SIMON FRASER UNIVERSITY
THINKING OF THE WORLD

ENSC387: Introduction to Electromechanical Sensors and Actuators

LAB 1: POSITION AND VELOCITY SENSORS

1 Passive Position Sensing

1.1 Introduction

Potentiometers are simple, yet useful devices for making displacement and velocity measurements. However, it is important to choose the proper style and output format of such a device for the intended application. There are two main types of potentiometers: linear (slider) and rotary. Within the rotary type there are single-turn pots (maximum angular range up to 360 degrees), multi-turn pots, and servo pots (infinite turn). Output formats can be linear, logarithmic, or sinusoidal resistances.

As the name implies, the linear style of potentiometer can only be used for measuring linear displacement and velocity of a moving object, while a device in a rotary style can be used for making only angular displacement and velocity measurements. The key advantage offered by a potentiometer for sensing applications is its ease of use and little signal conditioning required other than buffering. The obvious disadvantages of this type of device include limited operating range, dead zone, and mechanical wear between the wiper arm on the stationary resistive element over extended use.

In this lab, we will experiment with the servo pot which has no mechanical limitation of its angular position but it exhibits an electrical discontinuity when a particular range of angular input is reached.

1.2 Experimental Procedure

The *Digiac* training system has a servo pot that is internally connected to a plus and a minus 5 volt source. The wiper is brought out to the panel for use as an input to another electronic functional block. With this arrangement, a 0° displacement applied to the pot will yield 0 volt at the wiper, while a 90° input will yield +2.5 volts and 270° will yield –2.5 volts output.

a) Measure and plot the voltage output of the servo pot as a function of displacement angle (as outlined in exercise #4 on pages 43 and 44 in the *Digiac* manual). Note and comment on the linearity and also what happens to the potentiometer output near the 180° region (180° ∓ 5° where an electrical discontinuity occurs). Hint: engage the clutch so that the pot is being driven by the drive shaft. You will find that you have more precision over positioning the pot by following the instructions in the "Note" on page 44 of the *Digiac* manual.

Question: Is there a position on the servo pot that is ambiguous? (i.e., a position that can be confused with another position on the pot).

b) Connect the closed loop DC motor control circuit shown in figure 1 on the *Digiac* system using the servo pot as the feedback element.

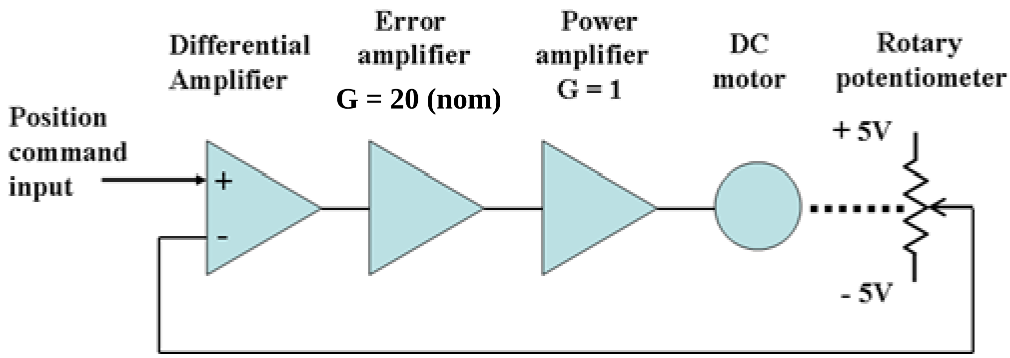


Figure 1: Closed-loop DC motor control using a servo potentiometer.

1. Make sure you null the DC offset of the error amplifier each time you change its gain setting.
2. Ground the command input to the circuit and manually rotate the servo pot (while it is engaged to the motor shaft), say, by 30°. Explain what happens to the motor as a result of your act.
3. Connect the function generator to the command input of your motor control circuit. Set the function generator output to triangular waveform, 1Hz, 2.5Vpp. Observe the function generator output and that of the servo pot using an oscilloscope. Explain why the 2 waveforms look the way they appear on the oscilloscope.
4. Slowly increase the amplitude of your function generator output and describe the behavior of the system.
5. Reset the input command voltage to 2.5Vpp and slowly increase its frequency. Try to describe the behavior of the system.
6. Reset the function generator output to 1Hz, 2.5Vpp. Gradually vary the gain of the error amplifying stage from its normal setting of 20 to within the range of 1 and 50 and observe the output waveform of the servo pot. How does the behavior of the motor change as a result?

Notes:

1) Error Amp = Digiac Amplifier #1 or #2
2) DC offset null can be measured using the Digiac analog volt meter; (-) to 0V and (+) to error amp output.
3) When using any function generator, measure the output signal level using the oscilloscope. Be sure to recheck the signal level when the generator output is connected to the load. *The display indicator on the function generator is often misleading!*
4) Oscilloscopes generally don't measure well at low Hz frequencies. Try setting the function generator parameters on a higher frequency multiplier scale first to get a stable indication on the scope, and then set the function generator to the desired lower multiplier range.

2 Active Angular Position Sensing

2.1 Introduction

Because of the limitations of potentiometers in angular position measurements, we now consider a different type of angular position sensor, the resolver. The resolver has no limitations on angular position and the sensing method is based on magnetic coupling which requires no mechanical contact such as in the case of a pot. The resolver consists of two pairs of stator coils (usually identical) positioned at 90° degrees from each other. A third winding is on the freely rotating rotor connected to the outside world via a pair of slip rings. See figure 2 below.

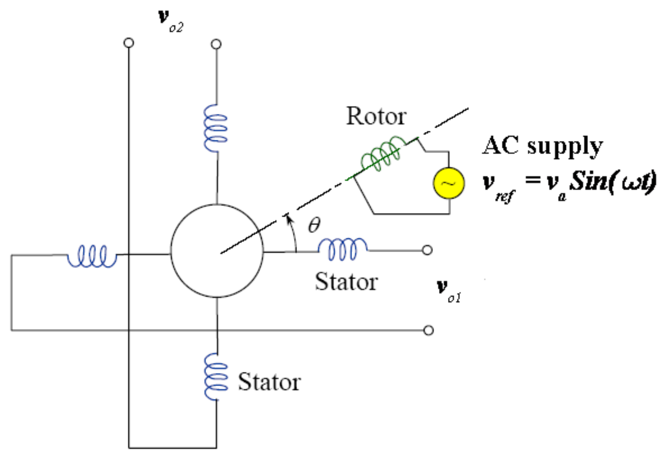


Figure 2: Circuit diagram of a resolver.

As discussed in class, there are 2 ways of using a resolver to make angular measurements. The first way (pictured above) is to energize the rotor winding with an AC reference signal (5 to 10 volts at a frequency of 1 KHz to 10 KHz). The AC reference signal will be coupled to the 2 stator windings, with the amplitude of each induced stator voltage being proportional to the cosine of the angle between the stator winding and the rotor winding. Because of the 90° separation between the 2 stator windings, the amplitude of the output voltage from the stator windings will be proportional to the sine and cosine of the rotor angle. Note that if the rotor angle is θ, (referenced to, say, stator winding #1) then the output voltage from stator windings #1 and #2 will be respectively (equations (2.1) and (2.2))

$$V_{01} = aV_a \sin(\omega t) \cdot \sin(\theta) \tag{2.1}$$

$$V_{02} = aV_a \sin(\omega t) \cdot \cos(\theta) \tag{2.2}$$

Now if we increase θ by 180 degrees, the output voltage from stator windings #1 and #2 will be

$$V_{01} = aV_a \sin(\omega t)\sin(\theta + \pi) = -aV_a \sin(\omega t)\sin(\theta) \tag{2.3}$$

$$V_{02} = aV_a \sin(\omega t)\cos(\theta + \pi) = -aV_a \sin(\omega t)\cos(\theta) \tag{2.4}$$

It is important to note the fact that while the amplitudes of these two signals have remained unchanged, their phases have reversed. Thus to decode a full 360°, we need some sort of phase sensitive detector, a simple rectifier will not be sufficient.

The second way to use a resolver in making angular measurements is to energize the two stator windings with two AC reference signals (5 to 10 volts at a frequency of 1 kHz to 10 kHz) bearing a 90° phase shift with each other and measure the induced voltage on the rotor winding (Figure 3).

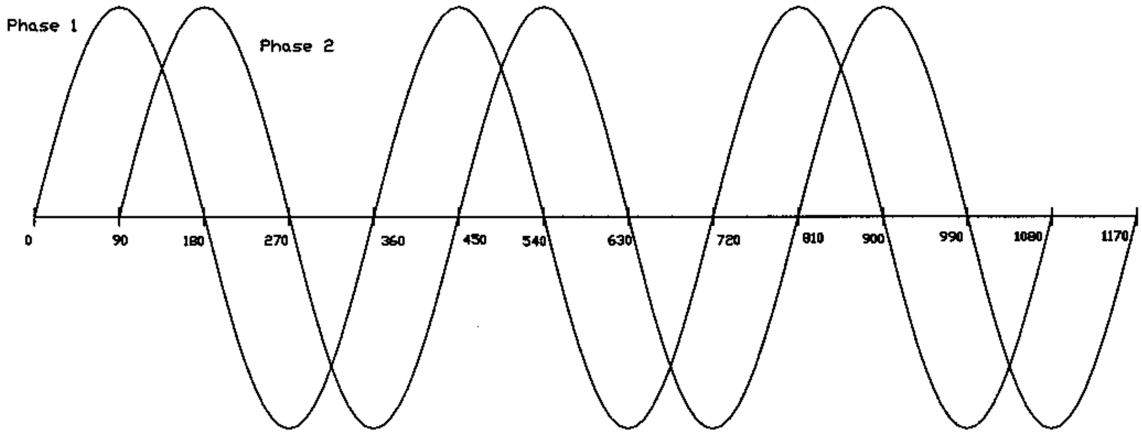


Figure 3: Pair of quadrature signals for connecting to the two resolver stator windings.

Since we have the 2 stator windings energized by two quadrature sinusoids, the induced voltage in the rotor will be equal to the vector sum of the two induced voltages from each stator winding.

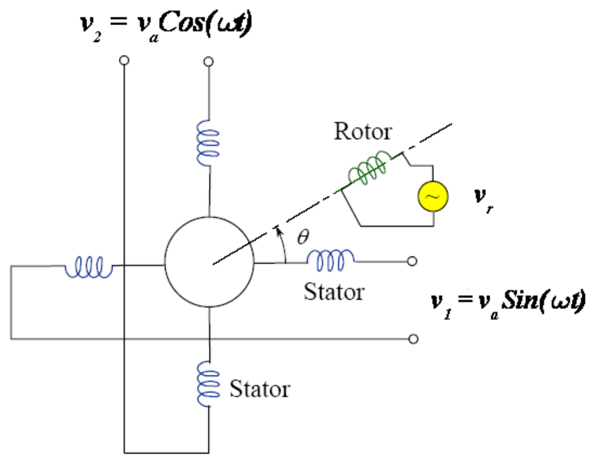


Figure 4: A resolver with its two stator windings driven by 2 quadrature input signals.

Note that magnitude of the induced rotor voltage from each stator winding will still be proportional to the sine (or cosine) of the angle between the rotor and that stator windings. Therefore, the rotor output voltage becomes (equation (2.5)).

$$V_r = aV_a \sin(\omega t)\cos(\theta) + aV_a \cos(\omega t)\sin(\theta) = aV_a \sin(\omega t - \theta) \tag{2.5}$$

The above equation manifests the fact that the electrical phase shift between V_r and V_1 actually represents the mechanical angular displacement applied to the device itself. Thus, when we measure the electrical phase angle between one stator winding voltage and the induced rotor voltage, we can measure the mechanical angle of the rotor. Figure 5 shows the time functions of these two signals.

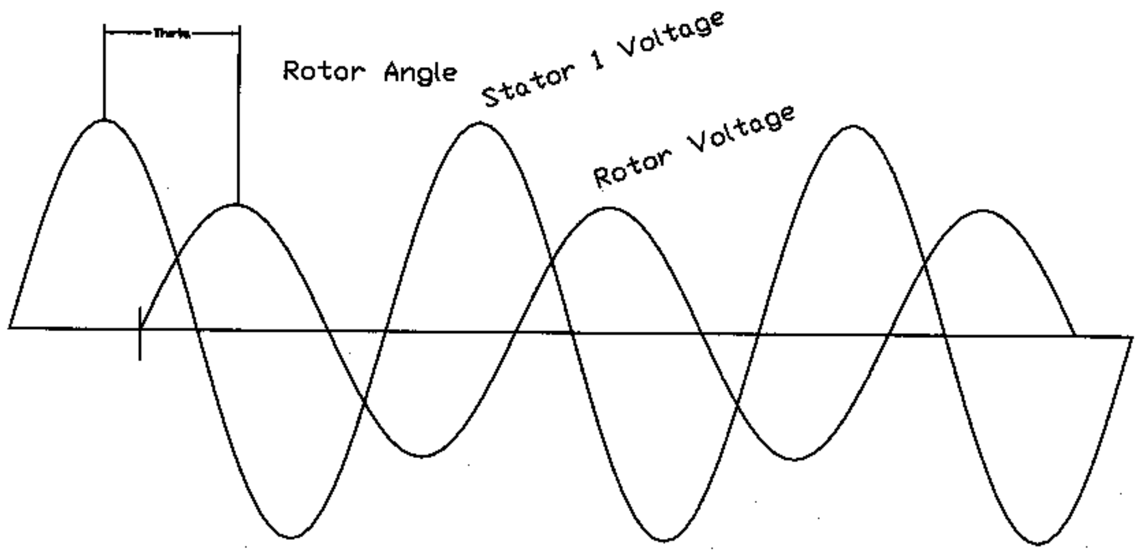


Figure 5: Physical angular displacement measurement can be obtained by measuring the electrical phase shift between the rotor output and one of the two stator inputs of the resolver.

2.2 Experimental procedure - resolvers

There are two methods to be used for this procedure.

2.2.1 Method 1

Connect the rotor winding to the signal generator (5 to 10 Vpp at 1 to 10 kHz) and observe the stator signals as you manually rotate the rotor. Take voltage measurements on both stator windings in 15° increments (or as best you can estimate) and note the phase reversal when the rotor angle increases by 180° and plot the results. You may wish to use the rotor signal as the external trigger for the scope and observe the two stator signals on channels 1 and 2.

Explain: Explain the operation of the resolver in this mode and a typical application.

D**escribe:** Also describe a simple design to fully decode 360° degrees of rotor rotation using this mode of operation.

2.2.2 Method 2

Use the quadrature amplifier (see Figure 6) to generate 2 sinusoidal signals with a 90° phase shift. Following the labeling on the board, connect the **+/-15** volt power supply current limited to 60mA and set the function generator to approximately 5 kHz and 5 Vpp sinusoid. Verify that the outputs of the quadrature amplifier are sinusoidal and approximately the same amplitude (5 Vpp) and with a phase shift of approximately 90°. If the amplitudes differ significantly, you can alter the input frequency slightly to make them equal. Ensure power supply is OFF while making connections. Connect the two quadrature amplifier outputs to the two stator ('field') windings on the resolver and, using oscilloscope CH1, observe the output voltage waveform induced in the rotor. Using oscilloscope CH2, monitor, and trigger on, the voltage across one of the stator ('field') windings. As you rotate the rotor, notice the continuous phase shift between the two signals.

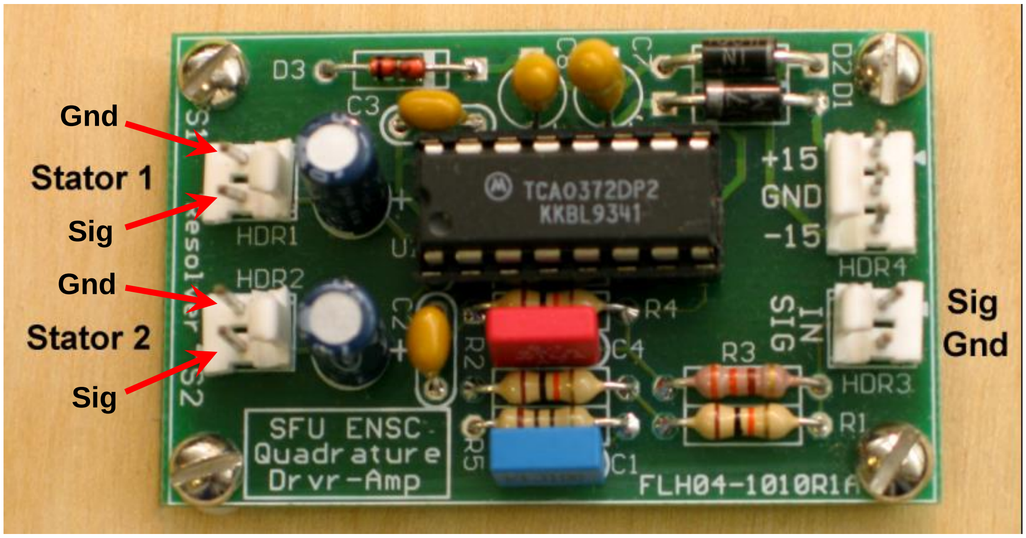
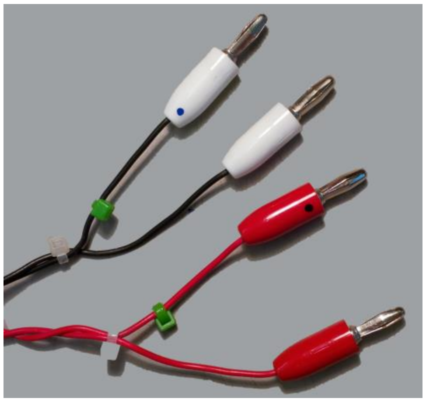


Figure 6: Amplifier for generating quadrature output signals at 5kHz.

Explain: The measurement procedure using the oscilloscope to measure the rotor angular position and estimate the measurement accuracy you can attain. If you required greater accuracy (say to 1 degree or better) how would you modify your measurement procedure?

Notes:

1) The Amplifier board requires +/- 15V, current limited to 60mA to operate. Failure to connect and set the power supply properly can result in permanent damage to the amplifier. To refresh your skills on power supply use, visit the tutorial on any lab computer. *Desktop > Reference Materials > Course Specific > Ensc-387*.



2) The technical support drawings for the amplifier unit are posted in the accompanying binder at the experiment workstation, as well as in the 387 lab computer folder (referenced above). Use these as a guide to ensure your connections are made correctly.

3) Supplied leadsets employ a coloured marker on the cable as well as a 'dot' on the banana plug to indicate the Gnd/Com. ***Be certain that the oscilloscope ground clips connect ONLY to these identified wires.***

3 Active Linear position Sensing

3.1 Introduction

3.1.1 Linear Variable Differential Transformer

The Linear Variable Differential Transformer (LVDT) is an active sensor similar to the resolver that requires an external excitation for its operation. The LVDT is an improvement on the use of a potentiometer for linear position sensing. There are no disadvantages in terms of mechanical wear or contacts, but there are electrical limits to the range of motion.

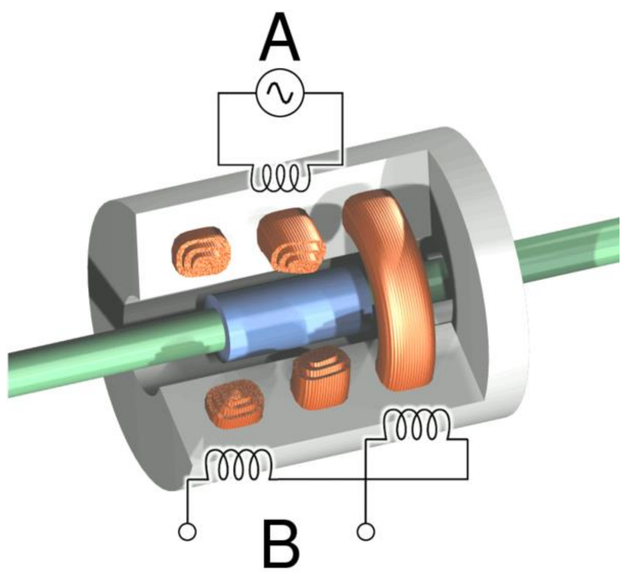


Figure 7: Cutaway view of an LVDT. Current is driven through the primary coil at A, causing an induction current to be generated through the secondary coils at B.

The LVDT basically consists of three transformer windings physically arranged in a line coupled together by a ferromagnetic core. The core can be freely moved in one dimension to alter the amount of magnetic coupling between the primary winding and the 2 secondary windings of the device. Normally the center (primary) winding is energized by an AC reference supply (10 Hz to 10 kHz). The two end windings are wired in series but with opposing polarities. Thus the output voltage generated from the two series windings is zero when the magnetic couplings from the primary winding to the two secondary windings are equal, i.e., the ferromagnetic core is in the "Null" position. If the ferromagnetic core is displaced from its center position, the coupling to the secondary windings is no longer symmetrical and the output voltage increases. This change in output voltage is linear with core position (as long as the core position is linearly changing the coupling between the two secondary windings). Note that as the ferromagnetic core is moved through the null position, the phase of the output signal changes, so to fully decode the LVDT output, both the amplitude and phase of the signal must be monitored.

3.1.2 Linear Variable Capacitor

A Linear Variable Capacitor (LVC) can be used to measure linear displacements. As discussed in class, the capacitance between two conductors separated by a dielectric is directly proportional to the dielectric constant, the area in common between the conductors and inversely to the distance between the conductors. Various mechanical configurations for an LVC are possible, and the one used on the Digiac unit is based on a co-axial configuration. A brass cylindrical sleeve (outer conductor of the capacitor) is used to receive the iron slug (inner conductor, from the LVDT device) to form a capacitor. The further the slug extends into the brass sleeve, the greater the area of the capacitor and thus the greater the capacitance. Thus you would expect a linear change in capacitance with respect to distance.

The electrical circuit used with this LVC measurement is simply a high pass filter shown in figure 8 with the transfer function given as:

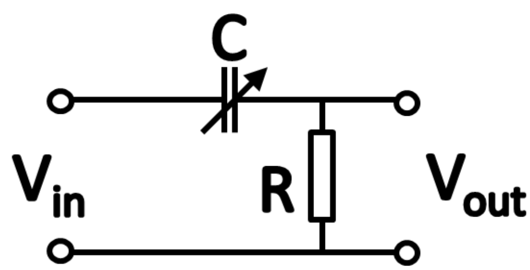


Figure 8. An LVC measurement circuit and its transfer function.

$$\frac{V_{out}}{V_{in}} = \frac{sCR}{sCR+1} = \frac{j\omega CR}{j\omega CR+1} \tag{3.2.1}$$

$$\left|\frac{V_{out}}{V_{in}}\right| = \frac{\omega CR}{\sqrt{1+(\omega CR)^2}} \tag{3.2.2}$$

From equation (3.2.2), we see that for a fixed frequency ω and when $(\omega CR)^2 \ll 1$, V_{out} is a linear function of the capacitance and thus the displacement between the two conductors of the capacitor. We can adjust the frequency to ensure the above inequality is valid.

3.2 Experimental procedure

For more information on the LVDT and LVC, consult the Digiac manual pages 131 to 134 and then complete Exercise #18 and #19. To enhance your understanding of these devices, consider making the following measurements while completing exercise #18: with an oscilloscope, monitor and trigger on the 40 kHz signal from the oscillator as well as look at the input to the rectifier bridge on the other channel. You should be able to see the phase reversal of the output signal as you pass through the null position.

Question: Why do you not see the effect of this phase reversal at the output voltage?

Explain: Extend the displacement range of the LVDT core until the output voltage begins to show some non-linearity (with respect to displacement) and explain this non-linearity.

For the LVC experiment as described in exercise #19:

Question: Is the output voltage approximately linear versus displacement?

Question: Given the values from the **Digiac** manual for R and C, is the approximation we made in the transfer function valid?

Explain: Extend the displacement range until you observe some non-linearity in the output voltage and explain why this non-linearity occurs.

Question: What unexpected results did you encounter with the LVDT at around the center position?

Question: Does the LVC suffer from the same problems near the center position?

To make measurements with the LVC, we must connect the AC amplifier (gain of 1000) to the LVC output (O/P) and from amplifier output to the 40 kHz filter. The output of the filter is connected to the rectifier bridge and its output is monitored with a digital voltmeter. The input (I/P) to the LVC is the 40 kHz oscillator. Now, for a number of different displacement values (suggest about 8 different values, 8 turns on the LVDT core) record the output voltage and plot your results.

4 Magnetic Velocity Sensors

4.1 Introduction

4.1.1 Hall-effect transducers

In 1879, E. H. Hall discovered that if you take a semiconductor element and apply a magnetic field to it such that it is perpendicular to the applied voltage transversal to the element, then there will be an output voltage generated across the element at right angles to both the applied voltage and the magnetic field. The output voltage is inversely proportional to the distance of the element from the magnetic field. These Hall-effect sensors can be used to measure distance (proximity sensors) but because of the inverse relationship with respect to distance, they are more often used as digital sensors to measure velocity. Consider the arrangement shown in Figure 8.

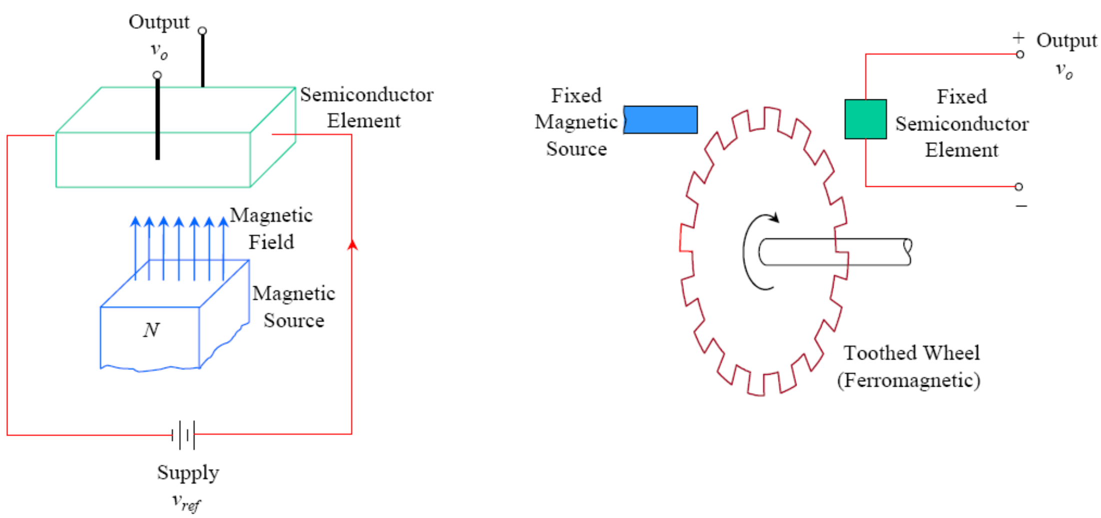


Figure 8: Schematic representation of a Hall-effect sensor and its application.

The ferromagnetic toothed wheel modulates the magnetic field that the Hall-effect sensor sees as the wheel rotates. The output voltage from the sensor is a square wave with a frequency directly related to the number of teeth passing the sensor per second. Thus, the frequency of the output signal is proportional to the angular velocity of the shaft.

4.1.2 DC Tachometer generator

A DC Tachometer or Tachogenerator is simply a small DC generator with its rotor mechanically coupled to a rotating object to measure its angular velocity. In operation, the output voltage from the generator is directly proportional to the angular velocity of the rotor. Usually the magnetic field for the stator of the DC Tachogenerator is supplied by a permanent magnet and the rotor is simply a small coil of wire wound on a soft iron core and connected to the outside world via a brush and commutator arrangement (Figure 9). The rotor is connected to the input shaft and is free to rotate between the poles of the permanent magnet. The commutator converts the AC induced voltage in the rotor coil to a DC signal for use in angular velocity measurements.

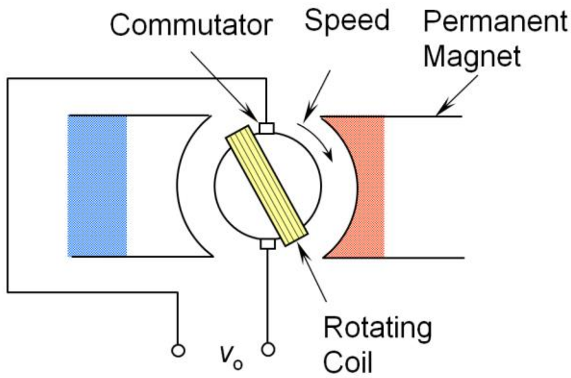


Figure 9: A permanent-magnet DC tachometer for use in angular velocity measurements.

4.2 Lab procedures – Velocity Sensing

Complete exercises #27 and #28 as described in the **Digiac** lab manual and answer the following questions:

1. For each of the two sensors, what difficulties did you have with getting measurements at the minimum and maximum RPM?
2. Which one of the two sensors would be better suited for high speed measurements? For low speed measurements?
3. Which of the two sensors indicates direction as well as speed? Why?
4. How might you be able to obtain directional information using sensors that do not provide you with the direction directly?

For more information on the Hall-effect sensor and the DC tachometer, see pages 186, 187, 191, and 192 in the **Digiac** manual.