Exercise 1.2.1 ***(3 points)***

Plot the gain of the motor against the input voltage. What do you observe? Does it follow the behavior of the simplified DC motor given by Equation 1.1?

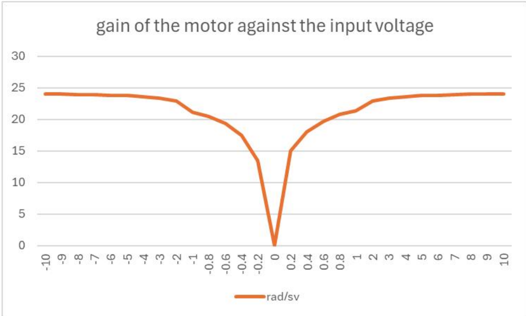


Figure 1

As we can see in figure 1, the Kv is not a constant, and increases as the absolute value of the voltage increases, and starts from 0 to stable around 24rad/s*volts, which does not satisfy the simplified formula
given.

Exercise 1.2.2 ***(2 points)***

What are the possible reasons for a potential non-perfect match of the response of the simulated model with the one of the actual system? Which are the possible causes of such errors?

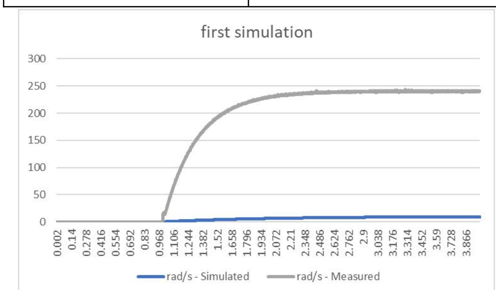
It may be measurement noise, time delay, or just model errors, etc. For the results of this measurement, it may be that the simplified model ignores the performance of Kv at a smaller voltage or there exists feedback, and interference is not taken into account.

Exercise 3.2.1 ***(4 points)***

Provide a detailed description of the experimental process as well as tables and figures of all the results.

After opening the program, enter the corresponding interface, and you can see that numerator coefficient b0 and denominator coefficient (a0, a1) are both 1 at the beginning, and the following figure 2 can be obtained after operation. According to measured data, by finding the time t1 at 0.632 (y1-y0) +y1 and subtracting t1 from the starting time t0, the theoretical value of a1 is obtained, and the theoretical value of b0 can get from exercise 1.2.2 that b0 is 24 when the step magnitude(voltage) is 10volts. And then adjust the value of gain and time constant until the measured figure is almost the same as the simulated figure, the following figure 3 can be obtained. Additionally, measure the parameters of the disk and get the diameter of the disk is 6.00cm, the height of the disk is 1.50cm.

Disk information		10 volts step	
Diameter (mm)	Height (mm)	Gain K	Time const. τ (s)
60.0	15.0	23.9294	0.332



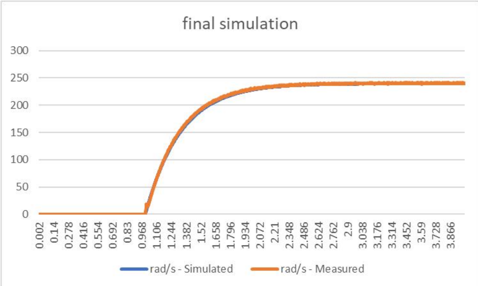


Figure 2

Figure 3

Exercise 3.2.2 ***(2 points)***

Derive the transfer function of the system for your disk.

According to the below figure, can get the transfer

function:$G(s) == \dfrac{K}{\tau s+1} = \dfrac{b_0}{a_1 s + a_0} = \dfrac{24}{0.33s+1}$

Exercise 3.2.3 ***(3 points)***

Discuss what is the impact of the physical size of the rotating mass on the transient and steady state response of the system. What are the implications of this on the required characteristics of the motor?

The increase of the size of the rotating object will also lead to the increase of the mass of the object, and the transient response of the system is affected by the moment of inertia, and the larger the mass usually means the larger the moment of inertia, which will lead to a slower response to the acceleration and deceleration of the applied force. In steady-state operation, greater rotational mass can help stabilize the system by maintaining a consistent rotational speed, reducing the impact of external disturbances. This mainly depends on the choice of the motor. A larger size will make the motor less disturbed by the outside world in the stable state, but the transient state requires more energy and relatively low response speed.

Exercise 4.2.1 ***(3 points)***

The motor shaft of the QUBE-Servo is attached to a *load hub* and a disk load. Based on the parameters given in Table 4.2, and the disk dimensions measured in Section 2, calculate the equivalent moment of inertia that is acting on the motor shaft for the disk you used.

$$J_{eq} = J_m + J_h + J_d \quad J_m = 4 \times 10^{-6} kg \cdot m^2 \quad J_h = 1.07 \times 10^{-6} kg \cdot m^2$$

$$J_d = \frac{1}{2} m r^2 = \frac{1}{2} \pi \rho h r^4 \quad \rho = 2.7 g/cm^3 \quad r = 3.0cm \ h = 1.5cm$$

$$\therefore J_d = 5.153 \times 10^{-5} kg \cdot m^2 \quad J_{eq} = 5.660 \times 10^{-5} kg \cdot m^2$$

Exercise 4.2.2 ***(4 points)***

Based on the analysis in Section 4 and using the Laplace transform, derive the transfer function of the complete system, between the input voltage and the angular velocity, for your disk. Does this transfer functions match the one derived in Section 3? If not, can you suggest any reasons for this mismatch?

Through using Laplace transform, can get this function:

$$V - RI - k_m \omega = 0 \quad J_{eq} s \omega = \tau = k_t I \Rightarrow$$

$$\frac{\omega}{V} = \frac{k_t}{R J_{eq} s + k_m k_t} = \frac{\frac{1}{k_m}}{\frac{R J_{eq}}{k_m k_t} s + 1} = \frac{\frac{1}{0.036}}{\frac{6.3 \times 5.66 \times 10^{-5}}{0.036 \times 0.036} s + 1} = \frac{27.78}{0.275s+1}$$

The other one in section 3 is $G(s)=\dfrac{24}{0.33s+1}$, there exist some deviations, the theoretical τ is smaller than the experimental τ, and the theoretical K is larger than the experimental K, the reasons leading this result may be the function of friction, or the data in list may not match the real data, and the ignorance of inductance also is possible cause.

Exercise 4.2.3 (2 points)

If the thickness of an imaginary disk is 10 mm, determine its diameter such that the resulting time constant will be 0.5 seconds.

To reach the target that resulting time constant is 0.5s, then through

$$\tau=\frac{RJ_{eq}}{k_m k_t}=\frac{6.3\times J_{eq}}{0.036\times 0.036}=0.5\Rightarrow J_{eq}=1.029\times 10^{-4}$$

$$J_{eq}=J_m+J_h+J_d \quad J_m=4\times 10^{-6}kg\cdot m^2 \quad J_h=1.07\times 10^{-6}kg\cdot m^2$$

$$J_d=\frac{1}{2}mr^2=\frac{1}{2}\pi\rho h r^4=9.82\times 10^{-5}kg\cdot m^2 \Longrightarrow r=\left(\frac{2J_d}{\pi\rho h}\right)^{\frac{1}{4}}=3.90cm$$

$$the\ diameter\ is\ 7.8cm$$

Exercise 4.2.4 *(2 points)*

Assuming that the gain K of the servo system is equal to 1, can you design and derive the transfer function of an appropriate resistor-capacitor (RC) circuit that can mimic the behaviour of your system? If the capacitor size is 47 μF, what would the resistor value be in order to get the same response as the one you got with your disk?

For one circuit with one resistor and capacitor in series, then use Laplace transform we can get $I=sCU_1 \quad I=\dfrac{U_2}{R} \Rightarrow \dfrac{U_1}{U}=\dfrac{\frac{1}{sC}}{R+\frac{1}{sC}}=\dfrac{1}{1+sCR}$ if C=47uF, then R=0.33/47*10^6=7021 Ohm.

Exercise 6.2.1 *(5 points)*

Based on the analysis shown in sections 5.1 and 5.2 and using your measurements obtained in this experiment, calculate the undamped natural frequency and damping ratio for your disk, and derive the corresponding transfer function.

According the data got from experiment, show in figure

$$T_P=0.36s,\ P.O.=33.73\%,\ T_P=\frac{\pi}{\omega_n\sqrt{1-\zeta^2}} \quad P.O.=100\%e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}}=\frac{100\%\ (y_{\max}-R_0)}{R_0}$$

Through matlab to solve this equation $\zeta=0.327, \quad \omega_n=9.234 \Longrightarrow \dfrac{Y(s)}{R(s)}=\dfrac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}=\dfrac{85.27}{s^2+6.04s+85.27}$

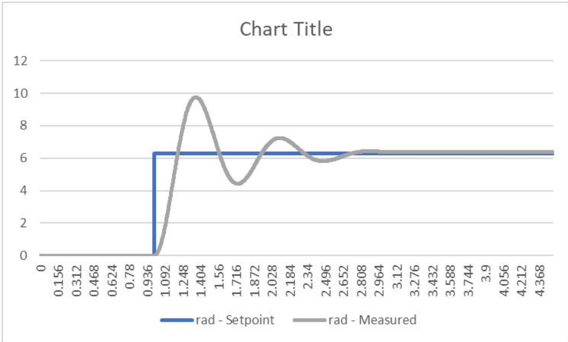


Figure 4

Exercise 6.2.2 ***(4 points)***
In Sections 2 and 3 you derived the transfer functions of the 1st order system (angular velocity control). Using these, and the analysis shown in section 5.3, derive the transfer function of the 2nd order angle control system. Does it match with the one you calculated in question 1? Discuss.

According to the figure 5 shown below,

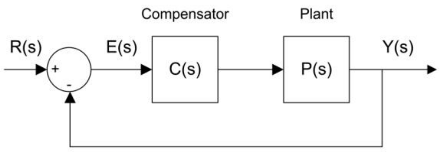


Figure 5.2: Unity feedback loop

Figure 5

$$C(s)=1,\ \ P(s)=\frac{\Theta_m(s)}{V_m(s)}=\frac{K}{s(\tau s+1)}\ \ \Rightarrow\frac{Y(s)}{R(s)}=\frac{\frac{K}{\tau}}{s^2+\frac{1}{\tau}s+\frac{K}{\tau}}$$

$$According\ to\ question 7,\ K=27.78,\ \ \ \tau=0.275\ \Rightarrow$$

$$\frac{Y(s)}{R(s)}=\frac{\frac{K}{\tau}}{s^2+\frac{1}{\tau}s+\frac{K}{\tau}}=\frac{101.02}{s^2+3.64s+101.02}$$

$$the\ actual\ value:\ \frac{Y(s)}{R(s)}=\frac{85.27}{s^2+6.04s+85.27}$$

The theoretical value of K is larger than the actual one about 15%, but the theoretical value of K/τ is larger than the actual one about 40%, due to the theoretical value of K is same for everyone, so the problem may exist in calculating τ or just the J_d, but I also think the process of getting actual value may exsit wrong steps, leading the K and K/τ differ with the effect of τ.

Exercise 6.2.3 ***(4 points)***
Similarly, calculate the peak time and percentage overshoot from the transfer function you calculated in question 6.2.2. How much does it differ from the one you measured in this experiment?
Can you suggest any reasons for any discrepancies in the measured/calculated parameters?

$$According\ to\ \ 2\zeta\omega_n = \frac{1}{\tau} = 3.63\ \ \omega_n^2 = \frac{K}{\tau} = 101.02 \Longrightarrow \omega_n = 10.05 \quad \zeta = 0.1806$$

$$T_P = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} = 0.318\ \ P.O. = 100\% e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}} = 56.2\%$$

$$the\ actual\ vlaue\colon T_P = 0.36s,\ P.O. = 33.73\%$$

The theoretical T_p is smaller than the actual one about 13%, and the theoretical P.O. is larger than the actual one about 40%. First of all, the system maybe not an ideal second-order system like the capacitor is not in consideration, the real system is more complex than the actual one. Secondly, the parameters from panel are affected by the image resolution, noise and other disturbance.

Exercise 6.2.4 ***(4 points)***
In terms of the disturbance rejection properties of the 2nd order system, what can be improved? Can you propose any solution?

1 Filter is used to filter out the noise introduced at different stages, thereby improving the quality of the results.
2. Use PID and other control algorithms to improve the anti-interference ability of the system.
3 Gain adjustment, adjust the system gain under different conditions, so that the noise is relatively reduced.
4 Improve the sensitivity of the sensor, reduce the hysteresis of the system, and then reduce the noise.

Exercise 6.2.5 ***(4 points)***
In the lecture, the concepts of position, velocity and acceleration error constants were introduced. Based on the models you developed in Question 2 above, calculate the velocity error constant K_v and from that the steady state system error for a ramp input with a slope of 10 and 100 rad/s. Observe the results, compare them with your measurements recorded in Table 6.2 and discuss your findings.

$$the\ velcity\ error\ cons\tan t\ K_v = \lim_{s\to 0} sG(s) = \lim_{s\to 0}\frac{Ks}{s(\tau s+1)} = K = 27.78$$

$$the\ steady\ state\ error\ e_{ss} = \frac{1}{K_v} = 0.036$$

$$for\ ramp\ imput\ with\ a\ slope\ of\ 10\ rad/s \quad e_{ss10} = \frac{10}{K_v} = 0.36$$

$$for\ ramp\ imput\ with\ a\ slope\ of\ 100\ rad/s \quad e_{ss100} = \frac{100}{K_v} = 3.6$$

According to figure 6 and figure 7, the actual values of e_{ss} are 0.51 and 4.2 respectively, and can get that the actual steady state system error is closer to the theoretical one for the larger slope of ramp, this may be led by disturbance and measurement noise.

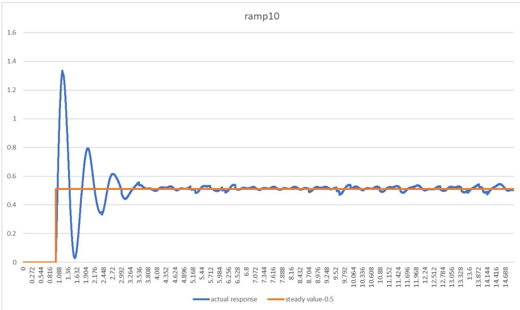


Figure 6

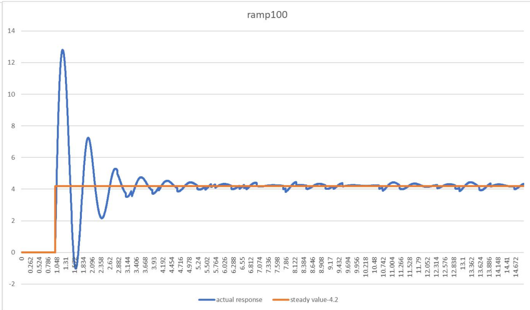


Figure 7

> **Exercise 7.2.1** From the measured $P.O.$ and t_p. determine the parameters K and τ of the 2nd order transfer function $P(s)$. *(4 points)*

According data that Tp=0.216, P.O.=0.368,

$$T_P = \frac{\pi}{\omega_n \sqrt{1-\zeta^2}} \quad P.O. = 100 e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}} = \frac{100\ (y_{\max} - R_0)}{R_0}$$

$$\omega_n = 15.263 \quad \zeta = 0.303 \quad \frac{\Theta_m(s)}{\Theta_r(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} = \frac{\frac{K}{\tau}}{s^2 + \frac{1}{\tau} s + \frac{K}{\tau}}$$

$$\frac{K}{\tau} = 232.96 \quad \frac{1}{\tau} = 9.256 \quad \Rightarrow \ K = 25.18 \quad \tau = 0.108$$

> **Exercise 7.2.2** With $P(s)$ now known, derive the transfer function of the complete system, including K_a and K_v. *(3 points)*

According to figure 8 below, can get formula that

$$\frac{\Theta_m(s)}{Y(s)} = \frac{P(s)}{1 + P(s) K_v s} = U(s) \quad \frac{\Theta_m(s)}{\Theta_r(s)} = \frac{K_a U(s)}{1 + K_a U(s)}$$

$$\Rightarrow \frac{\Theta_m(s)}{\Theta_r(s)} = \frac{K_a \frac{P(s)}{1 + P(s) K_v s}}{1 + K_a \frac{P(s)}{1 + P(s) K_v s}} = \frac{K_a P(s)}{1 + P(s)\,(K_v s + K_a)} \quad P(s) = \frac{K}{s(\tau s + 1)}$$

$$\frac{\Theta_m(s)}{\Theta_r(s)} = \frac{K_a}{\frac{1}{P(s)} + (K_v s + K_a)} = \frac{K_a}{\frac{s(\tau s + 1)}{K} + (K_v s + K_a)} = \frac{K K_a}{\tau s^2 + (K K_v + 1) s + K K_a}$$

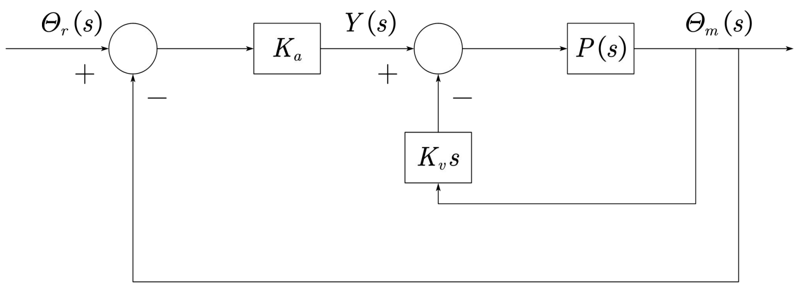


Figure 8

> **Exercise 7.2.3** Calculate K_a and K_v such that the resulting system has an undamped natural frequency $\omega_n = 30 rad/s$ and a percent overshoot $P.O. = 10\%$ *(8 points)*

$$\because P.O.=100\%e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}}=10\% \quad \therefore \zeta=0.591 \ and \ \because \ \omega_n=30rad/s \quad T_P=\frac{\pi}{\omega_n\sqrt{1-\zeta^2}}\Rightarrow$$

$$T_p=0.130s \ \because \frac{\Theta_m(s)}{\Theta_r(s)}=\frac{KK_a}{\tau s^2+(KK_v+1)s+KK_a}=\frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}\Rightarrow\omega_n^2=\frac{KK_a}{\tau}=900$$

$$2\zeta\omega_n=\frac{(KK_v+1)}{\tau}=35.47 \quad K=25.18 \quad \tau=0.108\Rightarrow K_a=3.86 \quad K_v=0.112$$

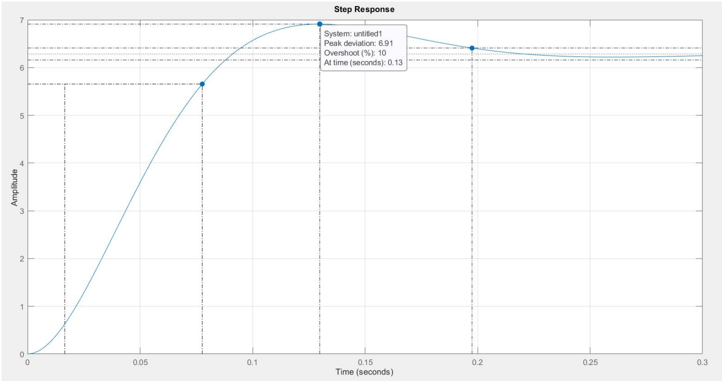


Figure 9

> **Exercise 7.2.4** Plot the step responses of the original system and the one with velocity feedback and comment on the efficiency of the design method. Does your system meet the specifications? *(4 points)*

The origin system is below, and the corresponding function is

$$\frac{Y(s)}{R(s)}=\frac{\frac{K}{\tau}}{s^2+\frac{1}{\tau}s+\frac{K}{\tau}}=\frac{233.15}{s^2+9.26s+233.15}$$

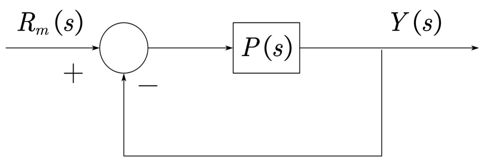


Figure 10

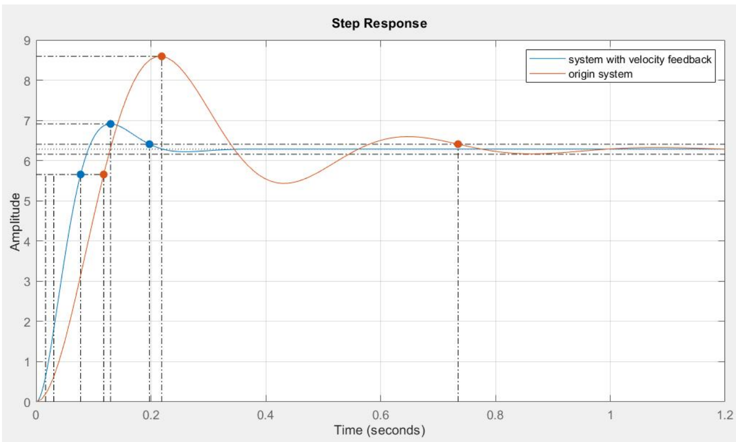


Figure 11

Compared with the system with velocity feedback, the overshoot of the origin system is significantly smaller， rise time, settling time are also smaller.

> **Exercise 7.2.5** Compare the experimental step responses that you obtained between the original, uncontrolled system ($K_p = 1$ and $T_d = 0$) and your velocity feedback controller. Are they a good match to the ones you obtained theoretically? *(3 points)*

$$For\ the\ theoretical\ result\ K_a = 4.33 \quad K_v = 4.33 \times 0.029 = 0.126$$

$$\frac{Y(s)}{R(s)} = \frac{25.18 \times 4.33}{0.108s^2 + (25.18 \times 0.126 + 1)s + 25.18 \times 4.33} = \frac{1009.53}{s^2 + 38.64s + 1009.53}$$

$$\Longrightarrow \omega_n = 31.77 \quad \zeta = 0.61 \quad P.O. = 0.0902 \quad T_p = 0.125$$

$$The\ actual\ result:\ P.O.\ is\ 0.0845 \quad T_p = 0.134$$

$$so\ the\ actual\ result\ almost\ match\ the\ theoretical\ result.$$

> **Exercise 7.2.6** Make an assessment of the performance of the velocity feedback control in terms of its disturbance rejection and setpoint tracking ability. *(3 points)*

As shown in the following figure, figure 12 and figure 13 are respectively two manifestations of velocity feedback control and no velocity feedback control under noise interference. Figures 14 and 15 are two representations with and without noise under swatooth and velocity feedback conditions, respectively. It can be seen that under the condition of velocity feedback, the disturbance rejection ability is obviously enhanced, and the track setpoint is better.

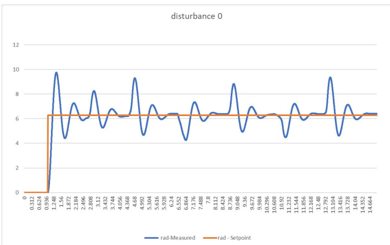


Figure 12

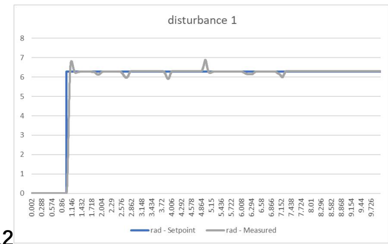


Figure 13

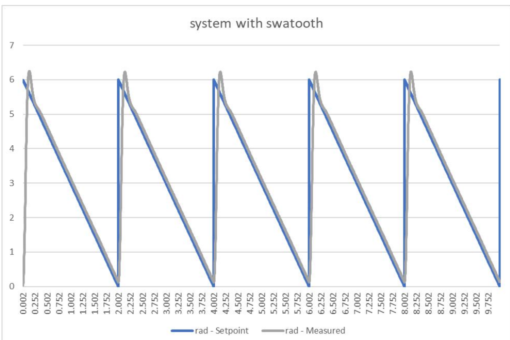


Figure 14

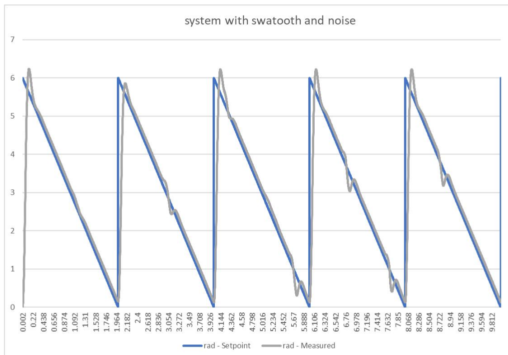


Figure 15

> **Exercise 7.3.1** Describe the experimental process you followed in Section 7.3 and include tables and representative figures of the results. It is important that your answer illustrates clearly your understanding of the process and your interpretation of the results. *(5 points)*

First, in order to make the response of the system to a step input is a sustained oscillation, Ti is inf, Td is 0, kp is about 2.9, kp can continue to adjust according to the result.

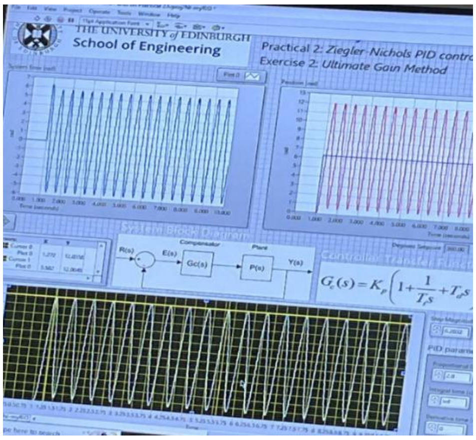


Figure 16

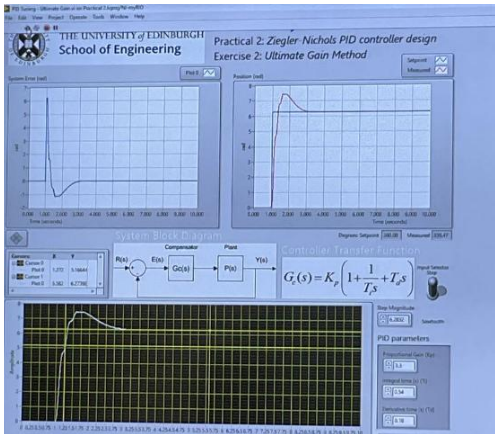


Figure 17

After obtaining sustained oscillation, the Tu is obtained by measuring 10 or 20 (the selected 10) cycles 4.31, and the single cycle 0.431 is calculated, so the Ku is 2.9 and the Tu is 0.431. According to the Ziegler-Nichols Ultimate Gain Table

Proportional Gain Kp = 0.6×Ku	Integral Time Ti = Tu/2	Derivative Time Td = Tu/8
1.74	0.2155	0.0539

Enter Kp, Ti and Td respectively to start the test. The results often need to be adjusted several times. Adjust them through the following table.

	Rise time (t_r)	Maximum overshoot (y_m)	Setting time (t_s)	Steady state error (e_{ss})
K_p	Decreased	Increased	Small change	Decreased
K_i	Decreased	Decreased	Increased	Zero
K_d	Small change	Decreased	Decreased	No impact

In the end, the final result:

Proportional Gain Kp = 0.6×Ku	Integral Time Ti = Tu/2	Derivative Time Td = Tu/8	Overshoot	P.O.
3.2	0.54	0.18	7.53	19.33%

Exercise 7.3.2 For a simple proportional controller ($C(s) = K_p$), use an appropriate theoretical method to calculate the transfer function of the complete system, and find the value of K_p for which the system becomes marginally stable as well as the period of oscillation of the marginally stable system. How do these compare with the experimentally obtained? *(6 points)* ■

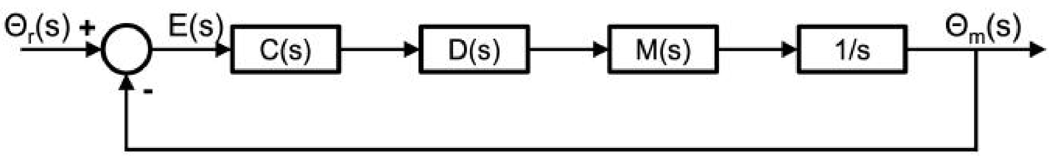


Figure 18

$$M(s)=\frac{K}{\tau s+1}\quad \textit{for this disc, } r=2.5cm \quad h=1cm$$

$$J_{eq}=J_m+J_h+J_d \quad J_m=4\times10^{-6}kg\cdot m^2 \quad J_h=1.07\times10^{-6}kg\cdot m^2$$

$$J_d=\frac{1}{2}mr^2=\ \frac{1}{2}\pi\rho h r^4=1.657\times10^{-5} \ J_{eq}=2.164\times10^{-4}$$

$$\tau=\frac{RJ_{eq}}{k_m k_t}=\frac{6.3\times J_{eq}}{0.036\times0.036}=0.105$$

$$C(s)=K_p \quad D(s)=\frac{0.4}{0.05s+1} \quad M(s)=\frac{27.78}{0.105s+1} \quad T(s)=\frac{1}{s}C(s)D(s)M(s)$$

$$\frac{\Theta_m(s)}{\Theta_r(s)}=\frac{T(s)}{1+T(s)}=\frac{K_p\frac{0.4}{0.05s+1}\frac{27.78}{0.105s+1}}{s+K_p\frac{0.4}{0.05s+1}\frac{27.78}{0.105s+1}}=\frac{11.112K_p}{0.00525s^3+0.155s^2+s+11.112K_p}$$

$$\begin{array}{llll}
s^3 & 0.00525 & 1 & \\
s^2 & 0.155 & 11.112K_p & \\
s^1 & 1-\dfrac{11.112K_p\times0.00525}{0.155} & 0 & \textit{for the marginally stable system} \\
s^0 & 11.112K_p & 0 & 1-\dfrac{11.112K_p\times0.00525}{0.155}=0 \Longrightarrow K_p=2.6569303
\end{array}$$

$$F=2.6569303\frac{0.4}{0.05s+1}\frac{27.78}{0.105s+1}=\frac{29.538}{0.00525s^2+0.155s+1}$$

Compared with the experimental value Kp=2.9, the theoretical value Kp=2.657 is little smaller, but I think it is within the acceptable range, the difference may be caused by noise, or the simplified model.

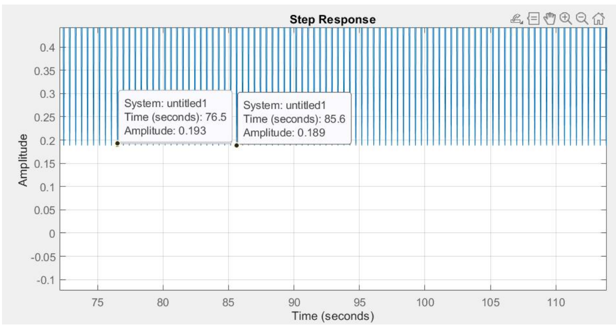


Figure 19

Exercise 7.3.3 Construct the Bode diagram of the system with the initial and the optimised Ziegler-Nichols parameters and determine the gain and phase margins. What do they say about the relative stability and the oscillatory behaviour of the systems? *(5 points)*

$$\textit{for open circuit } \frac{\Theta_m(s)}{\Theta_r(s)}=K_p\frac{0.4}{0.05s+1}\frac{27.78}{0.105s+1}\frac{1}{s}=\frac{3.2}{s}\left(1+0.18s+\frac{1}{0.54s}\right)\times$$

$$\frac{11.112}{0.00525s^2+0.155s^2+1}=\frac{3.2}{s}\frac{0.0972s^2+0.54s+1}{0.54s}\frac{11.112}{0.00525s^2+0.155s^2+1}$$

$$=\frac{3.456s^2+19.202s+35.558}{0.002835s^4+0.0837s^3+0.54s^2}$$

And through the bode diagram of system I can get the gain margin infinite, and the phase margin 35. A gain margin of 35 dB means that the gain of the system can be increased by 35 dB from the current level before the system reaches the edge of instability. The infinite phase margin means that the system can handle any number of phase lags without losing stability.

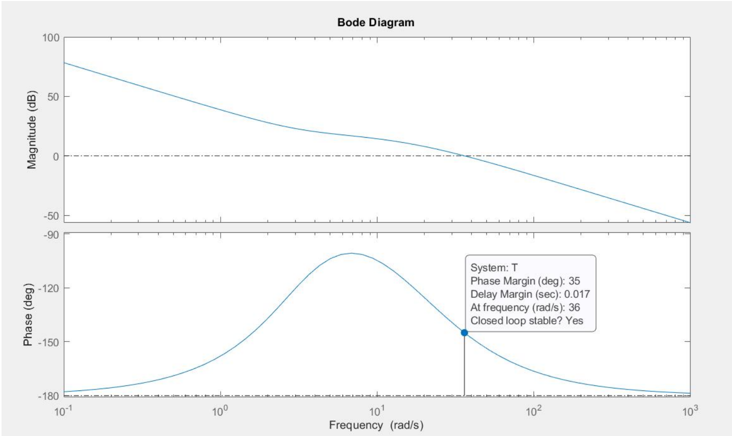


Figure 20

Exercise 7.3.4 Derive the transfer function of the complete closed-loop system with your final (optimised) controller. *(3 points)*

$$for\ close\ circuit\ \frac{\Theta_m(s)}{\Theta_r(s)}=\frac{T(s)}{1+T(s)}\quad T(s)=\frac{3.456s^2+19.202s+35.558}{0.002835s^4+0.0837s^3+0.54s^2}$$

$$\frac{\Theta_m(s)}{\Theta_r(s)}=\frac{\frac{3.456s^2+19.202s+35.558}{0.002835s^4+0.0837s^3+0.54s^2}}{1+\frac{3.456s^2+19.202s+35.558}{0.002835s^4+0.0837s^3+0.54s^2}}=\frac{3.456s^2+19.202s+35.558}{0.002835s^4+0.0837s^3+0.54s^2+3.456s^2+19.202s+35.558}$$

$$=\frac{3.456s^2+19.202s+35.558}{0.002835s^4+0.0837s^3+3.996s^2+19.202s+35.558}$$

Exercise 7.4.1 Describe the experimental process you followed in Section 7.4 and include tables and representative figures of the results. It is important that your answer illustrates clearly your understanding of the process and your interpretation of the results. *(5 points)*

Open the file named "PID Tuning-Reaction Curve.vi" to enter the corresponding interface, determine step magnitude (default is 100), set Kp to 1, Ti to inf, and Td to 0. After obtaining Reaction Curve, use a ruler to judge the intersection of the tangent line of the inflection point and the X-axis, so as to measure the size of T, L, L=1.164-1=0.164 T=1.674-1.164=0.51, and because the input size is 100 and the output size is 85, the gain value K is 0.85. therefore

Gain K	Time Constant τ	Delay L
0.85	0.51	0.164

Proportional Gain $K_p=\frac{1.2\tau}{K\times L}$	Integral Time Ti=2L	Derivative Time Td=0.5L
4.3646	0.328	0.082

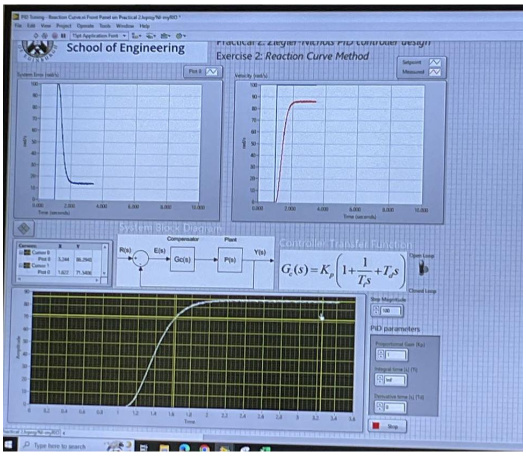


Figure 20

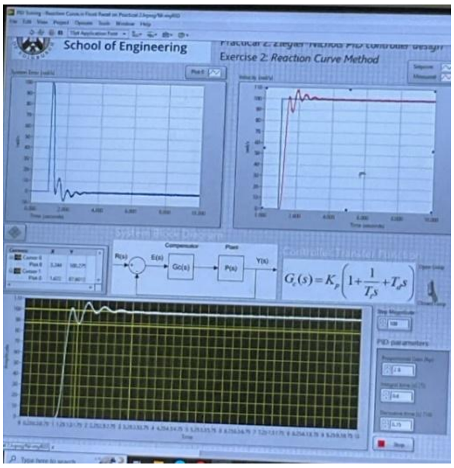


Figure 21

to achieve a maximum overshoot P.O. no more than 20%, use trial-and-error to optimize PID.

	Rise time (t_r)	Maximum overshoot (y_m)	Setting time (t_s)	Steady state error (e_{ss})
K_p	Decreased	Increased	Small change	Decreased
K_i	Decreased	Decreased	Increased	Zero
K_d	Small change	Decreased	Decreased	No impact

Kp	4.3646	3.8	2.9	2.9	2.9	2.9	2.9	2.9
Ti	0.328	0.328	0.328	0.25	0.3	0.35	0.6	0.6
Td	0.082	0.082	0.082	0.1	0.1	0.1	0.1	0.15

Through the above series of optimizations, the final P.O. result is 3.3%

Exercise 7.4.2 Compare the experimental step response curve that you obtained for the position control experiments between the original, uncontrolled system ($K_p = 1$, $T_i = inf$ and $T_d = 0$), the system with the controller parameters straight out of the Ziegler-Nichols table, and your final, optimised controller. Make an assessment of the achieved improvement in both the transient and the steady state response. *(5 points)*

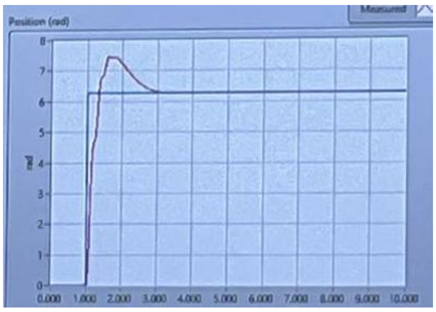


Figure 22

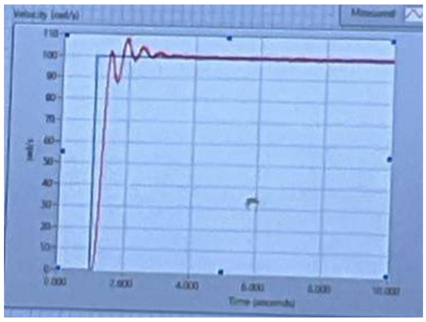


Figure 23

The first graph may represent the position over time, showing a larger rise and less overshoot in the optimized controller curve, indicating an improved transient response.

The second graph may be the speed response, where the optimized controller responds faster to the desired speed with less fluctuation, indicating better control in the transient state.

Exercise 7.4.3 It was shown in the PID controller design process that when it comes to selecting values for the P, I and D parameters there are decisions and compromises that may have to be made, related to controller configuration, the required response characteristics, in terms of its steady state error, maximum overshoot, rise time and settling time. Discuss your observations and explain how a decision on the required compromises can be made using real-world examples. *(4 points)* ■

P: A higher proportional gain can shorten the rise time, which is conducive to a fast response, but may also lead to an increase in overshoot, which can cause oscillations if too high.

I: The integral action eliminates steady-state error, but may result in overshoot and increased build up time. In systems where steady-state errors must be kept to a minimum,

D: Derivative action predicts system behaviour, thereby improving stability and reducing overshoot. However, it is sensitive to noise and may not be suitable for all systems, especially those with noise measurement signals.

For example, in the self-driving vehicle, it is necessary to respond quickly to sudden signals and improve the stability of the system. In the temperature control of chemical reactions, carefully adjusted I parameters are crucial.

Exercise 7.4.4 This year's invited lectures presented real-world applications of control engineering in the areas of flying and underwater robotics. What are the main challenges in controlling flying drones and underwater autonomous vehicles? How can PID controllers be used in these applications? Are there any other control techniques that can be utilised? *(4 points)* ■

1 Sensing, perception, communication, environmental factors, computational complexity.

2 PID, one type of feedback control loop mechanism, can be used in precise motion. By providing position feedback and adjustments, the robot can move smoothly and precisely to the programmed point.

3 DDP, differential dynamic programming, iteratively refine the trajectory by linearizing the dynamics and cost functions around the current trajectory, and then calculating control adjustments to minimize the total cost.

MPC, model predictive control, uses models to predict future system states, and by optimizing those predictions for optimal control.