University of New Hampshire

College of Engineering and Physical Sciences
Department of Mechanical Engineering

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November 25, 2017

Dr. Alireza Ebadi
University of New Hampshire
105 Main St
Durham, NH 03824

Dear Dr. Ebadi,

With the anticipation of the new water pump system for the University New Hampshire's Engineering Department, our organization is excited for the opportunity to be considered to be your team of researchers for this upgrade. Our organization can promise accurate results for your system.

Several quantitative and qualitative results for different system options are computed primarily using MATLAB. These systems include closed loop Proportional, Integral, and Proportional-Integrated Control. An open loop system is also presented for reference and comparison purposes. Right away we can say that the PI Controller is the optimal choice for the Engineering Department's water pump system, alternate systems are also shown to support the controller's ability for this application. For the purpose of simplicity, but still relevant results, a DC brush motor system is analyzed for each controller application. This document will focus on the scientific aspects rather than the economic aspects of design and pricing at these stages. Once a preferable design is presented and if you agreed upon, we will proceed to discuss costs of design.

Sincerely,

Group TJ

James Skinner, Taylor Maniatty

University of New Hampshire

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<table>
<tr><td colspan="2">Course Number and Name:

ME 747: Experimental Measurement and Modeling of Complex Systems</td></tr>
<tr><td>Semester and Year:
Fall 2017</td><td>Name of Lab Instructor:
Alireza Ebadi</td></tr>
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Velocity Control of a DC Brush Motor Under Load</td></tr>
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<tr><td rowspan="2">Names of Group Members:

James Skinner
Taylor Maniatty</td><td>Grader's Comments:</td></tr>
<tr><td>Grade:</td></tr>
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OBJECTIVES

The objective of this lab is to investigate different controls of the rotational speed of a DC brush motor. These tests will help further understanding of tracking an input signal and regulate the output with a feedback. The parameters of a DC brush were calculated and compared for accuracy of results. To determine the motor (MUT) constants, another DC motor was used to back-drive the MUT. The performance of P, I, and PI Controllers is analyzed both quantitatively and qualitatively using calculations and plots in MATLAB. Despite being given the gain values for the experiment, it is to be established in this experiment that the root locus method can be used to determine appropriate gain values of the control system.

EXECUTIVE SUMMARY

The three controllers we used were proportional (P), integral (I), and a proportional-integral (PI). These help the motor maintain the reference speed regardless of the torque load on the motor. It also helps the motor track an input velocity signal. Since the motor was driven by a power op-amp, the speed was measured using a tachometer. We were given the components for the controllers.

For the experimental setup, the electrical time constant was neglected due to the electrical time constant of the given motor was much faster than that of the mechanical. So from that, L=0. The power op-amp was wired for an open-loop gain of -1 which provided the necessary power to drive the motor. The op-amp was powered by a separate +15V and -15V from the BK Precision dual power supply.

For the DC motor back EMF constant, we found the K_e to be 4.9425 V/KRPM by back driving the motor under test (MUT) using an identical motor attached to the MUT by a flexure coupling. The torque constant Kt was then calculated using the assumption that Kt = Ke, thus giving a result of 6.6840 oz-in/A. Both of the motor and torque constant fell within the expected range from the specification sheet (Appendix E).

For the open-loop response to a voltage step input and a disturbance torque we measured the step response of the DC motor. From this, we were able to from τ and K of the system to be 0084 sec and 19.0922 (rad/s)/V respectfully. Also, when a disturbance load was placed on the system, we measured the steady-state speed error to be 0.6464. This was found using the equation for a type 0 system with a step input.

Lastly, the closed-loop response to a voltage step input and to a disturbance torque section was using a tachometer voltage as the feedback signal and a 741 op-amp as the system compensation. Measurements were taken for all three controllers; P, I, and PI. The system with the P controller was the fastest with the I controller being the slowest. Thus, the P controller has significant error and the I controller is implemented to remove most of that error. The combination of controllers is usually needed when optimizing a feedback design.

THEORY AND EXPERIMENTAL METHODS

The open loop system below includes a MUT, a tachometer, a power op-amp to drive the motor, and an additional motor as shown below in Figure 1. The additional DC motor was used to provide a disturbance load (Td) as well as back drive the motor under test.

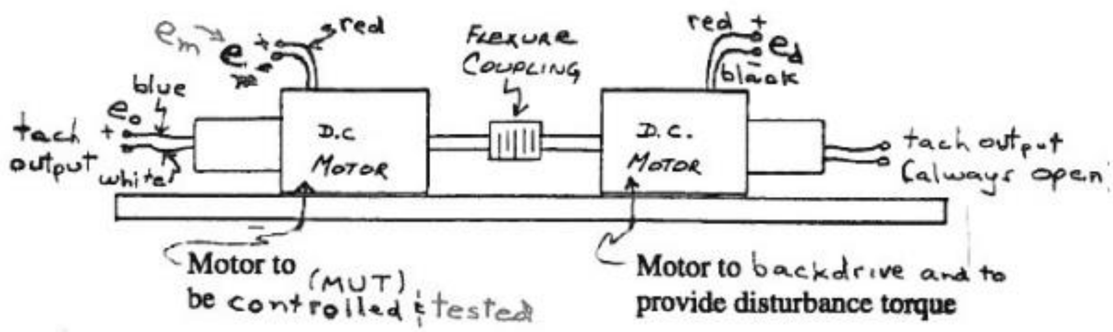


Figure 1: Experimental Setup

The open-loop motor block diagram is shown below in Figure 2. The electrical time constant was neglected due to the electrical time constant of the given motor was much faster than that of the mechanical.

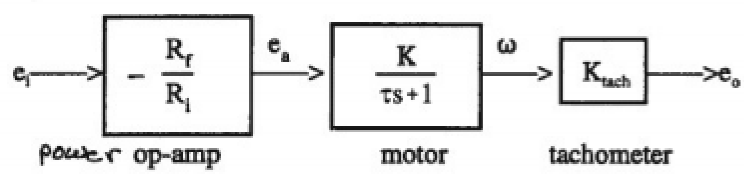


Figure 2: Open-Loop System Block Diagram

The power op-amp seen below, is wired for a gain of -1. This provides the necessary power to drive the motor but since both resistances, R_i and R_f, were 100kΩ, the power op-amp is equal to one and therefore does not create any changes in the system.

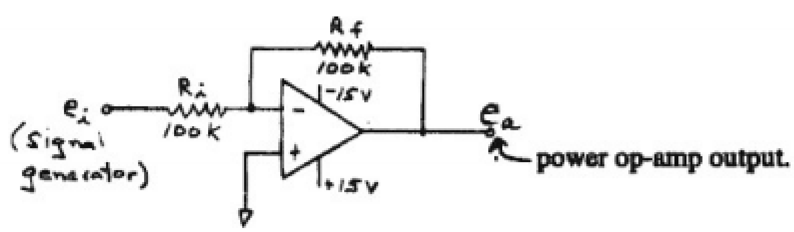


Figure 3: Power Op-Amp Wiring

For the DC motor back EMF constant, we found K_e by back driving the motor under test (MUT) using an identical motor attached to the MUT by a flexure coupling. This was analyzed at various speeds and we also measured the voltage at the MUT terminal leads. The system is connected to a +/-15V power supply and a DC input is simulated by inputting steady voltages from 1V to 10V at a frequency of 0.001Hz.

The slope of the best fit line for the motor voltage constant is shown in the equation below;

$$e_o = K_e\omega + b \tag{1}$$

Also,

$$K_t = 141.6119 * K_e \tag{2}$$

Using the assumption that for a DC brush motor Ke = Kt. Ke in terms of V/(rad/s) is equal to Kt in terms of N*m/A, this can be converted to oz-in/A using a constant factor of 141.6119. For the open-loop response to a voltage step input and a disturbance torque we measured the step response of the DC motor. From this, we were able to from τ and K of the system. The system of equations for the MUT were first found for both the electrical and mechanical parts of the model and can be seen below, respectively.

$$e_i - iR - K_e\omega_o - L\frac{di}{dt} = 0 \tag{3}$$

$$\mathrm{K_t i - B\omega_o - T_L = J\dot{\omega}_o} \tag{4}$$

Where 'e_i' is the input voltage, 'i' is the current through the system, R is resistance, K_e is the back EMF constant, ω_o is rotational velocity, L is the inductance, K_t is the motor constant, B is the damping coefficient, T_L is the load torque and J is the inertia of the system. The equation for the stall torque can be see below, then was simplified from the system of equations above.

$$T_{stall} = iK_t = \frac{e_i}{R}K_t \tag{5}$$

Where e_i is the input voltage of 6V and R had a resistance of 5Ω. The time constant was calculated from the 4V step input using the 63.2% method. Next, K was calculated by taking the ratio of the steady state output voltage value to the input step voltage of the system and dividing it by the tachometer sensitivity. This was then used to calculate the motor inertia (J) and the damping coefficient (B) of the system. The transfer function pf the first order system was then derived to be;

$$\frac{w_o}{E_i} = \frac{\frac{K_t}{BR+K_eK_t}}{\left(\frac{JR}{RB+K_eK_t}\right)s+1} = \frac{K}{\tau s+1} \tag{6}$$

To find the damping coefficient and the motor inertia, the following equations were used.

$$B = \frac{\frac{K_t}{K} - K_e K_t}{R} \tag{7}$$

$$J = \frac{\tau(RB + K_e K_t)}{R} \tag{8}$$

To find the settling time of the open-loop motor, the time constant is multiplied by four. The steady-state error equation is shown below

$$e(\infty) = \frac{1}{\lim_{s\to 0}\frac{1}{P(s)} + \lim_{s\to 0} C(s)} \tag{9}$$

Where P(s) is the plant function and C(s) is the controller function.

The 63.2% method was used again to calculate the time constant for the disturbance load. This was then compared to the time constant from the step change. The closed loop feedback control system can also be written in block diagram form shown below

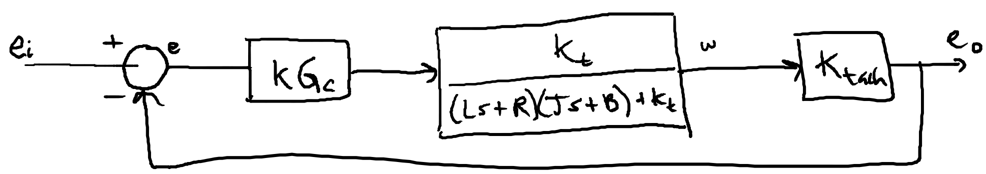


Figure 4-Closed-Loop Block Diagram

The different controllers have different compensations causing the systems to respond differently while the motor block stays the same with the calculated K and τ from the open-loop system. Below are how the compensations, G_c, for the different controllers are calculated.

$$P\ Control: KG_c = K\frac{R_f}{R_i} \tag{10}$$

$$I\ Control: KG_c = K\frac{R_f}{R_i} \tag{11}$$

$$PI\ Control: KG_c = K(R_f C_2 s + 1/R_i C_2 s\ ) \tag{12}$$

The open-loop transfer functions for the P, I, and PI controls, respectively, were found to be;

$$\frac{\frac{\frac{R_f}{R_i}K*K_{tach}K_{add}}{\tau}}{s+\frac{1}{\tau}} \tag{13}$$

$$\frac{\frac{\frac{1}{R_iC_1}K*K_{tach}K_{add}}{\tau}}{s^2+\frac{1}{\tau}s} \tag{14}$$

$$\frac{\frac{K*K_{tach}K_{add}R_fC_2s+K*K_{tach}K_{add}}{\tau R_iC_2}}{s^2+\frac{R_iC_2}{\tau R_iC_2}s} \tag{15}$$

Here, K_{add}, the addition gain term, allows the roots to be moved along the root locus. This was set to one for the calculation of the roots of the system. We used the equation below to find the poles of the system.

$$1 + G_c\frac{\frac{K}{\tau}}{s+\frac{1}{\tau}}K_{tach} = 0 \tag{16}$$

From this, the eigenvalues can be found through the s term. These correspond to the poles of the system, both I and PI controllers will have more than one pole. The speed, τ, can also be found from the s values calculated. The equation below is used to find speed for the P control system.

$$\tau = \frac{1}{s} \tag{17}$$

For the I and PI controllers, there is a second order system involved so the speed can be found from;

$$\tau = \frac{1}{\omega\zeta}$$

The speed of the systems can be compared from the time it takes to reach tau.

RESULTS AND DISCUSSION

Calibration of the MUT allowed for the back emf constant, Ke, to be calculated in order to find the motor torque constant, Kt. The tachometer sensitivity, given in the specification sheet, 3 V/KRPM was first converted to V/(rad/sec). The tachometer sensitivity used was 0.0286 V/(rad/sec). This conversion was made so the tachometer output voltages could be converted into rotational velocities. The tachometer rotational velocities were then plotted against the MUT motor terminal lead voltages, and can be seen below in Figure 4.

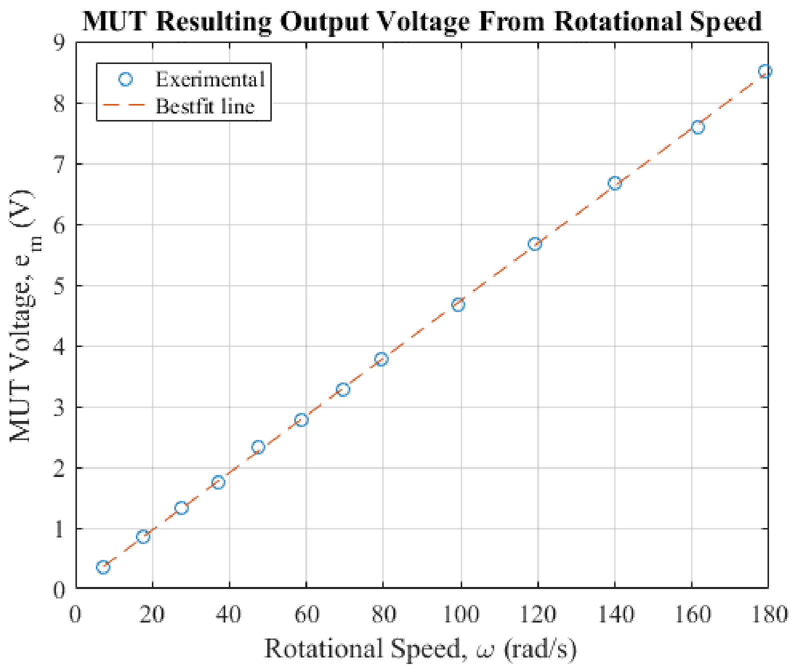


Figure 5- MUT output voltage vs rotational speed

Using the slope of the best fit line (Equation 1) from Figure 4, the motor voltage constant, Ke was found in V/(rad/sec), which was then converted to V/KRPM. Finding the motor voltage constant in V/KRPM and converting to V/(rad/s) allowed for Equation 2 to be used to calculate the torque constant of the system with units of oz-in/amp. The values for the motor voltage constant and motor torque constant can be seen in the below table.

Table 1- Motor voltage and torque constants

Motor Voltage Constant, Ke (V/(rad/s))	0.0472
Motor Voltage Constant, Ke (V/KRPM)	4.9425
Motor Torque Constant, Kt (oz-in/A)	6.6837

The experimental values for the motor voltage constant and the motor torque constant were compared to the values given in the specification sheet (Appendix E). From the specification sheet the motor voltage constant should have fallen into the range of 4.39-

5.37 V/KRPM and the motor torque constant should have been 6.6 ± 10% oz-in/amp. As shown in Table 1 the motor voltage constant falls well within the acceptable range since the actual value of Kt is only + 1.25% from 6.6 oz-in/A.

Analysis of the open-loop response to a voltage step input and to a disturbance load allowed for the first order parameters of the system to be calculated. A step response with a ±4V square wave output was input into the system allowing for the calculation of the motor stall torque (T), gain (K), time constant (τ), damping coefficient (B), and motor inertia (J) of the system. The calculated values can be seen in the table below.

Table 2-Open-Loop response system parameters

Motor Stall Torque, T (oz_f-in)	8.0204
Gain Term, K (rad/s/V)	19.0922
Time Constant, τ (ms)	8.4000
Damping Coefficient, B (oz-in/KRPM)	0.8633
Motor Inertia, J (oz-in/s^2)	7.0015e-04

Using the derived system of equations (Equations 3 and 4) the equation for motor stall torque was derived, Equation 5. Stall torque is the load needed to cause the motors rotational velocity to be zero and therefore "stall" the motor. With the assumption that the rotational velocity is zero, the input voltage of the system was 6V and the resistance was 5W, the torque was calculated. The Gain of the system, K, was then calculated. To find the gain term, the ratio of the steady state voltage and the input step voltage was taken and divided by the sensitivity of the tachometer. This was done because rotational speed of the motor is unknown. The time constant, t, was calculated using the 63.2% method with the data in the below figure, from the data collected with the step response of the DC motor.

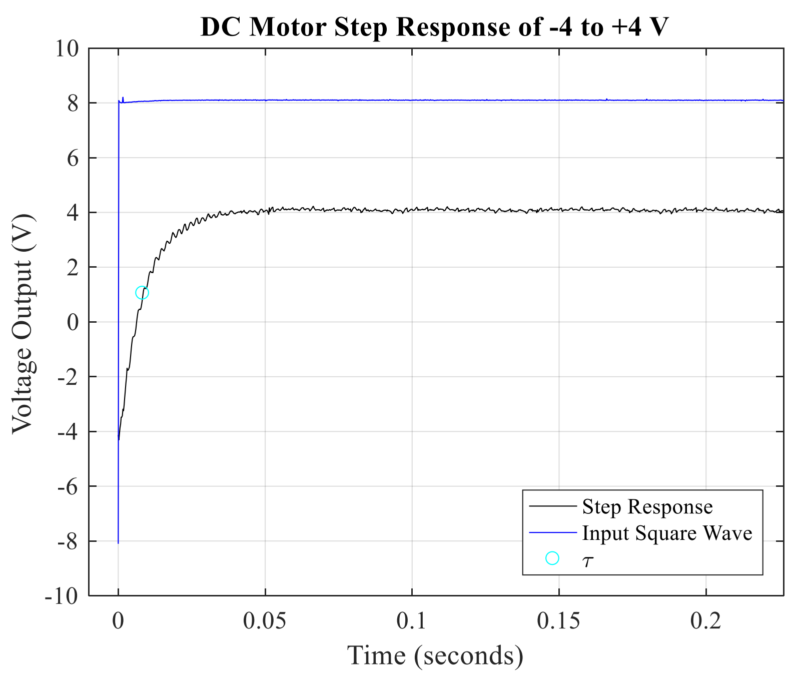


Figure 6- Step response for the open-loop system to determine the time constant

The 63.2% method evaluates the time at which it takes the step response to reach 63.2% of its final steady state value. Having found the time constant and the gain term for the system the damping coefficient and the inertia were then found, using Equations 7 and 8, respectively. The value for time constant, damping coefficient and inertia were then compared to the given values in the specifications sheet. Because two motors were used, the values for damping coefficient and motor inertia from the specification sheet (Appendix E) were doubled. The experimental values and the specification values can be seen in the table below.

Table 3- Experimental vs. expected values from the specification sheet

	Expected	**Experimental**	**Percent Error**
Time Constant (ms)	6.100	8.400	37.7 %
Damping Coefficient (oz-in/KRPM)	0.400	0.863	115.8%
Motor Inertia (oz-in-sec^2)	8.00e-4	7.00e-4	12.5%

The reason for such a large error in the damping coefficient is due to aging of the DC motors used. The specifications of the new motor date back to August 27th, 1998. Older motors, especially ones that have not been properly maintained with oil, will create more friction, adding to the damping of the overall system. Though the results are very different from the expected specifications, it does not necessarily mean they are wrong, as wear and friction play a large role in the damping of a system. The motor inertia was calculated using the damping coefficient, therefore, though there is less error, some is still present. The small amount of error in the calculation of the time constant shows that the data collected for the step response output was accurate. The settling time of the open-loop motor was then calculated by multiplying the time constant by four. The settling time for the system is 33.6 ms.

The steady state speed error of the motor when subjected to a disturbance load from the 5.0 Ω load resistor was the calculated using Equation 9. The steady state speed error was .6464. Lastly the time constant for the disturbance load was calculated using the 63.2% method and compared to the time constant from the step response. The comparison of the two time constants can be seen below.

Table 4- Time constant comparison with and without a disturbance load

Step Response Time Constant (ms)	**Disturbance Load Time Constant (ms)**	**Percent Difference**
8.4	7.8	7.8 %

The disturbance load time constant is less and therefore will reach steady state more quickly than the step response. With only a 7.8 % difference and the time of each system being measured in milliseconds, there is not much variation between the two time constants for the system. Refer to the figure below for a visualization of finding the time constant of the disturbance load.

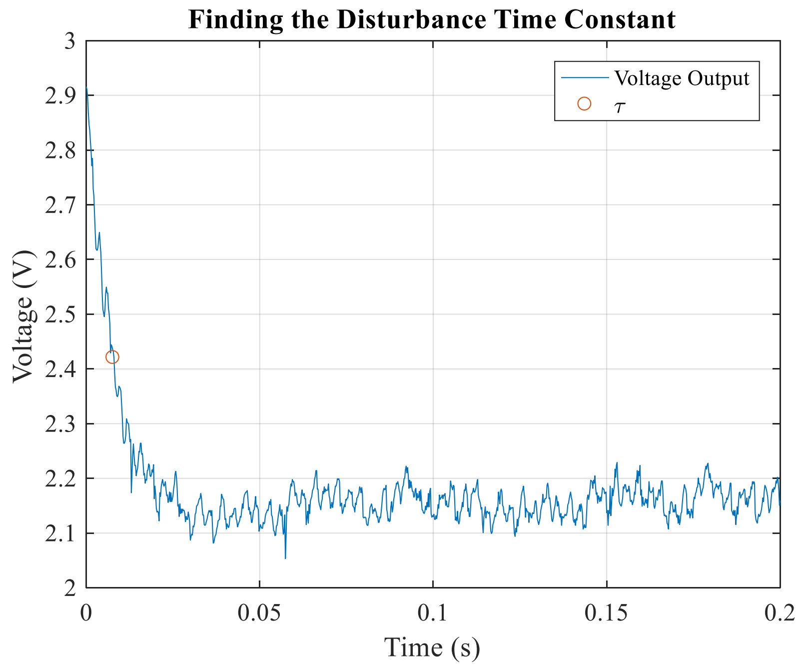


Figure 7- Determination of the time constant with a diturbance load of 5 Ω

Similar to Figure 4, the following block diagrams represent the closed loop systems analyzed and plugging in the governing controller block for the PI, P, and I controllers for G_c.

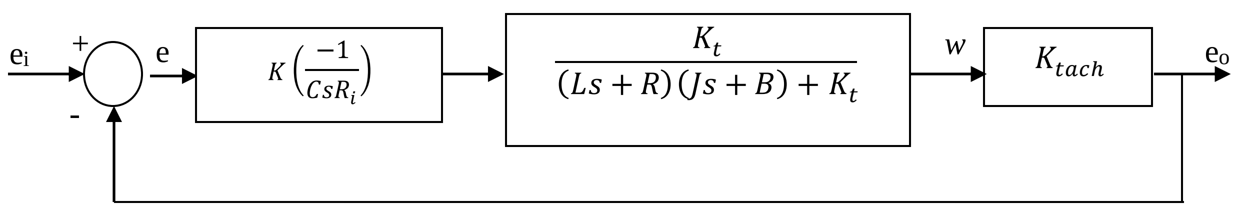


Figure 8- I Controller

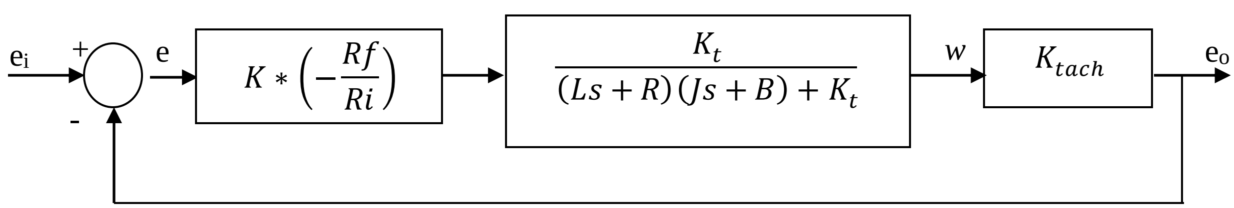


Figure 9 - P Controller

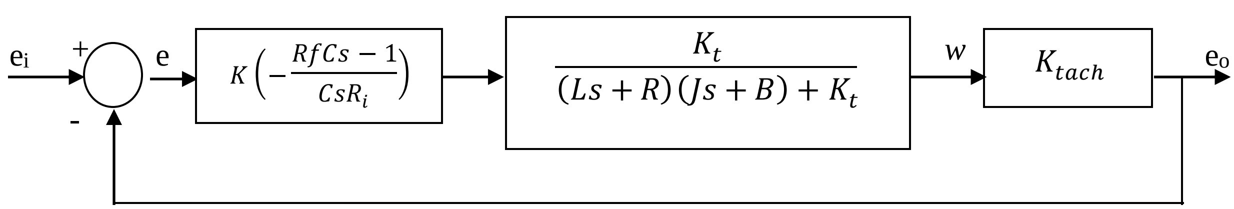


Figure 10- PI Controller

For each closed-loop feedback, root locus plots were drawn to show how different gain terms can change the rots of the system so the desired controller can be selected.

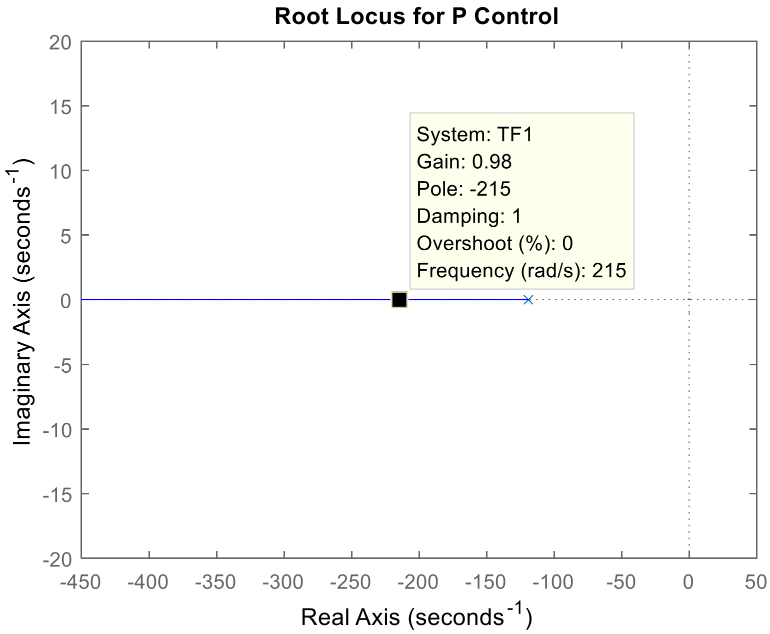


Figure 11- P Control root locus with roughly the closed loop pole noted

The closed loop pole for a gain of $K_{add} = 1$ is $s = -216.55$. The first pole occurs at -119 and continues to negative infinity along the real axis. The expected step response was plotted alongside the observed response for the P Controller below.

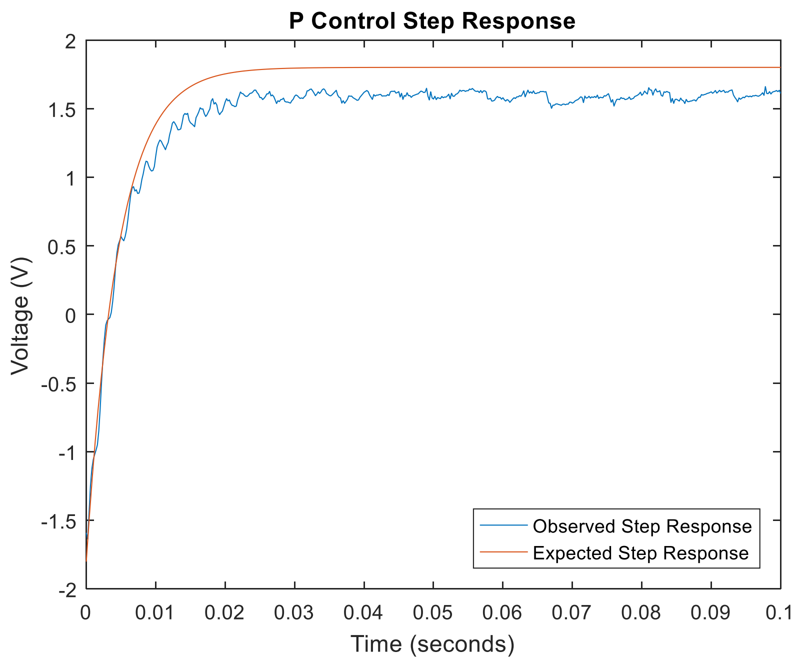


Figure 12- P Controller observed and expected step responses for +4 to -4 Volts

As seen in Figure 12 above, the expected response comes to a steady state at a slightly higher voltage. Note that the speed of the P Controller's response is the fastest but approximately halves the input step change of +/- 4 V when it reaches its steady state.

The I Controller's root locus plot can be seen in the figure below:

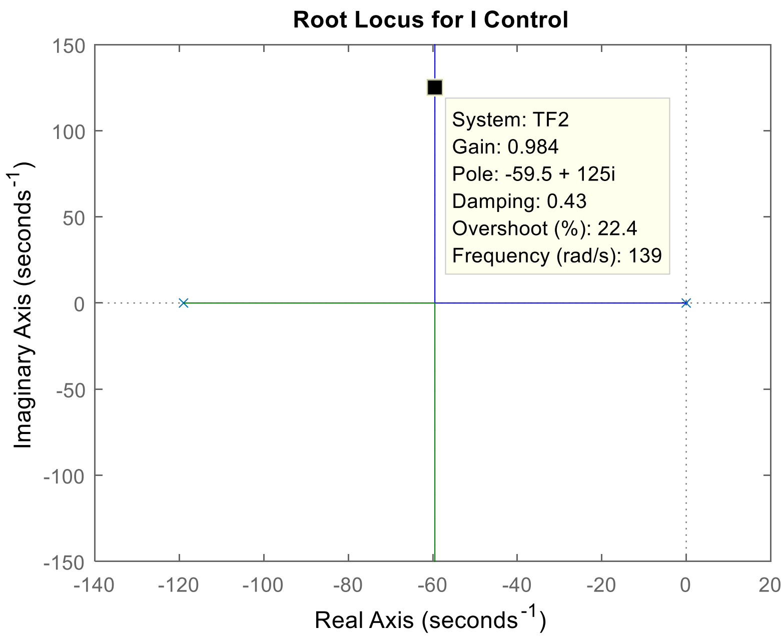


Figure 13- I Controller root locus plot

The root locus of the I Controller is drawn below with approximately the closed loop pole noted on Figure 13. The step response of this controller is shown below.

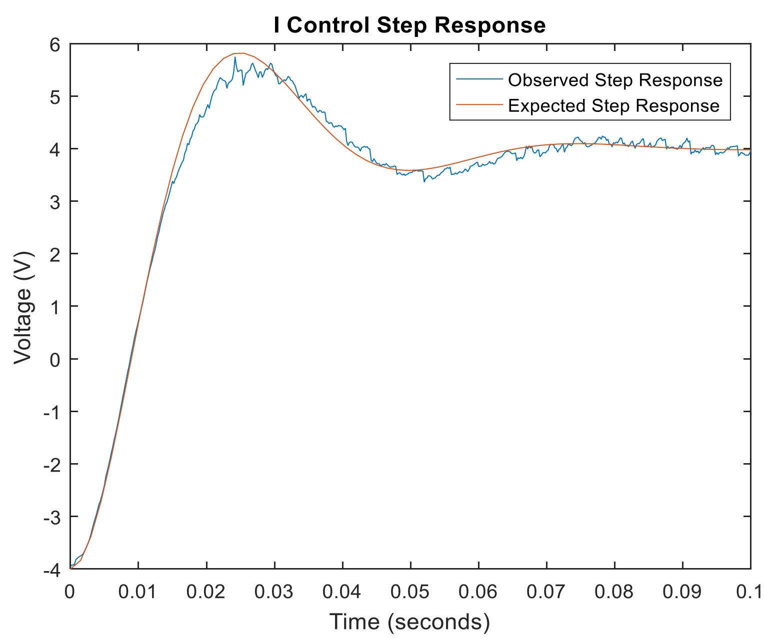


Figure 14-I Controller observed and expected step responses for +4 to -4

The I controller has the slowest response time as it takes the longest to reach a steady state value. This controller also shows a second order system from the initial over shoot and damping as it comes to a steady state. These experimental results were very accurate to the expected result as they nearly overlap one another on Figure 14.

The closed loop pole of $K_{add} = 1$ is s = -59.52 + 126.4i. The initial poles start at 0 and -119 and move along the imaginary axis until the asymptote at -59.52 and then head toward infinity on the imaginary axis. The root locus of the PI controller is drawn below.

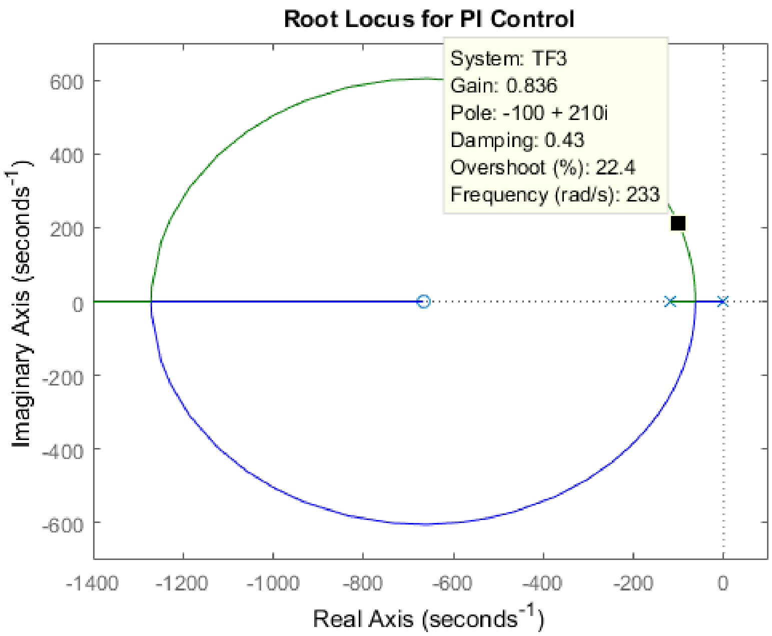


Figure 15- PI controller root locus plot with the approximate closed loop pole noted

The closed loop pole of $K_{add} = 1$ is s = -108.28 + 230.83i. There are poles at 0 and -119, as well as a zero occurring at -667 with a gain of infinity. The step response for this system is shown below in Figure 16.

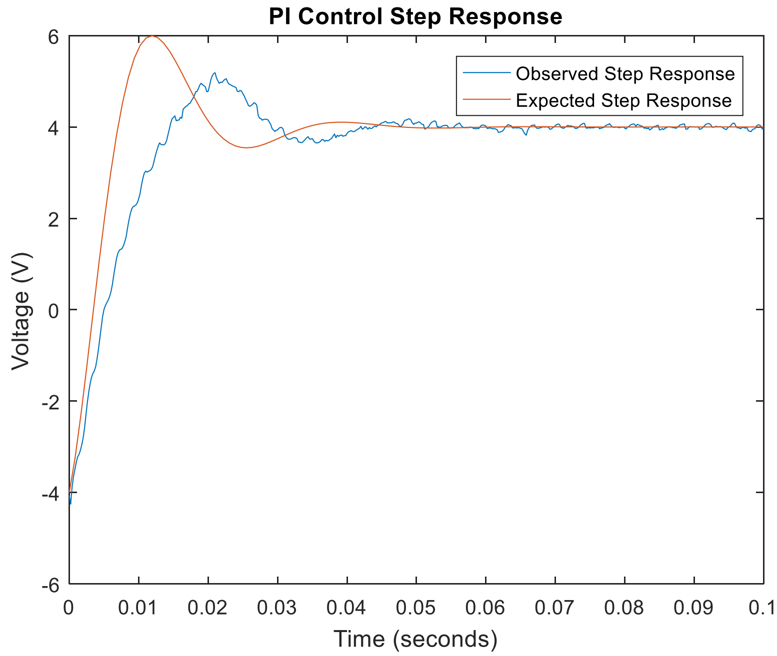


Figure 16-PI Controller observed and expected step responses for +4 to -4

The PI Controller is expected to have the second fastest response time of these controllers, as is shown in the figure above. Although the observed results doesn't appear to have as much overshoot as the expected result, they both settle at steady state approximately at the same time of 0.05 seconds.

The system time constants are tabulated below for the purpose of comparing the open and closed loop response times.

Table 5- Time constants for each system

System	**τ (ms)**
Open Loop	8.4
P Control	4.6
I Control	16.8
PI Control	9.2

As noted before, the P Controller has the fastest response time while the PI is second, and the I Controller is the slowest in comparison. The closed loop P Controller system has nearly twice the response time speed of the open loop, while the I Controller has exactly half the response time of the open. Additionally, the PI Controller has nearly the same time constant, thus nearly equal response time of the open loop system. The figure below shows the expected step response of each system and their corresponding 2 % settle times on the same plot for reference.

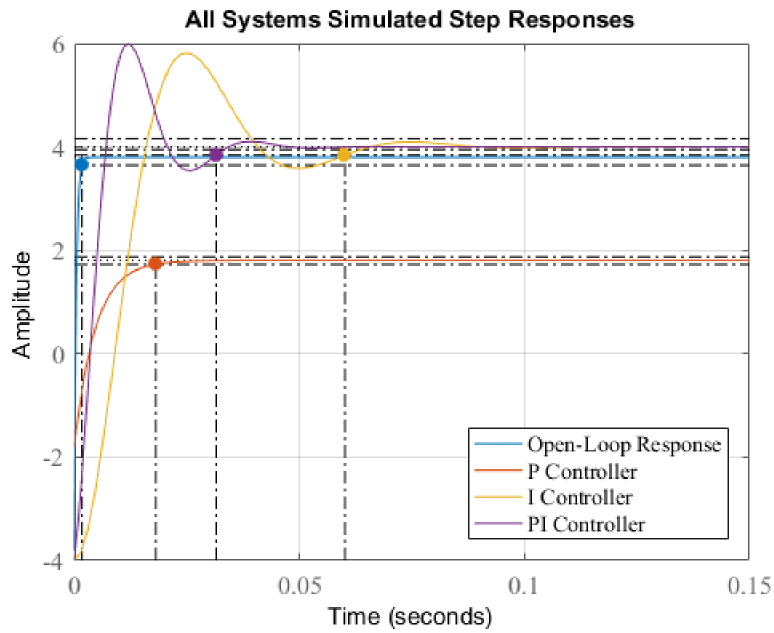


Figure 17-Each system's expected step responses for +/- 4 V step inputs

The steady state error of the three different controllers was calculated and compared when applying a disturbance load. The error values are calculated and tabulated below.

Table 6- Calculated steady state error for each system classified by their controller

System	Steady State Error
P Control	0.0573
I Control	∞
PI Control	∞

Using equation 9 the steady state error was calculated for each controller system. The P controller is the only system that does not result in infinity. The plant function is the same for the 3 different systems, but the controller functions for each is different. The infinity result is expected based on the controller functions for the I and PI controllers. Refer to the following Figure 18 for the resulting voltage output from the 5 Ω power resistor.

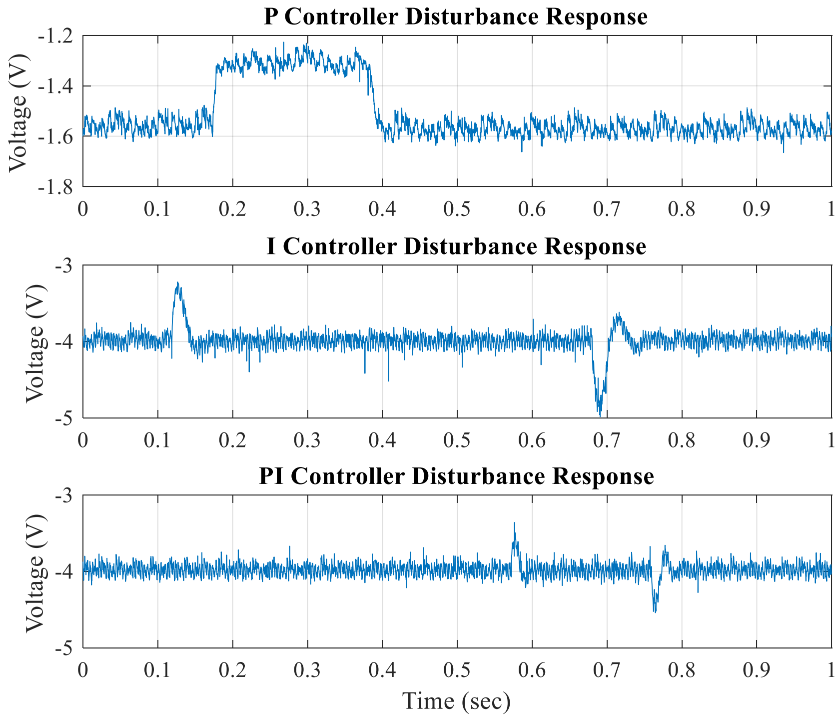


Figure 18- All 3 Controller's disturbance response from the power resistor

The error in the results for the closed loop systems is minimal depending on the application. Again, these errors in values is expected to be the wear of the motor over time and possibly improper care due to the many different users of the motor over the years. The error is assumed to be very insignificant to the design to the system's feedback design because of the speed and lack of ability to notice or effect outside counterparts of the system.

CONCLUSIONS

Taylor:

We investigated the different controls of the rotational speed of a DC brush motor. We also determined the parameters of a DC brush motor electro-mechanical model. On top of that, measuring the open-loop motor response gave us step inputs of voltage and load torque. We determined the motor constant by using another DC motor to back-drive the test motor.

The three controllers we used were proportional (P), integral (I), and a proportional-integral (PI). These help the motor maintain the reference speed regardless of the torque load on the motor. It also helps the motor track an input velocity signal. Since the motor was driven by a power op-amp, the speed was measured using a tachometer. We were given the components for the controllers.

Lastly, the closed-loop response to a voltage step input and to a disturbance torque section was using a tachometer voltage as the feedback signal and a 741 op-amp as the system compensation. Measurements were taken for all three controllers; P, I, and PI. The system with the P controller was the fastest with the I controller being the slowest. Thus, the P controller has significant error and the I controller is implemented to remove most of that error.

For further study, I recommend newer motors so that there is less friction leading to less deviation from the system specifications and more expected results for all aspects of the system.

Conclusions (continued…)

James:

Properties and the responses of a DC brush motor were investigated using different control systems for the rotational speed. The DC motor was back driven by and identical DC motor under test to confirm the specifications of the motor. Using an open loop system, the gain term, K and the time constant, τ, were found to be 19.0922 (rad/sec)/V and 8.4 ms, respectfully. From these, all the motor and system parameters were found.

The step response of the motor was measured and the unloaded speed and loaded speed were compared in the open loop system. The time constant of the open loop system, without a disturbance load, was τ = 6.5ms and the gain term of the first order system, was K = 19.0922 (rad/s)/V. Ignoring the electrical time constant, the damping coefficient and motor inertia of the system were determined. The damping coefficient and motor inertia were, B = 0.8633 oz-in/ KRPM and J =7.0e-4 oz-in/s^2 respectfully. Comparing the experimental values to the given values in the specification sheet, it can be seen that though the time constant and inertia values are accurate, the damping coefficient is quite different. This is due to old motors, having higher friction, causing the damping of the system to increase. A disturbance load was applied to the system with a 5 Ω power resistor. The time constant for the response with the disturbance load applied was
τ = 7.8 ms. The disturbance load is implemented to drive the process away from its desired behavior, which was later fixed with the implementation of closed loop controllers.

With these parameters, the closed-loop system was also able to be implemented. Proportional (P), Integral (I), and Proportional-Integral (PI) Controls, having different compensation values, were added to the system. Root-locus plots were drawn from the open-loop transfer functions and the poles of the systems were calculated. The P-control has a single pole, with that pole being able to increase to infinity with the change in gain of the system. The I Control has 2 poles that can move toward an asymptote before going to infinity. The PI Control has 3 poles along with a zero. The root-locus plots are useful for feedback design to determine the optimal amount of gain to use.

For future studies, a newer motor is recommended for the less damping increased experimental damping and thus more accurate representative results of the specified system, although again the damping and moment of inertia offset should be considered minimal in the old motor's effects on few components of the system. Another consideration would be to add a PID Controller for comparison since these are optimal in most systems for their utilization of all three controller types in one.

REFERENCES

[1] Ogata, K (1978). *System Dynamics* (4^{th} ed.) Englewood Cliffs, NJ: Prentice-Hall.

[2] Fussell, B., Prof. *Velocity Control of a DC Motor Under Load* (Lab 5, November 2017). ME 747

APPENDICES

A. Data Tables

Input Voltage (V)	Tachometer Voltage (V)	MUT Voltage (V)
1.5	.2088	.3646
2	.5010	.8683
2.5	.7895	1.33
3	1.06	1.73
3.5	1.36	2.32
4	1.68	2.77
4.5	1.99	3.27
5	2.27	3.78
6	2.85	4.65
7	3.42	5.67
8	4.01	6.67
9	4.63	7.59
10	5.13	8.51

B. Sample Calculations

```
% James Skinner and Taylor Maniatty
% ME 747 Section 3a
% Lab 5
% Due 11/24/17 10:00 PM
close all; clear all;
%% 2 DC Motor Back EMF Constant

% V input
ei = [1.5 2 2.5 3 3.5 4 4.5 5 6 7 8 9 10]; % V
% Tach
eo = -1*[-208.82/1000,-500.5/1000,-789.52/1000,...
    -1.06,-1.3661,-1.6815,-1.9901,-2.274,-2.851,...
    -3.42,-4.01,-4.632,-5.13]; % V
% MUT
em = [364.6/1000,868.27/1000,1.33,1.738,2.32,...
    2.772,3.27,3.78,4.658,5.672,6.67,7.5992,8.51]; % V

% a
% V/rad/s
Ktach = (3*60)/(2*pi*1000); % Ktach 2.7-3.3 V/KRPM within 100mV CW to
CCW
%sens_tach = sens_tach/1000; % V/RPM
%sens_tach = sens_tach*60/(2*pi); % V/(rad/s) = (V*s)/rad

% b

% calc Ke
omega = eo/Ktach;
p1 = polyfit(omega,em,1);
Ke_rads = abs(p1(1)); % (V/rad/s) Ke
Ke_VKRPM = (Ke_rads*2*pi*1000)/60; % V/KRPM
% Ke handout ~ 4.39-5.37

pfit = p1(1)*omega+p1(2);

% plot em v omega
figure
plot(omega,em,'o',omega,pfit,'--')
xlabel('Rotational Speed, \omega (rad/s)')
ylabel('MUT Voltage, e_m (V)')
title('MUT Resulting Output Voltage From Rotational Speed')
legend('Exerimental','Bestfit line','location','northwest')
set(gca,'fontsize',12,'fontname','Times')
grid on
box on

% c

% assume Kt = Ke
% Kt(Nm/A) = Ke(V/rad/s)
RR = 4.5;
BB = .2;
Keh = 5; % V/KRPM
```

```
ktach = 3;
Kt = Ke_rads*141.6119;% (oz-in/A) torque constant
%Kt2 = (RR*BB)/(ktach*(ei(end)/eo(end))*(1)-Keh)
% Kt from handout = 6.6 +/- 10%

%% 3. Open-Loop Response to a Voltage Step Input and to a Disturbance
Torque

%a)

nheaderlines = 35;
openresponse1 = importdata('3.7.lvm','\t',nheaderlines);

time = openresponse1.data(:,1);
e_o = openresponse1.data(:,2); %tach output of MUT, V
e_a = -openresponse1.data(:,4); %motor input (power amp output), V
e_i = 6; % constant 6V input

time = time(3868:end)-time(3868);
e_o = e_o(3868:end);
e_a = e_a(3868:end);

%b)

Vtau = e_o(1)+0.632*(e_o(end)-e_o(1));
indexVtau = find(e_o>Vtau-.1 & e_o<Vtau+.1);
tau = mean(time(indexVtau)); % Time Constant

% solving for K [(rad/sec)/V]
%omega_c = e_o/sens_tach; % this is big K for part c
%p2 = polyfit(omega,e_o);
%K [KRPM/V]
omega3_4 = e_o/Ktach;
p2 = polyfit(e_a,omega3_4,1); % (rad/s)/V
K_rads = p2(1); % (rad/s)/V
K_KRPM = (K_rads*60)/(2*pi*1000); % KRPM/V
p3 = polyfit(e_a,e_o,1);
KK = p3(1); % V/V

figure
plot(time,e_o,'k',time,e_a,'b',tau,Vtau,'co');
title('DC Motor Step Response of -4 to +4 V')
xlabel('Time (seconds)')
ylabel('Voltage Output (V)')
xlim([-.01 time(end)])
legend('Step Response','Input Square
Wave','\tau','location','southeast')
set(gca,'fontsize',12,'fontname','Times')
grid on
box on

%d)

nheaderlines = 35;
part_3_9 = importdata('3.9.lvm','\t',nheaderlines);
```

```
time39 = part_3_9.data(:,1);
eo39 = part_3_9.data(:,2); %tach output, V
ea39 = part_3_9.data(:,4); %power op-amp output, V


% rad/sec
omega39 = eo39/Ktach; % rad/s

figure
plot(time39,omega39)
xlabel('Time (s)')
ylabel('\omega (rad/s)')
title('Simulated Disturbance Load')
grid on
box on

figure
plot(time39,eo39)
xlabel('Time (s)')
ylabel('Tach Output (V)')
title('Simulated Disturbance Load')
grid on
box on

omegano39 = mean(omega39(1:2179));
omegadisturb39 = mean(omega39(2477:end));
sserror39 = (omegadisturb39-omegano39)/omegano39;

% Solving for Motor Stall Torque T
R1 = 5; %ohms
Td = (e_i*Kt)/R1; %oz-in
%c)

num = KK;
den = [tau 1];
motorTF = tf(num,den);
figure
bode(motorTF)

% break_freq = 119; % rad/s from bode plot
% whz = 119/(2*pi); % Hz = 1/s
% K_Hz = K_rads/(2*pi); % (1/s)/V
% J = (1/whz^2)*KK*T;% oz-in-s^2

% Solving for B [oz-in/KRPM] from K
R = 4.2; % ohm
B = ((Kt/K_KRPM)-(Ke_VKRPM*Kt))/R; % (oz-in/KRPM)

% this B was used to find J from K_rads
B_rads = ((Kt/K_rads)-(Ke_rads*Kt))/R; % oz-in/rad/s

% solving for J [oz-in-s^2]
J = (tau*((R*B_rads)+(Ke_rads*Kt)))/R;
J2 = (1.5*16*(KK/(2*pi))^2)/386; % This value is closer to expected
%settling time
```

```
settle = 4*tau;

lower = abs(mean(eo39(1:1000)));
upper = abs(mean(eo39(2000:3000)));

ss_speederror = (lower-upper);
ss_speederror_percent = ((lower-upper)/lower)*100;
ssagain = 1/(1+KK);
start_time = 2251; % sec

Vtau2 = eo39(start_time)+0.632*(eo39(end)-eo39(start_time));
indexVtau2 = find(eo39(start_time:end)>Vtau2-.1...
    & eo39(start_time:end)<Vtau2+.1);
tau2 = mean(time(indexVtau2)); % Decay Time Constant

figure;
plot(time39(start_time:end)-time39(start_time),eo39(start_time:end),...
    tau2,Vtau2,'o')
xlabel('Time (s)')
ylabel('Voltage (V)')
title('Finding the Disturbance Time Constant')
set(gca,'fontsize',12,'fontname','Times')
xlim([0 .2])
legend('Voltage Output','\tau')
grid on
box on

taus = [tau,tau2];
xbar = mean(taus);
PD = ((tau - tau2)/xbar)*100;

%% 4. Closed-Loop Response to a Voltage Step Input and to a Disturbance
Torque
clear all; close all;

% Ktach = 0.0286; % V/rad/s
% Kt = 6.684; % oz-in/A
% Ke = 0.0472; % V/rad/s
% B = .0082; % oz-in/rad/sec
% J = 7.0018e-04; % oz-in-s^2
% Ka = -1;
% R = 5; % ohm
%
% % P Control
%
% Ri = 100000; % ohm
% Rf = 150000; % ohm
%
% num = [Rf*Kt*Ktach];
% den = [Ri*R*J B*Ri*R+Ri*Kt*Ke];
%
% figure
% rlocus(num,den)
%
% % I control
```

```
%
% C1 = 0.033e-6;
%
% num = [Kt*Ktach];
% den = [R*J*C1*Ri R*B*C1*Ri+Ke*Kt*C1*Ri 0];
%
% figure
% rlocus(num,den)
%
% % PI Control
%
% C2 = 0.010e-6;
%
% num = [Ktach*Kt*Rf*C2 Kt*Ktach];
% den = [Ri*R*C2*J Ri*R*C2*B+Ri*C2*Kt*Ke 0];
%
% figure
% rlocus(num,den)

clear all; close all;

Ri = 100*1000;
Rf = 150*1000;

C1 = .0333*10^-6;
C2 = .01*10^-6;

Ktach = .0286; %rad/sec

K = 19.0922;
tau = .0084; %s

%% P Control

K_p = (Rf/Ri);

num1 = (K_p*K*Ktach)/tau;
den1 = [1 1/tau];

TF1 = tf(num1,den1);
figure
rlocus(TF1)
title('Root Locus for P Control')


G1 = feedback(TF1,1);
opt = stepDataOptions('InputOffset',-4,'StepAmplitude',8);
[y1,x1] = step(G1,opt,.15);

nheaderlines = 35;
P = importdata('4.5P.lvm','\t',nheaderlines);
p_time = P.data(:,1);
p_eo = -P.data(:,2);
p_ea = P.data(:,4);
```

```
p_time = p_time(2695:end);%-.1566;
p_time = p_time - p_time(1);
p_eo = p_eo(2695:end);

figure
plot(p_time,p_eo,x1,y1)
title('P Control Step Response')
xlabel('Time (seconds)');
ylabel('Voltage (V)');
legend('Observed Step Response','Expected Step
Response','location','southeast')
axis([0 .1 -2 2])

s1 = (1/tau)+K_p*Ktach*(K/tau);
taup = 1/s1;

%% I Control

K_i = 1/(Ri*C1);

num2 = (K_i*K*Ktach)/tau;
den2 = [1 1/tau 0];

TF2 = tf(num2,den2);

figure
rlocus(TF2);
title('Root Locus for I Control')
ylim([-150 150])

G2 = feedback(TF2,1);
opt = stepDataOptions('InputOffset',-4,'StepAmplitude',8);
[y2,x2] = step(G2,opt,.15);

nheaderlines = 35;
I = importdata('4.5I.lvm','\t',nheaderlines);
i_time = I.data(:,1);
i_eo = -I.data(:,2);
i_ea = I.data(:,4);


i_time = i_time(610:end);
i_time = i_time - i_time(1);
i_eo = i_eo(610:end);

figure
plot(i_time,i_eo,x2,y2)
title('I Control Step Response')
xlabel('Time (seconds)');
ylabel('Voltage (V)');
legend('Observed Step Response','Expected Step Response')
xlim([0 .1])
```

```
syms x
eqn = 1+(K_i*K*Ktach)/(tau*(x^2)+x) == 0;
solx = solve(eqn,x)
taui = 1/59.52;
%% PI Control

num3 = [(Rf*C2*K*Ktach)/(tau*Ri*C2) (K*Ktach)/(tau*Ri*C2)];
den3 = [(tau*Ri*C2)/(tau*Ri*C2) (Ri*C2)/(tau*Ri*C2) 0];

TF3 = tf(num3,den3);

figure
rlocus(TF3)
title('Root Locus for PI Control')
xlim([-1400 100])
G3 = feedback(TF3,1);
opt = stepDataOptions('InputOffset',-4,'StepAmplitude',8);
[y3,x3] = step(G3,opt,.15);

nheaderlines = 35;
PI = importdata('4.5PI.lvm','\t',nheaderlines);
pi_time = PI.data(:,1);
pi_eo = PI.data(:,2);
pi_ea = PI.data(:,4);

pi_time = pi_time(1443:end);
pi_time = pi_time - pi_time(1);
pi_eo = pi_eo(1443:end);

figure
plot(pi_time,pi_eo,x3,y3)
title('PI Control Step Response')
xlabel('Time (seconds)');
ylabel('Voltage (V)');
legend('Observed Step Response','Expected Step Response')
xlim([0 .1])

syms x
eqn = 1+((K*Ktach*Rf*C2*x)+(K*Ktach))/((tau*Ri*C2*(x^2))+(Ri*C2*x)) ==
0;
solx = solve(eqn,x)
taupi = 1/108.28;
%% Disturbances

clear all; close all;
Ktach = .0286; % V/rad/s
% P Control

nheaderlines = 35;
P = importdata('4.6P.lvm','\t',nheaderlines);
p_time = P.data(:,1);
p_time = p_time - p_time(1);
p_eo = P.data(:,2); % tach
p_ea = P.data(:,4); % power op amp
```

```
omegap = p_eo/Ktach;

figure
subplot(3,1,1)
plot(p_time,p_eo)
ylabel('Voltage (V)')
title('P Controller Disturbance Response')
set(gca,'fontsize',12,'fontname','Times')
grid on

error1 = abs((mean(omegap(896:3826))-...
    mean(omegap(1:855)))/mean(omegap(1:855)));

J = 7e-4; % oz-in-s^2
B = .8633; % oz-in/KRPM
Rf = 5; % ohms
Ri = 5; % ohms
R = 5; % ohm
Kt = 6.6837; % oz-in/A
Ktach = 3; % V/KRPM
K = 19.0922;
C1 = .0333*10^-6;
C2 = .01*10^-6;

syms s
plant = Kt/(R*(J*s+B)+Kt);
controllerp = K*(-Rf/Ri);
errorp = 1/(limit(1/plant,s,0)+limit(controllerp,s,0))

% I Control

nheaderlines = 35;
I = importdata('4.6I.lvm','\t',nheaderlines);
i_time = I.data(:,1);
i_time = i_time - i_time(1);
i_eo = I.data(:,2);
i_ea = I.data(:,4);

omegai = i_eo/Ktach;

subplot(3,1,2)
plot(i_time,i_eo)
ylabel('Voltage (V)')
title('I Controller Disturbance Response')
set(gca,'fontsize',12,'fontname','Times')
grid on

syms s
plant = Kt/(R*(J*s+B)+Kt);
controlleri = K*(-1/(C1*s*Ri));
errori = 1/(limit(1/plant,s,0)+limit(controlleri,s,0))

% PI Control

nheaderlines = 35;
```

```
PIs = importdata('4.6PI.lvm','\t',nheaderlines);
pi_time = PIs.data(:,1);
pi_time = pi_time - pi_time(1);
pi_eo = PIs.data(:,2);
pi_ea = PIs.data(:,4);

omegapi = pi_eo/Ktach;

subplot(3,1,3)
plot(pi_time,pi_eo)
xlabel('Time (sec)')
ylabel('Voltage (V)')
title('PI Controller Disturbance Response')
set(gca,'fontsize',12,'fontname','Times')
grid on

syms s
plant = Kt/(R*(J*s+B)+Kt);
controllerpi = K*(-(C2*s-1)/(C1*s));
errorpi = 1/(limit(1/plant,s,0)+limit(controllerpi,s,0))

%% Responses Together

K = 19.0922;
tau = .0084; %s

num4 = [K];
den4 = [tau 1];
TF4 = tf(num4,den4);
G4 = feedback(TF4,1);
opt = stepDataOptions('InputOffset',-4,'StepAmplitude',8);
[y4,x4] = step(G4,opt,.15);

figure
step(G4,G1,G2,G3,opt,.15)
title('All Systems Simulated Step Responses')
legend('Open-Loop Response','P Controller','I Controller','PI
Controller',...
    'location','southeast')
set(gca,'fontname','Times','fontsize',12)
grid on
```

C. Equipment List

- NI Function Generator
- LabView Signal Express (LV-SE)
- Breadboard
- BK Precision Dual Power Supply
- 741 Op Amp
- Tachometer
- 2 DC Brush Motor
- Flexure Coupling
- Resistors
- Capacitors
- Wire
- Toggle switch

D. Raw Data Sheets

Start

Velocity Control of a DC Brush Motor Under Load 37

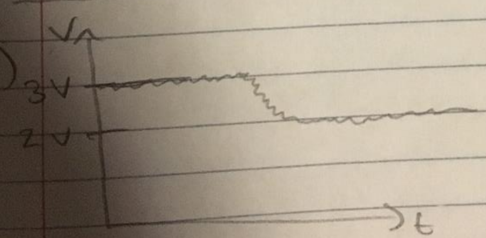
2.) DC Motor Back EMF Constant

4.)

Volts input e_o (V)	Tach e_o (mV)	MUT e_m (mV)
To start → (min) 1.5 V	-208.82	364.6
2.0 V	-500.5	868.27
2.5 V	-789.52	1.33 (V) [V]
3.0	-1.066(V)	1.738(V)
3.5	-1.3666	2.32
4.0	-1.6815	2.772
4.5	-1.9901	3.27
5.0	-2.274	3.78
6.0	-2.851	4.658
7.0	-3.42	5.672
8.0	-4.01	6.67
9.0	-4.632	7.5992
10	-5.13 V	8.51

3.) Open-Loop Response to a Voltage Step Input and to a Disturbance Torque

9.)



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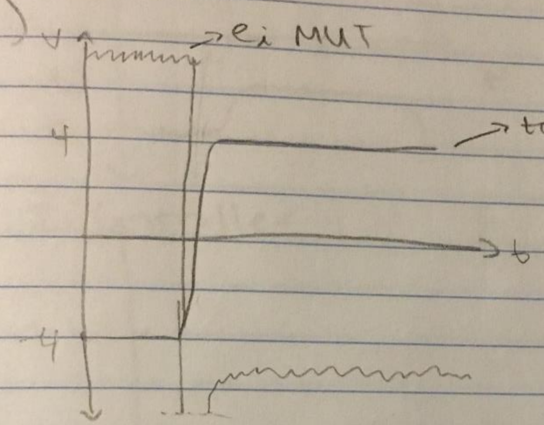
Velocity Control of a DC Brush Motor 38

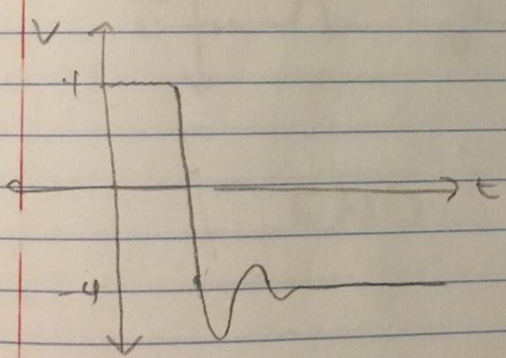
4) Closed-Loop Response to a Voltage Step Input and to a Disturbance Torque

P-Controller

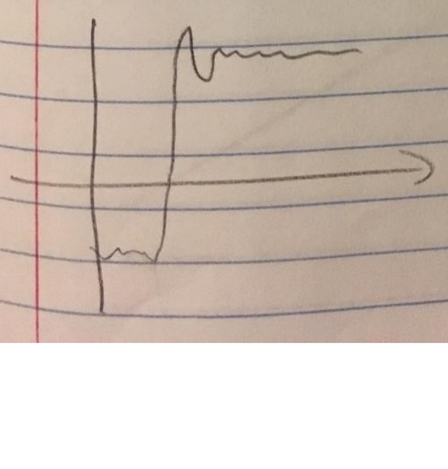
5)



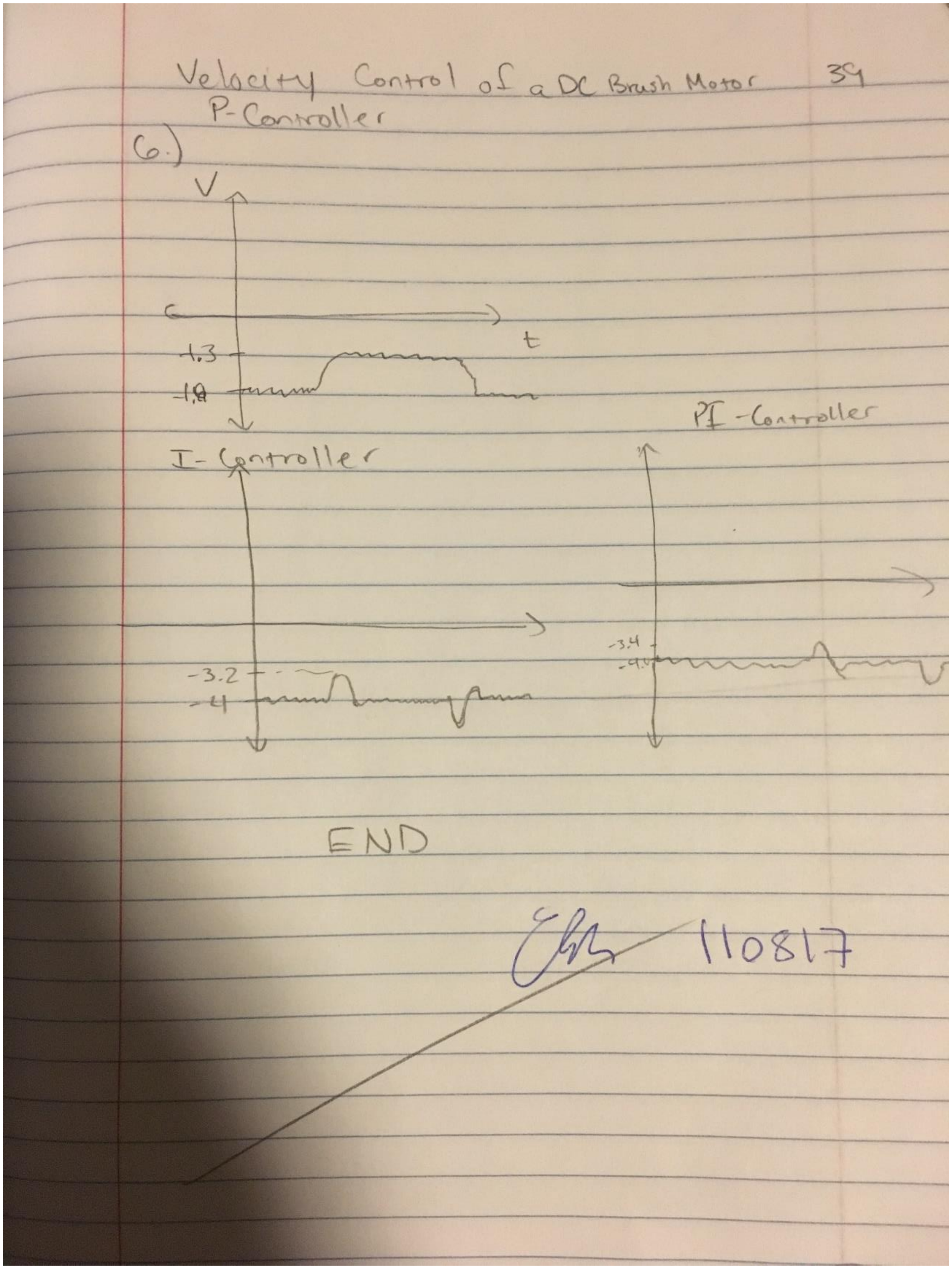
I-Controller



PI-controller



11/8



Velocity Control of a DC Brush Motor 39

P-Controller

6.)

I- Controller

PI -Controller

END

110817

E. Lab Instructions

University of New Hampshire
Department of Mechanical Engineering

ME 747 – Lab #5
(1 Nov 2017)

Velocity Control of a DC Brush Motor Under Load

Purpose:

In this lab you will investigate proportional (P), integral (I), and proportional-integral (PI) control of the rotational speed of a DC brush motor. The controller should help the motor follow (track) an input velocity signal and should also help it maintain the reference speed (regulate) regardless of the torque load on the motor.

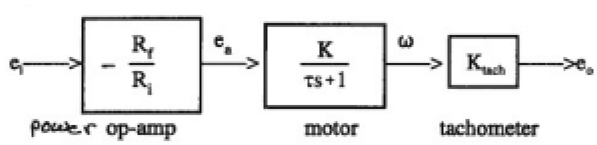
First, you will determine the parameters of a dc brush motor electro-mechanical model and measure the open-loop motor response to step inputs of voltage and load torque. The motor will be driven by a power op-amp, and the speed measured using a tachometer. Another dc motor will be used to back-drive the test motor for determination of the motor constant.

Second, you will determine the performance of P, I and PI closed-loop controllers using motor responses to step inputs of voltage and load torque. For this lab you are given the components for the controllers. If you were designing the control system, you would have to select appropriate gain values. The root locus method is useful for this, and will be utilized in this lab to explain the responses of the closed loop systems.

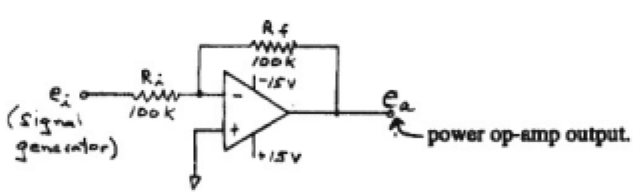
NOTE: Numbered questions are lab work, lettered questions are for the write-up. You should make sure that you have all necessary data to answer these questions.

1. Description of Experimental Setup

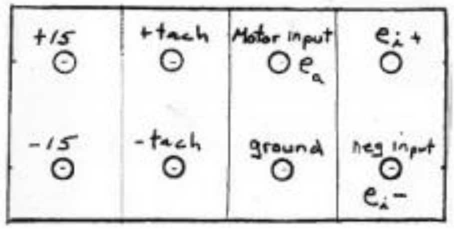
A block diagram of the open-loop motor and the power op-amp is shown below. Note that the electrical time constant of the given motor is much faster than that of the mechanical, i.e. a dominant mechanical pole, so the electrical time constant is neglected, i.e. L = 0.



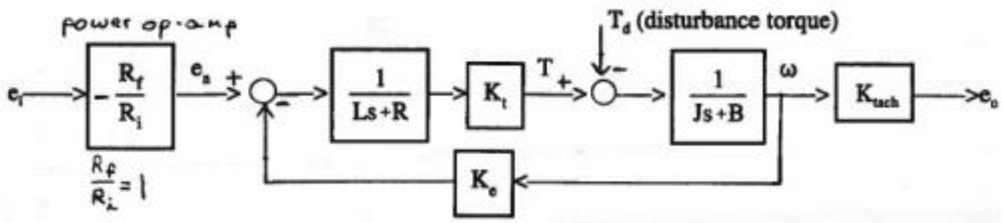
The power op-amp is wired for an open-loop gain of -1 as shown in the following figure. See the attached specification sheet for complete information on the op-amp. This op-amp provides the necessary power to drive the motor. It is powered by a separate +15V and -15V from the BK Precision dual power supply.



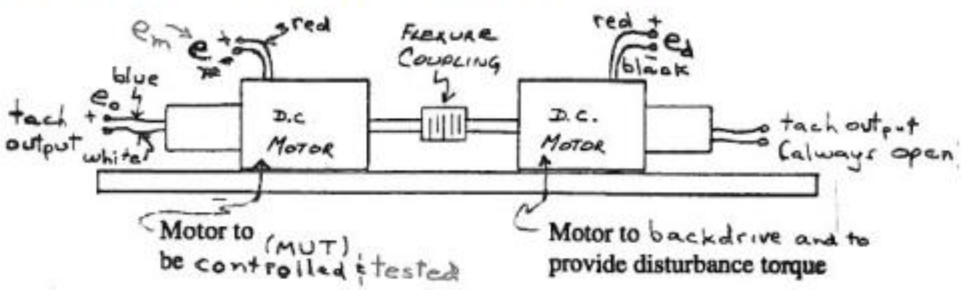
Note that the power op-amp is enclosed in a protective box with the following connections on the front of the enclosure.



The block diagram shown above assumes the electrical time constant is much faster than the mechanical, and as such can be ignored. The full block diagram of the open-loop system, including the electrical inductance, is shown below:



The experimental setup consists of the DC motor (motor under test, MUT) and tachometer, along with the power op-amp used to drive the motor, and an additional DC motor to provide a disturbance load (Td) and to back drive the DC motor so performance parameters can be measured.



2. <u>DC Motor Back EMF Constant</u>

You are to find the motor back emf constant K_e by back driving the motor under test (MUT) using an identical motor attached to the MUT by a flexure coupling (referred to as the back-drive mtor). You will drive the MUT at various speeds and measure the voltage at the MUT terminal leads, e_m.

1. <u>Make sure the wiring of the power op amp is correct, in particular, the BK power supply + 15 and – 15 volts must be correct or the op amp will be burned up and ruined. DO NOT TURN ON SETUP UNTIL TA'S CHECK YOUR CIRCUIT.</u>

2. Connect the back drive motor e_d leads, red (+) and black (-), to e_a (op amp output) and ground located on the enclosure front panel.

3. Connect the tachometer output e_o leads (white + and blue -) to channel 0 and MUT motor leads e_m to channel 1 of the scope.

4. Connect the output from the NI function generator to the e_i posts on the enclosure front panel. Input (e_i) steady voltages of 1 to 10 volts from the NI function generator using a frequency of 0.001 Hz (to simulate a dc input). For each steady input, measure the tach output e_o and the MUT motor terminal lead voltage e_m. Make sure you find the minimum voltage necessary to start the MUT motor.

   a) Find the tachometer sensitivity, K_{tach}, given in the specification sheet.

   b) Make a plot of e_m vs ω, using your tachometer sensitivity K_{tach}. Calculate K_e, the motor voltage constant and compare it to the value given in the motor specification sheet.

   c) Assuming that $K_t = K_e$, solve for the torque constant K_t (check your units) and compare to the specification sheet.

3. <u>Open-Loop Response to a Voltage Step Input and to a Disturbance Torque</u>

For this part you are to measure the step response of the DC motor in order to calculate τ and K of the system. Also, a disturbance load will be placed on the system (via a toggle switch) so you can measure the steady-state error, i.e. the difference between the unloaded speed (desired speed) and the loaded speed.

The motor under test (front motor) will now be powered by the power op amp. The input signal e_i will come from the function generator as in Part 2.

1. Turn off (disable) the BK power supply + 15 and – 15 volts and disconnect the e_d leads from the enclosure front panel.

2. Connect the motor under test (MUT) e_m leads, red (+) and black (-), to e_a (power op amp output) and ground located on the enclosure front panel.

3. Connect the tachometer output e_o and power op amp output e_a to channel 0 and 1 of the scope. The white lead of the tach should go to + on the scope.

4. Before powering the system, adjust the function generator to a 0.4 Hz square wave with an amplitude of +/- 5 volts.

5. With T.A. approval, enable the BK +15 V and – 15 V power supply.

6. Re-adjust the function generator amplitude such that e_0, the tachometer output of the test motor (MUT), is a +/- 4 V amplitude "square wave" output.

7. Set the trigger on the scope to store the tachometer output e_o and motor input e_a during a step change of e_0 from +4 volts to -4 volts. Save/export the data for analysis, and sketch the plot.

8. Turn the function generator off, and connect the back-drive motor leads e_d to the posts across the 5 Ω power resistor. Make sure the resistor load is disengaged, i.e. the switch is pulled toward you. (*Note: the toggle switch in the position away from you engages the 5 Ω resistive load and switching it toward you disengages the load.*)

9. Adjust e_i to a constant 6.0 volts using a square wave with a frequency of 0.001Hz. Click the "play" button on the function generator and you should see that the motor input voltage is a "constant" -6V. Flip the toggle switch on the back-drive motor leads e_d to connect a 5.0 Ω load resistor. Capture the MUT tachometer output e_o when switching on the resistive load. Save/export the data for this disturbance response and sketch the tachometer output.

    a) Derive the system equations for the motor under test (MUT). Remember the back-drive motor is coupled to the MUT.

    b) Calculate the motor stall torque (oz_f-in) for $e_i = 6V$.

    c) Find K and τ of the motor.

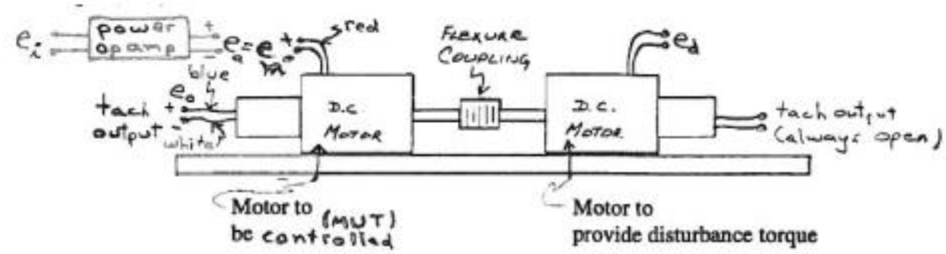
    d) Ignore the electrical time constant of the system and calculate J and B of the system. Use R = 4.2 ohms. Compare J and B to the specification sheet and note reasons for any difference.

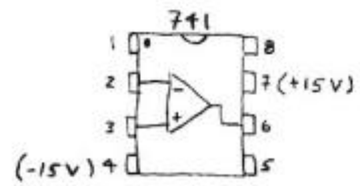
    e) Calculate the settling time (4τ) of the open-loop motor and the steady-state speed error of the motor when it is subjected to a disturbance load of the 5 Ω.resistor.

    f) Compare τ from the disturbance load (power resistor) step response to τ from the e_i step change.

4. Closed-Loop Response to a Voltage Step Input and to a Disturbance Torque

For this part, the system will be made closed-loop, using the tachometer voltage as the feedback signal and a 741 op-amp as the system compensation (741 op-amp is on the breadboard with power supplies connected). You will take measurements (same procedure as the open-loop) using a P, an I, and a PI controller.

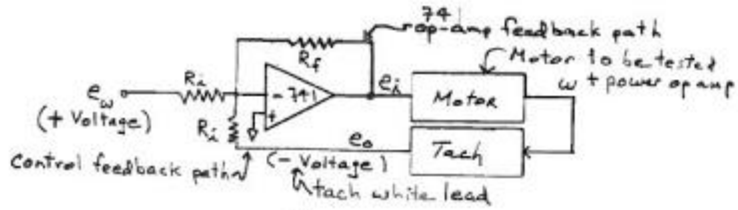




P Controller

$R_i = 100K$

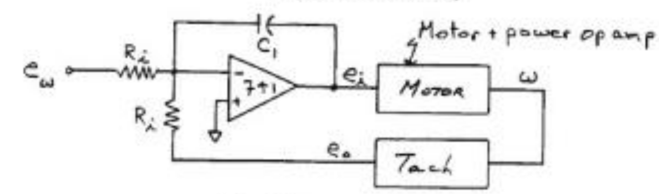
$R_f = 150K$



I Controller

$R_i = 100K$

$C_1 = 0.033\mu F$

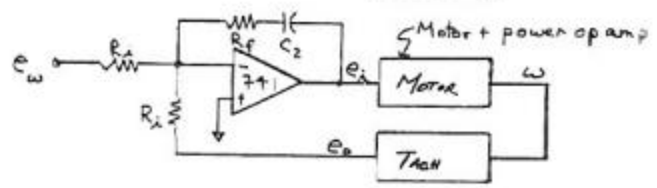


PI Controller

$R_i = 100K$

$R_f = 150K$

$C_2 = 0.010\mu F$



Make sure you turn off the BK +/- 15 V power supply before you make any changes to the 741 op-amp feedback controller

1. Make sure that the BK power supply is disabled and wire the P controller circuit. Have the TA check your wiring. Make sure you connect the white lead of the tachometer feedback signal, e_o, to the input of the 741 op-amp circuit. Make sure the blue lead of the tachometer is grounded.

2. Connect the tachometer output e_o and the power op amp output e_a to the scope. The white lead of the tach should go to + on the scope.

3. Before powering the system, adjust the function generator to a 0.4 Hz square wave with amplitude of +/- 4 volts. Verify, using the scope, that the function generator output is a square wave with an amplitude of +/- 4V.

4. With T.A. approval, enable the BK +15 V and – 15V power supplies.

5. Set the trigger on the scope to capture the tachometer output e_o and motor input e_a during a step change from +4 volts to -4 volts (0.4 Hz square wave). Sketch the response and store the data for analysis. (Note that e_a should be a clean signal but will have noise due to the power supply.)

6. Set e_i to a constant 4 volts by changing the frequency of the square wave to 0.001 Hz. Make sure the back-drive motor leads e_d are connected to the posts across the 5 Ω power resistor with the resistor load disengaged, i.e. the switch is pulled toward you. Now switch on (connect) the 5 Ω power resistor across the e_d wires of the back-drive (load) motor. Sketch and save the dynamic response.

7. Repeat steps 1 to 6 for the I controller circuit.

8. Repeat steps 1 to 6 for the PI controller circuit.

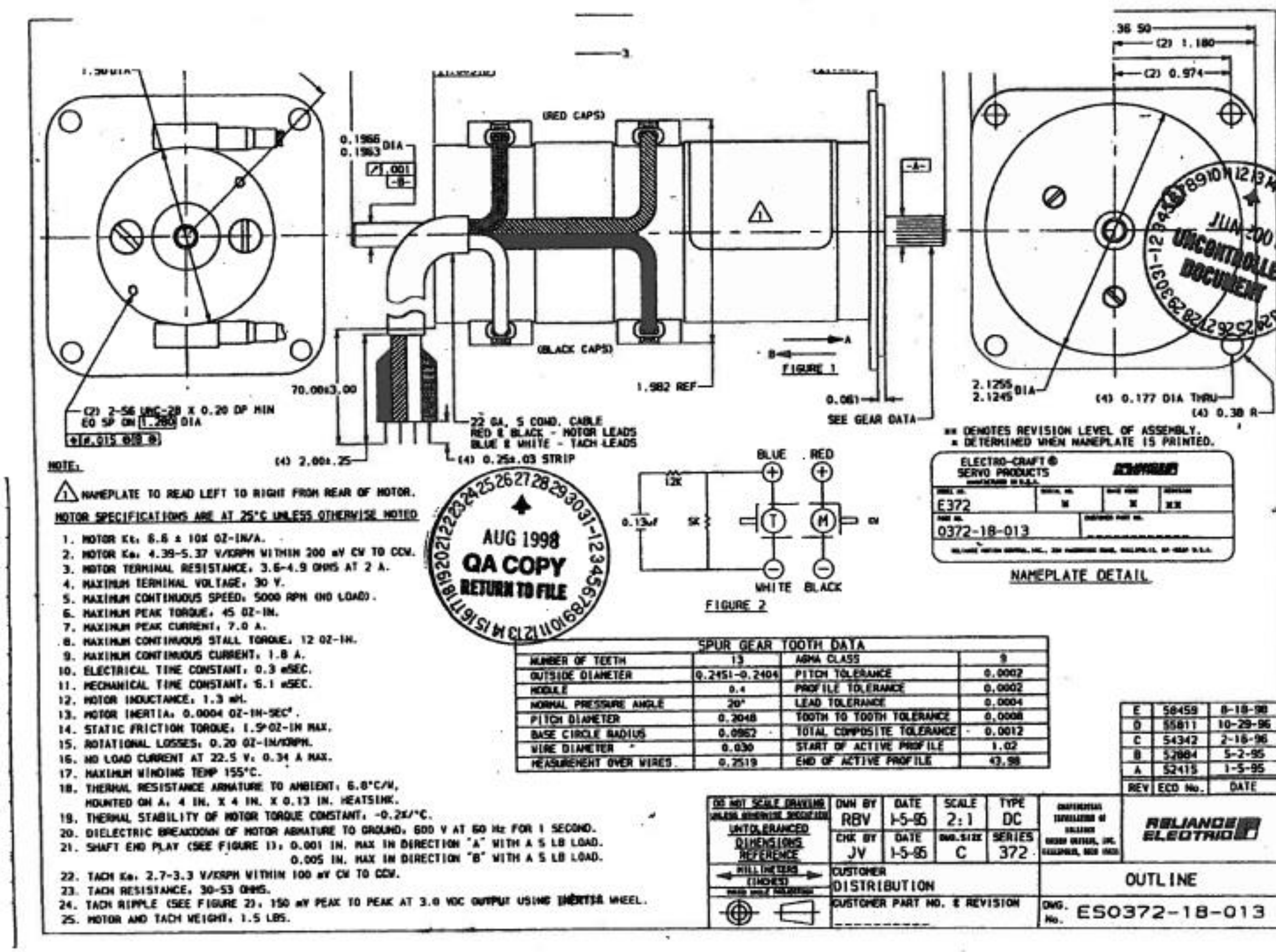
   a) Draw block diagrams for each of the feedback control systems tested, making sure that you develop a block that represents the controller, i.e., the P, I and PI op-amp circuitry.

   b) Draw a root-locus (Matlab) for each of the feedback control systems, <u>using the experimentally determined values K and τ of the open-loop motor when possible</u>. Assume that an additional gain can be added to all the controllers such that the roots can be moved along the locus by increasing this new gain term.

   c) Locate the roots of the closed-loop systems on the root locus plots and compare the expected step response to the observed step responses.

   d) Compare the speed of response of the tested motor control systems and the open loop system and also compare the steady state errors of the systems when subjected to a disturbance load.

   e) Comment on the differences between the experimental results and theoretical results. Why is there error and how significant is it in terms of the system feedback design.



.36 50
(2) 1.180
(2) 0.974
(RED CAPS)
(BLACK CAPS)
0.1966 DIA
0.1963
-A-
-B-
70.00±3.00
1.982 REF
FIGURE 1
0.061
SEE GEAR DATA
2.1255 DIA
2.1245
(4) 0.177 DIA THRU
(4) 0.30 R
(2) 2-56 UNC-2B X 0.20 DP MIN
EQ SP ON 1.280 DIA
(4) 2.00±.25
22 GA. 5 COND. CABLE
RED & BLACK - MOTOR LEADS
BLUE & WHITE - TACH LEADS
(4) 0.25±.03 STRIP
** DENOTES REVISION LEVEL OF ASSEMBLY.
* DETERMINED WHEN NAMEPLATE IS PRINTED.
ELECTRO-CRAFT ®
SERVO PRODUCTS
E372
0372-18-013
NAMEPLATE DETAIL
BLUE
RED
12K
0.13uf
5K
T
M
CW
WHITE
BLACK
FIGURE 2
JUN 2001
UNCONTROLLED DOCUMENT
AUG 1998
QA COPY
RETURN TO FILE
NOTE:
1 NAMEPLATE TO READ LEFT TO RIGHT FROM REAR OF MOTOR.
MOTOR SPECIFICATIONS ARE AT 25°C UNLESS OTHERWISE NOTED
1. MOTOR Kt: 6.6 ± 10% OZ-IN/A.
2. MOTOR Ke: 4.39-5.37 V/KRPM WITHIN 200 mV CW TO CCW.
3. MOTOR TERMINAL RESISTANCE: 3.6-4.9 OHMS AT 2 A.
4. MAXIMUM TERMINAL VOLTAGE: 30 V.
5. MAXIMUM CONTINUOUS SPEED: 5000 RPM (NO LOAD).
6. MAXIMUM PEAK TORQUE: 45 OZ-IN.
7. MAXIMUM PEAK CURRENT: 7.0 A.
8. MAXIMUM CONTINUOUS STALL TORQUE: 12 OZ-IN.
9. MAXIMUM CONTINUOUS CURRENT: 1.8 A.
10. ELECTRICAL TIME CONSTANT: 0.3 mSEC.
11. MECHANICAL TIME CONSTANT: 6.1 mSEC.
12. MOTOR INDUCTANCE: 1.3 mH.
13. MOTOR INERTIA: 0.0004 OZ-IN-SEC².
14. STATIC FRICTION TORQUE: 1.5 OZ-IN MAX.
15. ROTATIONAL LOSSES: 0.20 OZ-IN/KRPM.
16. NO LOAD CURRENT AT 22.5 V: 0.34 A MAX.
17. MAXIMUM WINDING TEMP 155°C.
18. THERMAL RESISTANCE ARMATURE TO AMBIENT: 6.8°C/W,
MOUNTED ON A: 4 IN. X 4 IN. X 0.13 IN. HEATSINK.
19. THERMAL STABILITY OF MOTOR TORQUE CONSTANT: -0.2%/°C.
20. DIELECTRIC BREAKDOWN OF MOTOR ARMATURE TO GROUND: 600 V AT 60 Hz FOR 1 SECOND.
21. SHAFT END PLAY (SEE FIGURE 1): 0.001 IN. MAX IN DIRECTION "A" WITH A 5 LB LOAD.
0.005 IN. MAX IN DIRECTION "B" WITH A 5 LB LOAD.
22. TACH Ke: 2.7-3.3 V/KRPM WITHIN 100 mV CW TO CCW.
23. TACH RESISTANCE: 30-53 OHMS.
24. TACH RIPPLE (SEE FIGURE 2): 150 mV PEAK TO PEAK AT 3.0 VDC OUTPUT USING INERTIA WHEEL.
25. MOTOR AND TACH WEIGHT: 1.5 LBS.
SPUR GEAR TOOTH DATA
NUMBER OF TEETH 13
OUTSIDE DIAMETER 0.2451-0.2404
MODULE 0.4
NORMAL PRESSURE ANGLE 20°
PITCH DIAMETER 0.2048
BASE CIRCLE RADIUS 0.0962
WIRE DIAMETER 0.030
MEASUREMENT OVER WIRES 0.2519
AGMA CLASS 9
PITCH TOLERANCE 0.0002
PROFILE TOLERANCE 0.0002
LEAD TOLERANCE 0.0004
TOOTH TO TOOTH TOLERANCE 0.0008
TOTAL COMPOSITE TOLERANCE 0.0012
START OF ACTIVE PROFILE 1.02
END OF ACTIVE PROFILE 43.98
REV ECO No. DATE
E 58459 8-18-98
D 55811 10-29-96
C 54342 2-16-96
B 52884 5-2-95
A 52415 1-5-95
DO NOT SCALE DRAWING
UNTOLERANCED DIMENSIONS REFERENCE
MILLIMETERS (INCHES)
DWN BY RBV
DATE 1-5-95
SCALE 2:1
TYPE DC
CHK BY JV
DATE 1-5-95
DWG.SIZE C
SERIES 372
CUSTOMER DISTRIBUTION
CUSTOMER PART NO. & REVISION
RELIANCE ELECTRIC
OUTLINE
DWG. No. ES0372-18-013

PA01 • PA73

Power Operational Amplifier

RoHS COMPLIANT

FEATURES

- LOW COST, ECONOMY MODEL — PA01
- HIGH OUTPUT CURRENT — Up to ±5A PEAK
- EXCELLENT LINEARITY — PA01
- HIGH SUPPLY VOLTAGE — Up to ±30V
- ISOLATED CASE — 300V

8-PIN TO-3
PACKAGE STYLE CE

APPLICATIONS

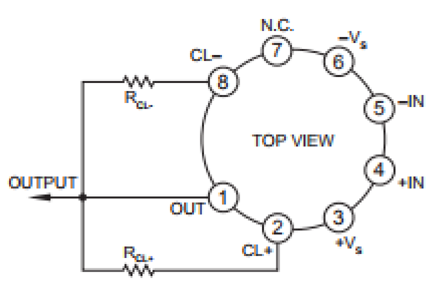
- MOTOR, VALVE AND ACTUATOR CONTROL
- MAGNETIC DEFLECTION CIRCUITS UP TO 4A
- POWER TRANSDUCERS UP TO 20kHz
- TEMPERATURE CONTROL UP TO 180W
- PROGRAMMABLE POWER SUPPLIES UP TO 48V
- AUDIO AMPLIFIERS UP TO 50W RMS

DESCRIPTION

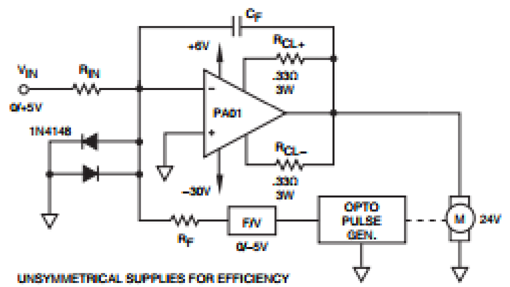
The PA01 and PA73 are high voltage, high output current operational amplifiers designed to drive resistive, inductive and capacitive loads. For optimum linearity, the PA01 has a class A/B output stage. The PA73 has a simple class C output stage (see Note 1) to reduce cost for motor control and other applications where crossover distortion is not critical and to provide interchangeability with type 3573 amplifiers. The safe operating area (SOA) can be observed for all operating conditions by selection of user programmable current limit resistors. These amplifiers are internally compensated for all gain settings. For continuous operation under load, a heatsink of proper rating is recommended.

This hybrid integrated circuit utilizes thick film (cermet) resistors, ceramic capacitors and semiconductor chips to maximize reliability, minimize size and give top performance. Ultrasonically bonded aluminum wires provide reliable interconnections at all operating temperatures. The 8-pin TO-3 package is hermetically sealed and electrically isolated. The use of compressible thermal washers and/or improper mounting torque will void the product warranty. Please see "General Operating Considerations".

EXTERNAL CONNECTIONS



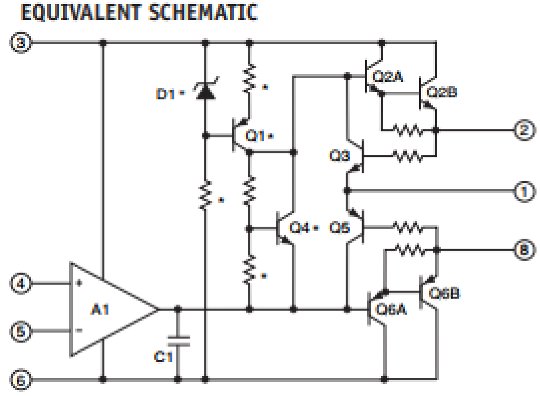
TYPICAL APPLICATION



Unidirectional Optical Speed Control

The pulse output of a non-contact optical sensor drives a voltage-to-frequency converter which generates feedback for the op amp. With the loop closed in this manner, the op amp corrects for any variations in the speed due to changing load. Because of operation in only one direction, an unsymmetrical supply is used to maximize efficiency of both power op amp and power supply. High speed diodes at the input protect the op amp from commutator noise which may be generated by the motor.

EQUIVALENT SCHEMATIC



NOTE 1: * Indicates not used in PA73. Open base of Q2A connected to output of A1.

ABSOLUTE MAXIMUM RATINGS

	PA01	PA73
SUPPLY VOLTAGE, $+V_S$ to $-V_S$	60V	68V
OUTPUT CURRENT, within SOA	5A	5A
POWER DISSIPATION, internal	67W	67W
INPUT VOLTAGE, differential	±37V	±37V
INPUT VOLTAGE, common-mode	$\pm V_S$	$\pm V_S$
TEMPERATURE, junction[1]	200°C	200°C
TEMPERATURE, pin solder -10s	350°C	350°C
TEMPERATURE RANGE, storage	–65 to +150°C	–65 to +150°C
OPERATING TEMPERATURE RANGE, case	–25 to +85°C	–25 to +85°C

SPECIFICATIONS

PARAMETER	TEST CONDITIONS[2]	PA01 MIN	PA01 TYP	PA01 MAX	PA73 MIN	PA73 TYP	PA73 MAX	UNITS
INPUT								
OFFSET VOLTAGE, initial	T_C = 25°C		±5	±12		*	±10	mV
OFFSET VOLTAGE, vs. temperature	Full temperature range		±10	±65		*	*	μV/°C
OFFSET VOLTAGE, vs. supply	T_C = 25°C		±35			*	±200	μV/V
OFFSET VOLTAGE, vs. power	T_C = 25°C		±20			*		μV/W
BIAS CURRENT, initial	T_C = 25°C		±15	±50		*	±40	nA
BIAS CURRENT, vs. temperature	Full temperature range		±.05	±.4		*	*	nA/°C
BIAS CURRENT, vs. supply	T_C = 25°C		±.02			*		nA/V
OFFSET CURRENT, initial	T_C = 25°C		±12	±30		*	*	nA
OFFSET CURRENT, vs. temperature	Full temperature range		±.05			*		nA/°C
INPUT IMPEDANCE, common-mode	T_C = 25°C		200			*		MΩ
INPUT IMPEDANCE, differential	T_C = 25°C		10			*		MΩ
INPUT CAPACITANCE	T_C = 25°C		3			*		pF
COMMON MODE VOLTAGE RANGE[3]	Full temperature range	$\pm V_S-6$	$\pm V_S-3$		*	*		V
COMMON MODE REJECTION, DC[3]	T_C = 25°C, $V_{CM} = V_S -6V$	70	110		*	*		dB
GAIN								
OPEN LOOP GAIN at 10Hz	Full temp. range, full load	91	113		*	*		dB
GAIN BANDWIDTH PRODUCT @ 1MHz	T_C = 25°C, full load		1			*		MHz
POWER BANDWIDTH	T_C = 25°C, I_O = 4A, V_O = 40V_{PP}	15	23		*	*		kHz
PHASE MARGIN	Full temperature range		45			*		°
OUTPUT								
VOLTAGE SWING[3]	T_C = 25°C, I_O = 5A	$\pm V_S-10$	$\pm V_S-5$		$\pm V_S-8$	*		V
VOLTAGE SWING[3]	Full temp. range, I_O = 2A	$\pm V_S-6$	$\pm V_S-5$		*	*		V
VOLTAGE SWING[3]	Full temp. range, I_O = 46mA	$\pm V_S-5$			*			V
CURRENT, peak	T_C = 25°C	±5			*			A
SETTLING TIME to .1%	T_C = 25°C, 2V step		2			*		μs
SLEW RATE	T_C = 25°C, R_L = 2.5Ω	1.0	2.6		*	*		V/μs
CAPACITIVE LOAD, unity gain	Full temperature range			1			*	nF
CAPACITIVE LOAD, gain > 4	Full temperature range			SOA			*	
POWER SUPPLY								
VOLTAGE	Full temperature range	±10	±28	±28	*	*	±30	V
CURRENT, quiescent	T_C = 25°C		20	50		2.6	5	mA
THERMAL								
RESISTANCE, AC, junction to case[4]	F > 60Hz		1.9	2.1		*	*	°C/W
RESISTANCE, DC, junction to case	F < 60Hz		2.4	2.6		*	*	°C/W
RESISTANCE, junction to air			30			*		°C/W
TEMPERATURE RANGE, case	Meets full range specifications	–25	25	+85	*	*	*	°C

NOTES:
- * The specification of PA73 is identical to the specification for PA01 in applicable column to the left.
1. Long term operation at the maximum junction temperature will result in reduced product life. Derate internal power dissipation to achieve high MTTF.
2. The power supply voltage specified under the TYP rating applies unless otherwise noted as a test condition.
3. $+V_S$ and $-V_S$ denote the positive and negative supply rail respectively. Total V_S is measured from $+V_S$ to $-V_S$.
4. Rating applies if the output current alternates between both output transistors at a rate faster than 60Hz.

CAUTION The internal substrate contains beryllia (BeO). Do not break the seal. If accidentally broken, do not crush, machine, or subject to temperatures in excess of 850°C to avoid generating toxic fumes.

PEER EFFORT

Taylor Maniatty - 50% ______________________________ Date : 11/25/17

James Skinner - 50% ______________________________ Date: 11/25/17