensitivity

1. This part is not applicable to the servo motor system because it is hard to change the process (motor) parameters (Ra, La, b and J).

Part 3: Disturbance rejection

1. Set the reference voltage using the attenuator to avoid saturation.
2. While the system is in its open loop configuration, apply the magnetic break as instructed by your lab supervisor. Observe the speed of the motor and monitor the output voltage on the oscilloscope.
3. For the same above settings, change the gain of the controller. Observe the change in motor speed (increased slightly, increased noticeably, decreased slightly or decreased noticeably) and monitor the output voltage on the oscilloscope.

4. For the same above settings, make the system closed loop, observe the speed of the motor and monitor the output voltage on the oscilloscope.
5. For the same above settings, change the gain of the controller. Observe the change in motor speed (increased slightly, increased noticeably, decreased slightly or decreased noticeably) and monitor the output voltage on the oscilloscope.

Discussion and Analysis:

1. What is the effect of increasing the controller gain on the closed loop system:
   a. Accuracy.
   b. Disturbance rejection.

2. Why did we choose the motor to operate in its speed control form not in its position form?

Experiment 12

Root Locus Design

Objectives:

The objective of this lab is to introduce controller design based on the root locus method.

Theoretical Background:

The root locus of a system is the plot of the paths (loci) of all possible closed loop poles as the controller gain changes from 0 to ∞. Closed-loop response depends on the location of closed-loop poles.

The root locus of an (open-loop) transfer function (plant) is a plot of the locations (locus) of all possible closed loop poles with proportional gain k changing from 0 to ∞ and unity feedback. The block diagram of such a system is shown in Figure 12.1. The MATLAB command used to plot the RL of the system is (rltool).

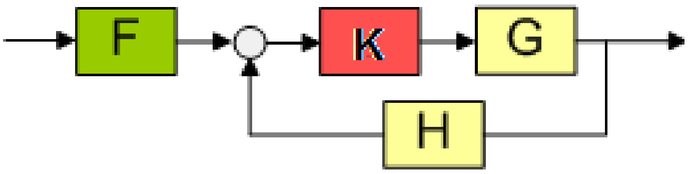


Figure 12.1: Block Diagram

The rltool is a graphical user interface (GUI) tool that allows analyzing and tuning SISO feedback control systems. Using the rltool, it is possible to graphically tune the gains and dynamics of the compensator (controller) (C) and prefilter (F) using a mix of root locus and loop shaping techniques. For example, the root locus view can be used to stabilize the feedback loop and enforce some minimum damping, and use the Bode diagrams to adjust the bandwidth, check the gain and phase margins, or add a notch filter for disturbance rejection.

Procedure:

The root locus design technique via MATLAB software is illustrated using the following example.

1- Define the transfer function of the system to be controlled on MATLAB work space as follows:

```
>> plant = tf(1, [1 -1 -6])
```

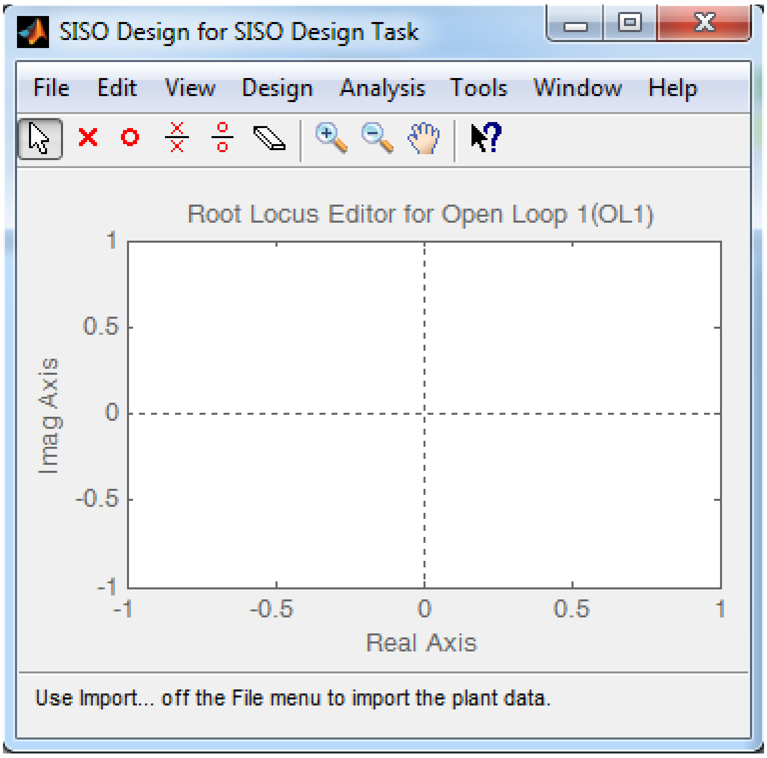
```
plant =

      1
  -----------
  s^2 - s - 6
```

2- Use the command (rltool) to open the rltool windows shown in Figure 12.2 and 12.3.

```
>> rltool
```

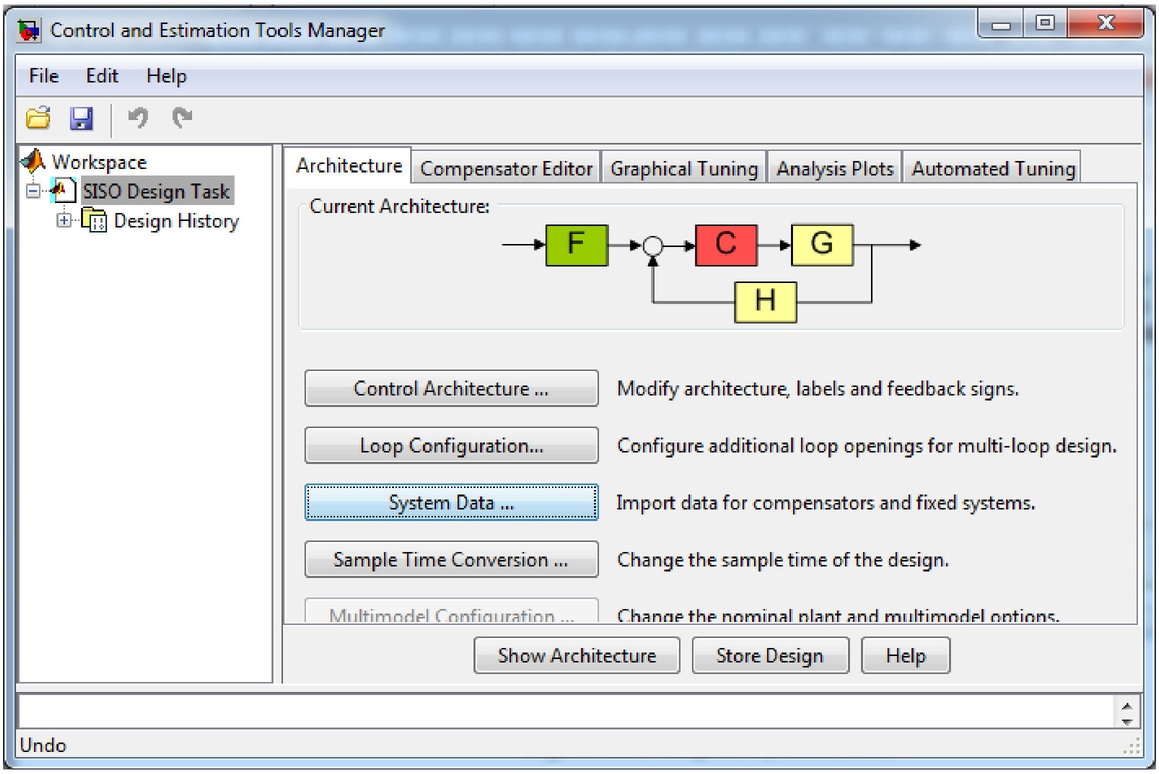
3- Import the transfer function of your system (open-loop function). At the top right corner of the window in Figure 12.2 select "import" from "File" menu or by pressing "System Data" in Figure 12.3 to open Figure 12.4. Now place it in the G block of the block diagram by selecting G then "browse" and select the transfer function **"plant"**. Leave the feedback gain H the, prefilter F and the compensator C as default (=1). When finish, click the OK button. After that the root locus of your system will appear as in Figure 12.5.



Use Import... off the File menu to import the plant data.

Figure 12.2: SISO Design for System Configuration

4- Figure 12.5 shows the root loci of the system. The poles and zeros of the open loop system are represented by crosses and circles respectively. Currently, the controller gain shown in Figure 12.6 is 1 and the pink squares represent the current location of the closed loop system poles. Change the gain of the compensator "**C**" and observe the new location of the poles.



Modify architecture, labels and feedback signs.

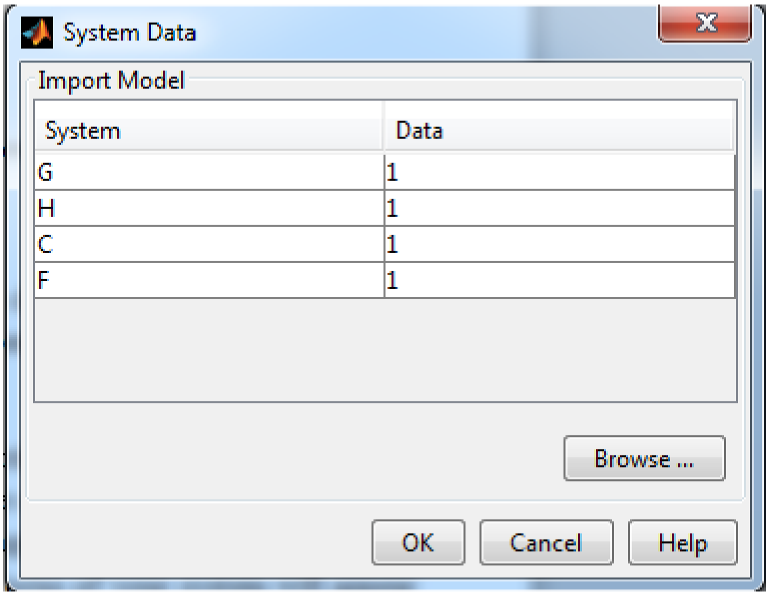
Configure additional loop openings for multi-loop design.

Import data for compensators and fixed systems.

Change the sample time of the design.

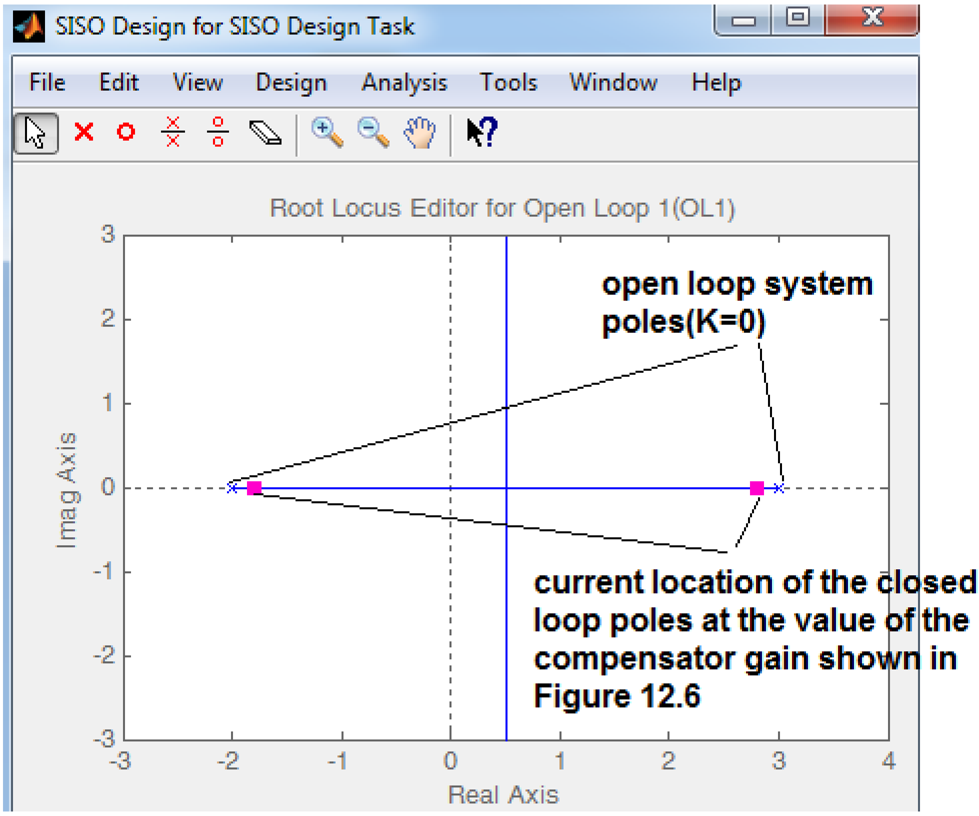
Change the nominal plant and multimodel options.

Figure 12.3: Control and Estimation Tools Manager



System	Data
G	1
H	1
C	1
F	1

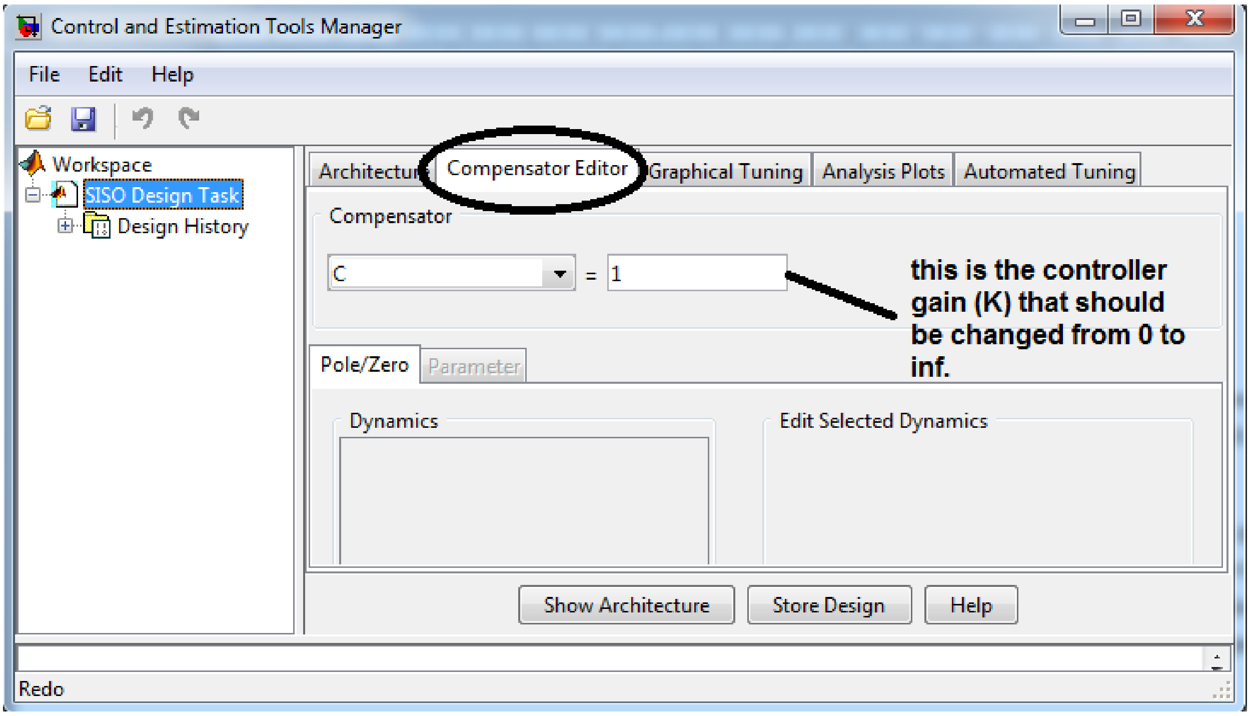
Figure 12.4: Import System Data



open loop system poles(K=0)

current location of the closed loop poles at the value of the compensator gain shown in Figure 12.6

Figure 12.5: The Root Locus of The Transfer Function "plant"



C = 1

this is the controller gain (K) that should be changed from 0 to inf.

Figure 12.6: The Root Locus of The Transfer Function "plant"

5- For the system "plant_2" in Figure 12.7, part of the root loci is located in the left hand side while the other part is located in the right hand side. The system is stable as long as both poles are on the right hand side. For this system, this will happen for K> 8.02. 8.02 is the compensator value where the right hand side pole crosses the Im-axis.

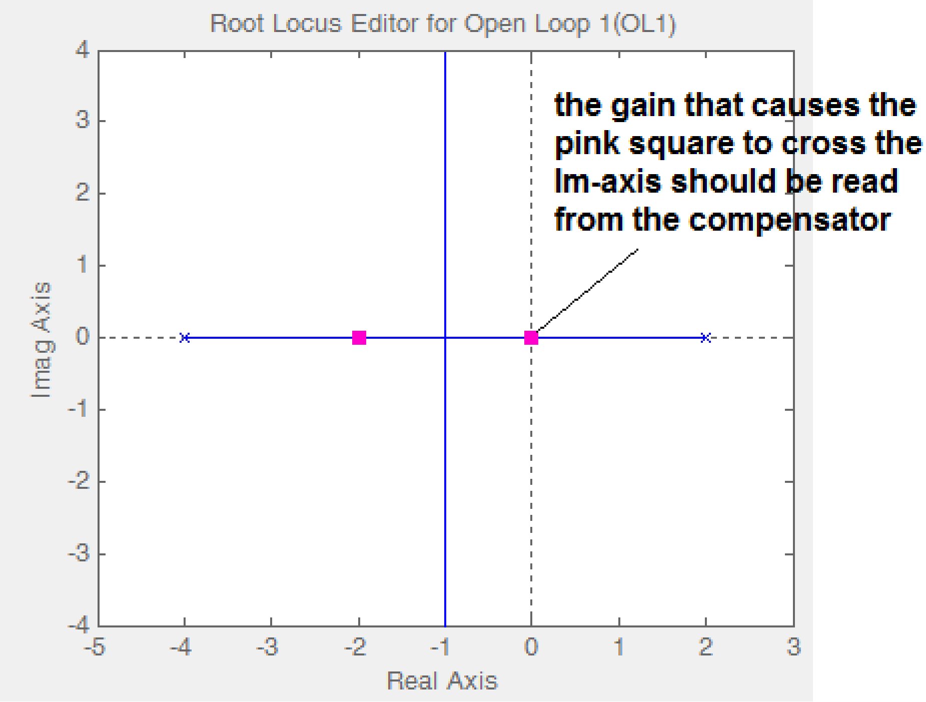


Figure 12.7: The Root Locus of The Transfer Function "plant_2"

6- Constrains such as overshoot, natural frequency, damping ratio and settling time etc…, can be added using the root locus design GUI of MATLAB. This can be done by right clicking the white space in the root locus figure, then "Design Requirements" then "new" as shown by Figure 12.8.

7- A compensator can be designed by adding poles and/or zeros or even importing a controller transfer function from the workspace. The gain of the can be obtained from "compensator" to achieve poles location within the constrains you assigned. The response of the closed-loop system to step input, step disturbance, bode response, open-loop Nyquist, and many other options can be obtained.

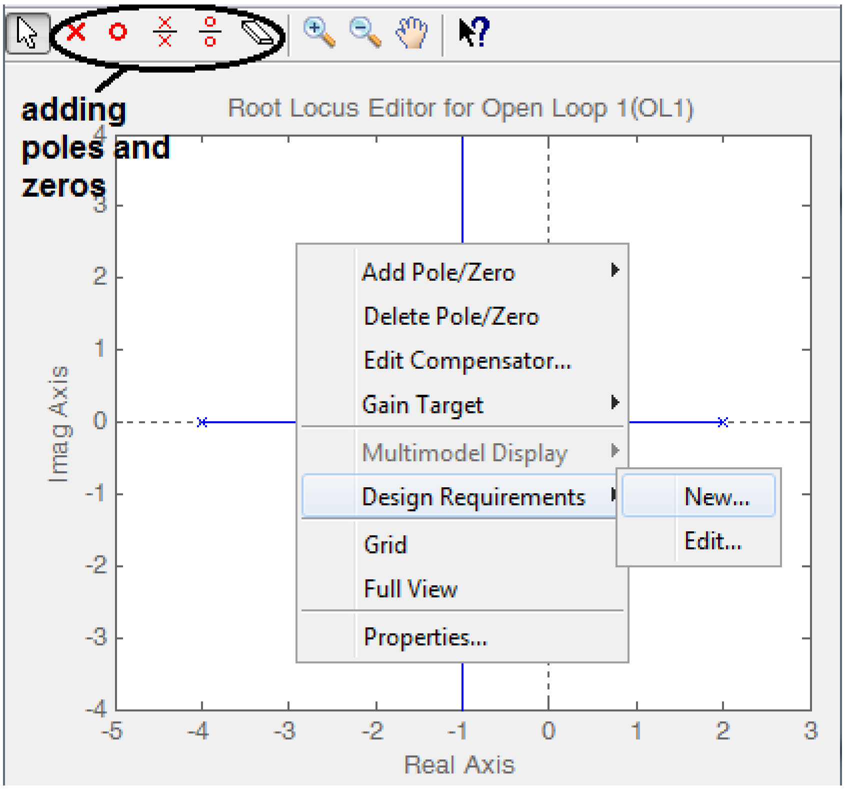


Figure 12.8: Adding Design Requirements

Discussion and Analysis:

For following open loop transfer function, use MATLAB root locus tool to answer the following;

$$T(s) = \frac{s}{s^2 + 2}$$

1. How many poles and zeros does the system have?
2. Use MATLAB to plot the root locus for the system.