MECH2650: Mechatronics & Measurement Systems

DC Motor Speed Control Using PI Control

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Contents

1 Introduction

In this experiment we are using a software called LabVIEW in order to create a PD controller to measure the effect that the proportional and integral control have on the speed of a DC motor. The motor will be attached to a rotary encoder in order to measure speed and the controller used to create the PI controller will be National Instruments device.

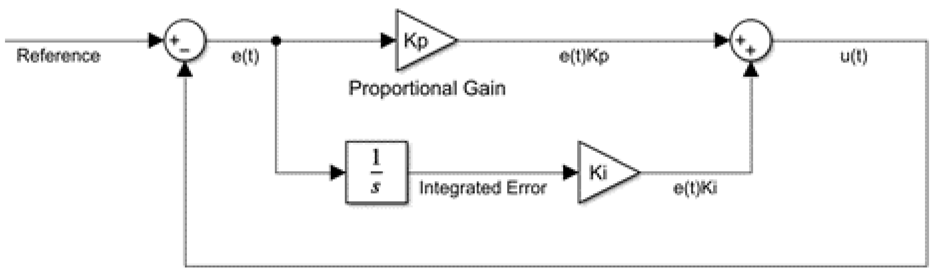

Figure 1: PI controller block diagram (from Simulink) showing the input and output signals. The reference in this case would be the desired (inputted) angular velocity at the beginning of the experiment. More specifically the u(t) output is the voltage sent to the motor which controls the speed rather than the speed of the motor directly.

2 Aims and Objectives

The aims for this experiment can be summed up as follows

- Identify the required components for a DC motor speed control system
- Construct a DC motor speed control system using the available components
- Understand LabVIEW diagram to obtain sensor signal
- Construct a PI control in LabVIEW
- Tune the PI control gains to achieve a desired performance
- Identify a transfer function between input and output signals

The overall objective for this experiment was to measure the effect of the PI controller on the speed of the motor and work out the transfer function of the motor itself. And to determine the effect of changing frequency on the response of the motor with an AC current.

3 Methodology

3.1 Apparatus

In this experiment we used a wide range of equipment both hardware and software all with specific purposes. In order to connect the two, we used a CompactRIO 9014 and a digital interface called LabVIEW FPGA (Field Programmable Gate Array). The main circuit consisted of a DC motor and the CompactRIO. The DC motor was being controlled by the PI controller which was input into the DC motor through the signals sent from the CompactRIO from the signals it received from the connections to the computer.

3.1.1 Hardware

In terms of hardware, we used several different components. The DC motor was the main piece of hardware that we were interested in. The DC motor speed is controlled by the CompactRIO 9014 connected to the NI-9505. These two devices converted the LabVIEW program into a voltage which is sent through the wired connections to the motor causing it to start to rotate. To measure the angular velocity of the motor a rotary encoder was used. This rotary encoder is specifically an optical encoder using a 4-stage binary system to calculate the counts. This works by using the light passing through the slits in the encoder and recording the time the light pulses occur and how long for, then with the known number of slits in the encoder the velocity of calculated. The rotary encoder is connected to the shaft of the motor, and this is what generates the rotation of the rotary encoder hence is used to calculate the speed. The angular velocity is converted to a voltage by the rotary encoder and is transported back to the CompactRIO and back to the computer where the angular velocity is noted and used in the control loop to determine what the new output voltage to the motor should be. In order to control the speed of the motor two National Instruments (NI) devises were used, the CompactRIO 9014 and the NI-9505 C series motor drive module. These two devices were connected through ports where the NI-9505 was connected directly to the CompactRIO. These are used to send the control signal to the motor. The NI-9505 is a h-bridge which controls the direction that the motor spins in. it provides a direction connection to actuators such as DC motors. It has a low power consumption and its compact, when combined with the LabVIEW environment it can be used to create very efficient control systems which is perfect in our case to use it as the base of our PI controller [1]. The CompactRIO controller uses LabVIEW to deploy logic created in the LabVIEW environment to the connected hardware. It is ideal for many processes including high-speed control which is necessary for this experiment [2].

3.1.2 Software

In the LabVIEW environment several different components were used to create the correct transfer function for the control of the motor. The FPGA modules allow us to read the information coming out of the motor by converting the voltage back to an angular velocity which is used as the next input into the control loop. The FPGA method node allows a certain command to be chosen to the system, specifically for this case depending on whether the enable motor Boolean is activated determining if the motors drive gear is on or off. The module is the information that is input into the motor, this is sent to the CompactRIO which will control the voltage supplied to the motor depending on the returning information from the rotary encoder. The sine wave function in LabVIEW is used to create the time varying desired command block that will create the desired frequency in Hz, for the second part of the experiment. The input frequency to the sine wave VI (virtual instrument) is in ticks and so to convert this to a frequency we need to use a conversion of a product of 25×10^{-9} as that is how many seconds a tick is equivalent to. Once the sine wave has been plotted with an amplitude of 200 it is offset by 200 giving it a range of 0-400rad/s. Hence, the motor should follow this speed. In LabVIEW, to create the integral control lots of basic operations had to be completed as it has no direct integral function. The final Integration used is displayed in Figure **??**. Finally, there is a tick counter which is used to record the elapsed time of the even which was used to plot the graph of the angular velocity against time. There is also the loop timer which controls the speed of iteration. In other words it controls the rate which data is taken from and sent to the DC motor.

3.2 Circuit

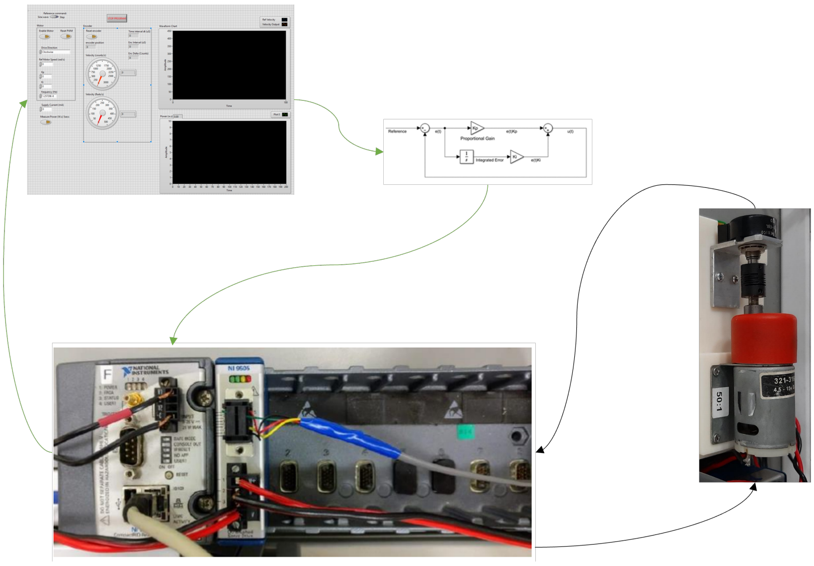

Figure 2 is a simple diagram depicting the circuit used to test the DC motor. The black lines indicate the connections between the mechanical parts of the circuit (the hardware) and the green lines show the connections with the computer and the software within the computer.

By using the program on LabVIEW the integration used was found and is displayed below in Equation 1.

$$I = K_i \times \int e^t dt \tag{1}$$

3.3 PI Control

This experiment is designed to measure the effects of changing the proportional and integral control of a PI controller on the response of of a motor speed. Step 1 is to set up the circuit as displayed in Figure 3.2. Next is to set all of the values on the LabVIEW display to 0 and then start to set then to what we want. The first setting to change is the demand speed of the motor. In this case as the high powered motor was used the speed was set to 200rad/s. Then before running the program make sure the reference command is set to step response and that the enable motor switch is turned on. Finally set the values of K_p and K_i to a value. The values used in this experiment are displayed in Table 1. Then the program can be ran and the motor should start turning providing the control values send a high enough voltage to the motor. Each time the motor is ran the power output is found using the voltage and the current as in Equation 2. In the LabVIEW set-up there is a box to enter the current and a switch to start measuring power when the current is entered into the text box. This is how the power is measured for each of the variations of the controller gains.

$$P = VI \tag{2}$$

3.4 Frequency Response

The methodology behind this experiment is very similar to the previous one. However, this time instead of changing the controller values they are kept the same and a different reference command (the sine wave) is used. This allows the frequency of the sine wave to be altered. The range used in this experiment was 0.1 to 0.8 (Hz) as displayed in Table 3. After a small period of time when the motor has been allowed to settle in the new frequency, measure the amplitude of the peak of the motor and compare it to the expected amplitude (400rad/s peak) to find the amplitude ratio. This is summed up in Equation 3. The next piece of information to find from the graph is the Time period of the wave. This can be done two ways; if the frequency if known the Equation 4 can be used otherwise the value can just be read off of the graph from the same point on one oscillation to the same point on the next. The final two things to be calculated from this experiment are the time difference and the phase angle. The time difference is calculated by finding the time of a certain measured value and comparing it to the time the reference value was at this point. The time difference is the time between these two points occurring. To more accurately find the difference average is taken of the various time differences along the curve. From this and the known frequency the phase difference can be calculated form Equation 5

$$Amplitude\ Ratio = \frac{Actual\ Amplitude}{Drive\ Amplitude(400rad/s)} \tag{3}$$

$$T = \frac{1}{f} \tag{4}$$

$$PhaseDifference = 360 \times Frequency \times TimeDifference \tag{5}$$

4 Results

Table 1: PI Control Gain Tuning

Proportional Gain (Kp)	Integral Gain (Ki)	Steady State Angular Velocity	Measured Power (W.s) 5 seconds
0.1	0	124.1702	4.21
0.4	0.005	196.4079	8.77
0.5	0	188.2226	8.72
0.5	0.005	192.2284	8.84
0.5	0.007	195.4486	8.75
0.5	0.010	195.3093	8.82
0.6	0.005	198.9333	8.97
1.0	0	194.3627	9.53
1.0	0.010	196.7785	9.11

Table 2: PI Control Gain Tuning

Proportional Gain (Kp)	Integral Gain (Ki)	Steady State Angular Velocity	Measured Power (W.s) 5 seconds
0.1	0	124.1702	4.21
0.5	0	188.2226	8.72
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0.4	0.005	196.4079	8.77
0.5	0.005	192.2284	8.84
0.6	0.005	198.9333	8.97
0.5	0.007	195.4486	8.75
0.5	0.010	195.3093	8.82
1.0	0.010	196.7785	9.11

Tables 1 ands 2 both present the same data, respectively they show the effect of the changing K_i with a constant K_p and the effect on changing K_p when K_i is kept constant.
The lowest value of K_p used was 0.1 as any value smaller than this would not have been strong enough to cause the motor to rotate.

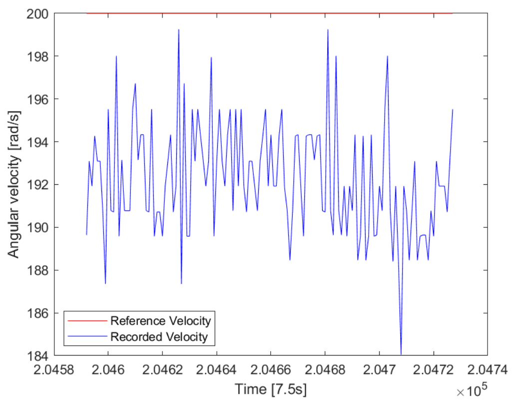

Figure 3 displays a graph of the steady state angular velocity of the motor with inputs of $K_p = 0.5$ and $K_i = 0.005$.

Table 3: Frequency Response

Frequency (Hz)	Actual Amplitude (rad/s)	Amplitude Ratio	Time Period (s)	Time Difference	Phase angle
0.1	414.35	1.036	9.87	0.267	9.601
0.2	411.75	1.029	3.90	0.200	14.400
0.3	409.42	1.024	2.67	0	0
0.4	403.36	1.008	2.11	0.076	10.973
0.5	409.55	1.024	1.77	0.120	21.600
0.6	402.04	1.005	1.49	0.036	7.862
0.7	398.42	0.996	1.30	0.113	28.426
0.8	391.44	0.979	1.14	0.071	20.477

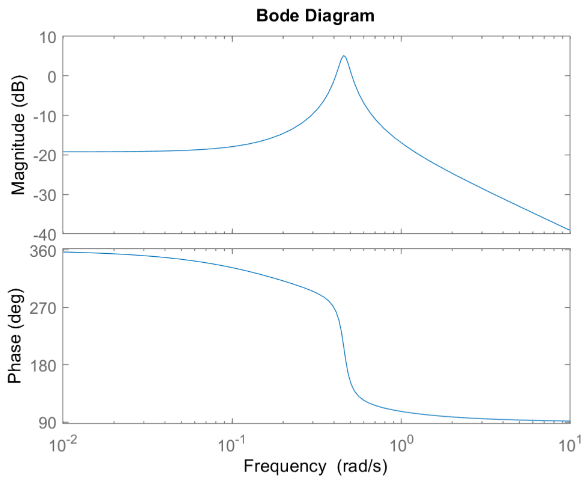

Figure 4 is the bode diagram found from the code in task 5.

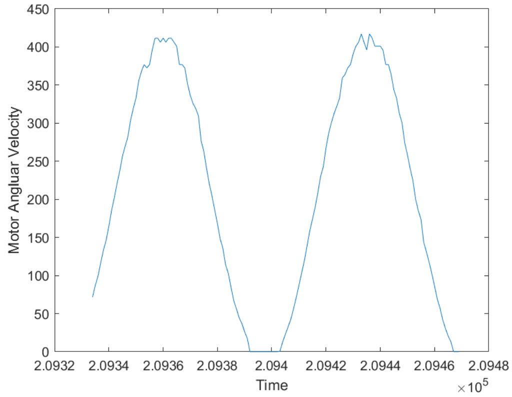

Figure 5 displays the graph at a frequency of 0.1 Hz of the angular velocity of the motor against time.

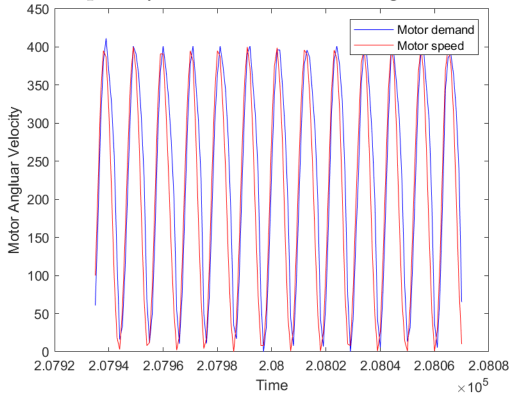

Figure 6 shows the response of the motor to a sine wave function at a frequency of 0.7 Hz.

The data recorded from the experiments is in Table 1 and Table 3. Table 1 shows the effect of changing the proportional and integral control on the DC motor speed and the power output from this speed. For this part the reference velocity as shown in Figure 1 is set to 200rad/s as the high powered motor was used in this case. For this situation the required velocity output should be 200rad/s but as is shown in Table 1 that is not always the case due to the varied PI control.

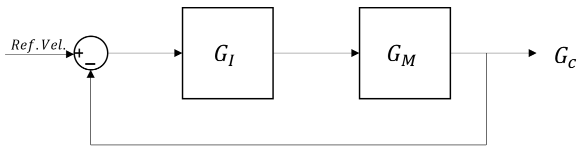

Figure 7 is the box diagram that represents the transfer function of the motor.

The overall transfer function of the control of the motor is presented in the transfer function shown below in Equation ??. It is a combination of the transfer function of the motor and the PI controller. It can be derived from the box diagram (Figure 7) as shown in Appendix 7.1.

$$G_c = \frac{G_M G_I}{1 + G_M G_I} \tag{6}$$

$$G_c = \frac{-0.1104s + 0.0230}{s^2 + 0.0668s + 0.2106} \tag{7}$$

From this equation and having found transfer function G_I previously, where G_I is the transfer function for the PI control, G_M can be calculated. Equation 6 can be rearranged to make G_M the subject of the equation so it can be calculated to find the transfer function of the motor.

$$G_M = -\frac{G_c}{G_I(G_c - 1)} \tag{8}$$

By substituting in the values of the know transfer functions (G_c and G_i) the transfer function of the motor can be found.

$$G_i = K_p + \frac{K_i}{s} \tag{9}$$

$$G_M = \frac{s(0.1104s - 0.0230)}{(K_p + \frac{K_i}{s})(-s^2 - 0.1772s - 0.1876)} \tag{10}$$

5 Discussion

5.1 PI Control

The results from this experiment are shown in Table 1. From Table 1 we can see the effects that K_p and K_i have on the steady state angular velocity and on the power output. However, they did not just affect these two parameters. They also had an effect on the time to reach the steady state velocity (the settle time) and they affected the rise time also with different slopes for different values.

By using a constant value of K_i the effect of changing K_p is shown by the results in Table 2. The general trend is that when the K_p value increases, so does the steady state angular velocity. As well as also increasing the power output of the motor. This is expected as when proportional control gain increases the steady state error should decrease (Chapter 11, Page 526-527 [3]) and thus the velocity would be closer to the reference velocity. Increasing the proportional gain will also increase the rate that the motor responds at. I.e. the higher the value the faster the motor reaches the desired value but it can cause overshoot of the system. This has little effect on the final steady state value so past a certain value and above the steady state velocity should remain the same (200rad/s) only the time taken to reach this state would increase.

When using K_p as a control point i.e. K_p is kept at a constant value hence the change in the response must be due to the change in K_i. By changing K_i the steady state angular velocity increased the higher the value of K_i that was used. Thus the error was decreasing as the target value for the velocity was 200rad/s. The integral control helps to eliminate steady state error by summing up the errors over time (Chapter 11, Page 526-527 [3]). Which is what is shown in the table as when the integral control is changed the value of the steady state velocity is higher every time but not just with a high K_p as it is higher for a value of 0.4 proportional gain. The best combination for this particular motor was a K_p value of 1.0 and a K_i value of 0.01 resulting in an average steady state error of just 1.64% compared to an error of 61.1% with K_p equal to 0.1 and K_i equal to 0. Initially this shows that increasing both has a positive impact on the error reducing it significantly. However, after analysing the other data it is clear that there is an optimum combination of K_p and K_i and with different values of each another value of the other is better suited. For example when K_p and K_i were 0.4 and 0.005 respectively the steady state velocity was only fractionally smaller than the maximum value for the velocity recorded.

5.2 Frequency Response

As the frequency increased generally the actual amplitude decreased, meaning it became closer to the reference amplitude which was 200 rad/s. Following the same trend the amplitude ratio decreased and became closer to 1 as frequency increased. There is one outlier at a frequency of 0.5Hz which could be because of the errors stated below. The way to test this and to change for the future would be to repeat the experiment several times and find the average value. As the frequency increased the amount of peaks measured also increased meaning that the chances of the higher frequencies being more accurate is higher than the lower frequencies. The time periods of the waves also decreased and with an increasing frequency this was also expected and can be seen through Equation 4. As the frequency increased the time difference tended to decrease and seemingly get more accurate. From Table 3 this is the overall trend. However, there are some outliers to this suggesting that it may just be a coincidence that the trend decreases and that the only reason the phase difference and time difference were not the same every time is due to the errors. As phase difference is calculated from the time difference a similar thing is found except from the overall trend is an increase rather than a decrease. A value of 0.1Hz caused the system to be saturated, meaning the output is held at its maximum or minimum value. This is clear to see from Figure 5. At the maxima it is also clear to see the noise that was produced from the circuit. Overall it is likely that this point has many inaccuracies so wouldn't be used as a reference point for the rest. At a frequency of 0.7Hz the system doesn't appear to be saturated at any point and has sharp points at the minima and maxima. Although it is less clear in this example the noise can also be seen as the red line has slight 'wobbles' in it which represent the noise from the experimental set-up.

5.3 Errors

The experiment yielded accurate results from the two experiments but there is some possible inaccuracy due to errors. One such error is in the set-up of the equipment. In the set up the motors used are quite old and we are assuming in this experiment that they are 100% efficient however, this is likely not the case and this can be seen as the steady state error never completely reaches the reference steady state line. It is also represented in the electrical noise that is produced from the rotary encoder measurements. In this set up there is also the possibility that the shafts that connect the motor and the rotary encoder are slightly misaligned due to the amount of usage and age of the equipment. This may have also contributed to the motor never reaching the reference velocity due to increased frictional forces on the shaft.

The results of the error is shown in Figure 3. This graphs shows the amount of noise that was in the DC motor. Ideally with a perfectly efficient system system the blue line would be entirely horizontal and the output speed of the motor would be at a constant value.

In Figure 5 at the minima and maxima of this graph there is an obvious error due to the saturation of the motor. This is shown by the more horizontal lines rather than a sharp peak as shown in Figure 6. However, in the graph Figure 6 there is a different error. As the frequency of the sine wave input to the motor is so large there is much fewer points in a time period that can be measured due to how the interval measurement was set up. This means that the values at the minima and maxima may have some inaccuracy. When the motor demand was 0 the recorded value of the angular speed may have been higher as a value was not taken exactly at 0 so it doesn't show that the motor stops. But when performing the experiment it was clear that the motor was stopping each time when the demand was 0. On some occasions the motor demand recorded never reached 0 either because of the high frequency. When the frequency was low sometimes because of the resistance of the motor and the residual momentum, it would not instantly become 0 and by this time the demand would be higher again so it is likely in some cases the motor demand did not reach 0 completely.

6 Conclusion

In conclusion, in the first experiment the as K_p was increased so was the steady state angular velocity. This increase was towards the line corresponding to an angular velocity of 200rad/s. Also in this experiment as K_i was increased again was the steady state error was decreasing and the steady state velocity tended towards 200rad/s once again. However, it was found that having two high values for K_p and K_i was just as accurate as good at correcting the steady state velocity as two average values with the correct combination. The second experiment yielded the result of the bode diagram and the calculation of G_M. With an increasing frequency the amplitude and amplitude ratio decreased, initially becoming closer to the actual amplitude and then at a frequency of 0.7 continuing to decrease lower than the reference amplitude. Finally, from this experiment it was clear that there were some errors in the equipment which led to slight errors in the results. However, these results still showed the expected trends and as expected and were compliant with what we already know about control theory. Therefore we can conclude that the errors overall had a minimal effect on the overall result from the two experiments.

7 Appendix

7.1 Appendix 1

Box diagram reduction to the overall transfer function

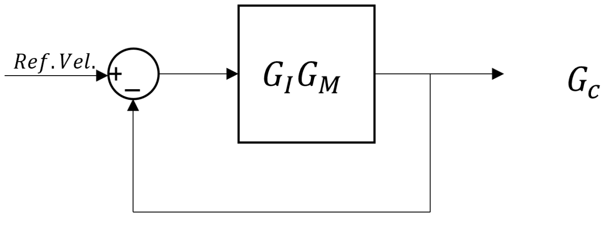

Figure 8 shows the fist stage of simplification of the box diagram. The two separate transfer functions surrounded by the same control loop, have been multiplied together to for a single transfer function and a control loop.

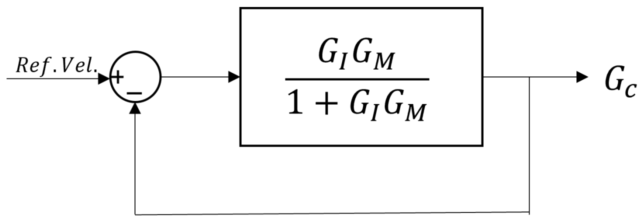

Figure 8 shows the second and final simplification stage of the box diagram reduction. The transfer function has been combined with the control loop to form an overall transfer function that when used individually is the same as the entire box diagram.

References

[1] Ni.com. sbrio-9505. https://www.ni.com/en-gb/support/model.sbrio-9505.html, 2021.

[2] Ni.com. Compactrio controller. https://www.ni.com/en-gb/shop/hardware/products/compactrio-controller.html, 2021.

[3] David G Alciatore. *Introduction to mechatronics and measurement systems.* McGraw-Hil, fifth edition, 2018.