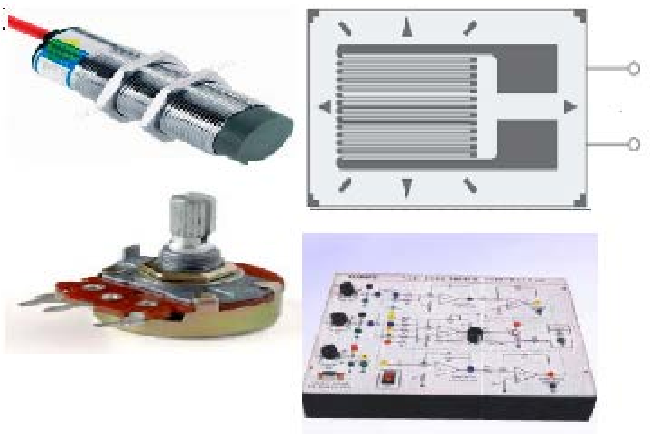
Hashemite University

Mechatronics Engineering Department

Transducer and Control

Laboratory Manual



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.

Apparatus:

- Proximity sensors (inductive, capacitive, magnetic, optical)
- Relay
- LED
- Digital multimeter (DMM)
- Power supply
- Resistances (1 kΩ)

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).

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 oscillator is not affected by moisture and dusty/dirty environments. Regenerates and the sensor returns to its normal state.

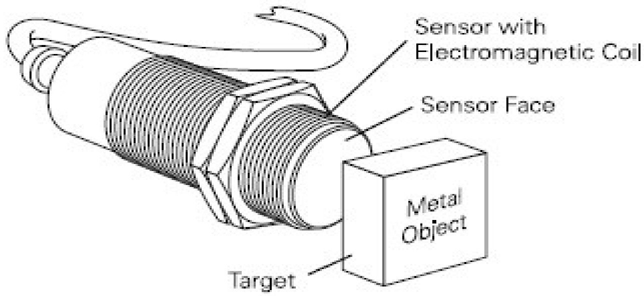


Figure 1.1: Inductive proximity sensor.

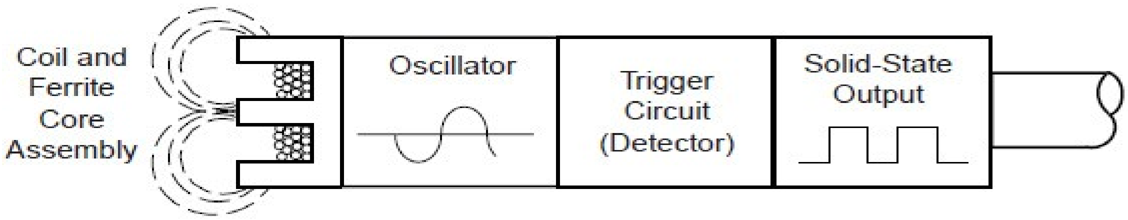


Figure 1.2: Construction of an inductive proximity sensor.

This response is shown in Figure 1.3. 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.

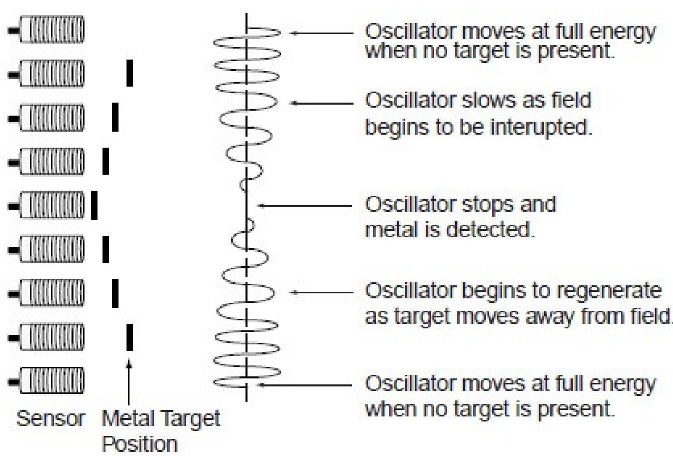


Figure 1.3: Response of an inductive proximity sensor.

An effect that must considered when using inductive 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 1.4.

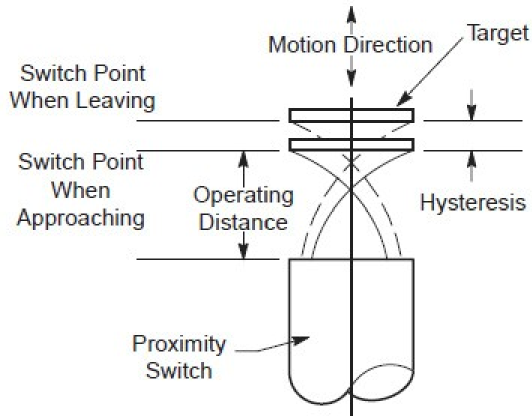


Figure 1.4: Hysteresis effect in an inductive proximity sensor.

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 1.5. 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.

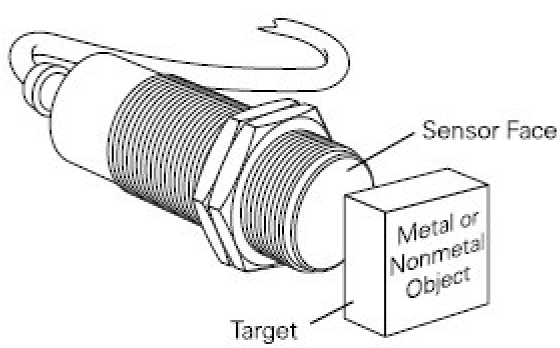


Figure 1.5: Capacitive proximity sensor.

Capacitive proximity sensors consist of four main components: capacitive probe or plate, oscillator, signal level detector, output switching device, Figure 1.6. 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 1.6.

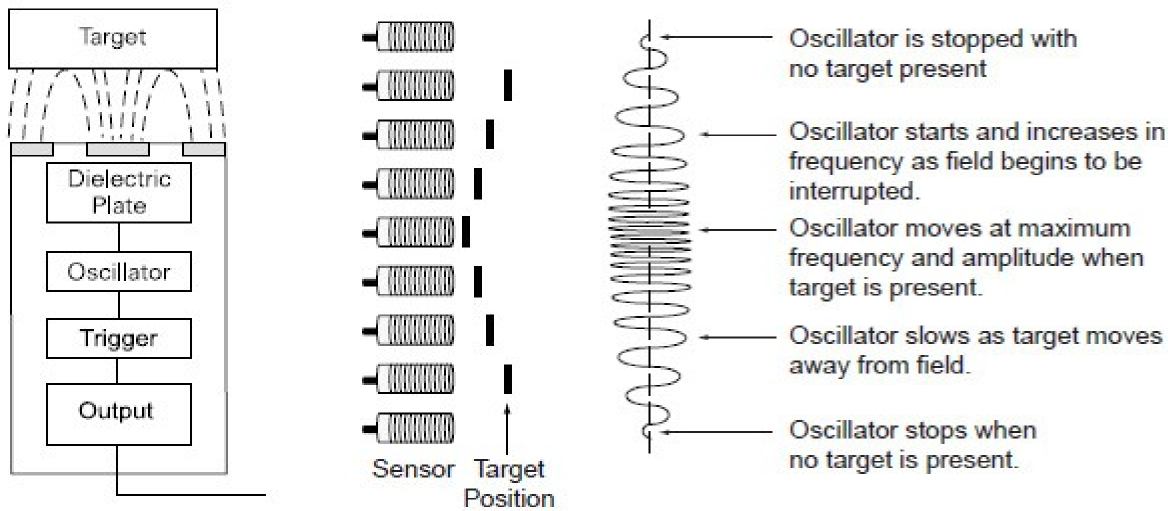


Figure 1.6: Capacitive proximity sensor set-up and operation

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 1.7.

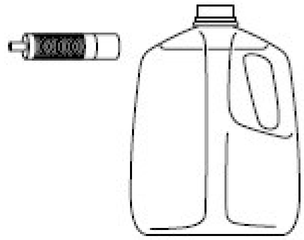


Figure 1.7: Application for capacitive proximity sensors.

Magnetic Proximity Sensors

Magnetic proximity sensors are noncontact proximity devices utilize inductance, Hall Effect principles, variable reluctance, or magneto resistive technology. 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, Figure 1.8. Their operating principle is based on the use of "reed contacts", 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.

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.

As with other proximity sensors, magnetic proximity sensor suffers from hysteresis phenomenon as shown by Figure 1.8.

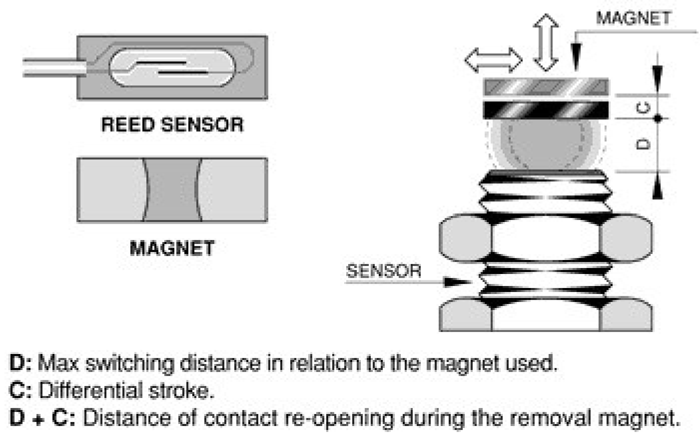


Figure 1.8: Hysteresis in magnetic proximity sensor.

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 (1 in) to one hundred meters or more (several hundred feet). 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 is 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 1.9. 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).

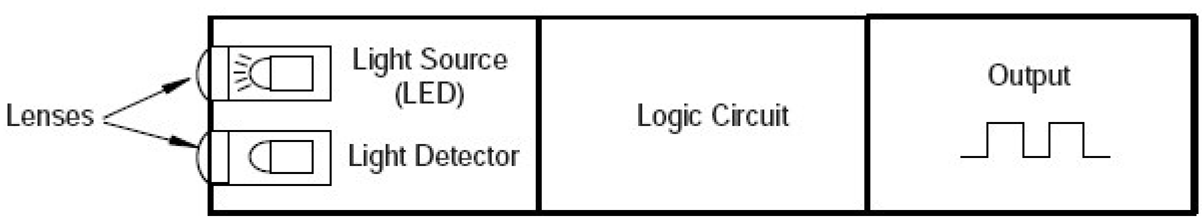


Figure 1.9: Optical proximity sensor.

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 1.10.

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.

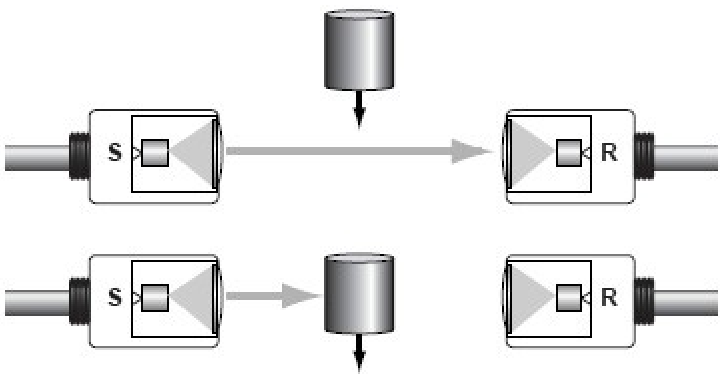


Figure 1.10: Transmitted beam sensor.

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.

Retroreflective Sensors

A retroreflective 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 1.11.

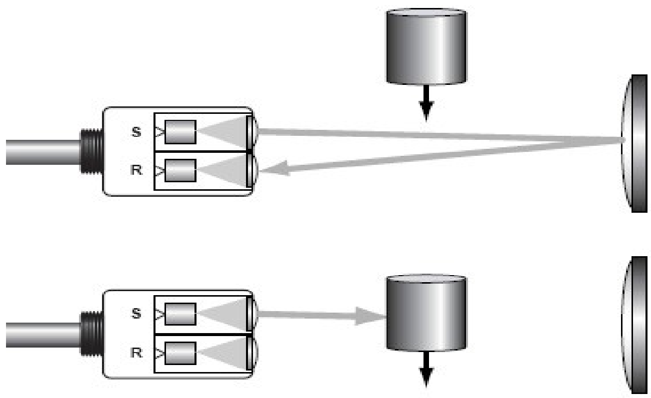


Figure 1.11: Retroreflective sensor.

A wide selection of reflectors is available. The maximum available sensing distance of a retroreflective 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. Retroreflective 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 retroreflective 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

Transmitted beam and retroreflective sensing create a beam of light between the emitter and receiver or between the sensor and reflector. 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 1.12.

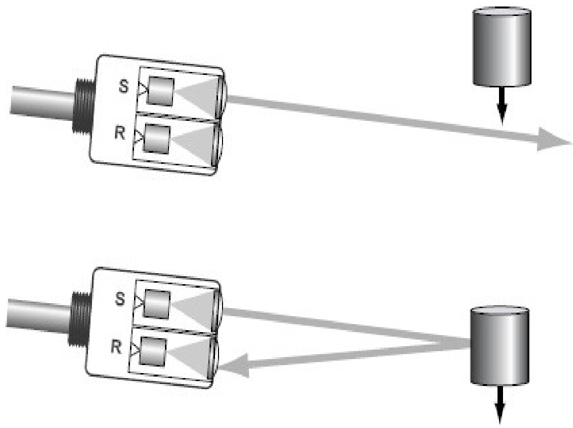


Figure 1.12: Diffuse sensor.

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.

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.

Hysteresis also appears in optical sensors and is defined as the difference between the distance when a target can be detected as it moves towards the sensor and the distance it has to move away from the sensor to no longer be detected. As the target moves toward the sensor, it is detected at distance X. As it then moves away from the sensor, it is still detected until it gets to distance Y, Figure 1.13. The high hysteresis in most photoelectric sensors is useful for detecting large opaque objects in retroreflective and transmitted beam applications

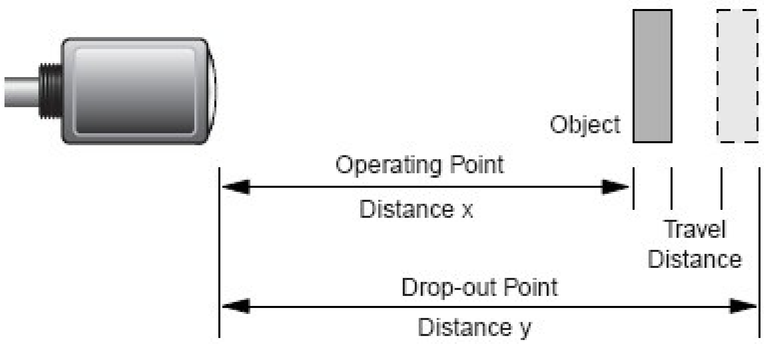


Figure 1.13: Hysteresis in optical proximity sensors.

Procedure:

Proximity sensors measurements

1. Connect the circuit shown in Figure 1.14:
2. Approach each of the sensors 1, 2, 3 and 4 with each following materials: plastic, metal, and magnet.
3. For each material and sensor:
   - Approach the sensor then record the distance at which the LED/Buzzer turn on.
   - Pull away from the sensor and record the distance at which the LED/Buzzer turn off.

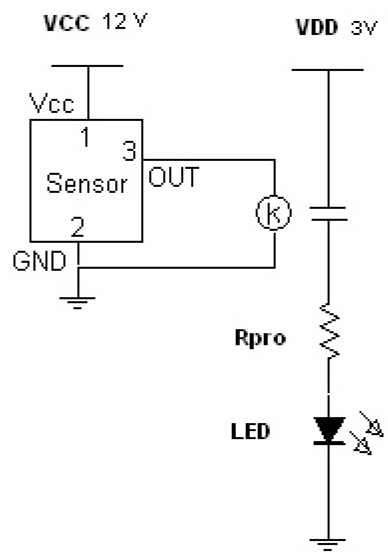


Figure 1.14: Experimental setup.

Discussion and Analysis:

1. What is the type of each of proximity sensor 1, 2, 3, and 4?

2. Which sensor has the maximum sensing distance? Which one has the minimum sensing distance?

3. 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?

4. For the plastic response to the optical sensor case, draw the output state of the LED versus the distance indicating the hysteresis range. (Use 2 colors in your figure, one for approaching and one for retracting)

Experiment 2

Thermal Sensors
RTD

Objectives:

This experiment will include:

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

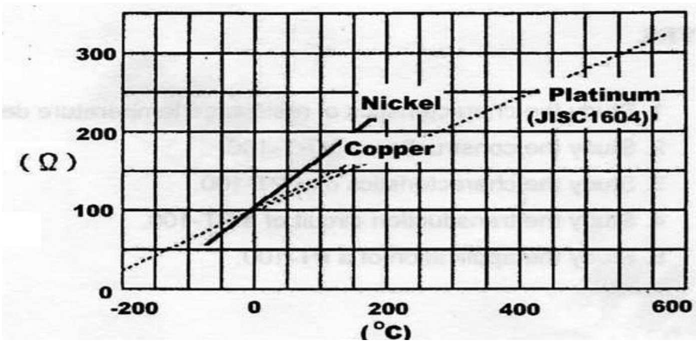


Figure 2.1: Resistance vs. Temperature Curve

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

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

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.

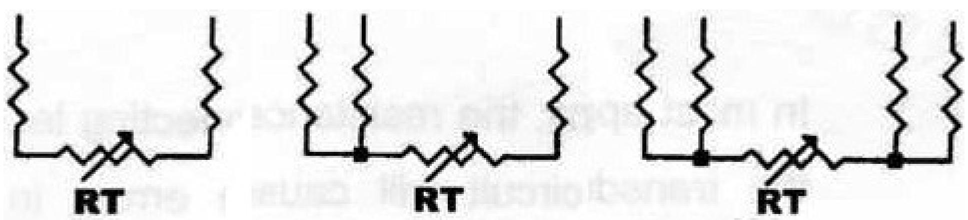


Figure 2.2: Internal schematic diagram for RTD

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.

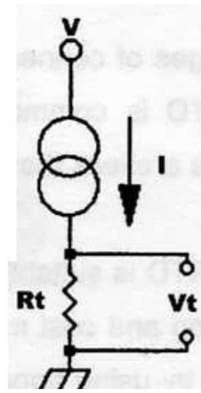


Figure 2.3: RTD measuring circuit

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.

$$Vt = I * Rt = I * Ro\,(1 + \alpha T) \qquad \textbf{(2.3)}$$

$$T = (Vt - I * Ro)/(\alpha * I * Ro) \qquad \textbf{(2.4)}$$

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.

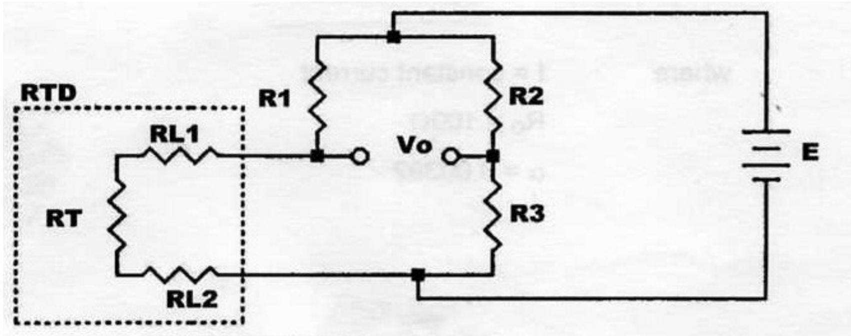


Figure 2.4: Wheatstone bridge for two-wire RTD

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 (*RL*1 = *RL*2 = *RL*3). In Figure 4.5a, lead-resistance changes in the RTD leg of the bridge are compensated for by equal changes in the *R*3 leg when the resistance *R*3 is approximately equal to the resistance of RTD.

In Figure 2.5a, when the bridge balance is reached

Assume $R_1 = R_2$, thus:

$$R_3 + RL2 = R_t + RL1 \qquad \textbf{(2.5)}$$

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.

$$R_1 (R_3 + RL2) = R_2 (R_t + RL1) \qquad \textbf{(2.6)}$$

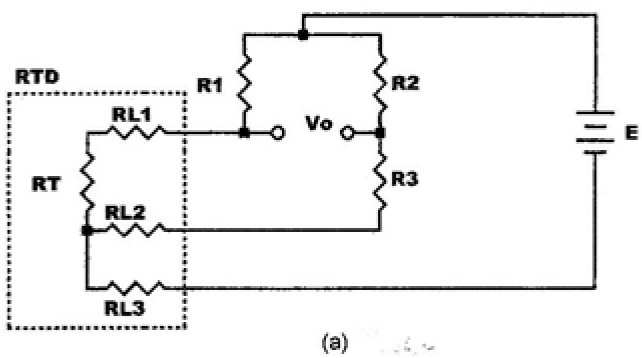


Figure 2.5 (a): Wheatstone bridge for three-wire RTD**.**

In Figure 2.5b, when the bridge balance is reached, Assume *R*2 = *R*3, thus:

$$R_2 (R_t + RL1) = R_3 (R_1 + RL2) \qquad \textbf{(2.7)}$$

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.

$$R_t + RL1 = R_1 + RL_2 \qquad \textbf{(2.8)}$$

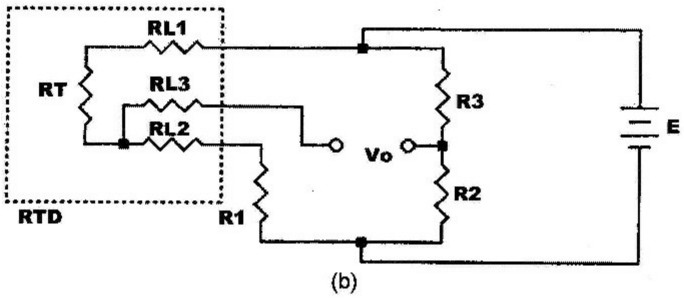


Figure 2.5 (b): Wheatstone bridge for three-wire RTD

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.

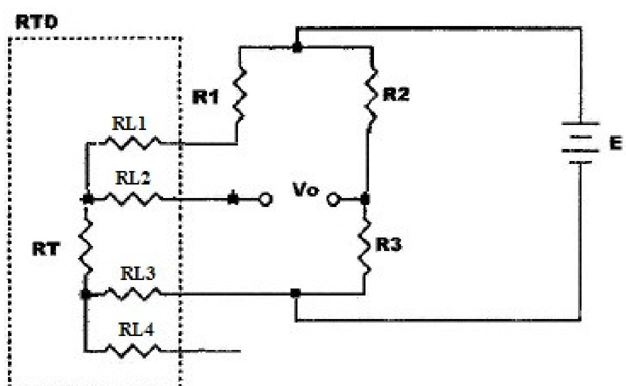


Figure 2.6: Wheatstone bridge for four-wire RTD

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 2.7. 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.

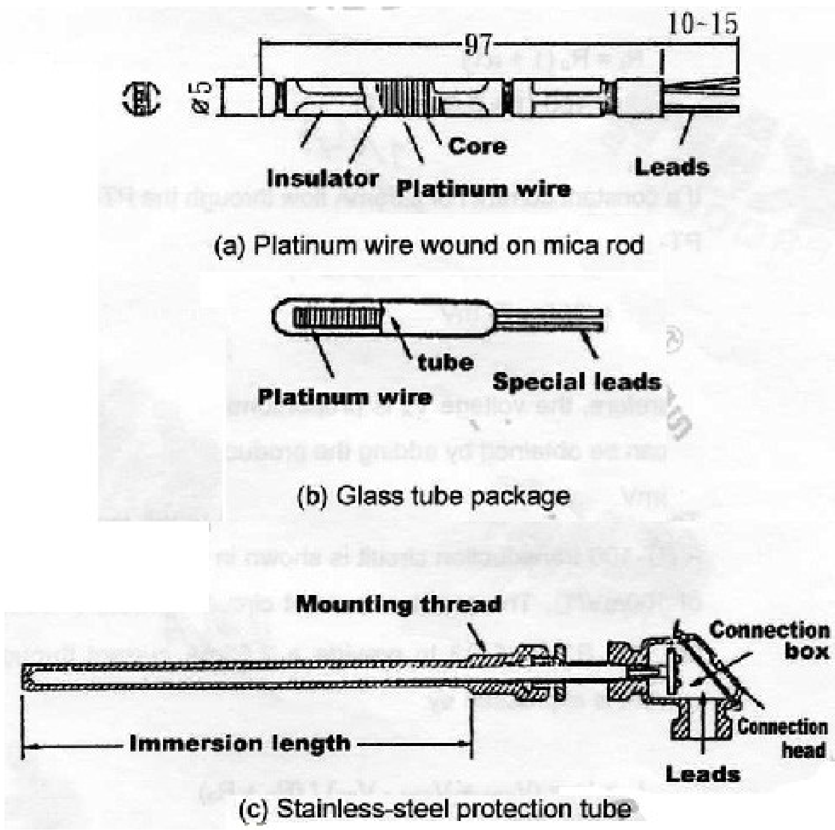


Figure 2.7: PT 100 construction

In order to completely understand the interfacing circuits used in this experiment, a review of some concepts is illustrated.

A Zener diode is a type of diodes that permits current not only in the forward direction like a normal diode, but also in the reverse direction if the voltage is larger than the breakdown voltage known as "Zener knee voltage" or "Zener voltage". Figure 2.8 demonstrate the characteristics of Zener diode.

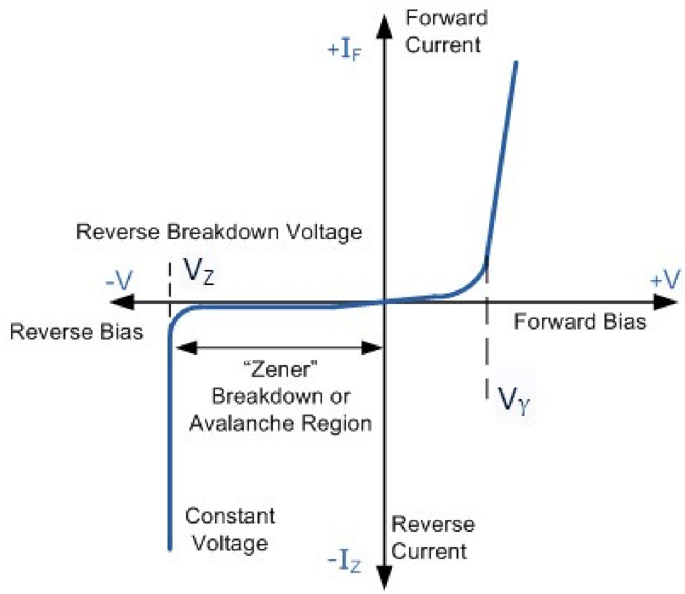


Figure 2.8: Zener diode characteristic curve

Zener diode symbol is shown in Figure 2.9. Zener diodes are used to maintain a fixed voltage. They are designed to 'breakdown' in a reliable and non-destructive way so that they can be used in reverse to maintain a fixed voltage across their terminals. As shown by Figure 2.8, the Zener diode works in three regions.

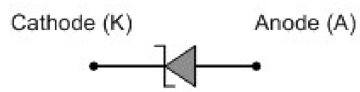


Figure 2.9: Zener diode symbol

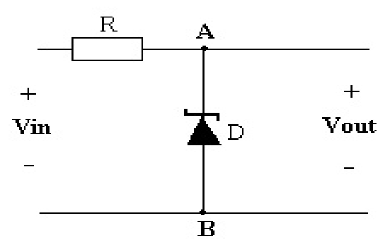


Figure 2.10: Zener diode in a circuit

With the aid of Figure 2.10, we will discuss next each of these regions briefly:

- $V_{BA} > V_\gamma$: the Zener diode is forward biased, which means that it acts as normal diode and will have a drop voltage of V_γ across it, Figure 2.11.

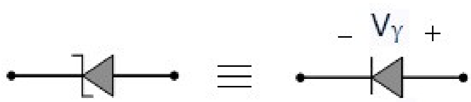


Figure 2.11: Zener diode equivalent circuit in forward bias mode.

- $V_Z < V_{AB} < V_\gamma$: the Zener diode is open circuited, Figure 2.12.

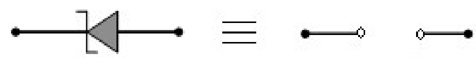


Figure 2.12: Zener diode equivalent circuit in cut off bias mode

- $|V_{AB}| > |V_Z|$: the Zener diode is reveres biased and acts as a voltage regulator “battery” that has a magnitude of V_Z , Figure 2.13.

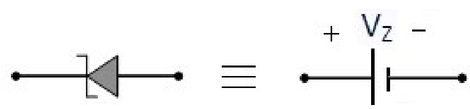


Figure 2.13: Zener diode equivalent circuit in reverse bias mode

A bipolar junction transistor (BJT) is a three-terminal electronic device constructed of doped semiconductor material and may be used in amplifying or switching applications. The BJTs work in four different modes. Based on those modes, the application of the BJT is determined. Figure 2.14 shows the two types of BJTs.

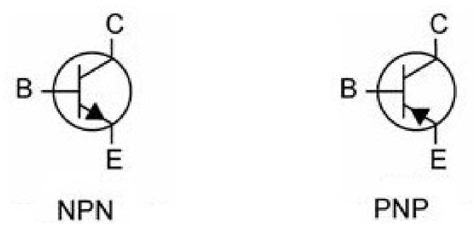


Figure 2.14: BJT circuit symbol.

The basic circuit of an “NPN” transistor is shown in Figure 2.15. The working modes of an “NPN” BJT are:

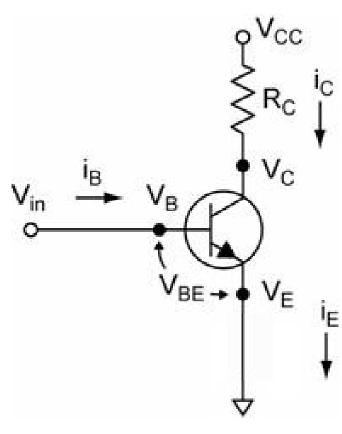


Figure 2.15: Basic BJT circuit.

Forward Active Mode: $V_{BE} > 0$, $V_{BC} < 0$

This mode is used in amplification because the emitter and the collector currents are proportional to the base current via the gain β.

Saturation Mode: $V_{BE} > 0$, $V_{BC} > 0$

The emitter and collector currents are no longer related to the base current. The transistor is saturated which means that V_{CE} is almost zero. So if we are taking the output voltage to equal V_C *in* a logic circuit, then this will be equivalent to "low" state.

Cut-Off Mode: $V_{BE} < 0$, $V_{BC} < 0$

The emitter, base and collector currents are zero. The transistor is off which means that V_C equals V_{CC} . So if we are taking the output voltage to equal V_C in a logic circuit, then this will be equivalent to "High" state.

Reverse-Active Mode: $V_{BE} < 0$, $V_{BC} > 0$

In the reverse active mode, the function of the emitter and the collector is reversed. The bias of the base-emitter junction is reversed and the bias of the base-collector junction is forwarded. But this mode is rarely used.

The four modes are illustrated in Figure 2.16.

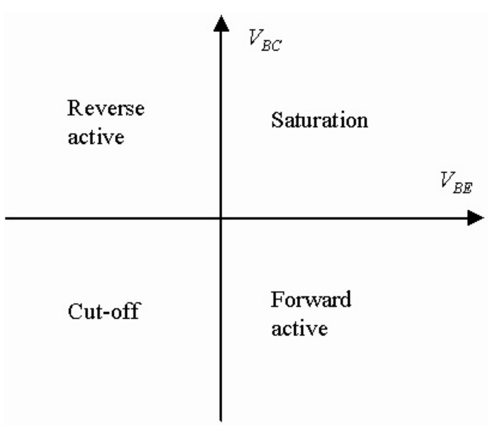


Figure 2.16: Bias modes of operation of a bipolar junction transistor

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 2.17.
- 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.

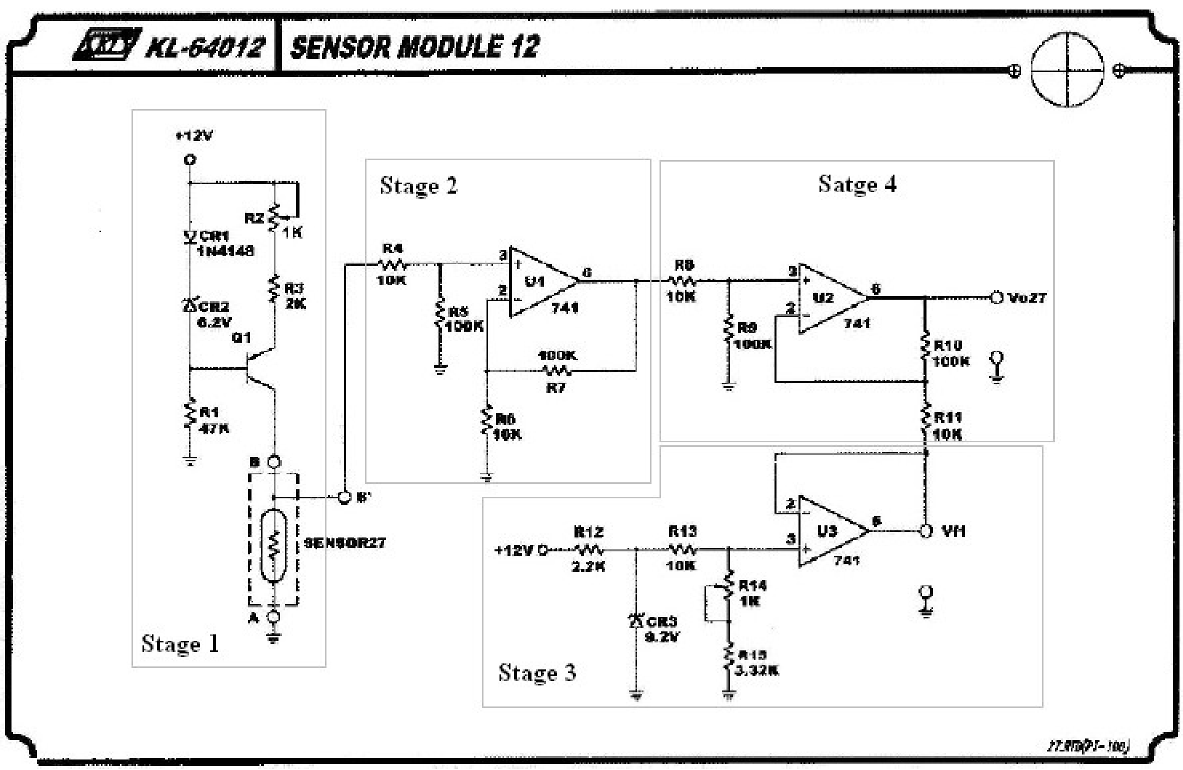


Figure 2.17: PT-100 transduction circuit.

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 2.17 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°.

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, 1000 kΩ)

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.

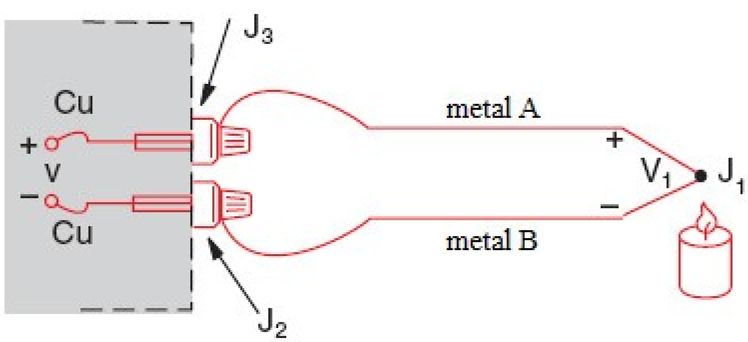


Figure 3.2: Extension leads of thermocouples.

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.

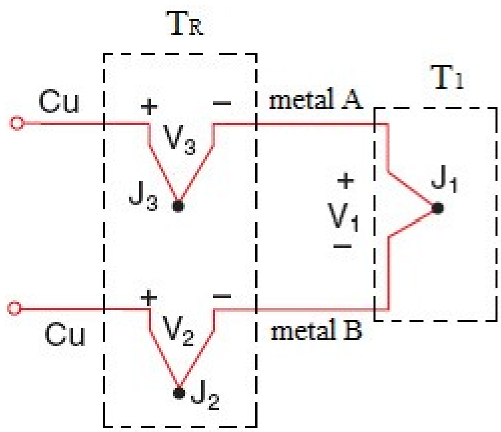


Figure 3.3: Equivalent circuit of Figure 3.2.

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◦.

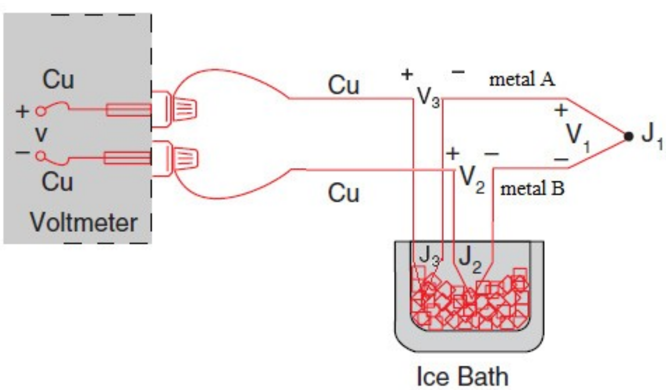


Figure 3.4: Reference junctions at 0C◦.

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:

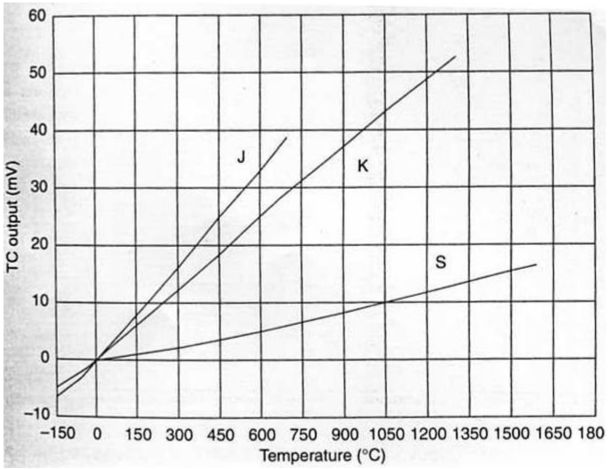


Figure 3.6: Curves of thermocouple voltage versus temperature.

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◦).

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

Table 3.1: K-type TC table at T*ref* =0*o*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 mV.

Procedure:

Thermocouple Manufacturing

You will manufacture a thermocouple simply by welding the dark blue and red wires from **one side**. The dark blue and red wires are the BS color code for a K-type thermocouple.

Thermocouple Measurements

1. Weld the copper extension leads to the thermocouple wires (make sure that the copper wires are of the same length).

2. Connect the circuit shown in Figure 3.7.

3. Set R1 to 1 kΩ and R2 to 1000 kΩ.

4. Null the operational amplifier using the potentiometer R3.

5. Connect the DMM to measure the output voltage.

6. Measure the room temperature and record it.

7. Insert the thermocouple into the Thermostatic container.

8. Measure and record the output voltage for each temperature setting on Table 3.2.

9. Repeat the steps from 3 to 7 for R1=1 kΩ and R2=2000 kΩ. and fill in Table 3.3.

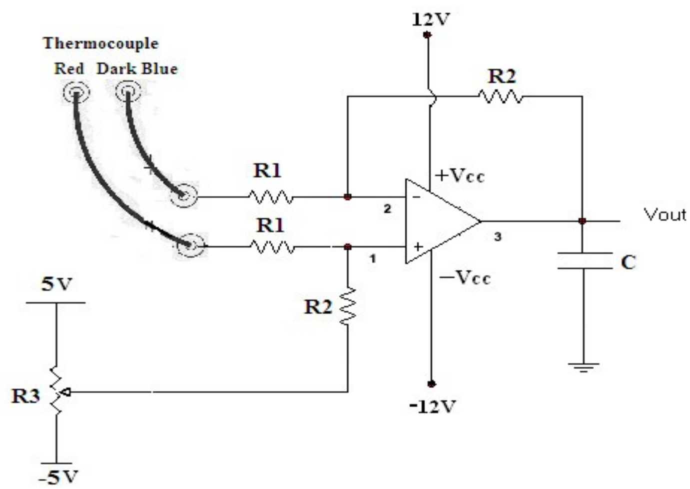


Figure 3.7: TC interfacing circuit.

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 junction 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 results.

Experiment 4

Thermal Sensors
Thermistor

Objectives:

This experiment will allow you to:

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

Apparatus:

- Thermistor (NTC)
- Copper wires
- Operational amplifier
- Ohmmeter
- Thermometer
- Thermostatic container
- Resistances (10 kΩ)

Theoretical Background:

A **thermistor** is a type of resistor whose resistance is dependent on temperature, more so than in standard resistors. Thermistors are widely used as inrush current limiter, temperature sensors (NTC type typically), self-resetting overcurrent protectors, and self-regulating heating elements.

Thermistors differ from resistance temperature detectors (RTDs) in that the material used in a thermistor is generally a ceramic or polymer, while RTDs use pure metals. The temperature response is also different; RTDs are useful over larger temperature ranges, while thermistors typically achieve a greater precision within a limited temperature range, typically −90 °C to 130 °C.

Thermistors can be classified into two types, depending on the behavior of resistance with change in temperature. If the resistance increases with increasing temperature, the device is called a positive temperature coefficient (PTC) thermistor, if the resistance decreases with increasing temperature, the device is called a negative temperature coefficient (NTC) thermistor. Resistors that are not thermistors are designed to have a coefficient as close to 0 as possible, so that their resistance remains nearly constant over a wide temperature range.

For accurate temperature measurements, the resistance/temperature curve of the device must be described in more detail as shown by Figure 4.1.

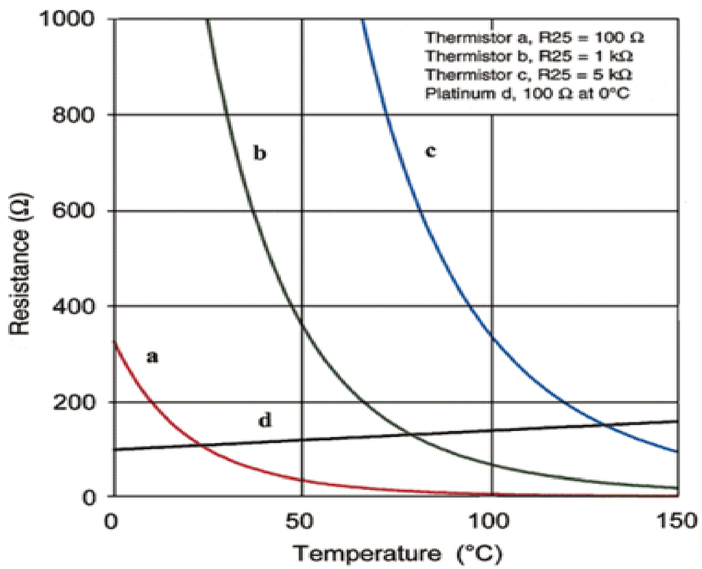


Figure 4.1: NTC Thermistor and RTD characteristics

Figure 4.1 shows that:

- The relationship between resistance change and a temperature change is nonlinear.
- As the value of the nominal resistance increases, the range of temperature resistance increases.
- RTD output resistance range is small compared to thermistors.

The **Steinhart–Hart equation** is a widely used third-order approximation of the thermistor behavior:

$$\frac{1}{T} = a + b\ln(R) + c\left(\ln(R)\right)^3 \qquad \textbf{(4.1)}$$

Where a, b and c are called the Steinhart–Hart parameters, and must be specified for each device. T is the absolute temperature and R is the resistance.

Many NTC thermistors are made from a pressed disc, rod, plate, and bead or cast chip of semiconducting material such as sintered metal oxides. They work because raising the temperature of a semiconductor increases the number of active charge carriers - it promotes them into the conduction band. The more charge carriers that are available, the more current a material can conduct.

Connection to instruments is a simple 2-wire configuration, as — unlike RTDs — we do not need to compensate for lead resistances: this is small compared to the thermistor's resistance (typically between 1 and 100 kΩ).

Thermistors, because of their high sensitivity, are ideal for detecting small changes in temperature, especially when it is the change and not the absolute value that is important.

Self-heating phenomenon

When a current flows through a thermistor, it will generate heat which will raise the temperature of the thermistor above that of its environment. If the thermistor is being used to measure the temperature of the environment, this electrical heating may introduce a significant error if a correction is not made. Figure 4.2 illustrate a voltage divider with a thermistor. Let's examine what happens here.

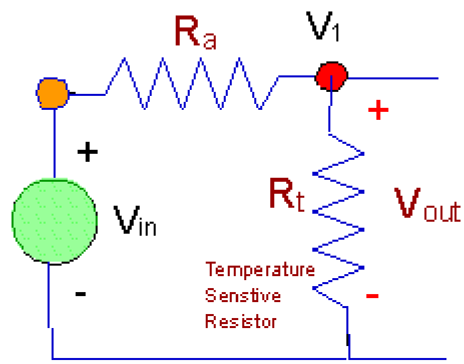


Figure 4.2: thermistor in a voltage divider circuit

In this circuit, the voltage source, Vin, acts to produce a current in the resistor, Ra, and the thermistor temperature sensor, represented by Rt. The current that flows in the circuit is given by equation 4.2:

$$I = Vin/ (Rt + Ra) \qquad \textbf{(4.2)}$$

Notice that the resistance of the thermistor comes into play when you compute the current through the series combination of resistors. Now imagine the following sequence of events.

- The current flowing through the thermistor generates some heat because the thermistor dissipates electrical power.
- The heat causes a temperature rise in the thermistor.
- The temperature rise in the thermistor causes the resistance of the thermistor to decrease.
- The decrease in resistance causes an increase in current through the thermistor.
- The increased current through the thermistor generates more heat.
- The additional heat raises the temperature even higher. And the process repeats.

The process stops if the voltage is low enough or the series resistance is high enough. However, even if the process stops, the thermistor is at a temperature higher than its surroundings. That means that the temperature it measures is not the surrounding temperature (which is what you want it to be), but one that is higher. This phenomenon is called self-heating.

When using thermistor circuits, you want to minimize self-heating. You do that by minimizing the current through the thermistor.

Self-heating is not the worst thing that can happen. If the voltage is high enough, and if the series resistor, Ra, is low enough, the entire process can accelerate with the result being thermal runaway. When you have thermal runaway, the thermistor just keeps getting warmer at a faster rate. The end result is a very hot, damaged, and unusable thermistor.

How to select an NTC thermistor

1. **Dissipation Constant (D.C.)**

The dissipation constant of NTC thermistor is typically defined as the ratio (at a specified ambient temperature) of the power dissipated in the thermistor to the resultant change in the temperature of the thermistor. The constant is expressed as the power in milliwatts required self-heating the thermistor 1°C above ambient temperature. The current through the thermistor must be small enough to produce negligible self-heating error in the thermistor at the maximum measuring or controlling temperature. At the same time, the current should be as large as possible to maximize system sensitivity. For example, if the D.C. of a thermistor assembly had been determined as 3mW/°C in a stirred oil bath (the medium to be measured) and it was desired to measure the oil bath to an absolute temperature accuracy of ± 0.1°C, the maximum power that should be developed in the thermistor by the measuring current is 0.15mW. This is to keep the self-heat factor to 50% or less of the measurement accuracy. The formula for this is:

$$3mW/°C \times 0.1°C \times 50\% = 0.15mW \qquad \textbf{(4.3)}$$

Power is calculated by using Ohm's Law:

$$P = E \times I \qquad \textbf{(4.4)}$$

2. **Thermal Time Constant (T.C.)**

The time constant is the time in seconds required for the thermistor to change through 63.2% of the difference between its initial and final body temperatures, when subjected to a step change in temperature under zero-power conditions.

3. **Selection Of Resistance Value**

Typically, NTC thermistors are specified and/or referenced to + 25°C. However, it is equally important to consider the minimum and maximum resistance values at the extremes of the operating temperature range. The minimum resistance at the maximum temperature point must not be too low to meet the input requirements of the measuring circuit. If the resistance is too low, errors due to contact resistance, line resistance and self-heating increase. It is recommended to have at least 500 ohm - 1000 ohm at the high end of the temperature range. Conversely, the maximum resistance at the minimum temperature point must not be too high for the measurement circuit input. Range switching with two or more probes should be considered if the minimum/maximum resistance values cannot be met with one thermistor. Sensitivity also is an important consideration in the selection of the correct resistance value. Usually, the minimum and maximum allowable resistance values typically limit this selection. It then must be determined which resistance values maximize the output of the measuring system over the entire range, taking into consideration the maximum input current as determined by the dissipation constant and allowable self-heat error.

Applications for NTC

1. As inrush-current limiting devices in power supply circuits. They present a higher resistance initially which prevents large currents from flowing at turn-on, and then heat up and become much lower resistance to allow higher current flow during normal operation. These thermistors are usually much larger than measuring type thermistors, and are purposely designed for this application

2. As sensors in automotive applications to monitor things like coolant or oil temperature inside the engine, and provide data to the ECU and to the dashboard.

3. Thermistors are also commonly used in modern digital thermostats and to monitor the temperature of battery packs while charging.

4. Thermistors are often used in the hot ends of 3D printers; they monitor the heat produced and allow the printer's control circuitry to keep a constant temperature for melting the plastic filament.

5. In the Food Handling and Processing industry, especially for food storage systems and food preparation. Maintaining the correct temperature is critical to prevent food borne illness.

6. Throughout the Consumer Appliance industry for measuring temperature. Toasters, coffee makers, refrigerators, freezers, hair dryers, etc. all rely on thermistors for proper temperature control.

As the sensor is a resistive sensor many conditioning circuits can be implemented such as bridge circuits and op-amp circuits, but these circuits differs in its sensitivity and linearity. Figure 4.3 shows a conditioning circuit that linearizes the output voltage with changes in temperature on the expanse of sensitivity.

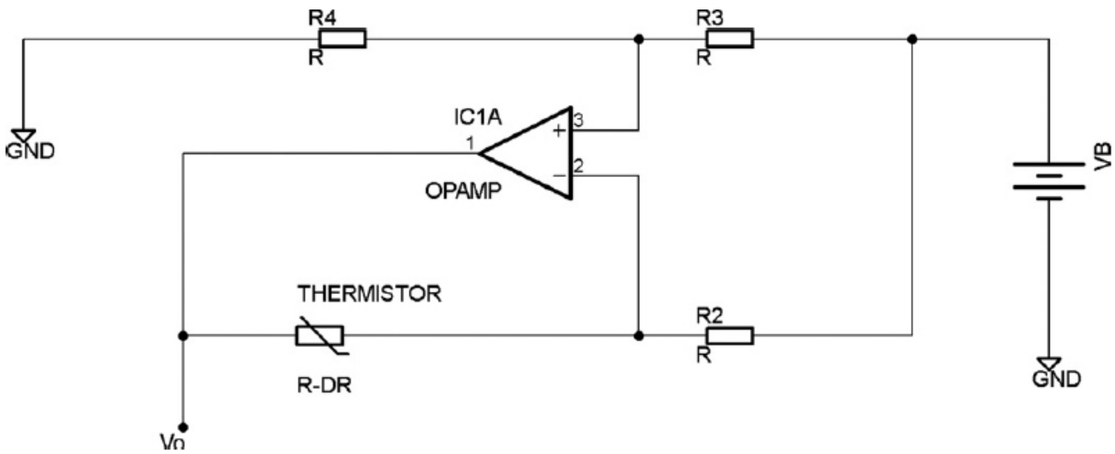


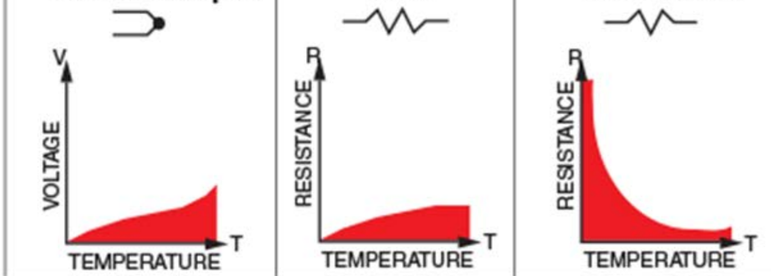
Figure 4.3: Op-amp bridge circuit

For the circuit of Figure 4.3, the output voltage can be expressed as

$$Vo = V\beta * \frac{\Delta R}{2R} \qquad \textbf{(4.5)}$$

Where ΔR is the change in the resistance of the thermistor and *VB* is the bridge voltage. Equation 4.5 shows that the output voltage depends directly on the change in the resistance of the thermistor with temperature. This implies that the output voltage can be used as an inference of the temperature change directly.

Table 4.1: Thermal Sensor Comparison



	Thermocouple	RTD	Thermistor
Advantages	Self-powered Simple Rugged Inexpensive Wide variety Wide temperature range	Most stable Most accurate More linear than thermocouple	High output Fast Two-wire ohms measurement
Disadvantages	Non-linear Low voltage Reference required Least stable Least sensitive	Expensive Current source required Small Δ R Low absolute resistance Self-heating	Non-linear Limited temperature range Fragile Current source required Self-heating

<u>Procedure</u>:

Thermistor Measurements

1. Using the ohmmeter find the sensor resistance at room temperature.

   $T_{room\text{-}temp}$ = ------------------------------
2. Connect the circuit shown by Figure 4.4.
3. Set Vcc to 5V and R1 to 10KΩ.
4. Put the thermometer inside hot water and record the output voltage values.

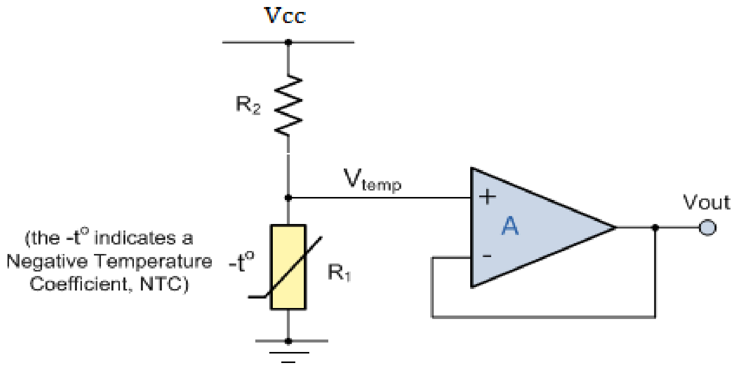


Figure 4.4: TC interfacing circuit.

<u>Discussion and Analysis:</u>

1. What is NTC thermistor?
2. What is the best tool for describing the NTC thermistor R/T characteristic?
3. Are NTC thermistors sensitive to temperature changes?
4. Plot the relation between temperature and output voltage.

Experiment 5

Displacement Sensors
Strain Gauges

Objectives:

This experiment will include:

- Principle, construction, and characteristics of a strain gauge.
- Transduction circuit of a strain gauge.
- Application of a strain gauge.

Apparatus:

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

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).

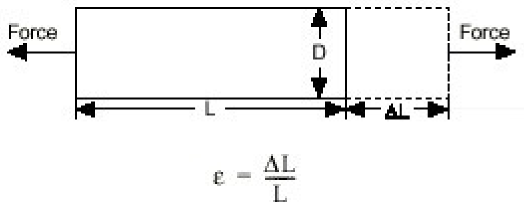


Figure 5.1: Strain in a conductor.

The intrinsic resistance of a conductor can be given by:

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

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:

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

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

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.

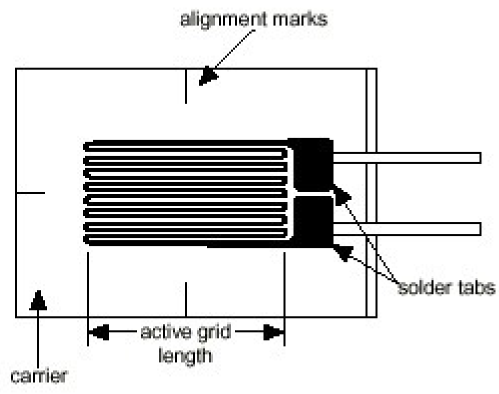


Figure 5.2: Strain Gauge.

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 typical 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.

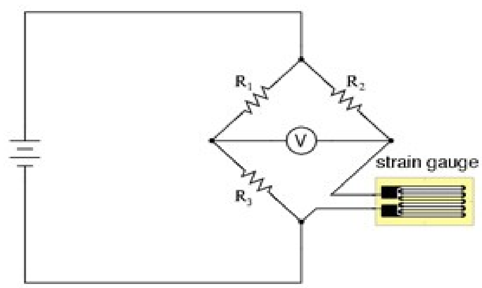


Figure 5.3: Quarter-bridge strain gauge circuit.

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.

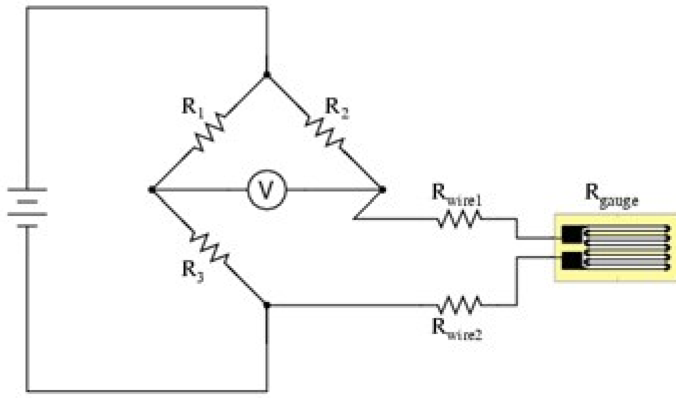


Figure 5.4: Leads effect on measurements.

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.

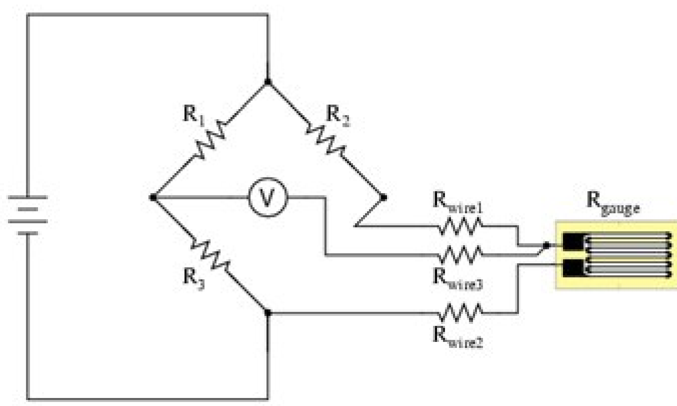


Figure 5.5: Three wire, quarter bridge strain gauge circuit.

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.

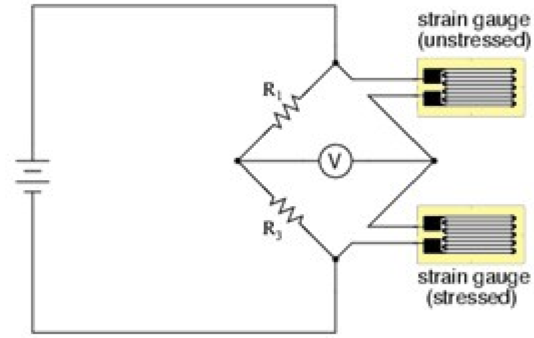


Figure 5.6: Quadratic bridge strain gauge circuit with temperature compensation

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.

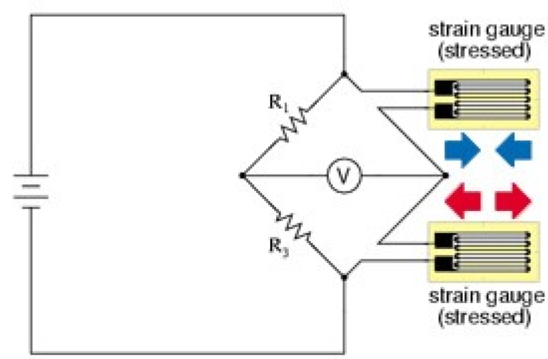


Figure 5.7: Half bridge strain gauge circuit.

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.

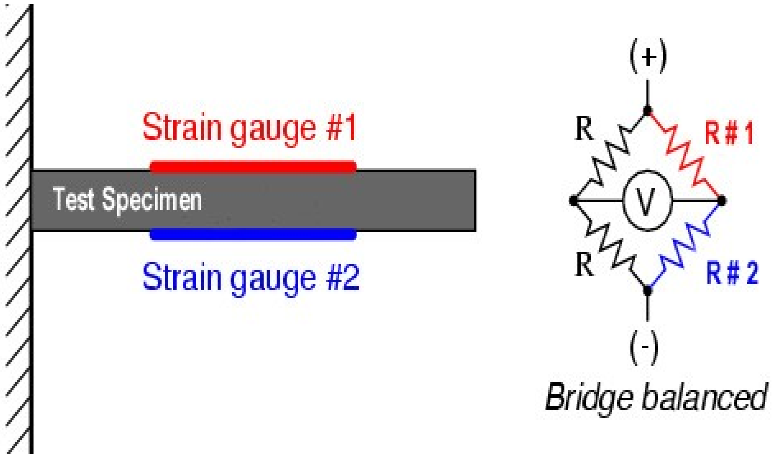


Figure 5.8: Unstrained test specimen.

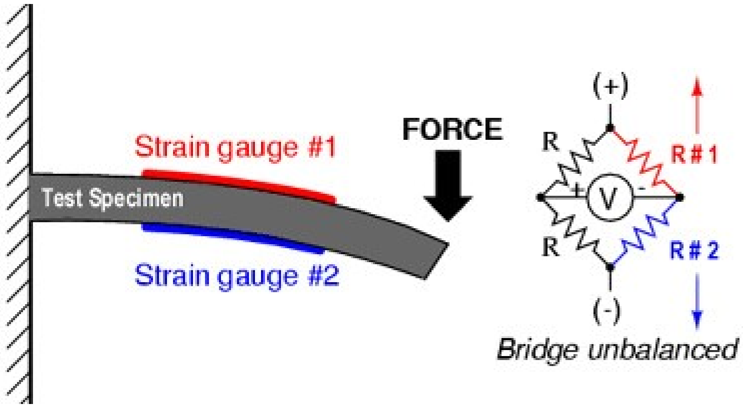


Figure 5.9: Strained test specimen

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. When possible, the full-bridge configuration is the best to use.

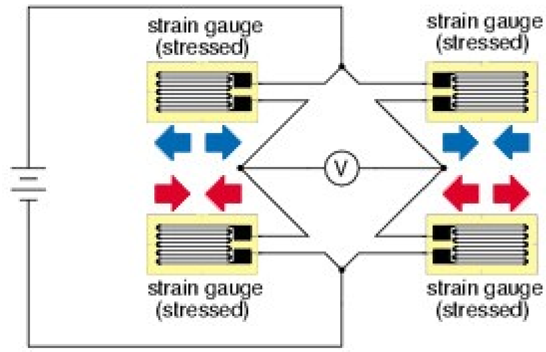


Figure 5.10:Full bridge strain gauge circuit

This is true not only because it is more sensitive than the others, but because it is linear while the others are not. 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).

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.

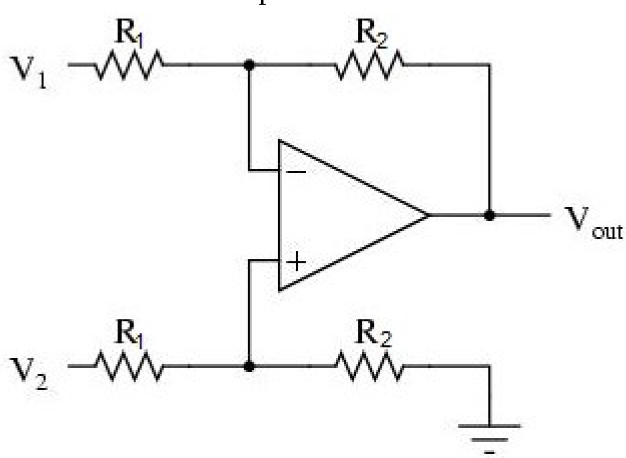


Figure 5.11: Differential amplifier.

The following equation represents the relationship between the inputs and the output of the differential amplifier shown in Figure 5.11:

$$Vout = \frac{R2}{R1}\left(V2 - V1\right) \qquad \textbf{(5.4)}$$

The above equation shows that if a large gain is to be obtained from this kind of ampli- fier, *R*1 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 5.12.

Instrumentation Amplifier

The differential amplifier configuration shown in Figure 5.12 is a good configuration.

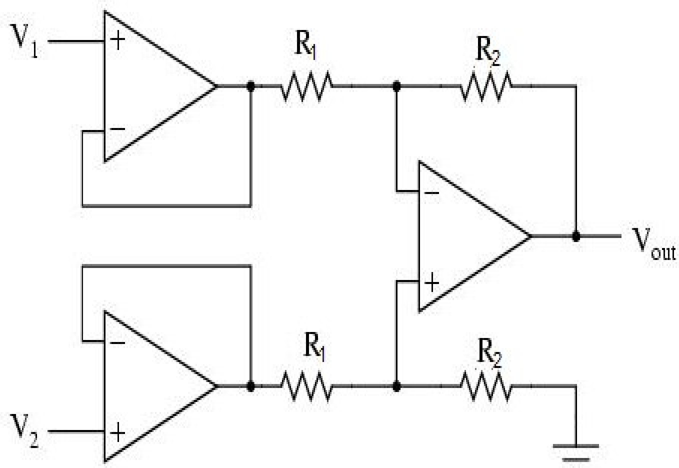


Figure 5.12: Differential amplifier with buffered inputs.

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 5.13.

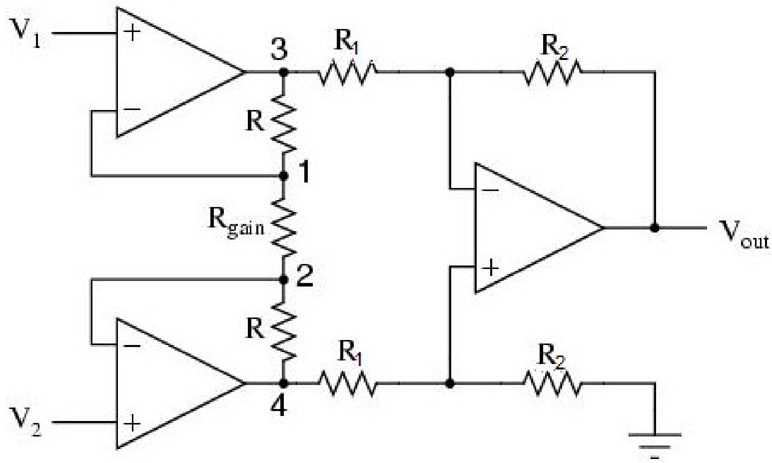


Figure 5.13: Instrumentation amplifier

The relationship of the instrumentation amplifier shown in Figure 5.13 to its input voltages is given by the following equation:

$$Vout = 1 + \frac{2R}{Rgain}(R2/R1)(V2 - V1) \qquad \textbf{(5.5)}$$

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; R*gain*. 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 R*gain* completely open (infinite resistance).

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 5.14, an instrumentation amplifier consists of operational amplifiers U4, U5, and U6, with a total gain of

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

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, and the output transduction ratio is not exactly at 2.7 mV/kg. The former can be improved with providing an offset voltage to the input of the instrumentation amplifier, and the latter 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.

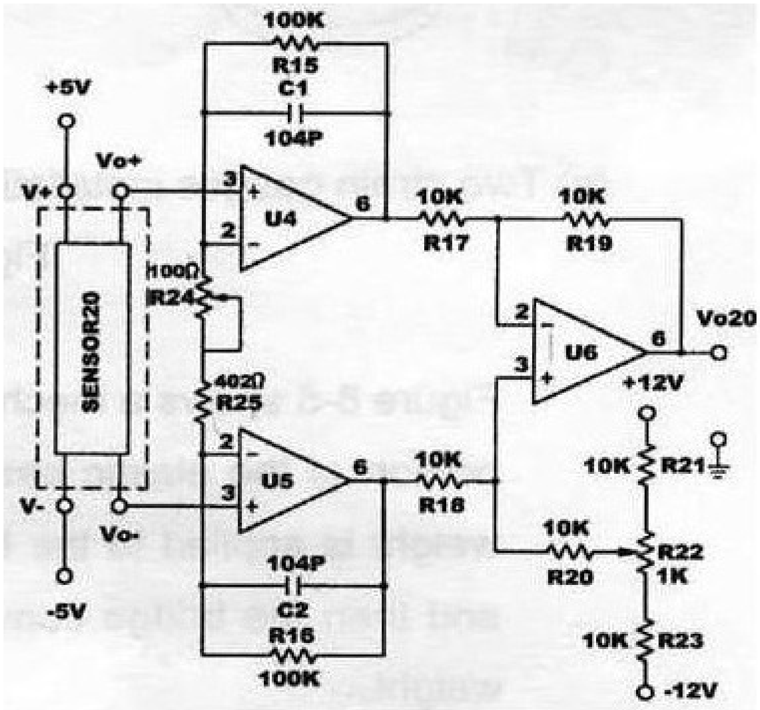


Figure 5.14: Strain gauge transducer circuit

<u>Procedure</u>:

Task 1

1. Set the strain gauge transducer module KL-64007 block 20 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

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 $R15$, $R16$, $R24$, $R25$, $R19$, and $R17$ 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 conditions.

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 6.1a and the TK294K in Figure 6.1b.

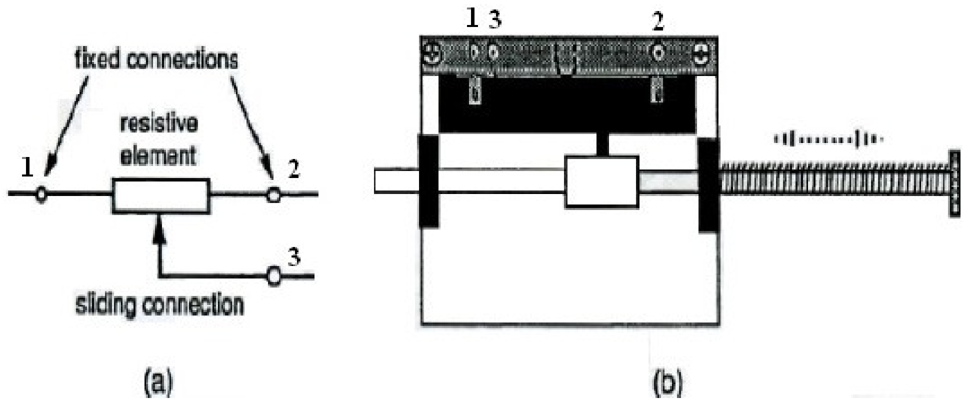


Figure 6.1: (a) Schematic diagram of a variable length transducer and (b) Picture of TK294K.

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. Assemble the TK294K onto the TK294 by aligning the two holes in the assembly with the two pins on the sub-unit, and then dropping the sub-unit into place. The sub-unit is then secured to the assembly by tightening the finger screw. The sub-unit includes a return spring and is operated by pressure applied to the end of the operating rod by the micrometer shaft.

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

$$Vout = (-Rf / Rin) * Vin \qquad \textbf{(6.2)}$$

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

Procedure:

1. Connect up the circuit of Figure 6.2.
2. Return the slider to its furthest right position such that the sensor is uncompressed again.
3. Record your readings.
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.

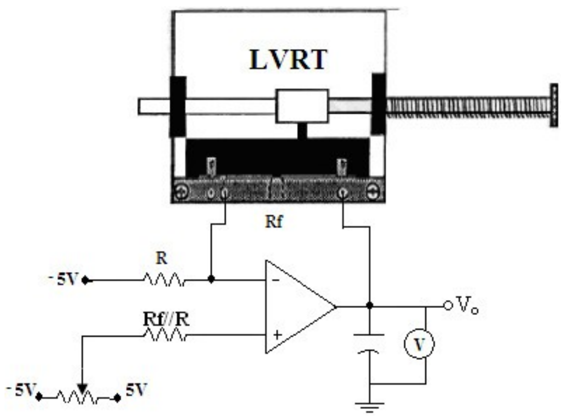


Figure 6.2: A variable length transducer connected to an Op Amp.

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 7

Displacement Sensors
Rotary Optical Encoders

Objectives:

This experiment will allow you to:

- Discriminate between types of optical encoders.
- Able to obtain encoder resolution.

Apparatus:

- Incremental Rotary Encoders Copper wires
- Absolute Rotary Encoders.

Theoretical Background:

A rotary encoder, also called a shaft encoder, is an electro-mechanical device that converts the angular position or motion of a shaft or axle to an analog or digital code.

There are two main types: absolute and incremental (relative) optical encoders. The output of absolute encoders indicates the current position of the shaft, making them angle transducers. The output of incremental encoders provides information about the motion of the shaft, which is typically further processed elsewhere into information such as speed, distance and position.

Optical encoders use a glass or plastic disc with alternating transparent and opaque fields, with a light source on one side and a light-sensitive sensor on the other. As the disc rotates, the light source is alternately blocked and revealed to the sensor. Whenever the light source hits the sensor, the encoder transmits an electric pulse that can be interpreted by a controller. The pulse ends when an opaque field on the disc blocks the light source. Rotation of the disc results in a square-wave pulse output. Most rotary encoders use an infrared light-emitting diode as a light source, and photodiodes or phototransistors as receivers. If no other functions are added to the encoder, the only output is a square wave that indicates that the disc is rotating. The direction of rotation and absolute position cannot be determined from a square wave output alone. Therefore, additional components are added to many rotary encoders to provide additional data about the rotation.

Types of Encoders

Incremental Rotary Encoders

Incremental rotary encoders supply a certain number of pulses for each shaft revolution. Measuring the cycle duration or counting the number of pulses during a pre-determined unit of time determines rotational speed. If the pulses are measured after a reference point is added, the calculated value represents a parameter for a scanned angle or the distance covered. Two-channel encoders (those with a phase shift of 90°) enable the controller to determine the direction of rotation and can enable bi-directional positioning. Three-channel incremental encoders provide a “zero signal” for each revolution, giving a fixed point of reference.

How does a Quadrature Encoder work?

The code disk inside a quadrature encoder contains two tracks usually denoted Channel A and Channel B. These tracks or channels are coded ninety electrical degrees out of phase, as indicated in the Figure 7.1, and this is the key design element that will provide the quadrature encoder its functionality. In applications where direction sensing is required, a controller can determine direction of movement based on the phase relationship between Channels A and B. As illustrated in Figure 7.2, when the quadrature encoder is rotating in a clockwise direction its signal will show Channel A leading Channel B, and the reverse will happen when the quadrature encoder rotates counterclockwise.

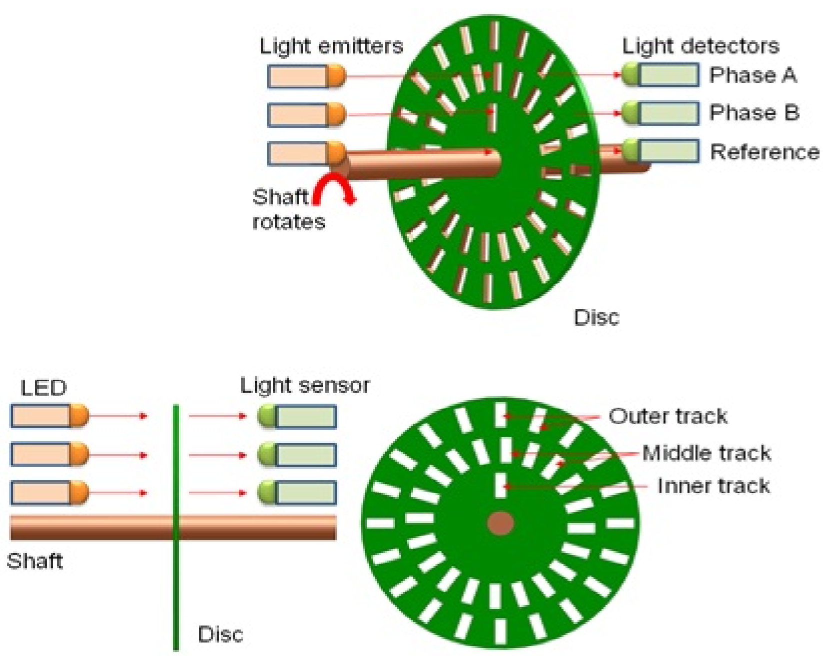


Figure 7.1: Rotary optical encoder principle

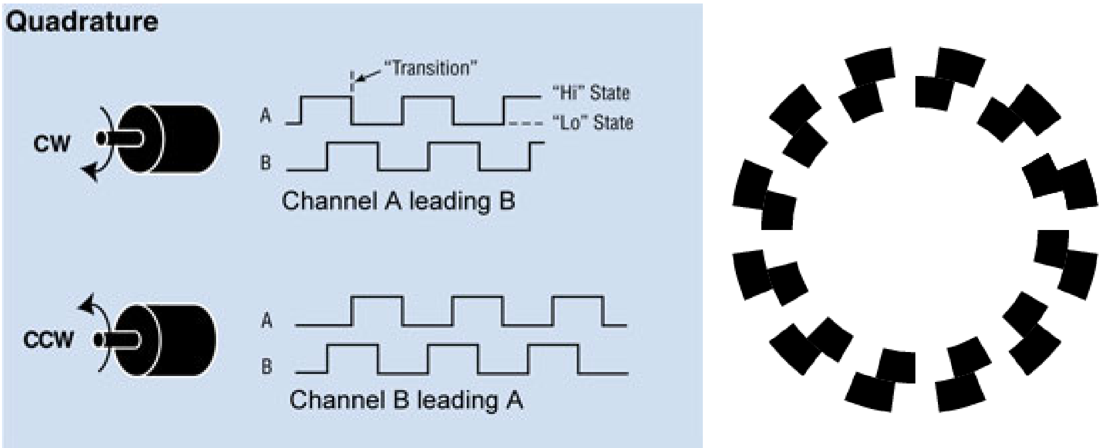


Figure 7.2: Rotary optical encoder channels.

Apart from direction, position can also be monitored with a quadrature encoder by producing another signal known as the "marker", "index" or "Z channel". This Z signal, produced once per complete revolution of the quadrature encoder, is often used to locate a specific position during a 360° revolution.

Quadrature encoders are used in bidirectional position sensing and length measuring applications. However, in some unidirectional start-stop applications, it is important to have bidirectional information (Channel A & B) even if reverse rotation of the shaft is not anticipated. An error in count could occur with a single-channel encoder due to machine vibration inherent in the system. For example, an error in count may occur with a single-channel encoder in a start/stop application if it mechanically stops rotating when the output waveform is in transition. As subsequent mechanical shaft vibration forces the output back and forth across the edge the counter will up-count with each transition, even though the system is virtually stopped. By utilizing a quadrature encoder, the counter monitors the transition in its relationship to the state of the opposite channel, and can generate reliable position information.

Absolute Rotary Encoders

Absolute encoders provide a uniquely coded numerical value for each shaft position. Absolute rotary encoders eliminate the need for expensive input components in a positioning application because they have built-in reference data. In addition, reference runs after a power failure or when the machine is switched off are not required because the encoder provides the current position value immediately. **Single-turn** absolute encoders divide the shaft into a defined number of steps. The maximum resolution is represented using the number of bits (n) as 2^n, which means that up to 2^n positions can be defined. By using a multi-step gear, **multi-turn** absolute encoders not only provide the angular position within a revolution, but also the number of revolutions. Multi-turn encoders have a number of bits (m), with resolution 2^m to indicate the number of turns, which means that up to 2^m revolutions, can be identified. Overall resolution with (n+m) bits (n bits per turn + m bits for the number of turns) is 2^{m+n} measuring steps. Parallel absolute encoders transmit the position value to external analyzing electronics through multiple wires, one for each bit. In the case of serial absolute encoders, the output data can be transmitted by means of standardized interfaces and protocols.

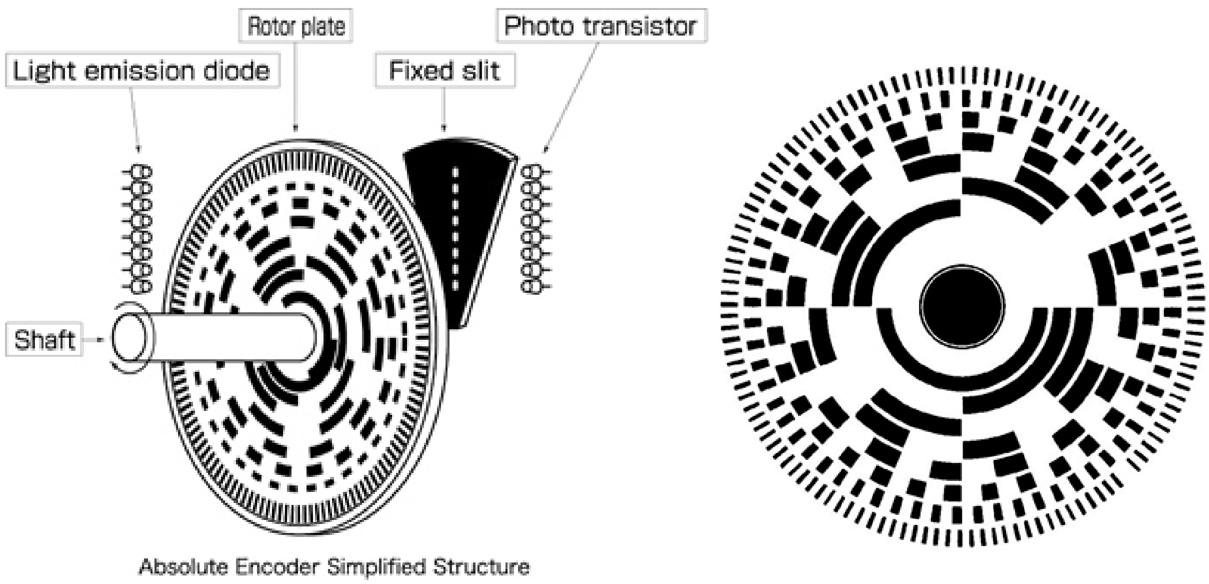


Figure 7.3: Single-turn Absolute Optical Encoder

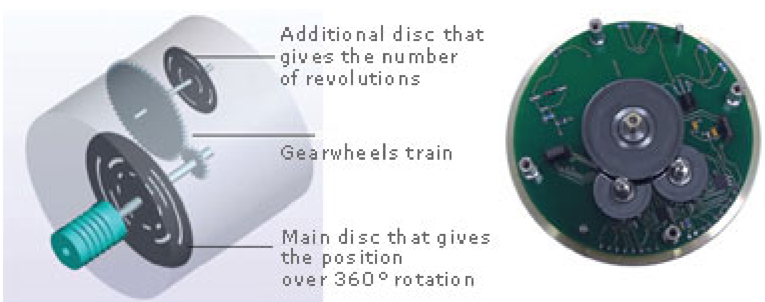


Figure 7.4: Multi-turn Absolute Optical Encoder

Incremental Encoder Output Circuits

Each output line of the incremental optical encoder may have one of the three configurations shown by Figure 7.5. The open collector configuration needs a pull-up resistor. The line drive configuration needs a pull down resistor, while the push-pull type gives a direct voltage on the output.

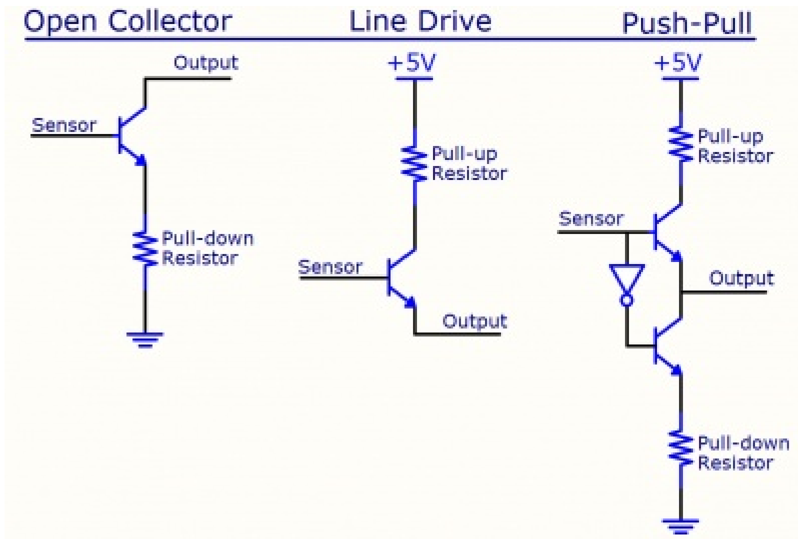


Figure 7.5: Encoder Output Circuit Configurations

Encoder Resolution

For incremental encoders, resolution is defined as counts per turn. For absolute single-turn encoders, it is positions per turn, expressed as a multi-bit word. Multiturn encoders (those that track over multiple 360° turns) are specified in positions per input-shaft turn, and the number of internal gear-ratio turns.

The maximum electrical response speed is determined by the resolution and maximum response frequency as in Figure 7.6:

$$\text{Maximum electrical response speed (rpm)} = \frac{\text{Maximum response frequency}}{\text{Resolution}} \times 60$$

Figure 7.6: Encoder maximum electrical response speed

This means that the Rotary Encoder will not operate electrically if its speed exceeds the maximum electrical response speed.

The **advantages** optical encoders' technology over other angular position sensors:

- Optical and digital technology
- No mechanical parts in contact (except for the bearings)
- Non–magnetic product
- Excellent angular accuracy based on resolution
- Fuses optical and digital technology
- Can be incorporated into existing applications
- Compact size

The biggest advantage of absolute and incremental encoders are that they are inherently digital, which means they can interface easily to modern control systems. An encoder sends digital quality signals back to the computer. There is no need for an engineer to get involved in the wiring and integration of signal electronics.

An encoder is also fast: some 12-bit optical encoders can provide a reading of absolute position on a shaft rotating at 12,000 rpm. As mentioned before, encoders are available with absolute or incremental output. Incremental encoder units find a great deal of use as tachometers because their spot-on digital output allows for more accurate speed control than is available from an analog tachometer. These devices are also void of the analog tachometer brushes and therefor they have a longer life.

The **disadvantages** of optical encoders :

- Direct light source interference (Optical Encoders)
- Susceptible to dirt, oil and dust contaminates

The biggest limitations of encoders are that they can be fairly complex and contain some delicate parts. This makes them less tolerant of mechanical abuse and restricts their allowable temperature. One would be hard pressed to find an optical encoder that will survive beyond 120ºC. Optical encoders can be harmed by contamination – their fine-pitch scales, LEDs and photo detectors can be put out of action by oil, dirt, or dust. Probably the biggest drawback to optical encoders is its reputation for mechanical fragility. The heart of most optical encoders is a thin glass disk that can be broken by excessive shock or misaligned by shock or severe vibration. Encoders traditionally have been complex electronic devices that contain integrated circuits as well as LEDs and photo detectors, and a severe electrical disturbance could damage them.

Procedure:

Rotary optical encoder Measurements

1- Examine the optical encoders provided by your lab supervisor. What is the type of each encoder?

Discussion and Analysis:

1. What is the difference between incremental and absolute rotary encoder.
2. Discuss the three encoder Output Circuit Configurations illustrated in this experiment.

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. Servo amplifier : SA150D
2. Servo motor :DCM150F
3. Power supply : PS150E
4. Attenuator unit : AU150B
5. Operational amplifier : OU150A
6. Tachometer : GT150X
7. Voltmeter – Oscilloscope – Function generator
8. Pre –Amplifier Unit [PA150C].
9. Output Angular Potentiometer.

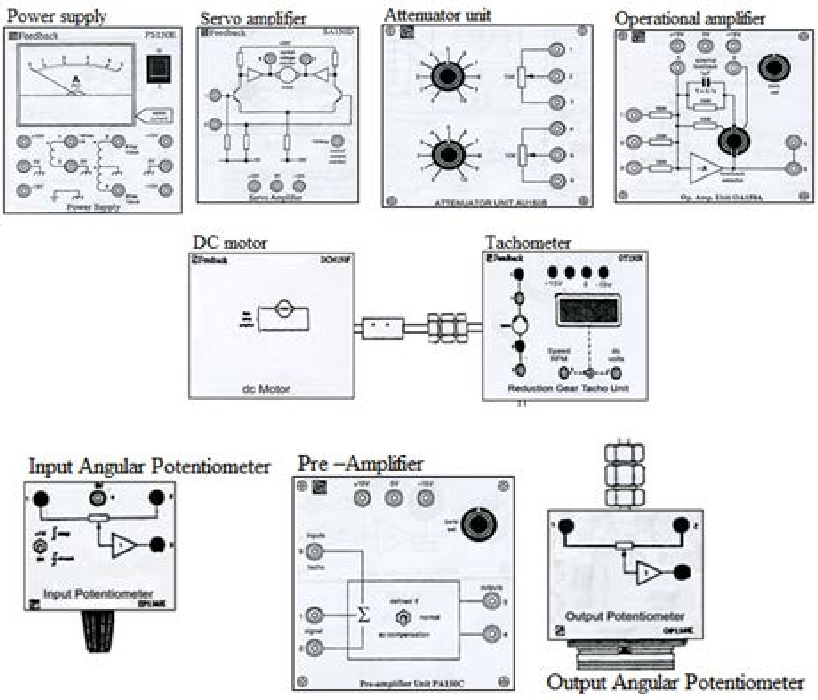


Figure 1.1: Servo Motor System Components

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. These constants can be identified experimentally.

The tachometer works essentially as a voltage generator, with the output voltage a proportional to the magnitude of the angular velocity of the input shaft. 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.

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

1. Servo amplifier [SA150D]:

This unit operates the motor from signals applied to the input sockets 1 or 2. These two inputs allow reversing the motor rotation. The servo amplifier is connected to the servo motor by a plug and cable. The gain of this unit K_{servo} = 7.4 Terminals for ± 15 volts and ground (common) are variable on this unit.

2. Servo motor [DCM150F]:

This unit is a DC motor that produces a torque. The tachometer with terminal +, - and common (ground) is attached to the motor. The transfer function of the motor is:

$$\frac{\Omega(s)}{E(s)} = km\frac{1}{1+s\tau_m} \quad (1)$$

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, then the output speed (with zero initial condition) is:

$$\omega(t) = k_m(1-e^{-\frac{t}{\tau m}}) \quad (2)$$

3. power supply [PS150E]:

This unit provides the various supplied required for the servo components. There are terminals for ± 15 volts, and common (ground). An ammeter is also included. The maximum current is 2 A. A socket and cable connects this unit to the servo amplifier.

4. Attenuator unit [AU150B]:

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. This unit can be used as either attenuator or controller.

5. Operational amplifier unit [OU150A]:

This unit is an operational amplifier. A selector switch allows the use of the unit as a summer, integrator or with any external circuit in the feedback path. The unit is used as an error detector which determines the difference between the demand and response. Before using the unit, measure the output of the unit and adjust it to zero with the zero control, when the input voltage at sockets 1 and 2 are zero.

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.

6. Pre –Amplifier Unit [PA150C]:

This unit has two inputs are effectively summed, allowing two signals to be applied.

A positive signal applied to either input causes the upper output (3) to go positive, the output (4) staying constant value near ground.

A negative input causes the lower output (4) to go positive, the output (3) staying constant value near ground.

7. Tachometer unit [GT150X]:

This unit contains a speed reduction gearbox with a ratio of 30/1 from the high speed input shaft to the low speed output shaft.

Procedure:

1. Turn off the power supply.
2. Connect a certain input to each component and measure the output to find the dc gain of each component.

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 2
First and Second Order Systems

Objectives:

- To implement an open and closed loop speed control systems.
- To implement an 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 system.

Apparatus:

1. Servo amplifier : SA150D
2. Servo motor :DCM150F
3. Power supply : PS150E
4. Attenuator unit : AU150B
5. Operational amplifier : OU150A
6. Tachometer : GT150X
7. Voltmeter – Oscilloscope – Function generator
8. Pre –Amplifier Unit [PA150C].
9. Output Angular Potentiometer.

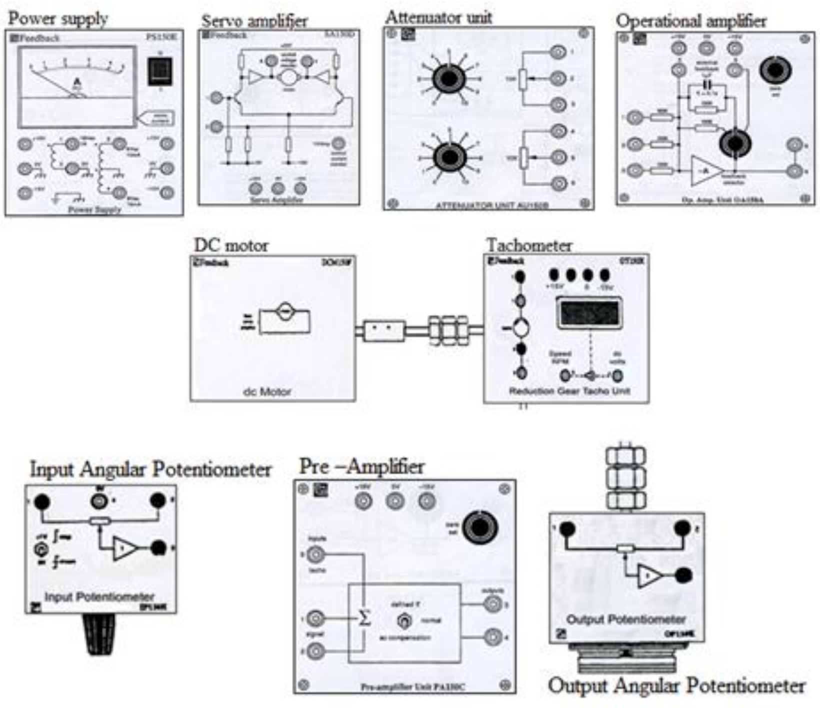


Figure 2.1: Servo Motor System Components

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 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:

$$\frac{1}{b}\dot{y} + \frac{a}{b}y = r(t) \tag{2.1}$$

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

$$\frac{Y(s)}{R(s)} = \frac{b}{s+a} \tag{2.2}$$

The time domain response of system to a **unit step** input is given by Figure 2.1 and equation 2.3.

$$y(t) = \frac{b}{a}(1 - e^{-at}) \tag{2.3}$$

The characteristics of the system can be defined with help of Figure 2.1 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:

$$K = \lim_{s\to 0} sY(s) = \lim_{s\to 0} s(\frac{1}{s}\frac{b}{s+a}) = \lim_{t\to\infty} y(t) \tag{2.4}$$

or from Figure 2.1,

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

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 2.2.

$$\tau = \frac{1}{a} \tag{2.5}$$

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.

$$T_r = \frac{2.2}{a} \tag{2.6}$$

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.

$$T_s = \frac{4}{a} \tag{2.7}$$

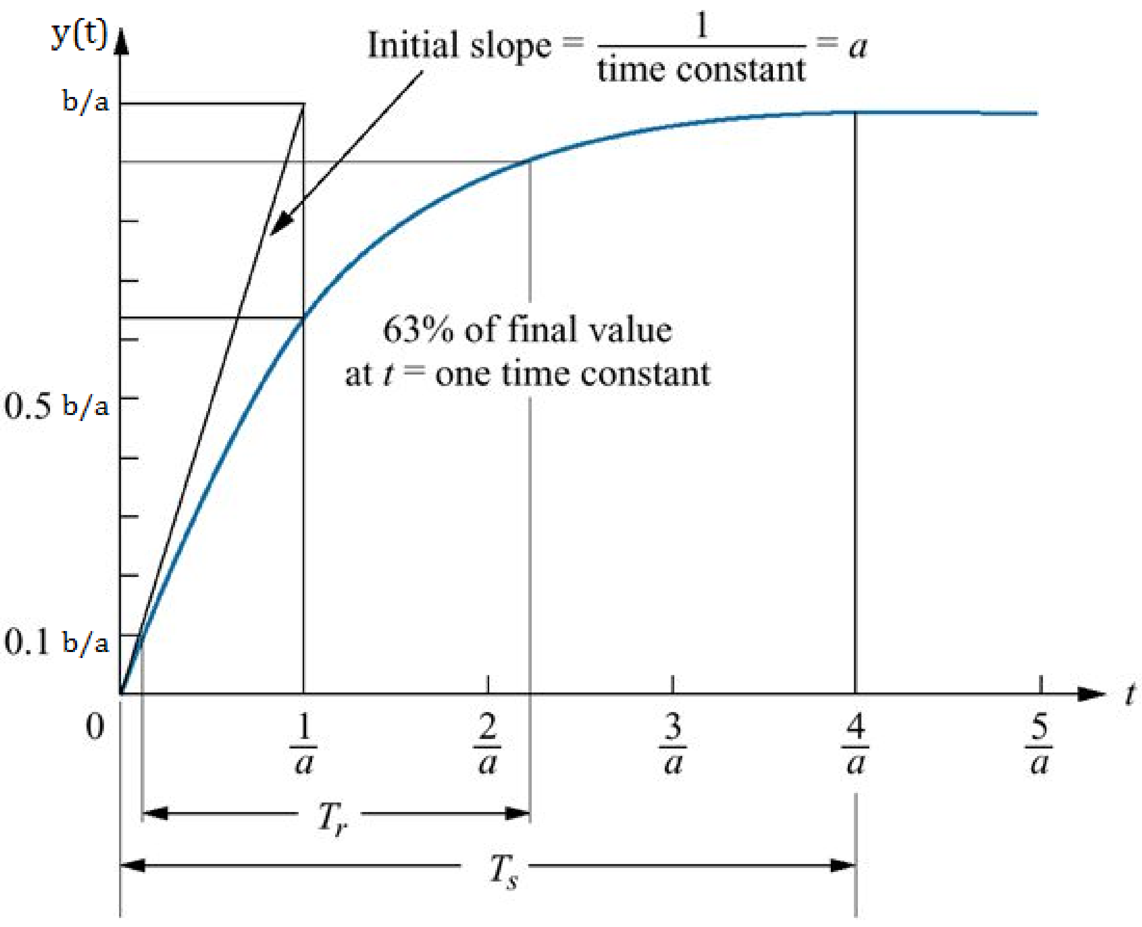


Figure 2.2: unit step response of a first order system to a unit step input.

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

$$T(s) = K\frac{\omega_n^2}{s^2+2\omega_n\zeta s+\omega_n^2} \tag{2.8}$$

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 **<u>unit step</u>**, then,

$$Y(s) = K\frac{\omega_n^2}{s(s^2+2\omega_n\zeta s+\omega_n^2)} \tag{2.9}$$

The characteristic equation of this system is;

$$s(s^2+2\zeta\omega_n s+\omega_n^2) = 0 \tag{2.10}$$

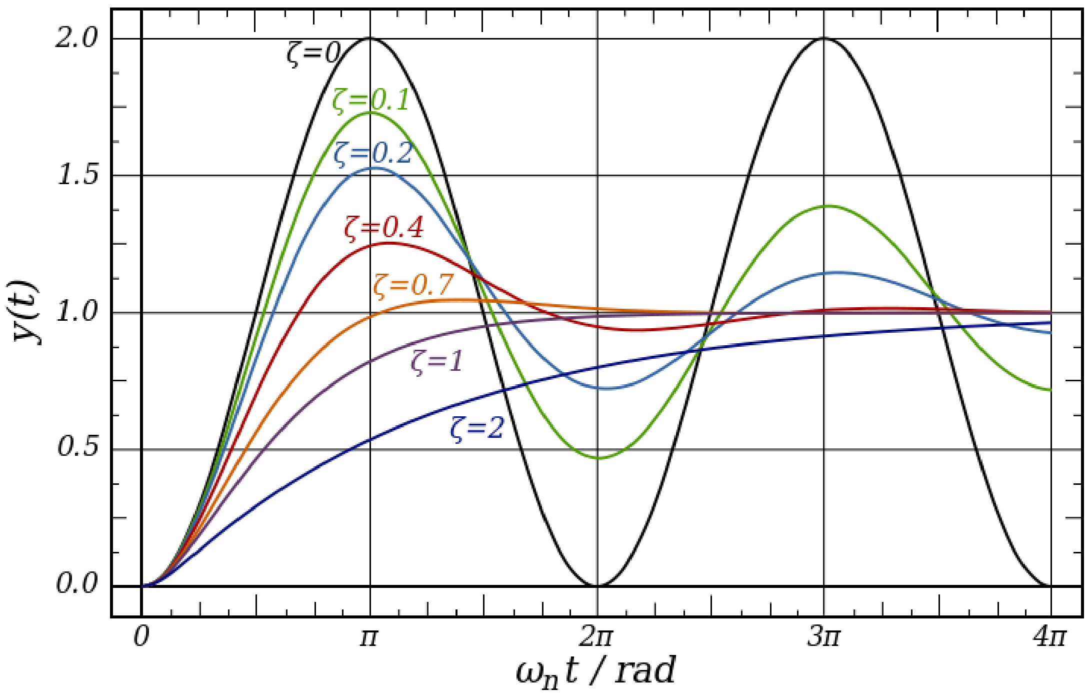
$s = 0$ pole at origin or $s^2+2\omega_n\zeta s+\omega_n^2 = 0$ then;

$$s_{1,2} = -\zeta\omega_n \pm \omega_n\sqrt{\zeta^2-1} \tag{2.11}$$

From equation 2.11, 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 2.3 shows the step response for different values of ζ.



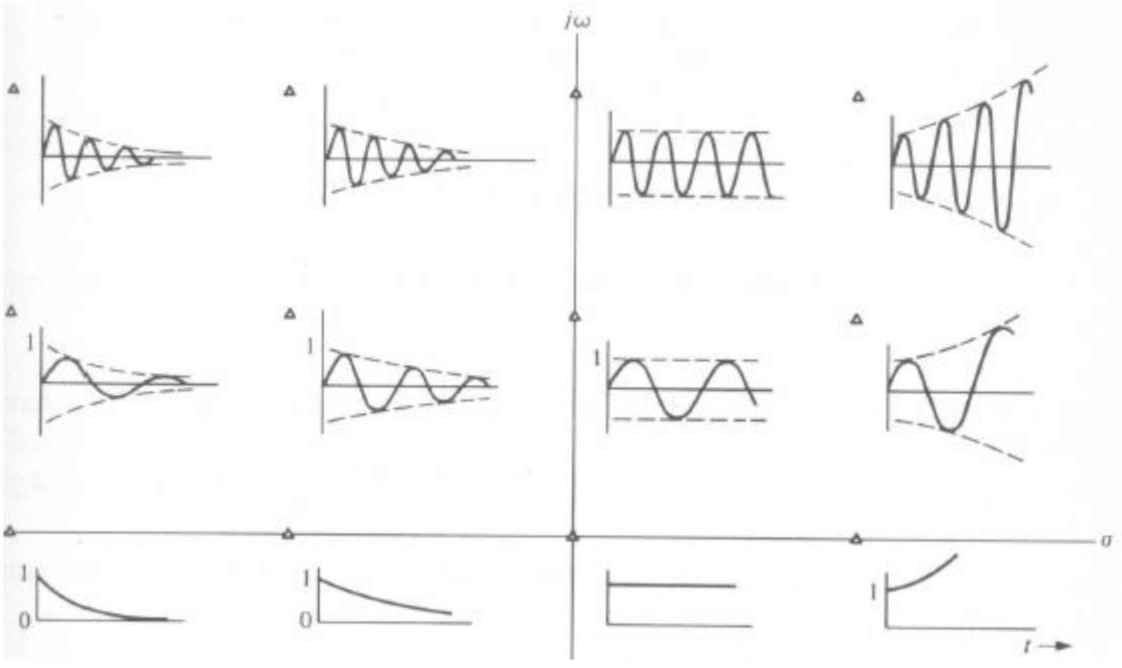


Figure 2.3: Second Order System Responses

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

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

$$s_{1,2} = \underbrace{-\zeta\omega_n}_{\text{Real part}} \pm \underbrace{j\omega_n\sqrt{1-\zeta^2}}_{\text{Imaginary part}} \tag{2.12}$$

Taking the Laplace inverse of equation 2.9 in case ($0 < \xi < 1$)

$$y(t) = 1 - \frac{1}{\sqrt{1-\xi^2}} e^{-\xi w_n t} \sin\left(w_n\sqrt{1-\xi^2} * t + \cos^{-1}\xi\right) \tag{2.13}$$

The following figure shows the under damped response the system and some of the performance specifications. These system specification are given by the following equations

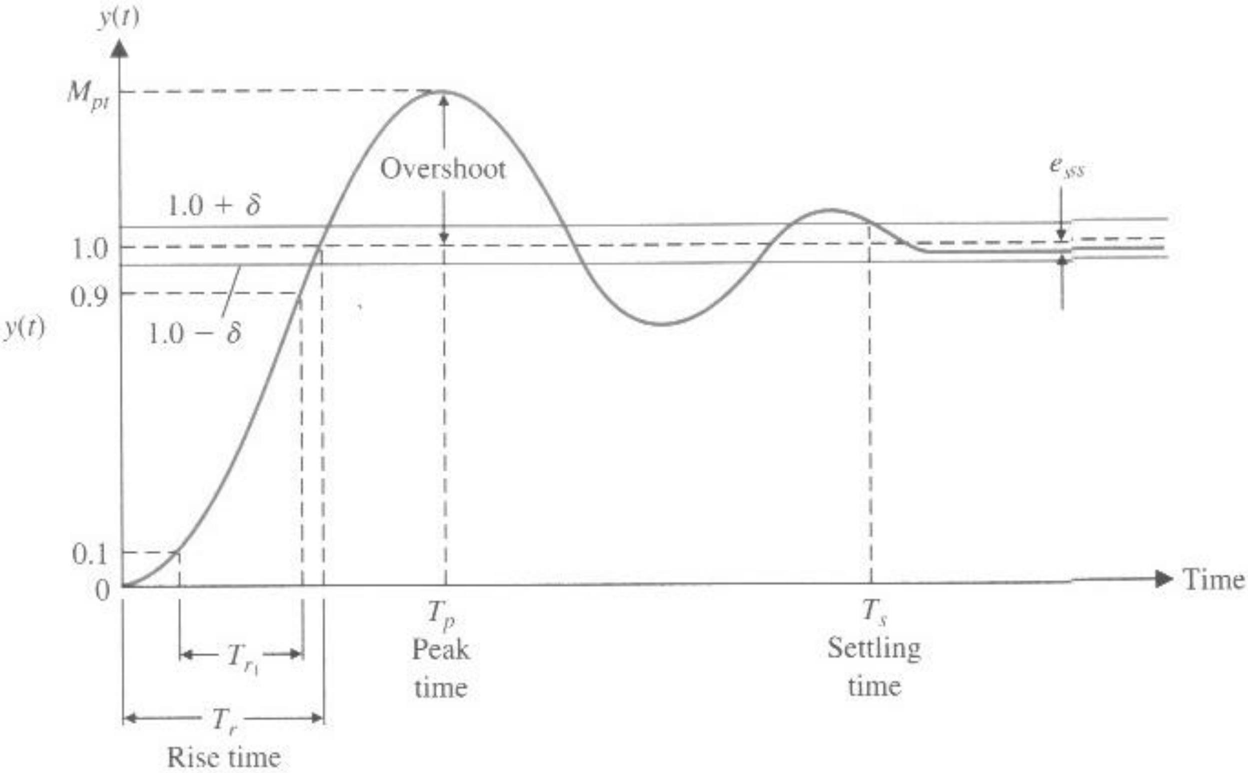


Figure 2.4: Underdamped Second Order System Response

Percent overshoot

$$PO\,\% = 100\, e^{-\xi\pi / \sqrt{1-\xi^2}} \tag{2.14}$$

Maximum value (peak)

$$M_p = \left(1 + \exp\left(-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}\right)\right) * y_{ss} \quad (2.15)$$

Peak time

$$T_p = \frac{\pi}{w_n\sqrt{1-\xi^2}} \quad (2.16)$$

Settling time (2% error)

$$T_s = \frac{4}{\xi w_n} \quad (2.17)$$

Rise time

$$T_{r1} = \frac{2.16\xi + 0.64}{w_n} \quad (2.18)$$

$$K = \lim_{s\to 0} sY(s) = \lim_{t\to\infty} y(t) \quad (2.19)$$

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

$$N = \frac{4\sqrt{1-\zeta^2}}{2\pi\zeta} \quad (2.20)$$

Note that all system specifications 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.

The tachometer works essentially as a voltage generator, with the output voltage a proportional to the magnitude of the angular velocity of the input shaft. 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.

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

Procedure:

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

1. Speed Control System

2. Zero set the OP-AMP, (i.e. the input voltage to op-amp must be zero and measure the output Vout, turn the knob until Vout = 0).
3. Connect the servomotor in its speed control form based on Figure 2.5. Don't forget to connect the power supply to the summing amplifier.
4. Connect the output of the tachogenerator to the oscilloscope and monitor the response.

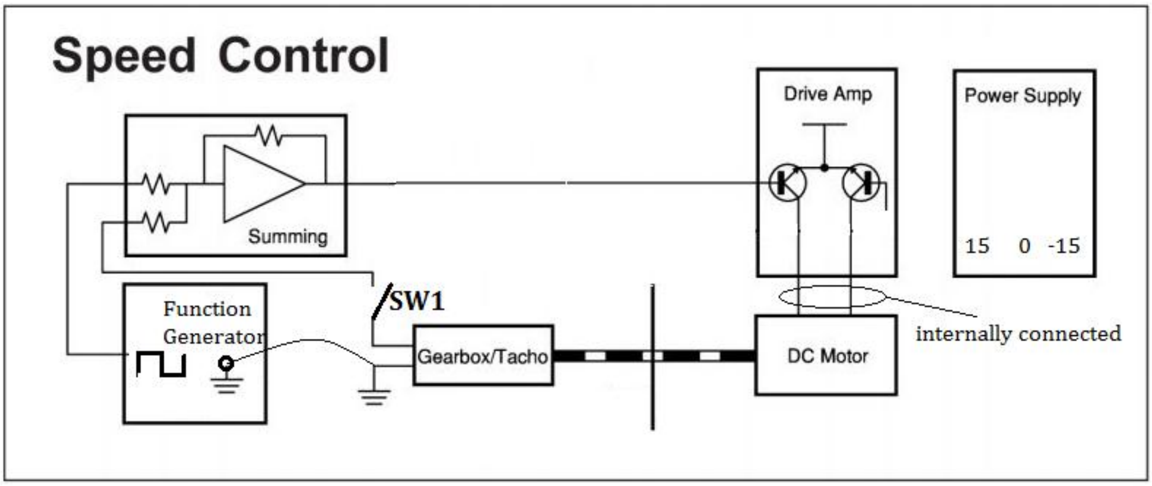


Figure 2.5: Speed Controlled Servomotor

2. Position Control System

1. Zero set both the OP-AMP and 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 based on Figure 2.6. Don't forget to connect the power supply to the summing amplifier, the pre-amplifier and the output potentiometer.
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.

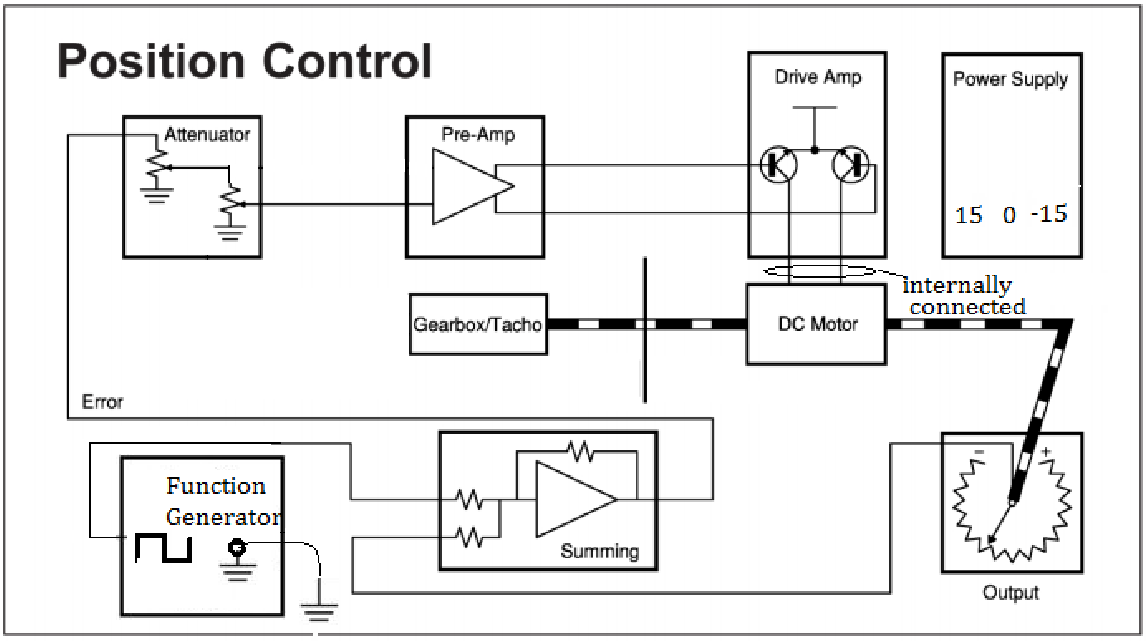


Figure 2.6: Position Controlled Servomotor

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, and transient response 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 to variation in forward-path gain
    - Accuracy
    - Closed-loop system disturbance rejection improvement
    - The extent to which loop gain affects these performance characteristics

Apparatus:

1. Servo amplifier : SA150D
2. Servo motor :DCM150F
3. Power supply : PS150E
4. Attenuator unit : AU150B
5. Operational amplifier : OU150A
6. Tachometer : GT150X
7. Voltmeter – Oscilloscope – Function generator

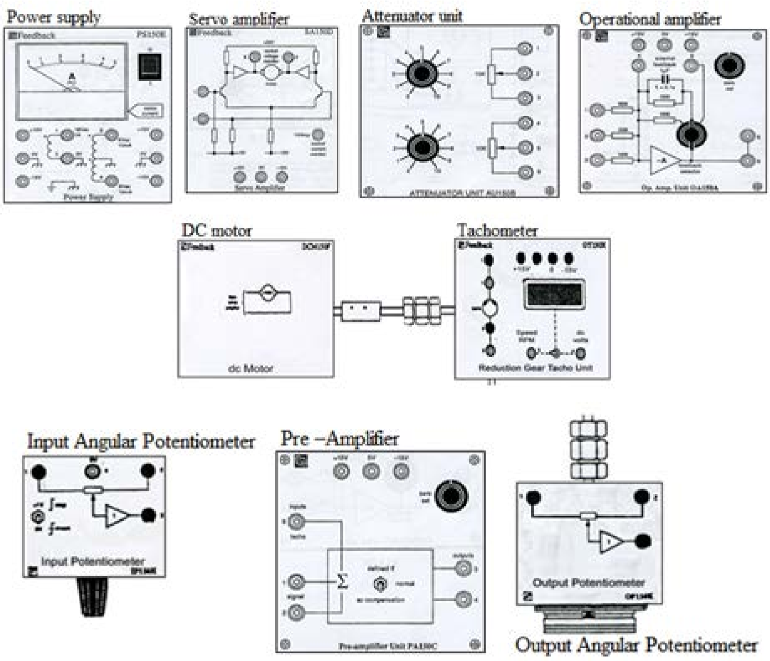


Figure 3.1: Servo Motor System Components

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 3.3.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 3.2: Process to Be Controlled.

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 3.2.

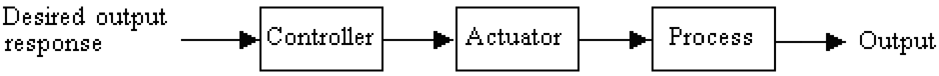


Figure 3.3: Open-loop Control System

In contrast a closed-loop system utilizes an additional measure of the actual output to compare the actual output 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 3.4.

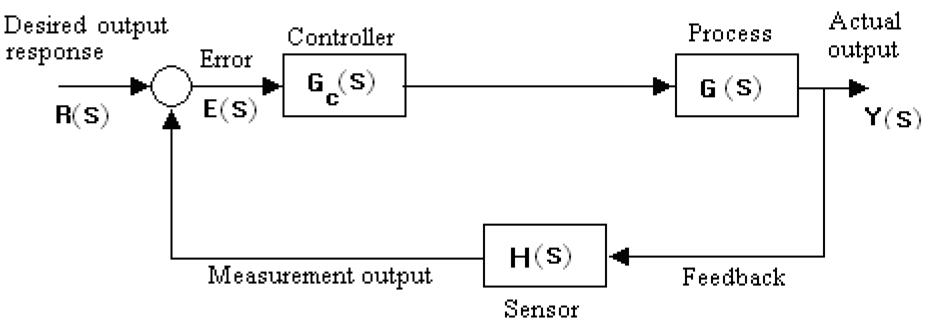


Figure 3.4: Closed-loop feedback control system

Control systems performance is judged by several characteristics such as Accuracy and steady-state error, 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 3, the error is

$$E(s) = R(s) - Y(s)H(s) \tag{3.1}$$

Assuming unity feedback

$$E(s) = R(s) - Y(s) \tag{3.2}$$

Then

$$E(s) = \frac{1}{1 + G_C G(s)} R(s) \tag{3.3}$$

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

$$e_{ss} = \lim_{t \to \infty} e(t) = \lim_{s \to 0} sE(s) \tag{3.4}$$

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 the change of the process transfer function (or parameter) for a small incremental change.

System transfer function is

$$T(s) = \frac{Y(s)}{R(s)} = \frac{Gc(s)G(s)}{1 + Gc(s)G(s)} \tag{3.5}$$

Therefore, the sensitivity is defined as:

$$S_G^T = \frac{\Delta T(s)/T(s)}{\Delta G(s)/G(s)} \tag{3.6}$$

In the limit, for small incremental changes, Equation 3.6 becomes:

$$S_G^T = \frac{\partial T / T}{\partial G / G} = \frac{\partial T}{\partial G} \cdot \frac{G}{T} \tag{3.7}$$

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 3.7. The system transfer function of the closed-loop system is:

$$T(s) = \frac{Gc(s)G(s)}{1 + Gc(s)G(s)} \tag{3.5}$$

Therefore the sensitivity of the feedback system is:

$$S_G^T = \frac{\partial T}{\partial G} . \frac{G}{T} = \frac{Gc}{(1 + GcG)^2} . \frac{G}{GGc/(1 + GcG)} \tag{3.8}$$

Or:

$$S_G^T = \frac{1}{1 + Gc(s)G(s)} \tag{3.9}$$

3. Disturbance Rejection

For the open loop in Figure 3.5.a

$$\mathrm{Y(s)} = Gc(s)G(s)R(s) + GD(s) \tag{3.10}$$

$$\mathrm{Y_R(s)} = Gc(s)G(s)R(s) \tag{3.11}$$

$$\mathrm{Y_D(s)} = GD(s) \tag{3.12}$$

For the closed-loop system in Figure 3.5.b, assuming no input signal (R(s)=0) and unity feedback, then

$$\mathrm{Y_D(s)} = \frac{\mathrm{G}}{1 + G_C G} D(s) \tag{3.13}$$

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

$$\mathrm{Y_R(s)} = \frac{Gc(s)G(s)}{1 + Gc(s)G(s)} R(s) \tag{3.14}$$

Then,

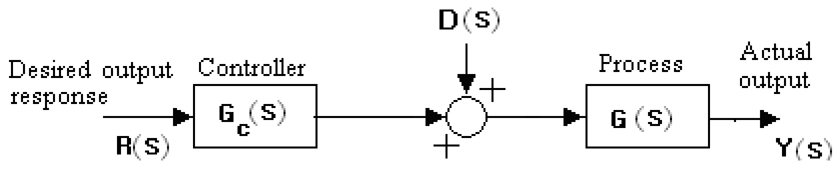
$$Y(s) = \frac{Gc(s)G(s)}{1+Gc(s)G(s)}R(s) + \frac{G}{1+G_C G}D(s) \qquad (3.15)$$

where,

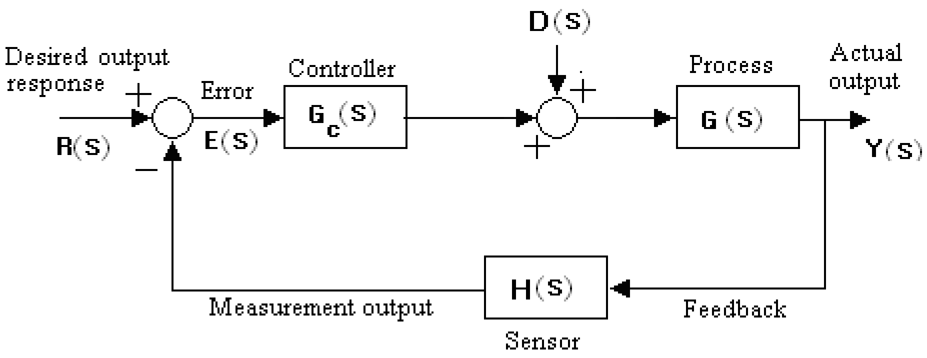
Y_R is the output due to the input signal

Y_D is the output due to the disturbance signal

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



(a)



(b)

Figure 3.5: (a): Open Loop Control system with Disturbance Signal

(b)Closed-loop Control System with Disturbance Signal

Procedure:

Connect the servomotor system where its input is voltage and its output is speed as shown by Figure 3.6. Don't forget to connect the power supply to the summing amplifier and the tachogenerator LCD.

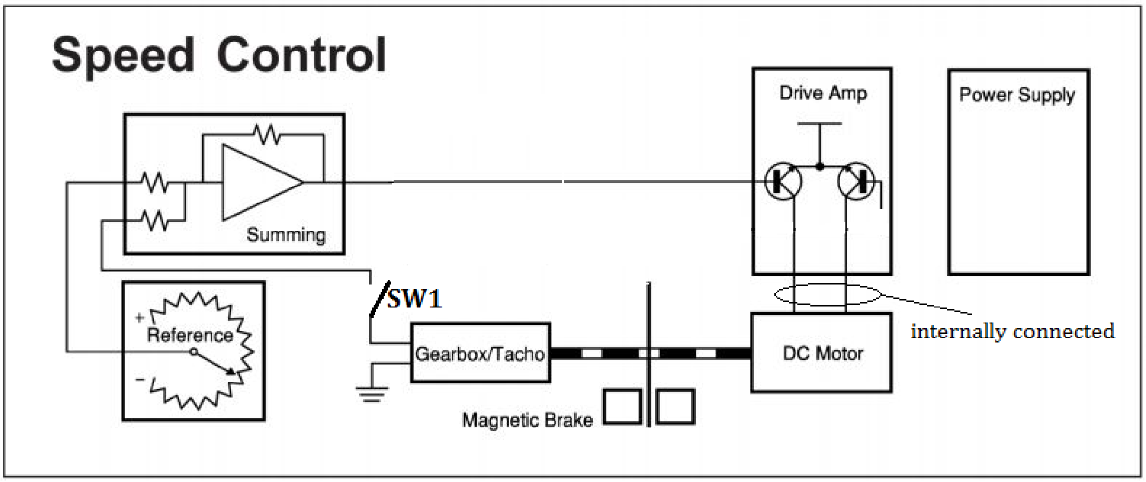


Figure 3.6: Speed Controlled Servomotor

Part 1: Steady state error.

1. Set the reference voltage to 1V and the summing amplifier gain to 1.
2. While the switch SW1 is open and the magnetic break is removed, observe the speed of the motor and record the LCD voltage reading.
3. Increase the gain of the summing amplifier to 2 by changing its feedback resistance. Observe the change in motor speed (increased slightly, increased noticeably, decreased slightly or decreased noticeably) and record the LCD voltage reading.
4. For the same above settings, close the switch SW1, observe the speed of the motor and record the LCD voltage reading.
5. Decrease the gain of the summing amplifier to 1 by changing its feedback resistance. Observe the change in motor speed (increased slightly, increased noticeably, decreased slightly or decreased noticeably) and record the LCD voltage reading.

Part 2: Sensitivity

1. Set the reference voltage to 1V and the summing amplifier gain to 1.
2. While the switch SW1 is closed and the magnetic break is removed, observe the speed of the motor and record the LCD voltage reading.
3. Increase the gain of the summing amplifier to 2 by changing its feedback resistance. Record the LCD voltage reading.
4. Increase the gain of the summing amplifier to 3 by changing its feedback resistance. Record the LCD voltage reading.

Part 3: Disturbance rejection

1. Set the reference voltage to 1V and the summing amplifier gain to 1.
2. While the switch SW1 is open, apply the magnetic break as instructed by your lab supervisor. Observe the speed of the motor and record the LCD voltage reading.
3. For the same above settings, increase the gain of the summing amplifier to 2 by changing its feedback resistance. Observe the change in motor speed (increased slightly, increased

noticeably, decreased slightly or decreased noticeably) and record the LCD voltage reading.

4. For the same above settings, close the switch SW1, observe the speed of the motor and record the LCD voltage reading.
5. For the same above settings, decrease the gain of the summing amplifier to 1 by changing its feedback resistance. Observe the change in motor speed (increased slightly, increased noticeably, decreased slightly or decreased noticeably) and record the LCD voltage reading.

Discussion and Analysis:

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

Experiment 11

PID Controller and Tuning

Objectives:

- To investigate the characteristics of a PID controller and the effect of each control gain on the dynamic response of the system.
- To implement a PID controller using operational amplifiers
- To implement control systems using the PID kit.
- To improve the response of control system using PID controller.

Apparatus:

Figure 4.1 shows PID kit used in this experiment.

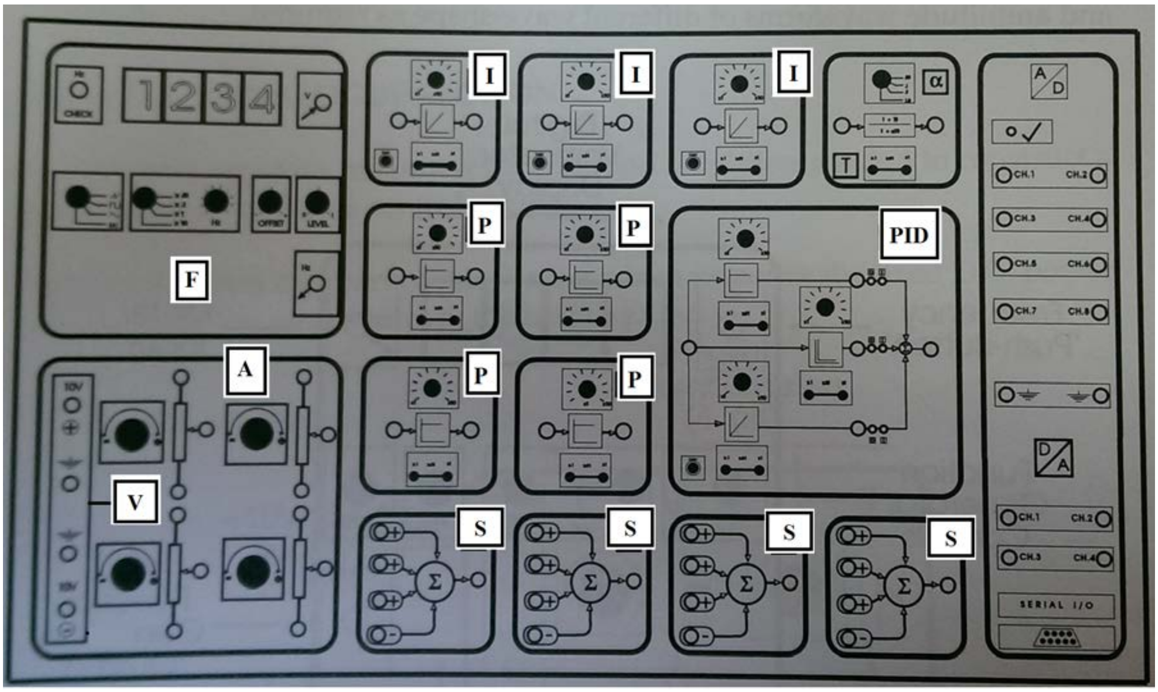


Figure 4.1: PID Kit

Theoretical Background:

1. PID Controller

You've probably seen the terms defined before: **P -Proportional**, **I - Integral, D - Derivative**. These terms describe three basic mathematical functions applied to the error signal, Verror = Vset - Vsensor. This error represents the difference between where you want to go (Vset), and where you're actually at (Vsensor). The controller performs the PID mathematical functions on the error and applies their sum to a process (motor, heater, etc.) So simple, yet so powerful! If tuned correctly, the signal Vsensor should move closer to Vset.

The PID controller has the following transfer function;

$$PID = k_P + sk_D + \frac{k_I}{s} = \frac{s^2 k_D + sk_P + k_I}{s} \qquad (4.1)$$

Tuning a system means adjusting three multipliers Kp, Ki and Kd adding in various amounts of these functions to get the system to behave the way you want. Table 4.1 and 4.2 below summarizes the PID terms and their effect on a control system.

Table 4.1

Term	Math Function	Effect on Control System
P Proportional	**KP x Verror**	**Typically the main drive in a control loop, KP reduces a large part of the overall error.**
I Integral	**KI x ∫ Verror dt**	**Eliminates the final error in a system. Summing even a small error over time produces a drive signal large enough to move the system toward a zero error.**
D Derivative	**KD x dVerror / dt**	**Counteracts the KP and KI terms when the output changes quickly. This helps reduce overshoot and ringing. It has small effect on final error.**

Table 4.2

CL RESPONSE	RISE TIME	OVERSHOOT	SETTLING TIME	S-S ERROR
Kp	Decrease	Increase	Small Change	Decrease
Ki	Decrease	Increase	Increase	Eliminate
Kd	Small Change	Decrease	Decrease	Small Change

Note that these correlations may not be exactly accurate, because Kp, Ki, and Kd are dependent on each other. In fact, changing one of these variables can change the effect of the other two. For this reason, the table should only be used as a reference when you are determining the values for Ki, Kp and Kd.

2. Implementing the PID Controller Using Op-Amp

Figure 4.2 shows how to separately implement a P, D and an I controllers.

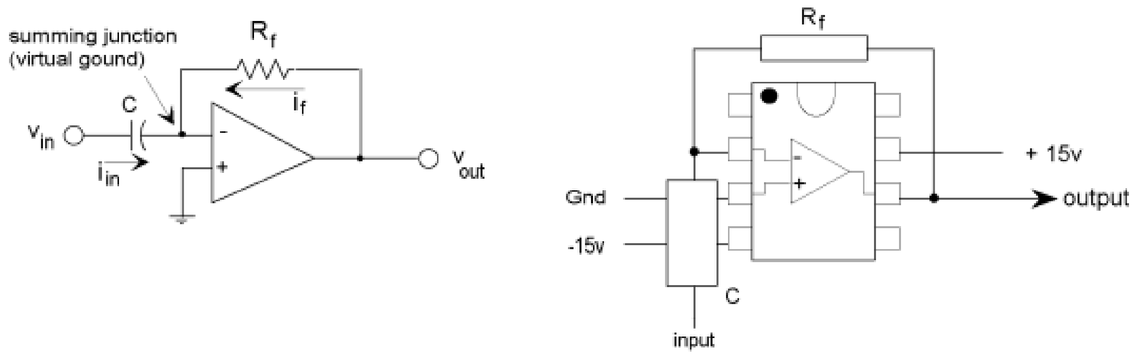


Figure 4.21.a: Derivative Controller

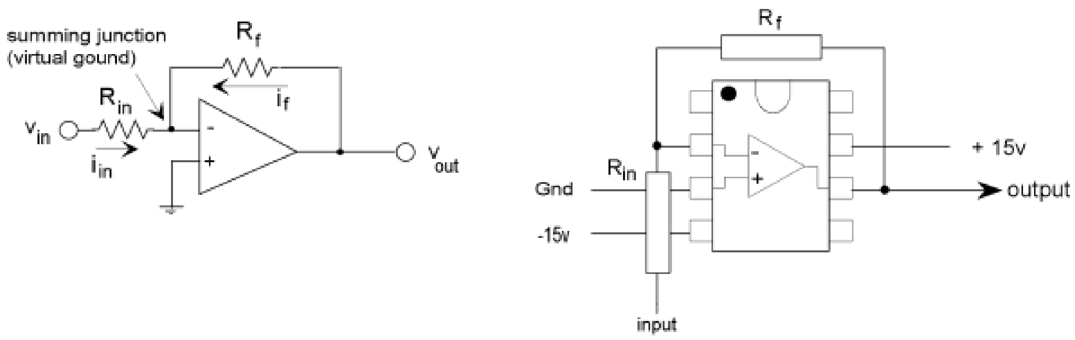


Figure 4.2.b: Proportional Controller

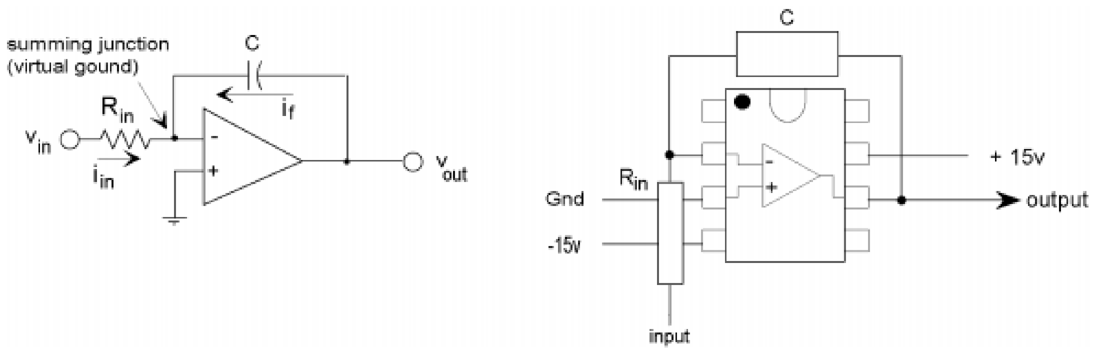


Figure 421.c: Integral Controller

3. Tuning the PID Controller

Tuning the PID controller can be like learning to roller blade, ski or maybe riding a bull. Until you have done it a few times, the literature you have read really doesn't hit home. But after few attempts (and falls), you find it wasn't so bad after all - in fact it was kind of fun!

Although you'll find many methods and theories on tuning a PID, here's a straight forward approach to get you up and solving quickly.

1. SET KP. Starting with KP=0, KI=0 and KD=0, increase KP until the output starts overshooting and ringing significantly.

2. SET KD. Increase KD until the overshoot is reduced to an acceptable level.

3. SET KI. Increase KI until the final error is equal to zero.

4. Keep adjusting the parameters until you reach the desired response.

4. Implementation of Control Systems Using the PID Kit

Figure 4.3 shows the PID kit used in the laboratory. And Table 4.3 explains the uses of each part of this kit.

The best way to explain the PID kit used the laboratory is through an example.

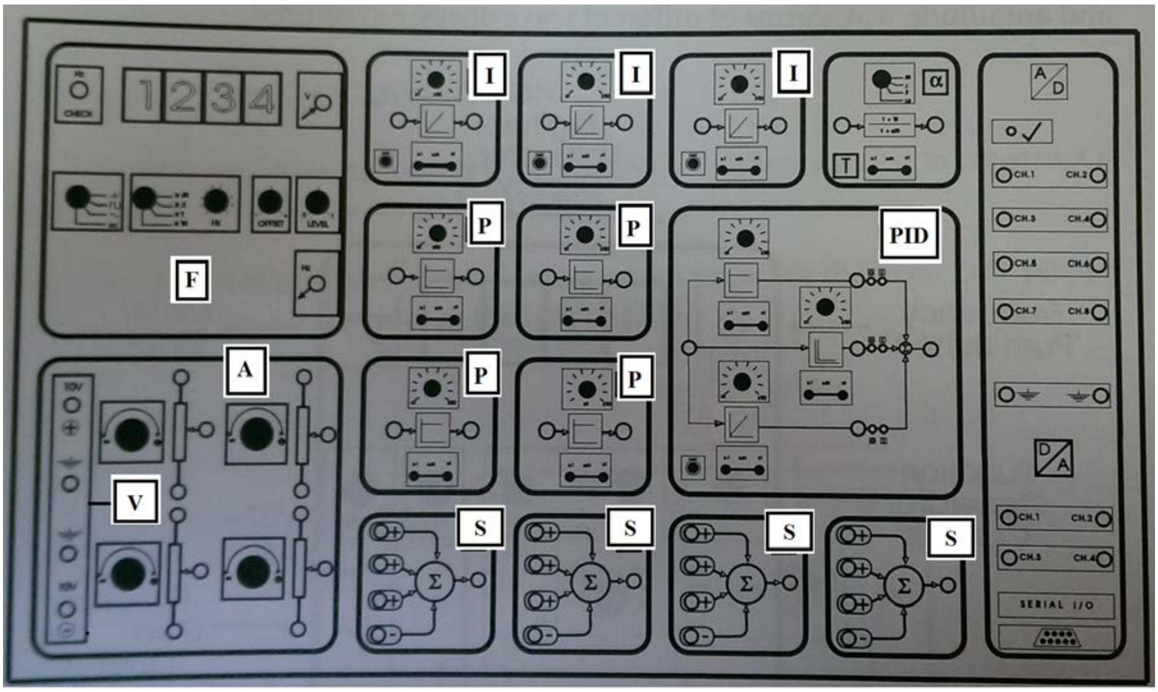


Figure 4.2: PID Kit

Table 4.3

F	**Function generator**
V	**Dc power supply (±10V)**
I	**Integrator**
P	**Proportional**
PID	**Proportional , integral, derivative Controller**
S	**Summing point**
A	**Attenuator (Potentiometer)**

Procedure:

It is best to shoe the procedure through a practical example.

Example:

Connect the open loop transfer function T(s), then use the PID controller to control the performance of that system?

$$T(s) = \frac{1}{s^2 + 5s + 10}$$

Solution:

1. Rewriting the transfer function:

$$T(s) = \frac{Vo}{U} = \frac{1}{s^2 + 5s + 10} \qquad (4.2)$$

2. Rearranging the equation such that the highest derivative is at one side of the equation

$$Vo'' = U - 5Vo' - 10Vo \qquad (4.3)$$

3. The equal sign (=) in equation 4.3 is analogous of the summation point in the block diagram, such that all terms in the RHS of the equation are the inputs to the summation point, and the LHS of the equation (the highest derivative) is the output of the summation point as illustrated by Figure 4.4

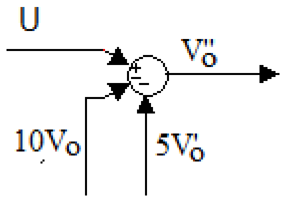


Figure 4.4: Step 3 of the Procedure

4. From the highest derivative integrate until you reach the zero derivative (which is the output of the system). In this example you need to integrate twice. See Figure 4.5.

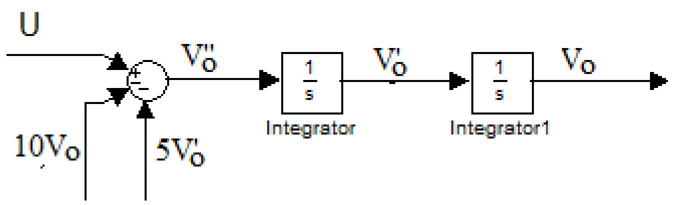


Figure 4.5: Step 4 of the Procedure

5. Complete the block diagram by adding the gain(s) to formulate the missing terms in the summation point. In this example 2 gains are required to formulate 5V'o and 10Vo terms. The system described by equation 4.4 is represented in block diagram in Figure 4.6

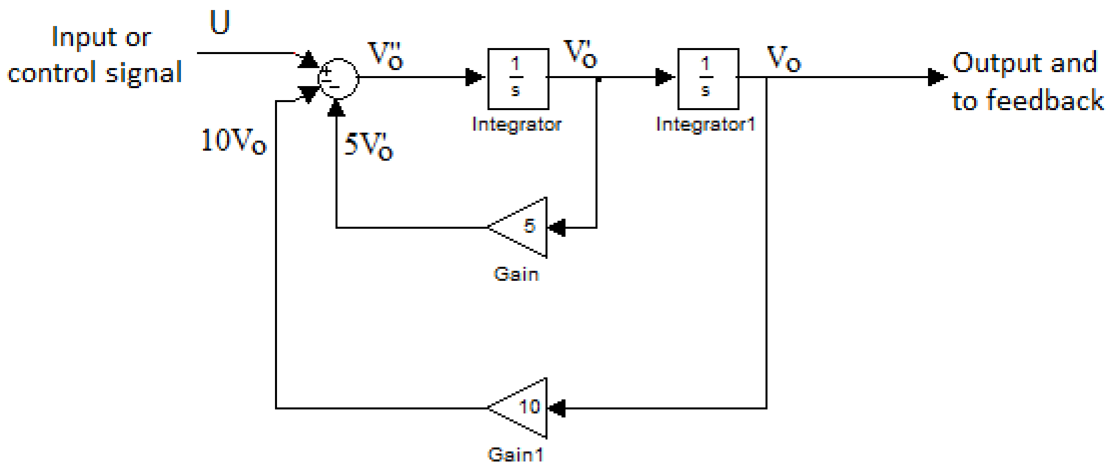


Figure 4.6: Block Diagram for T(s)

6. Now we can build the system using our kit in figure 4.7
7. To control the system using a closed loop PID controller complete as in Figure 4.8. The input to the system can be obtained from the function generator or the potentiometer for the PID kit or to any external power supply. See figure 4.8

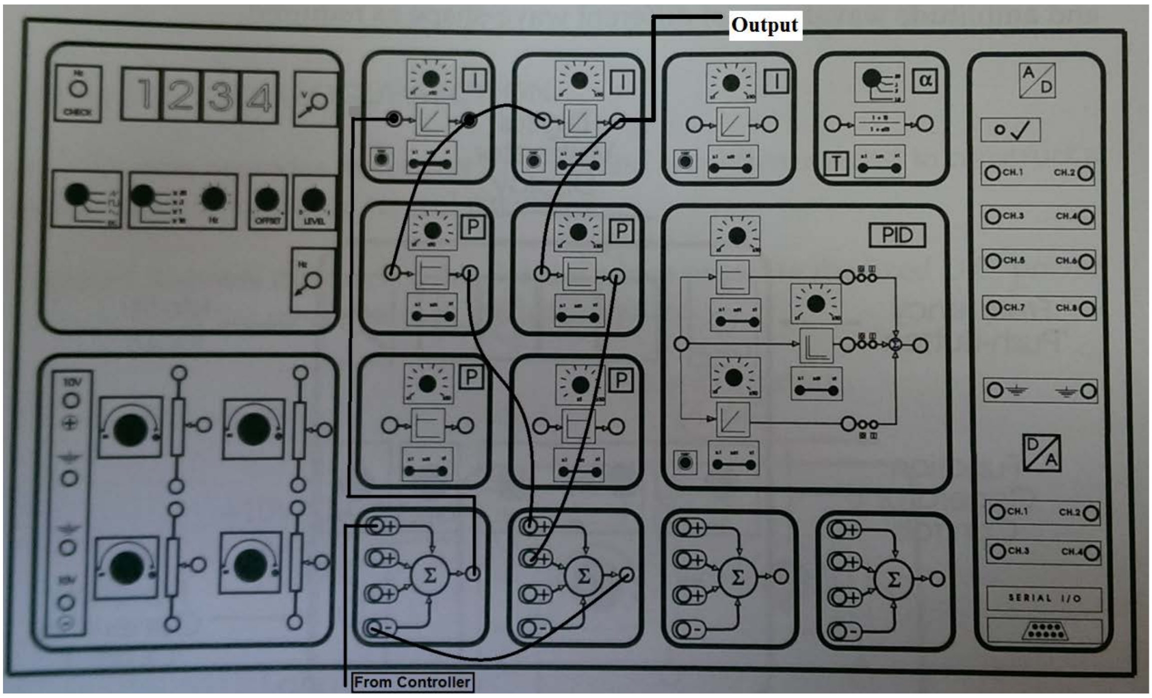


Figure 4.7: Implementation of T(s)

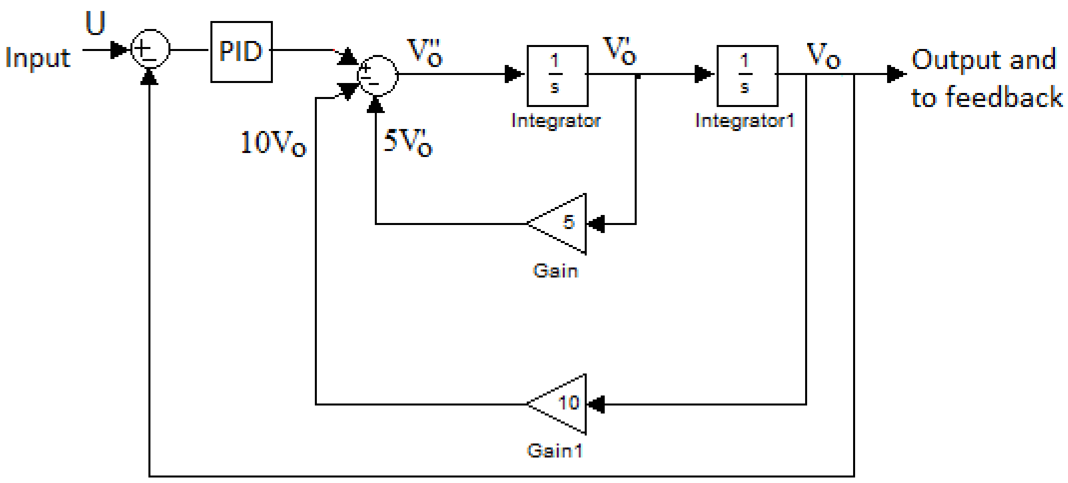


Figure 4.8: Closed Loop System with PID Controller Block Diagram

8. Implement the system on the kit as in Figure 4.9. Both inputs and output can be connected to an oscilloscope to observe the response of the system.

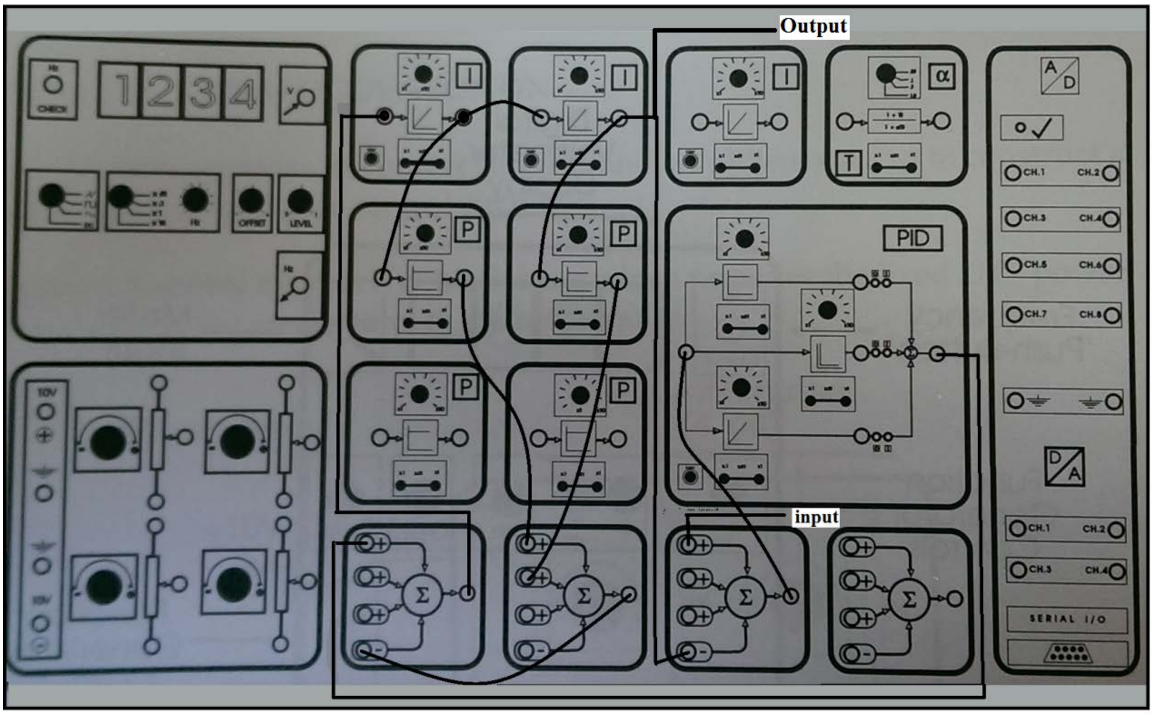


Figure 4.9: Closed Loop PID Control System for T(s)

Discussion and Analysis:

1. What is the effect of increasing each controller gain on:
   a. Steady state error.
   b. Percentage overshot.

2. For flowing system :

$$T(s) = \frac{2s}{3s-1}$$

a. Implement the system using the PID kit and notice the stability of unit step response
b. Add a PID controller to stabilize the system.