ENSC 387 – Lab No. 1
Position and Velocity Sensors

Names of students

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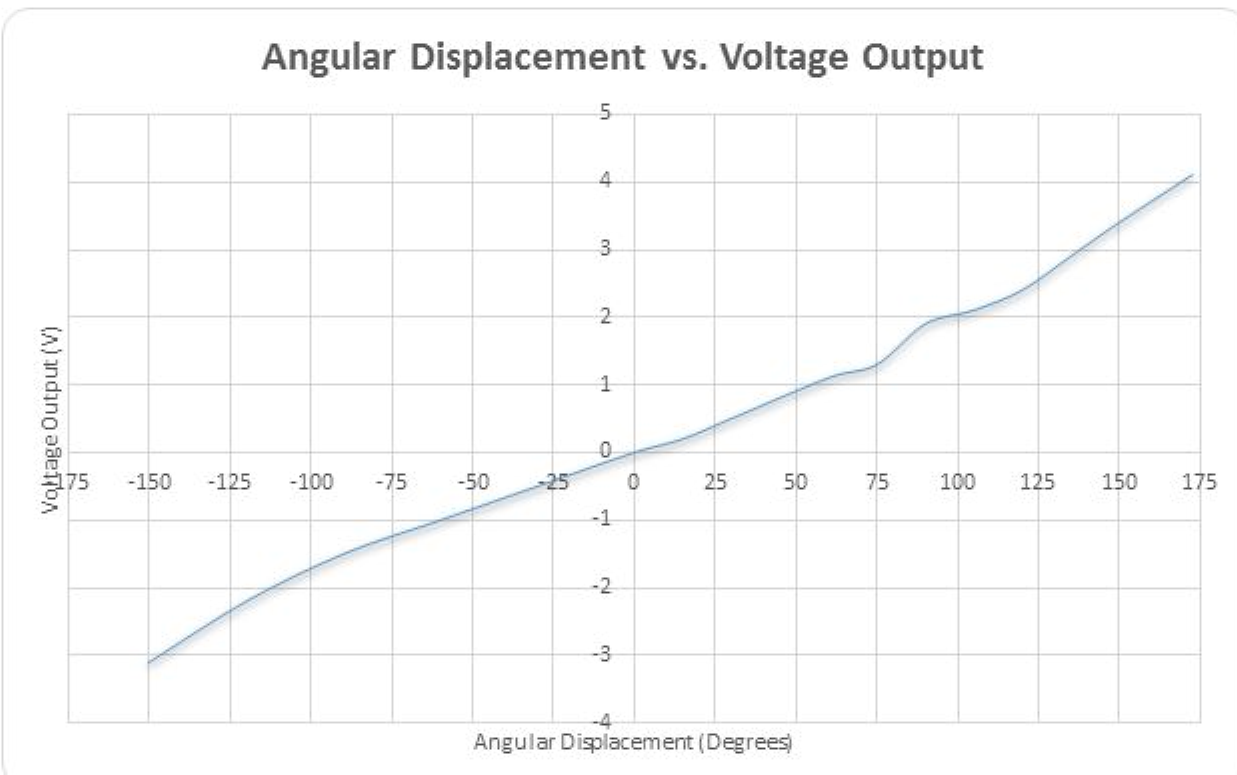
Experiment 1 - Passive Position Sensing

1.1 Introduction

In this experiment, we used a rotary type potentiometer available in the Digiac training system called the servo pot. We used this sensor to measure the linear displacement and velocity of a moving object, in this case a DC motor. Using the servo pot, we measured the servo pot's voltage output with respect to its angular displacement. Then we configured the closed loop DC motor control circuit (see Figure 1.1) to observe the servo potentiometer voltage output as we changed various parameters of the circuit. We observed that the servo potentiometer has no mechanical limitation of its angular position, but it exhibited an electrical discontinuity when a particular range of angular input is reached.

1.2 Measured Results

Exercise #4



Graph 1.1 - Voltage output of the servo potentiometer as a function of displacement angle

1.3 Analysis of the Results

Using the data collected during exercise #4 in the *Digiac* manual, table 1.1, we plotted the results, shown in Graph 1.1. After careful observation, we noted that the most linear relationship between angular displacement and voltage output occurs between -60 to 60 degrees and around 180 degrees, the output voltage measured flipped its sign value. In addition, there is a position (set angle) on the servo potentiometer that is ambiguous. As mentioned in the introduction, the servo potentiometer has no mechanical limitation but it does have an electrical discontinuity around 180 degrees. Around 180 degrees, sign of the output voltage flips. As a result, every 180 degrees the position would give an output measurement so differ from previously measured output.

After nulling the DC offset of the error amplifier we observed the output using the oscilloscope. When the DC offset of the error amplifier is correctly nulled, the DC motor did not turn. Also, when the command input is grounded and manually rotating the servo pot to a set angle would allow the DC motor to turn. However, as the motor shaft turned, the servo potentiometer also turned. At the null angle (near 0 or 360 degrees of the servo potentiometer), the DC motor came to a stop.

The output voltages were captured using the oscilloscope (see Graph 1.2 and Graph 1.3). The two waveform outputs are similar to the original input, triangular waveform 1Hz, +2.5V. However, the output measured at the servo potentiometer's end is not exactly the triangular wave as expected. This is likely due to the electrical discontinuity of the servo potentiometer. At null position, potentiometer changes its polarity and as a result, the DC motor reverses its direction of rotation. As a result, the output waveform looks 'wavy' (refer to Graph 1.3).

When the input wave is set at 1Hz, pk-pk 2.5V, triangular wave, the DC motor and the servo pot moved much like a pendulum, changing its angular displacement but not fully rotating. As we slowly increased the amplitude of function generator output up 5V and above, we noticed that the potentiometer started oscillate with greater range angle between 0 and 360 degrees and eventually the oscillation stops and the servo potentiometer fully rotates in the direction of the DC motor's operation.

After resetting input command voltage to +2.5V, we slowly increased its frequency. As we increased the frequency, the range of angular displacement decreased while oscillating more frequently. Due to increase in frequency, the servo potentiometer is no longer able to oscillate between its maximum range of oscillation.

Finally, we observed output waveform of the servo potentiometer on the oscilloscope as we gradually changed the error amplifier's gain from 1 to 50. We collected these outputs in Graph 1.4 showing how the increase in amplification of error amplifier results in the output waveform matching closer to the original input triangular wave. At gain 1, the output signal looks almost like a sine wave, but when the gain is increased, the output signal contained more "fluctuations". Shown in Graph 1.4, output wave coloured teal represents the input triangle wave, and the yellow wave represents the output (servo potentiometer).

1.4 Conclusion

In this experiment, we observed that the servo potentiometer has no mechanical limitation of its angular position. With the servo potentiometer, we can passively measure linear displacement and velocity. Also, we observed the electrical discontinuity occurs around angle of 0 or 360 degrees. Since the servo pot requires a physical contact between the moving device, the DC motor and its shaft, measurement of displacement and velocity is heavily dependent on the DC motor itself. Due to this dependency, we noticed 'wavy' output signal as shown in Graph 1.3 and Graph 1.4. At a low gain or low frequency or low amplitude setting of the input signal, the closed-loop DC motor control using the servo pot exhibited oscillation like motion. However, as we slowly increased the amplitude of input wave and increased amplifier gain, the DC motor is no longer held back by the electrical discontinuity of the servo potentiometer and fully turns with the DC motor and shaft, instead of oscillating between 0 degree position.

Experiment 2 - Active Angular Position Sensing

2.1 Introduction

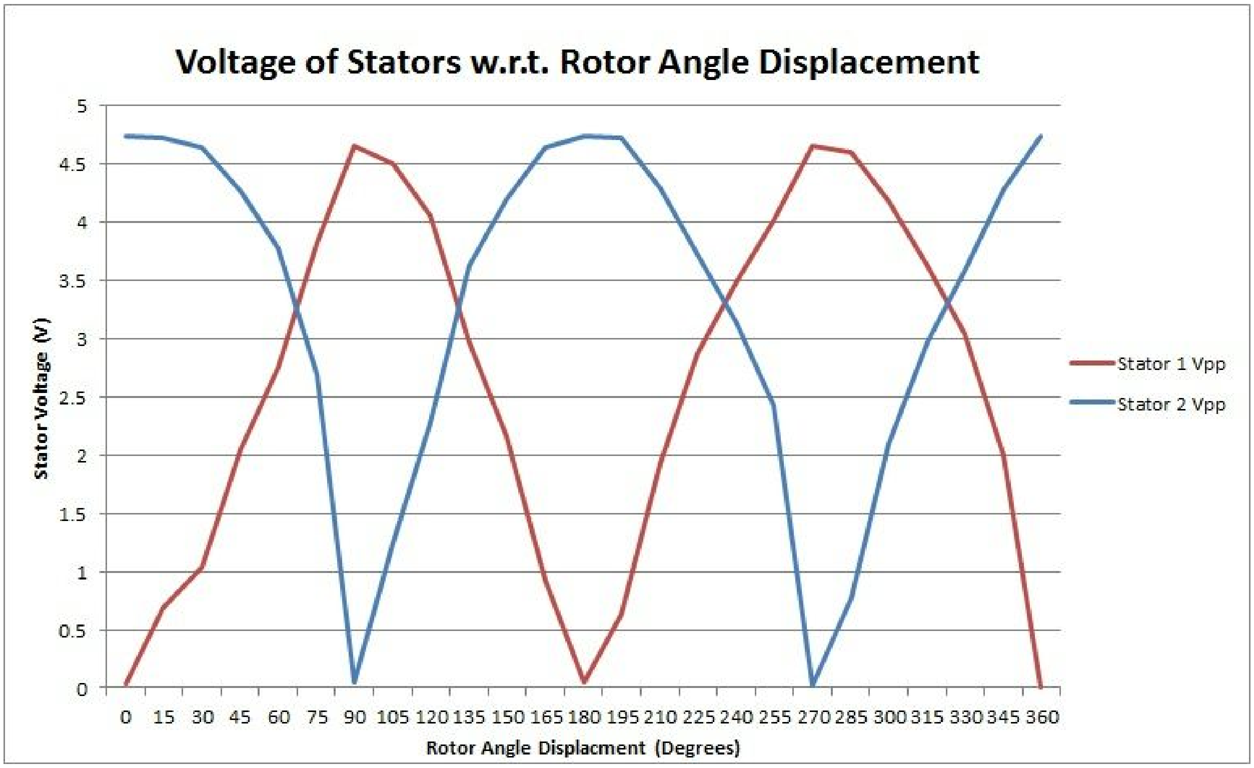
To overcome the limitations of potentiometer in angular position measurements, we tested another type of rotary potentiometer called the resolver. The resolver senses position based on magnetic coupling between two pairs of identical stator coils placed at 90 degrees from each other. Third winding rotates freely to be used to set specific angular displacement (see Figure 2.1). When the third winding is set at each 90 degree angle between the two coupled stators, we expect there is no change in amplitude but the output wave from stator 1 and stator 2's phase would reverse. This phenomenon occurs at every 90 degree angles. We tested two different methods to measure angular position. First method, we connected function generator to the resolver and observe voltage measurements across two stators as we manually rotate the rotor.

The second method, using the quadrature amplifier (see Figure 2.2) we observed changes in voltage measurements as we manually rotate the rotor.

2.2 Measured Results

Method 1

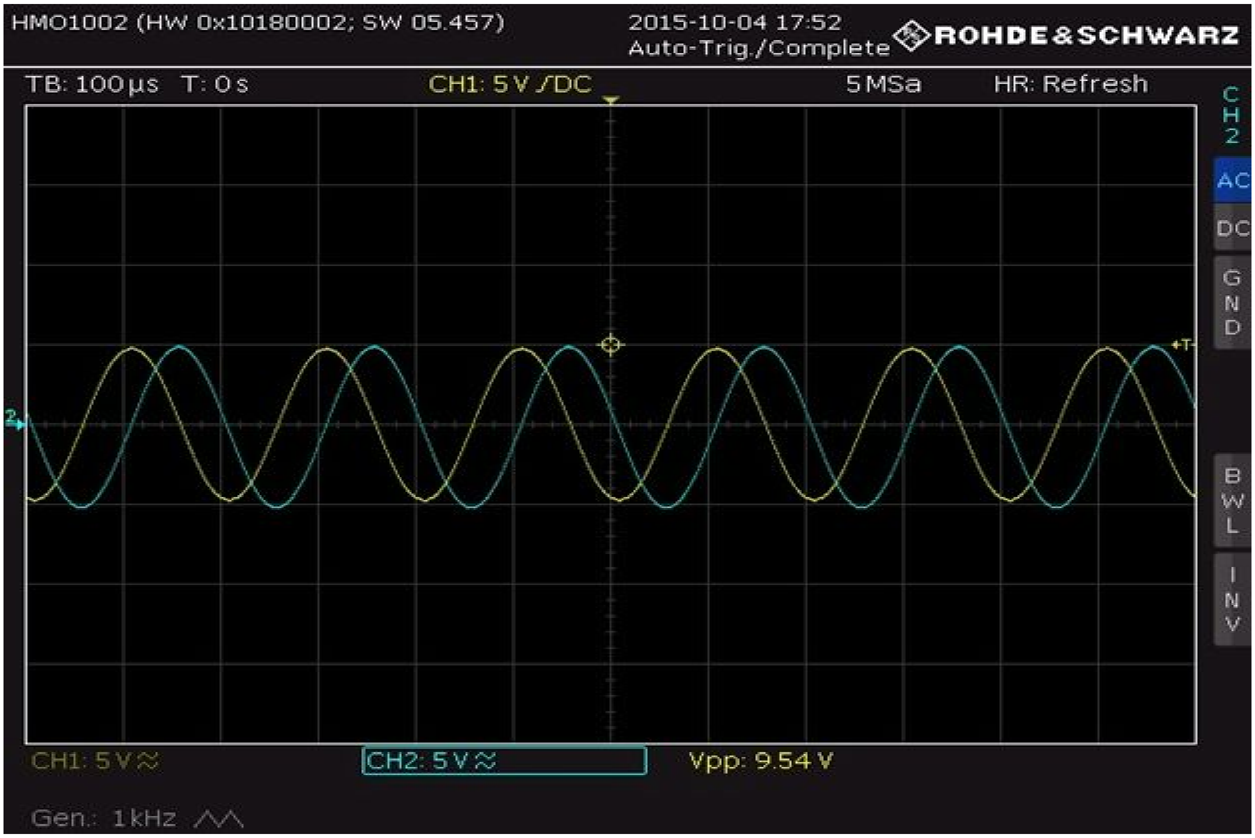
After collecting the voltage measurements on both stator windings in 15 degree increments (see Figure 2.3), and plotted the results (see below Graph 2.1). We used input signal at 5 V_{PP} and 5 kHz to produce the output results.



Graph 2.1 - Voltage output of stators as the rotor angle increments by 15 degrees, similar results to figure 5 in the lab manual 1

Note that our measurement of zero angle followed angular coordinate system (due East as 0 degrees).

Method 2



Graph 2.2 - Output of the quadrature amplifier captured using the oscilloscope

2.3 Analysis of the Results

2.3.1 Method 1

Once the input signal (5 V_{PP} at 5 kHz) is connected to the rotor, we observed clear sinusoidal wave output with phase difference in the oscilloscope. After collecting data and plotting it (see Graph 2.1 above), we noticed that the phase difference of 90 degrees exists between two sinusoidal output waves. We defined zero angle as the position of the rotor with respect to the main stator coil. At 0 degrees, there is a minimum voltage amplitude for stator 1 (sine winding) and maximum voltage amplitude for stator 2 (cosine winding) and as the rotor angle setting changes stator 1 produces a voltage output, $V_1 = V_s Sin(\omega t)$ and stator 2 produces voltage output, $V_2 = V_s Cos(\omega t)$. This type of operation of the resolver is used in applications like servo motors, communication position systems, aerospace, and other factory automation process. The resolver is often used in many applications because unlike the previous passive position sensor, servo pot, the resolver is an analog device and the electrical output they produce are continuous through one mechanical rotation of the rotor. To fully decode 360 degrees of angular rotation of the rotor, we just need to take arctan of the ratio of the two voltages of the stators 1 and 2. Using data collected in Table 2.1, and using Equation 2.1 below, we can fully decode rotor's rotation (see Table 2.2).

$$\theta = tan^{-1}\left(\frac{sin\theta}{cos\theta}\right) \qquad \text{Equation 2.1}$$

2.3.2 Method 2

As shown in Graph 2.2 above, the outputs of the quadrature amplifier are sinusoidal and has approximately the same amplitude (5 V_{pp}) with a phase shift of approximately 90 degrees. As we rotated our rotor, we observed similar continuous phase shift between two output signals from method 1.

When using the oscilloscope to measure the rotor angular position, we need to consider calibration. We produced Graph 2.1 by plotting one sine and one cosine wave cycle in relation to the angular displacement of the rotor. With better calibrated plot, we can better estimate the rotor's angular position by looking at the oscilloscope measurement and tuning the device for better accuracy.

2.4 Conclusion

In this experiment, we tested the resolver to make angular measurements. We found that unlike previous sensor, servo potentiometer, this rotary potentiometer has no limitations on angular position (infinite theoretical resolution) and requires no mechanical contact. Also, it was difficult to take voltage measurements on both stator windings in 15 degree increment because the rotor's measurements were very limited (and blurred measurement lines), we could not accurately estimate the position from the zero angle. As a result, our Graph 2.1, contains sharp drop or rise of the stator output measurements. Accuracy of the resolver measurement will be limited by the interpolation of output waves measured by the oscilloscope.

Experiment # 3. Active Linear Position Sensing

3.1 introduction

The Linear Variable Differential Transformer is an active sensor that is similar to the resolver which require an external excitation for its operation. The LVDT consists of three transformer windings physically arrange in a line coupled together by a ferromagnetic core. The output voltage generated from the two series winding is zero when the magnetic couplings from the primary winding to the two secondary windings are equal. In this experiment, a Linear Variable Capacitor was used to measure linear displacement. The capacitance between two conductors are separated by a dielectric. This measurement is directly proportional to the dielectric constant. The LVC found on the *Digic* unit is based on a co-axial configuration.

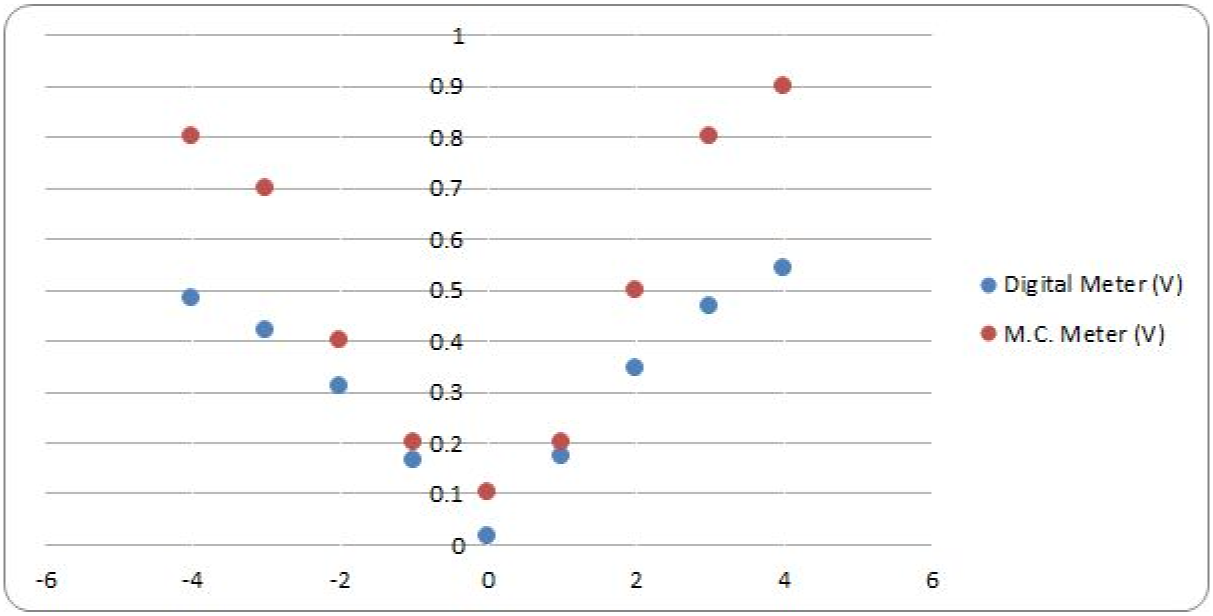
3.2 Measured Results

Exercise #18

The data collection began by rotating the operational screw to its neutral position. Then, we rotated the core control screw in steps of approximately 1 to 4 turns in the clockwise and 4 turns in the counterclockwise and we collected output voltage using digital meter and M.C. meter.

Core Position (turns from neutral)		-4	-3	-2	-1	0	1	2	3	4
Output voltage	Digital meter	0.48358	0.42053	0.31138	0.16462	0.01638	0.1741	0.34373	0.46578	0.54328
	M.C meter	0.8	0.7	0.4	0.2	0.1	0.2	0.5	0.8	0.9

Table 3.1- the output voltage in result from the different core positions



Graph 3.1 - output voltage against core position (Table 3.1)

3.3 Analysis of the Results

With an oscilloscope, monitor and trigger on the 40 KHz signal from the oscillator as well as observe the input to the rectifier bridge on the other channel. We saw the phase reversal of the output signal as we pass through the null position of the LVDT as shown in Figure 3.1 of appendix.

We did see the effect of the phase reversal in the null position, but we were not able to see it at the output voltage because the Full Wave rectifier distorts the signal.

As the displacement range of the LVDT core is extended the voltage begins to show non-linearity (with respect to displacement. The output voltage begins to show nonlinearity since the core of ferromagnetic material is inducing the maximum amount of voltage in one coil while the other coil is still increasing this the output voltage versus displacement is no longer linear.

Exercise #19

When we set the amplifier gain to 1000 and rotated the operating screw in steps of approximately 1 turn counterclockwise to reduce the capacitance, and recorded the output voltage (shown below in Table 3.2)

Capacitance	Max							Min	
Turns of Screw	0	1	2	3	4	5	6	7	8
Output voltage	2.533	2.533	2.533	2.532	2.532	2.532	2.532	2.531	2.531

Table 3.2 - Output voltage resulted different screw turns

Given the values from the Digiac manual:

- Variable Capacitor - 25pF - 50pF max, 15mm (mechanical travel)
- Resistor 10K Ohm.
- w = 40kHz

the approximation we made in the transfer function is valid since our assumption was if (wCR)^2 << 1 then, the output voltage will have linear relationship (0.0158) is far less than 1.

As the LVDT was moved away from its null position, output voltage begins to show non-linearity (with increasing displacement). The output voltage began to show nonlinearity because the core of ferromagnetic material was inducing the maximum amount of voltage in one coil while the other coil was still increasing. This output voltage versus displacement was no longer linear.

We encountered unexpected results near the center position of the LVDT. We were unable to zero the output measurement made by the multimeter, it was near zero but not exactly zero. This suggests that there is a dynamic error result from the inability of the measuring system to accurately follow a time varying output.

3.3 Conclusion

A linear-variable-differential transformer(LVDT) is basically a transducer that converts mechanical motion into an electrical signal through mutual induction. LVDT Dynamic errors can result from the inability of a measuring system to accurately follow a time varying output. This type of error is often caused by friction, damping, or inertia of the moving elements of the sensor. Near the center position of the LVDT, we were unable to zero the output measurement. With LVC, on the other hand, we did not see this problem as placing LVC furthest away meant that the LVC would have zero capacitance.

Experiment # 4- Magnetic Velocity Sensors

4.1 introduction

In this experiment, we looked closely at Hall-effect sensors and DC Tachometer generator. Hall-effect sensor can be used to measure distance (proximity sensor) but due to its inverse relationship with distance, they are more often used as digital sensors to measure velocity. 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.

DC Tachometer is a small DC generator with rotor mechanically coupled to a rotating object to measure its angular velocity. The output voltage from the generator is directly proportional to the angular velocity of the rotor.

4.2 Measured Results

Exercise #27

Output Voltage	DMM reading
no mag field (+)	0.460 mV
no mag field (-)	0.455mV
MAX mag field (+)	0.527mV
MAX mag field (-)	0.460mV

Table 4.1 - DMM reading when magnetic field (not)/induced from exercise #27

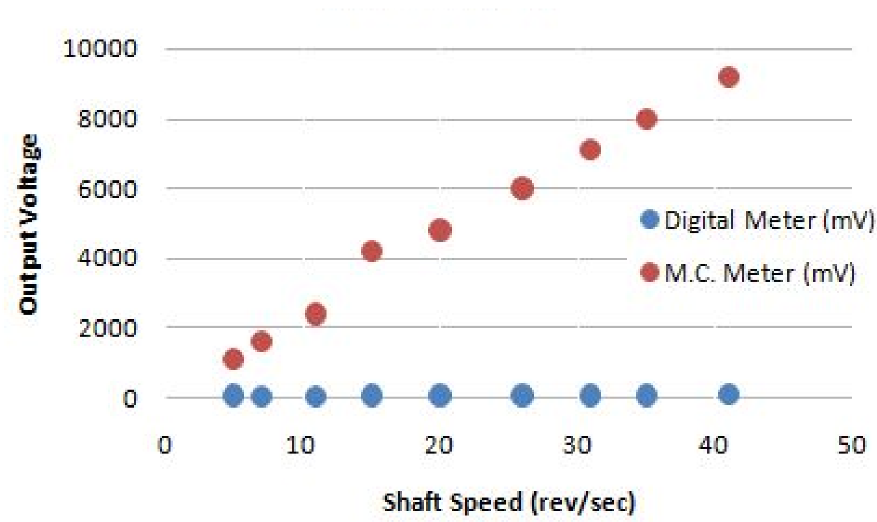
Note : The gain had to be changed to 5x with the MC,
Setting the Magnet directly above the Hall Effect device had the following result.

Output voltage (with no magnetic field) = -0.7 V
Output Voltage (Maximum magnetic field) = 6.8 V

The data obtained for the difference between Hall-effect and slotted opto on shaft speed is shown in Table 4.2 in the appendix

As a result of our comparison the Hall-effect device prevented the motor from running at the first resistance setting (A at max and C at min).

Exercise #28



As the M.C. Meter displays the amplified voltage output, the output voltage was linearly proportional to the shaft speed.

Calibration of the M.C. Meter to indicate the speed directly, as 10V represented 2000 rev/min.

voltmeter reading	6V	3V
shaft speed	(6x20=1200 rev/min) 20 rev/sec	(6x10=600 rev/min) 10 rev/sec
Actual shaft speed	**19 rev/sec**	**9 rev/sec**

This exercise also required calibration of our sensor. 10V represent 1000 rev/min. Thus each voltage represented 100 rev/min =5/3 rev/sec.

voltmeter reading	6V	3V
assumed shaft speed	(=6*5/3 rev/sec) 10 rev/sec	(=3*5/3 rev/sec) 5 rev/sec
Actual shaft speed	**10 rev/sec**	**4 rev/sec**

4.3. Analysis results

Some difficulties we faced while using the two sensors, Hall-effect sensor was not able to collect measurements around the minimum RPM whereas the DC tachometer suffered from error and possible overflow of values near the maximum RPM. High speed measurements are much more reliable with the the Hall-effect sensor. Low speed measurements are much more reliable with the DC Tachometer.

Hall-effect sensor are used for proximity switching, positioning, and speed detection. However, the DC Tachometer was ideal for the purpose of control and measurement applications which require directional indication. DC Tachometer is better for direction and speed because it contains feedback component.

We can determine/obtain directional information while using sensors without direction directly, by using two of the same sensor. For instance, we can place two identical sensors, in this case the hall-effect sensor, off phase by 90 degree with one another. By placing the two sensors 90 degrees apart from one another, we can determine the direction of rotation once the output measurements are gathered. We would expect sensor 1 to reach its peak before sensor 2 if it is rotating clockwise and visa versa for the counterclockwise direction.

4.4 Conclusion

With hall-effect sensors,the frequency of the output signal is proportional to the angular velocity of the shaft. Its disadvantages are that it is difficult to obtain data around the minimum RPM. The hall-effect transducers' advantage is that it is better suited for measuring high speed. Whereas, near minimum RPM, the DC tachometer will be better suited for measuring low speed and direction identification.

Appendix

Experiment 1

Figure 1.1 - Closed-loop DC motor control using a servo potentiometer

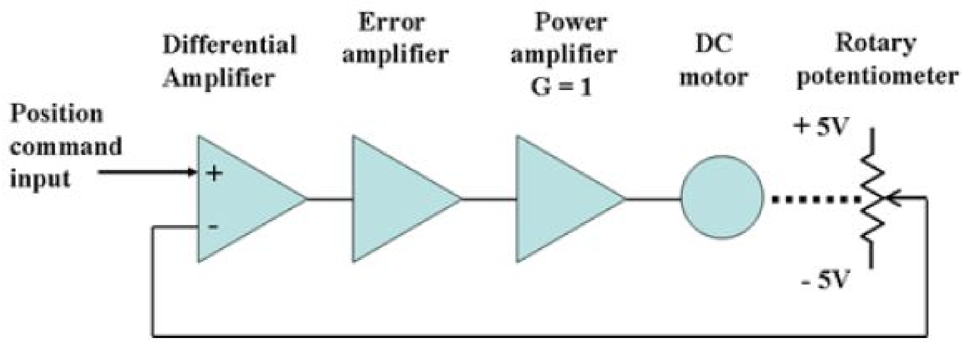
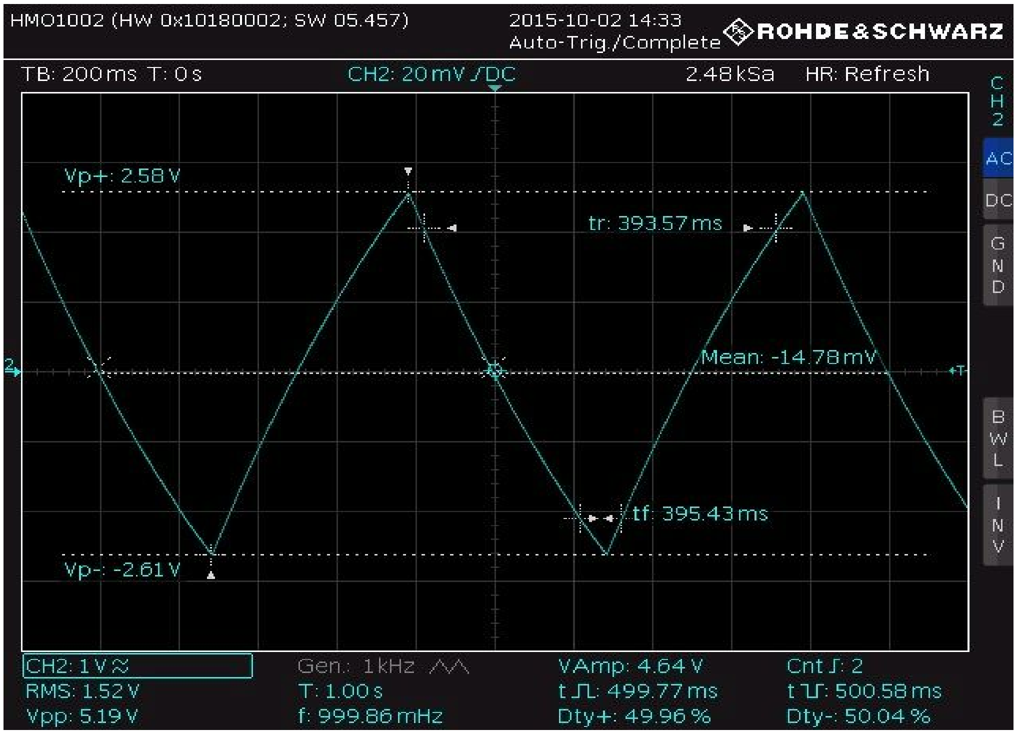


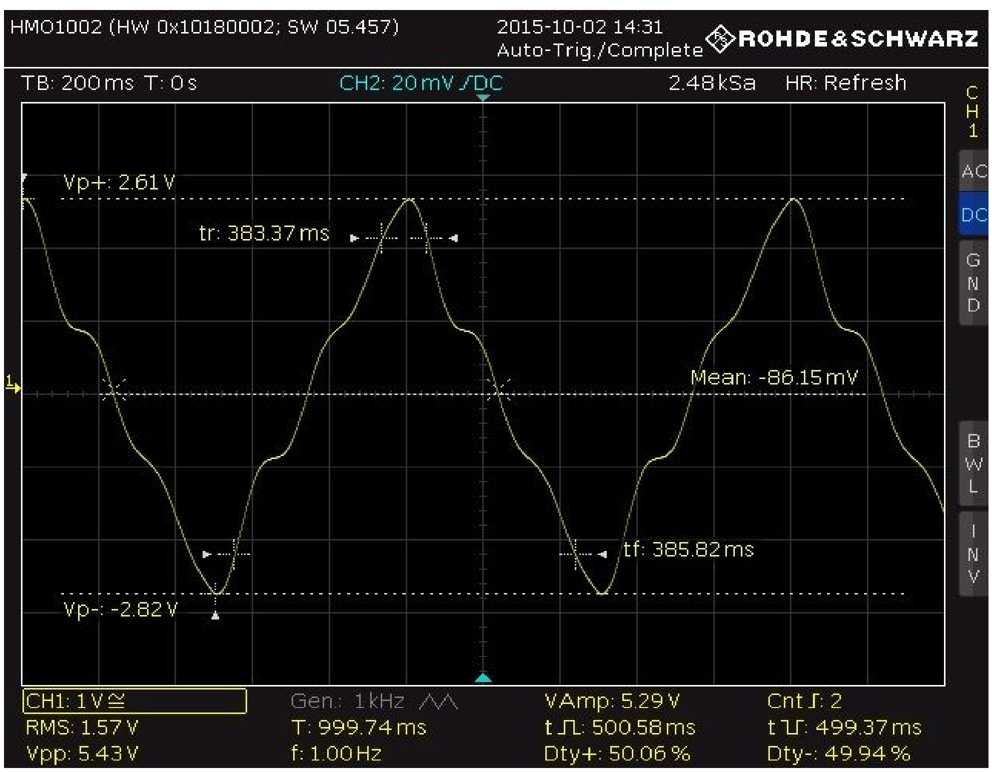
Table 1.1 - Measured voltage outputs with displacement angles (Exercise #4)

Dial Setting (Degrees)	Voltage Output (V)
172.5	4.1
150	3.4
135	2.9
120	2.4
105	2.1
90	1.9
75	1.3
60	1.1
30	0.5
15	0.2
0	0
-30	-0.5
-60	-1
-90	-1.5
-120	-2.2
-150	-3.1

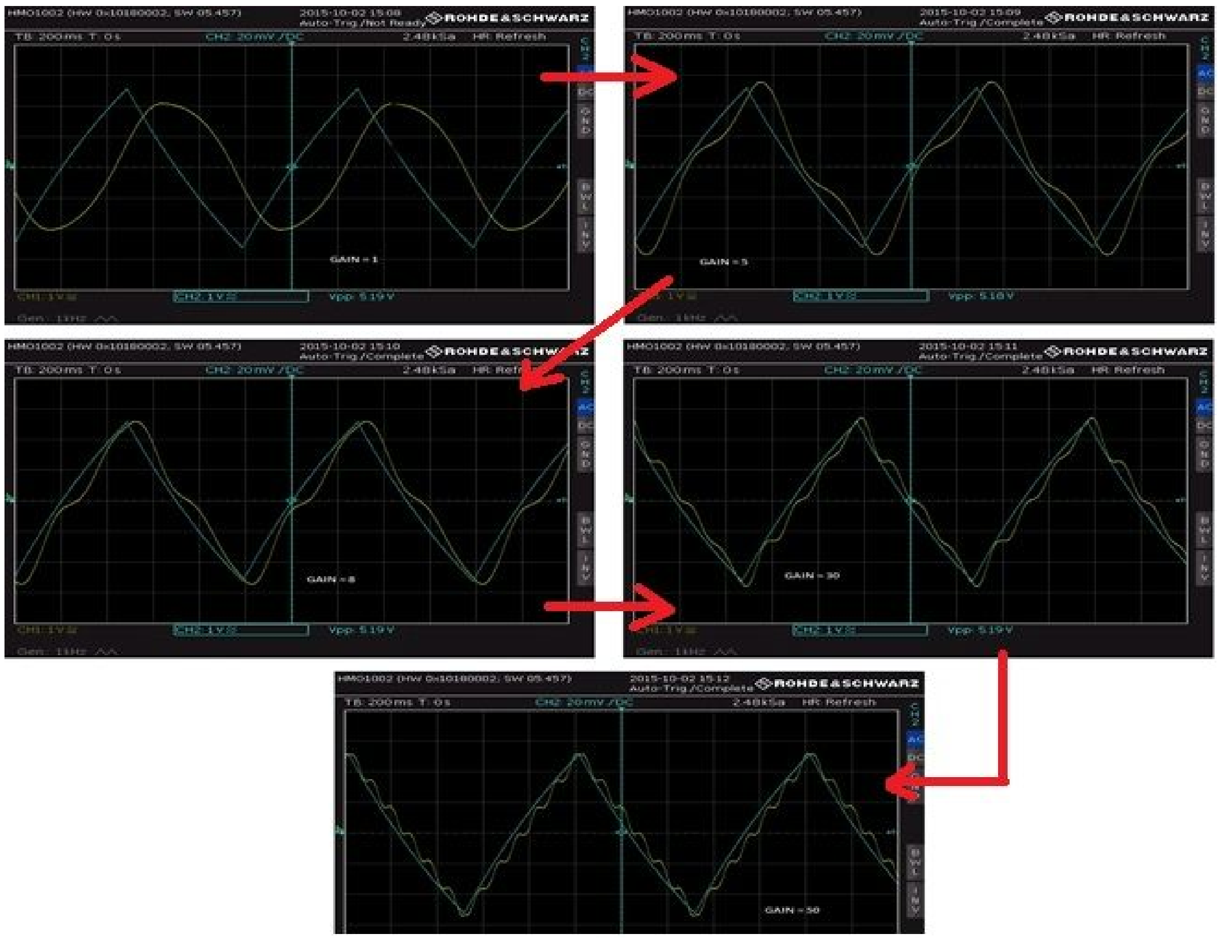
Graph 1.2 - Function Generator output to 1Hz +2.5V triangular waveform



Graph 1.3 - Function Generator output measured at the Servo Potentiometer



Graph 1.4 - Servo pot output waveform with increased error amplifier gain from 1 to 50. Red arrows indicate rise in amplification from min of 1 to max of 50



Experiment 2

Figure 2.1 - Circuit diagram of a resolver

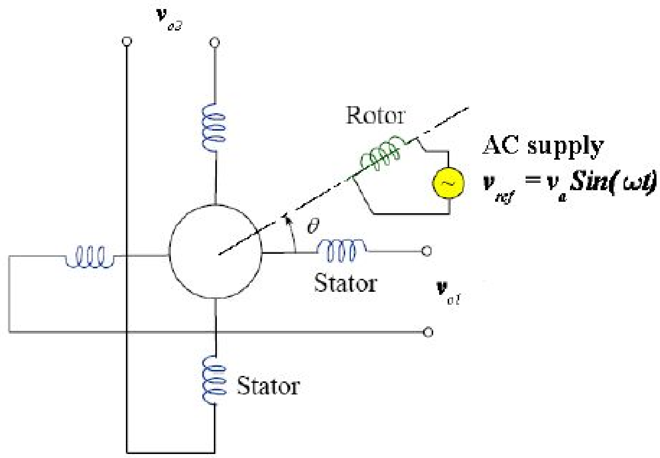


Figure 2.2 - Quadrature Amplifier, used to generating output signals at 5 kHz

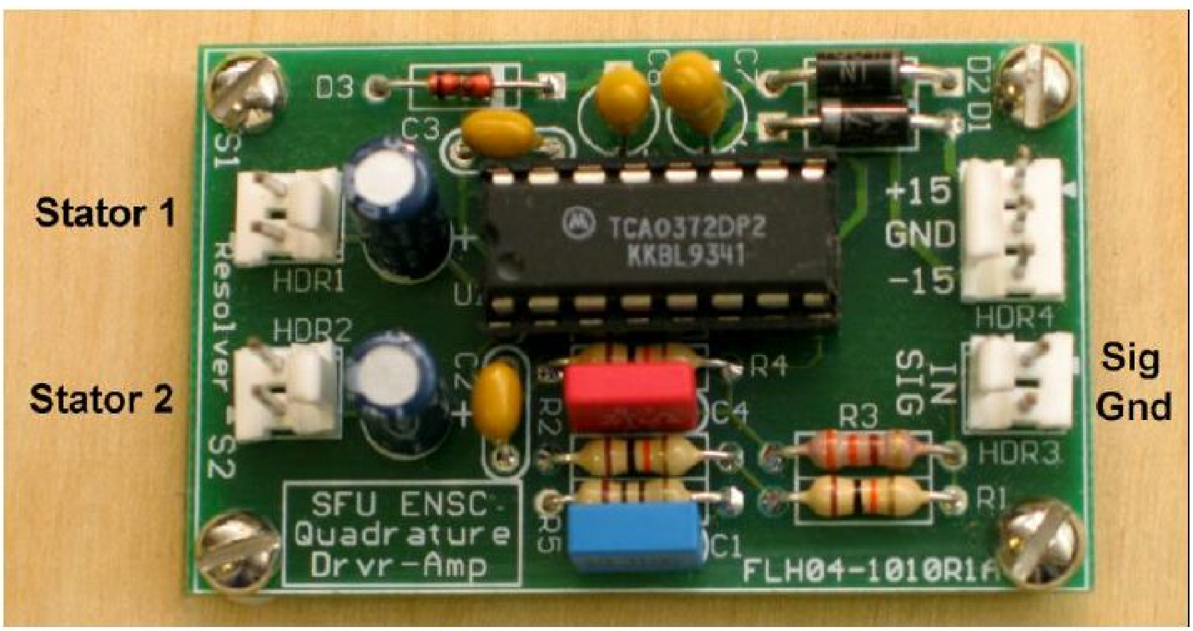


Table 2.1 - Voltage measurements on Stators as the rotor setting increase by 15 degrees

Rotor Setting (Degrees)	Stator 1 Voltage Output (V)	Stator 2 Voltage Output (V)
0	0.0313	4.74
15	0.68305	4.72
30	1.04	4.64
45	2.05	4.26
60	2.75	3.78
75	3.82	2.7
90	4.66	0.0437
105	4.5	1.24
120	4.06	2.28
135	2.97	3.62
150	2.17	4.2
165	0.9273	4.64
180	0.0512	4.74
195	0.6385	4.72
210	1.93	4.29
225	2.87	3.73
240	3.49	3.14
255	4.01	2.43
270	4.65	0.01869
285	4.6	0.7668
300	4.18	2.09
315	3.62	2.97
330	3.04	3.58
345	2	4.28
360	0.00977	4.74

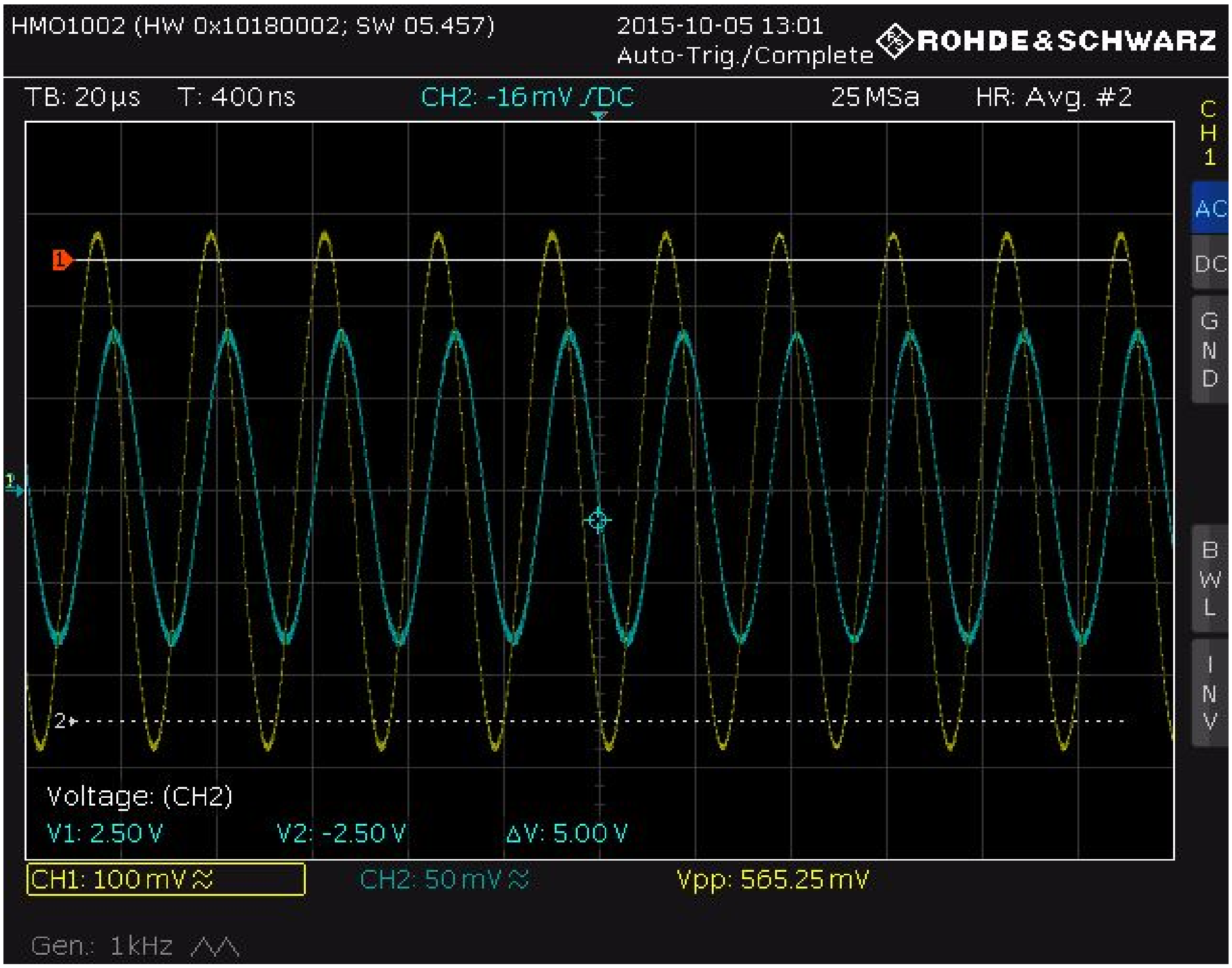
Table 2.2 - Arctangent calculation data used to decode 360 degree rotation of rotor

$Sin(\theta)$	$Cos(\theta)$	Arctan $\frac{sin(\theta)}{cos(\theta)}$
0	1	**0**
0.2588190451	0.9659258263	**0.2617993878**
0.5	0.8660254038	**0.5235987756**
0.7071067812	0.7071067812	**0.7853981634**
0.8660254038	0.5	**1.047197551**
0.9659258263	0.2588190451	**1.308996939**
1	0	**1.570796327**

0.9659258263	-0.2588190451	**-1.308996939**
0.8660254038	-0.5	**-1.047197551**
0.7071067812	-0.7071067812	**-0.7853981634**
0.5	-0.8660254038	**-0.5235987756**
0.2588190451	-0.9659258263	**-0.2617993878**
0	-1	**0**
-0.2588190451	-0.9659258263	**0.2617993878**
-0.5	-0.8660254038	**0.5235987756**
-0.7071067812	-0.7071067812	**0.7853981634**
-0.8660254038	-0.5	**1.047197551**
-0.9659258263	-0.2588190451	**1.308996939**
-1	0	**1.570796327**
-0.9659258263	0.2588190451	**-1.308996939**
-0.8660254038	0.5	**-1.047197551**
-0.7071067812	0.7071067812	**-0.7853981634**
-0.5	0.8660254038	**-0.5235987756**
-0.2588190451	0.9659258263	**-0.2617993878**
0	1	**0**

Experiment 3

Figure 3.1- shows the different signals for the Full wave rectifier and the output of the 40kHz Oscillator



Note: Ch1 -yellow - input of the Full wave rectifier & Ch2 -blue - output of the 40 kHz Oscillator

Experiment 4

Table 4.2- the difference between Hall-effect and Slotted opto on shaft speed (exercise 27)

Hall-effect (rev/sec)	slotted opto (rev/sec)
0	4
17	16
29	29
43	43
46	46