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.

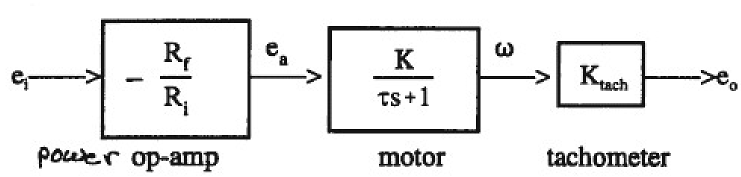
First, you will determine the parameters of a dc brush motor electro-mechanical model and measure the open-loop motor response to step inputs of voltage and load torque. The motor will be driven by a power op-amp, and the speed measured using a tachometer. Another dc motor will be used to back-drive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

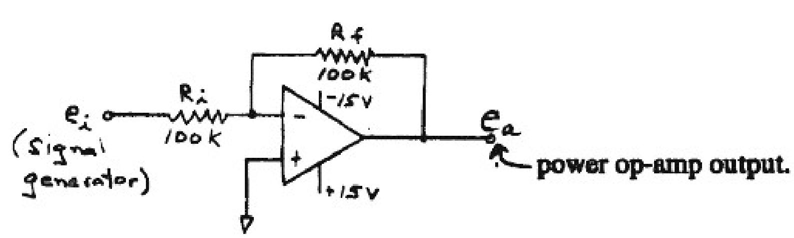
NOTE: Numbered questions are lab work, lettered questions are for the write-up. You should make sure that you have all necessary data to answer these questions.

1. Description of Experimental Setup

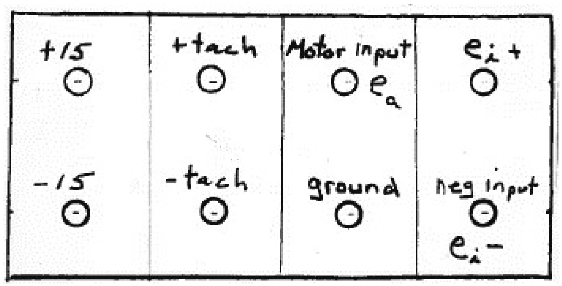
A block diagram of the open-loop motor and the power op-amp is shown below. Note that the electrical time constant of the given motor is much faster than that of the mechanical, i.e. a dominant mechanical pole, so the electrical time constant is neglected, i.e. L = 0.



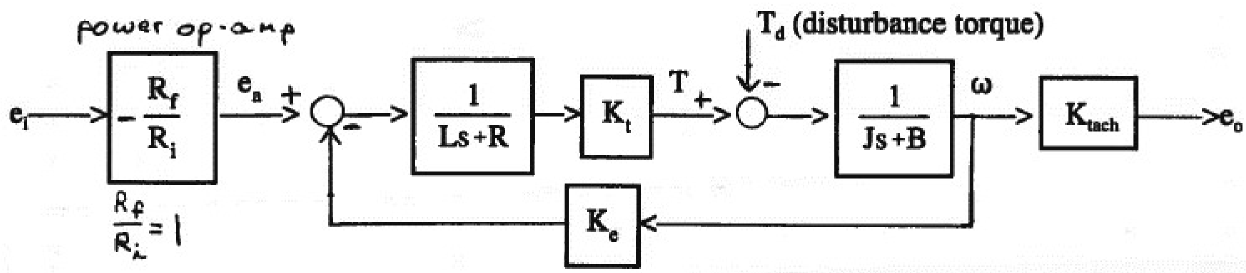
The power op-amp is wired for an open-loop gain of -1 as shown in the following figure. See the attached specification sheet for complete information on the op-amp. This op-amp provides the necessary power to drive the motor. It is powered by a separate +15V and -15V from the BK Precision dual power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



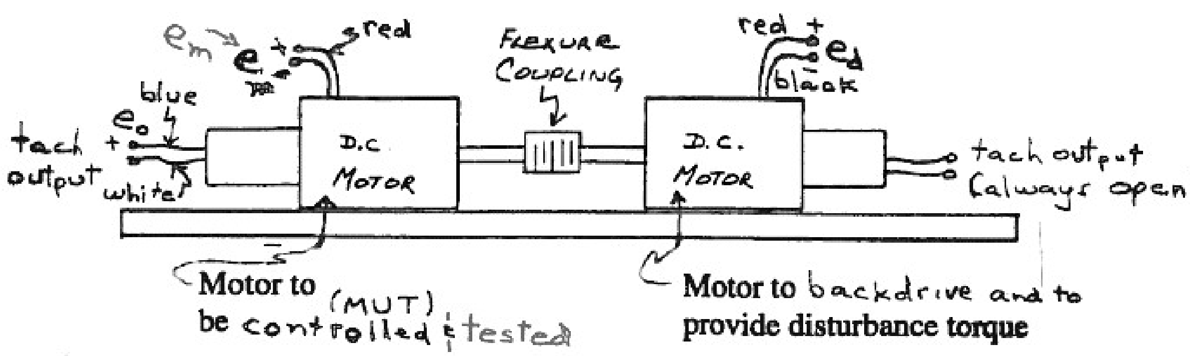
Note that the power op-amp is enclosed in a protective box with the following connections on the front of the enclosure.



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. DC Motor Back EMF Constant

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. 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.

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

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.

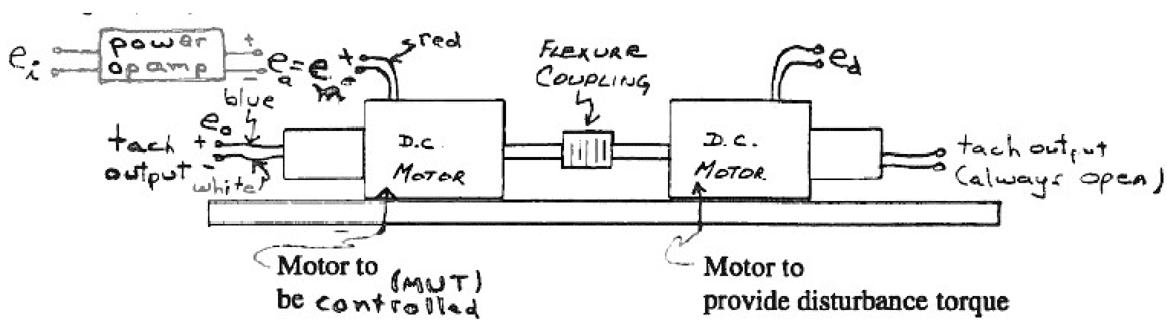
   d) Ignore the electrical time constant of the system and calculate J and B of the system. Use R = 4.2 ohms. Compare J and B to the specification sheet and note reasons for any difference.

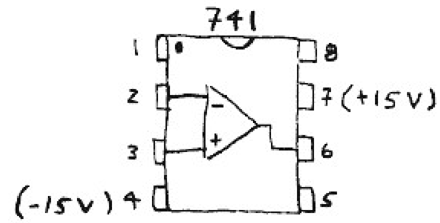
   e) Calculate the settling time (4τ) of the open-loop motor and the steady-state speed error of the motor when it is subjected to a disturbance load of the 5 Ω.resistor.

   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.

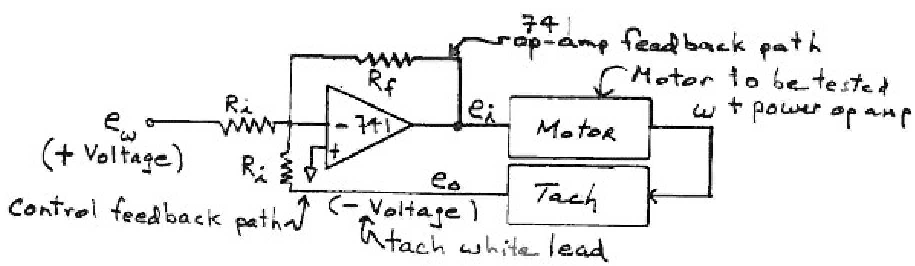




P Controller

$R_i = 100K$

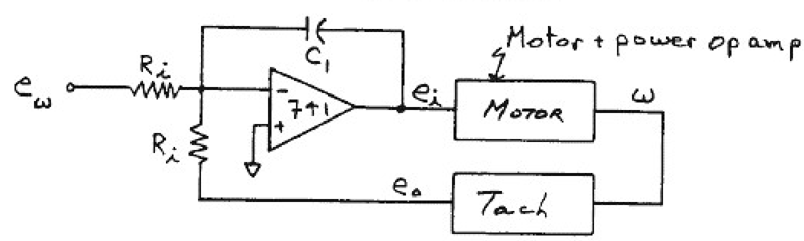
$R_f = 150K$



I Controller

$R_i = 100K$

$C_1 = 0.033\mu F$

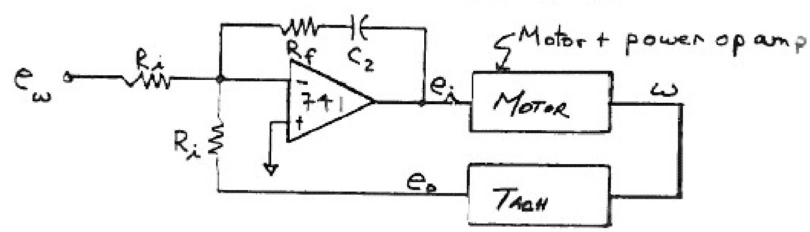


PI Controller

$R_i = 100K$

$R_f = 150K$

$C_2 = 0.010\mu F$



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 <u>white lead</u> 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.

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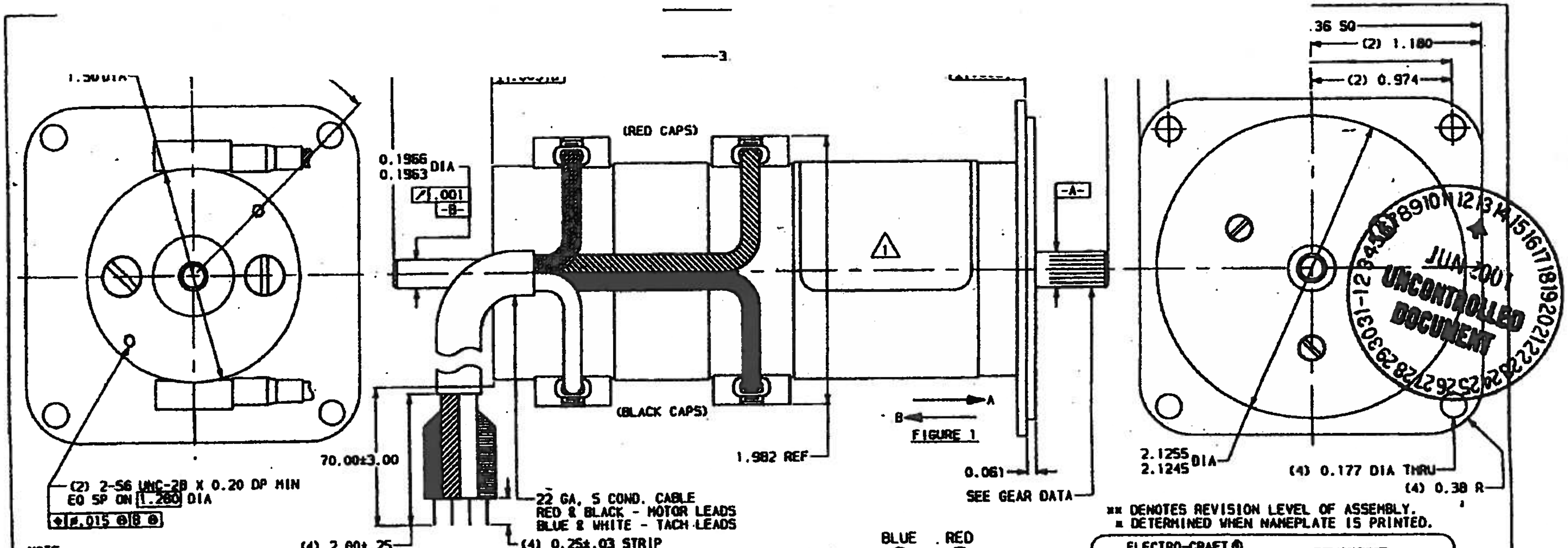

** DENOTES REVISION LEVEL OF ASSEMBLY.
* DETERMINED WHEN NAMEPLATE IS PRINTED.

ELECTRO-CRAFT ® SERVO PRODUCTS			
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PART NO. 0372-18-013	CUSTOMER PART NO.		

NAMEPLATE DETAIL

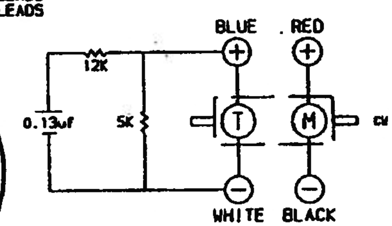


FIGURE 2

NOTE:

⚠ 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-SEC^2.
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	AGMA CLASS	9
OUTSIDE DIAMETER	0.2451-0.2404	PITCH TOLERANCE	0.0002
MODULE	0.4	PROFILE TOLERANCE	0.0002
NORMAL PRESSURE ANGLE	20°	LEAD TOLERANCE	0.0004
PITCH DIAMETER	0.2048	TOOTH TO TOOTH TOLERANCE	0.0008
BASE CIRCLE RADIUS	0.0962	TOTAL COMPOSITE TOLERANCE	0.0012
WIRE DIAMETER	0.030	START OF ACTIVE PROFILE	1.02
MEASUREMENT OVER WIRES	0.2519	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 UNLESS OTHERWISE SPECIFIED UNTOLERANCED DIMENSIONS REFERENCE	DWN BY RBV	DATE 1-5-95	SCALE 2:1	TYPE DC
MILLIMETERS (INCHES) THIRD ANGLE PROJECTION	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

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

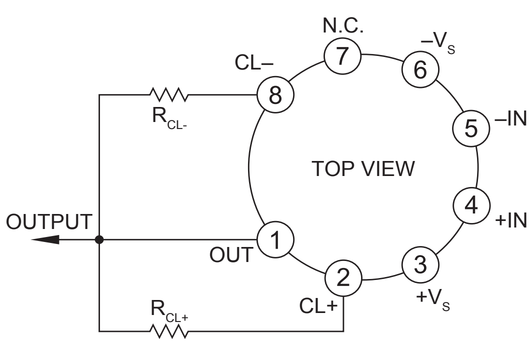
- MOTOR, VALVE AND ACTUATOR CONTROL
- MAGNETIC DEFLECTION CIRCUITS UP TO 4A
- POWER TRANSDUCERS UP TO 20kHz
- TEMPERATURE CONTROL UP TO 180W
- PROGRAMMABLE POWER SUPPLIES UP TO 48V
- AUDIO AMPLIFIERS UP TO 50W RMS

DESCRIPTION

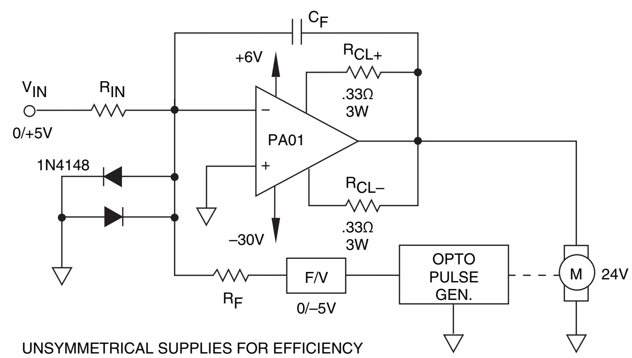
The PA01 and PA73 are high voltage, high output current operational amplifiers designed to drive resistive, inductive and capacitive loads. For optimum linearity, the PA01 has a class A/B output stage. The PA73 has a simple class C output stage (see Note 1) to reduce cost for motor control and other 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



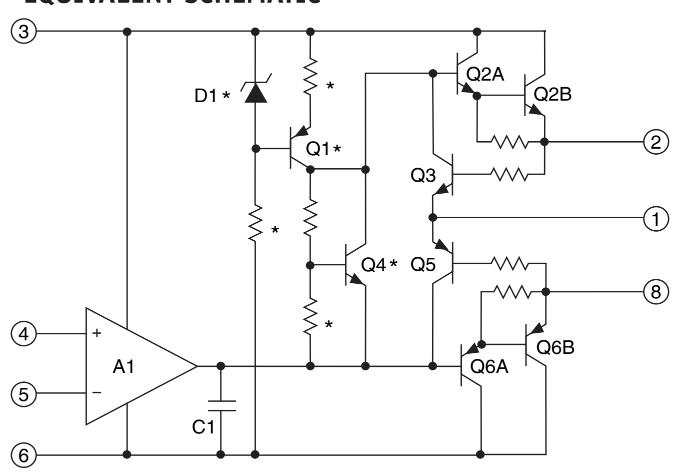
TYPICAL APPLICATION



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.