

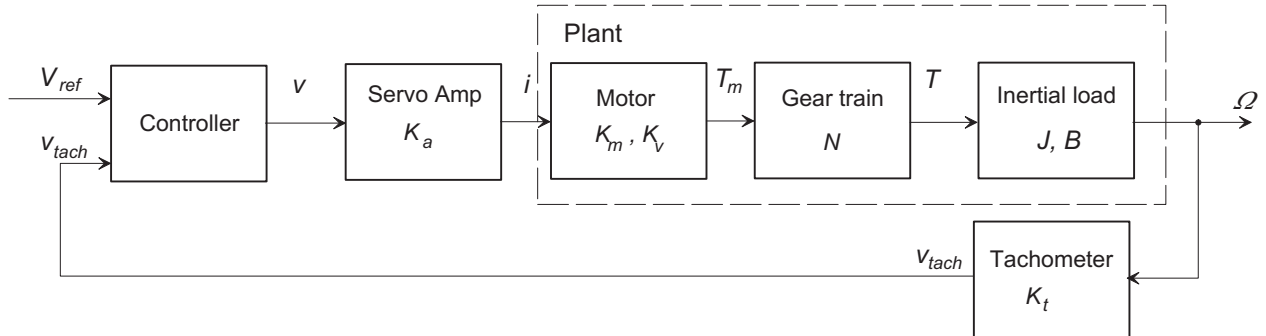
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2.004 Dynamics and Control II
Spring 2008

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Lab Session 2: Calibration of Lab System Components¹

Introduction: In the future lab sessions you will be studying closed-loop control of the rotational plant. The elements of the complete system are shown below:



In Lab 1 you looked at the mechanical properties J and B of the rotational plant, but it is also important that we have an adequate model, and numerical values for the parameters, of the electro-mechanical motor/load and the rotational speed sensor (tachometer) at your lab station. In this session your goal is make measurements on the other system components and to determine their parameters. The specific objectives are:

- To measure the gain K_a of the servo-amplifier.
- To measure the motor torque constant K_m .
- To measure the motor back-emf constant K_v .
- To measure the tachometer gain constant K_t .
- To demonstrate that a DC electric motor obeys power conservation.

Preparation:

- Read the class handout *The DC Motor*
- Do Problem 1 of Problem Set 2.
- Data sheets for the Maxon 148867 DC servo motor, and the US Digital ETACH2 optical tachometer are attached.

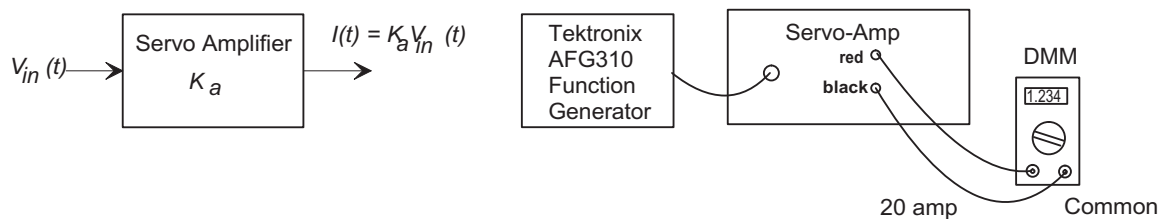
¹February 25, 2008

Measurements:

Amplifier Gain Constant K_a : The servo-amplifier is a *voltage-controlled current-source*, that is it generates an output *current* that is proportional to the *voltage* that is applied at the BNC input connector. The amplifier will adjust its output voltage to maintain the output current (up to its saturation limits of ± 40 volts). Within the linear range the input/output relationship is

$$I_{out}(t) = K_a V_{in}(t)$$

The nominal amplifier gain is $K_a = 2$ A/V, and the maximum sustained current that the amplifier can supply is 5 A. Individual amplifiers may vary from this value and your task is to measure the actual gain constant K_a of the amplifier at your lab station.



Note: The black terminal on the servo amp is **not** ground (0v DC). You must NEVER connect a grounded connection from an instrument, such as an oscilloscope, to this terminal. Serious damage to the instrument and the servo amp could result. The digital multi-meter (DMM) is not grounded, and is therefore safe to use.

Procedure: Your instructor will show you how to set up the the Tektronix AFG310 Function Generator to generate a steady (DC) voltage. Connect the Function Generator output to the servo-amplifier input. Make sure the amplifier is turned off and disconnect the servo-motor from the red and black terminals. Connect the Wavetek DMM using its 20 amp current input terminal. Set the meter to the AMP range and press the yellow button to select DC measurements. Note: Be careful making these connections – you can damage the DMM and/or the amplifier through incorrect connections.

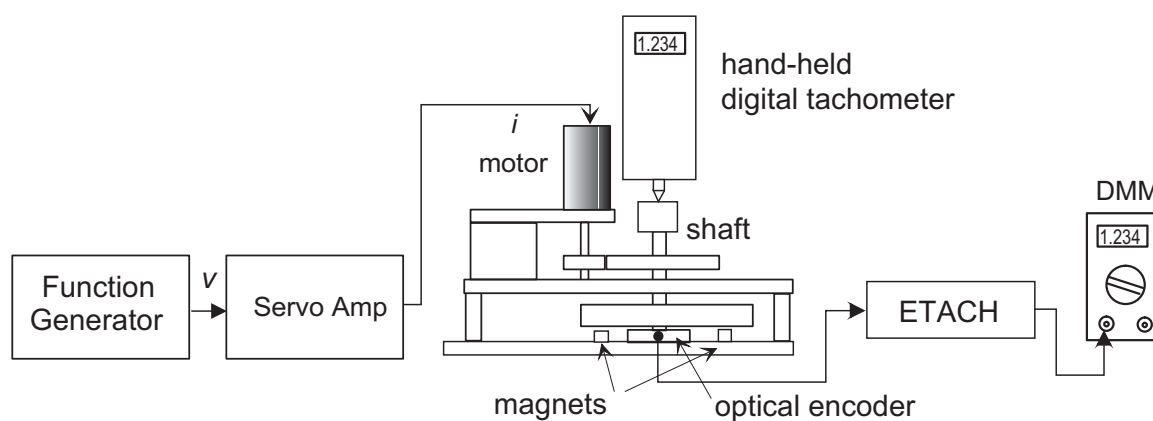
Choose a set of three appropriate input voltages, and for each turn on the function generator and measure the current. Plot a graph (use Excel or MATLAB) and calculate the gain constant from the slope of your graph. Record your measurements and your estimated value of K_a in the box below.

The Tachometer Gain Constant K_t : The tachometer serves as the angular velocity sensor for closed-loop control. The US Digital ETACH2 uses a transparent optical disk, with 2048 radial lines scribed around the circumference. As the shaft spins these lines interrupt a beam of light, and the electronic unit measures the rate of the interruptions and produces a voltage v_t proportional to the angular velocity Ω of the shaft,

$$v_t(t) = K_t \Omega(t).$$

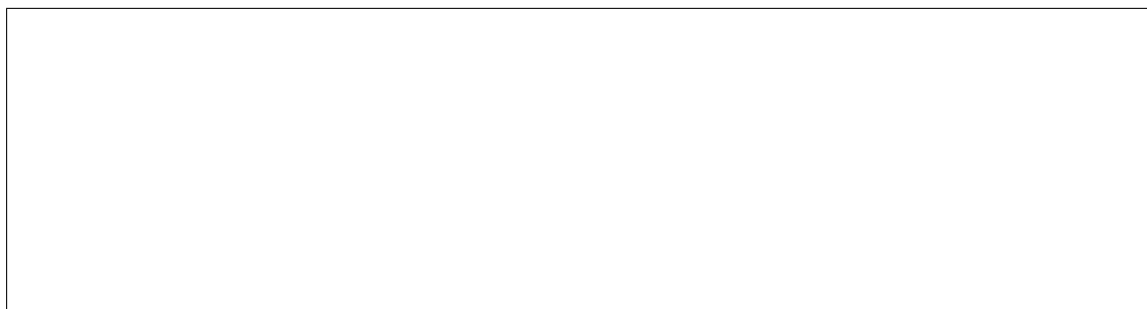
The task is to measure the constant K_t for your tachometer.

The ETACH2 data sheet is attached. The tachometer should already be set up for a gain constant $K_t = 16 \text{ mv/rpm}$, (0.016 volt/rpm), with a maximum angular velocity of $\pm 256 \text{ rpm}$, and an output voltage range of $\pm 4.095 \text{ volts}$. Your task is to verify this value of K_t .



Procedure: Place two magnets under the flywheel to create some viscous drag. Connect your DMM to the tachometer output. Use the Tektronix function generator to apply a small DC voltage to the servo amp and let the motor spin. (You can vary the speed by changing the function generator output.) The lab instructor will help you to measure the angular velocity with a digital tachometer. Record both the measured speed and the tachometer voltage and compute the gain constant K_t . Compare your measured value with the manufacturer's nominal value. Repeat for three values of motor speed and compute the slope of the resulting speed/voltage curve.

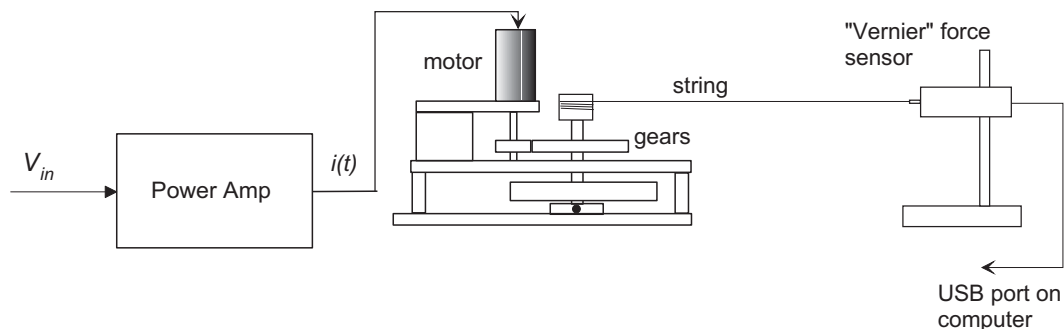
Note: The lab has only two portable digital tachometers, and it will be necessary to share them between groups.



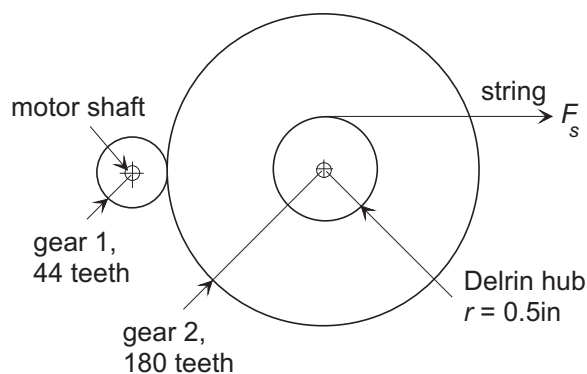
The Motor Torque Constant K_m : For a permanent-magnet DC motor the torque produced is proportional to the armature current:

$$T(t) = K_m i(t)$$

where K_m is a constant. The task is to measure the torque constant K_m .



Procedure Estimate the value of the torque constant K_m . The general approach will be to determine the torque generated by the motor for a given current, and then use equation (3) above to find K_m . You will perform a static test by wrapping a string around a hub on the flywheel shaft, and measuring the tension in the string as a function of the motor current. The tension will be monitored using a Vernier force sensor (0 – 50 N). Then by plotting a straight line to your data points you will determine the torque constant K_m (N.m/amp). The geometry of the set-up is shown below:



You must first derive an expression to relate the tension in the string, F_s , to the motor torque T_m . Note that the figure above is not to scale. In fact,

$$\begin{aligned} r_{hub} &= 0.5\text{in} \\ \frac{n_1}{n_2} &= \frac{44}{180} \end{aligned}$$

The procedure for measuring F_s is as follows.

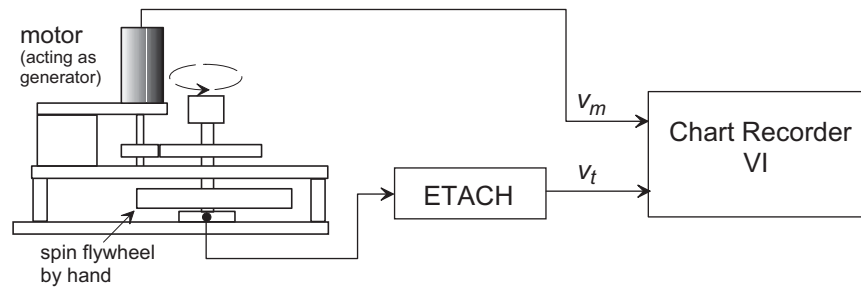
- Set the function generator to produce a DC voltage. Make sure that the 50Ω terminator resistor is connected to the output. If you are unsure of what this means, ask an instructor. Connect the function generator to the input of the servo amplifier. Make sure the “output switch” of the servo amplifier is set to the “OFF” position.
- Connect the output of the servo amplifier to the electrical leads of the motor THROUGH the digital volt/ohmmeter. Make sure the digital volt/ohmmeter’s dial switch is set to measure DC current on the 20 amp range. Ask your instructor to check the wiring before you turn the system on.
- Secure the digital force sensor to the magnetic stand, and make sure that it plugged into the USB port on the front of the computer. Start the Vernier *Data Logger Pro* software.
- Wrap the string around the Delrin bushing and connect to the force sensor. Make sure that the string is wrapped in the correct direction (so that it is under tension when the current is applied).
- You will measure the motor torque at several currents up to a maximum of 5 amps. The power amplifier produces a current of 2 amps per volt at its input. To make a measurement at, for example, 1 amp you will need to set the function generator to a voltage of 0.5 volt. (In DC mode the voltage is set by the OFFSET control).
- Rotate the copper disk to ensure there is no slack in the string.
- Have your partner flip the output switch of the servo amplifier to the ON position.
- Record the current and the force. Flip the output switch of the servo amplifier OFF.
- Repeat to obtain measurements for 4 or 5 different current levels (up to a maximum of 5 amps.)
- Enter the data into a spreadsheet, make a plot of TORQUE vs CURRENT and obtain its slope. Make sure you include the effect of the gear train in your calculations.



The Motor Back-emf Constant. The back-emf v_b is generated whenever the motor spins, and is proportional to the rotational speed Ω , that is

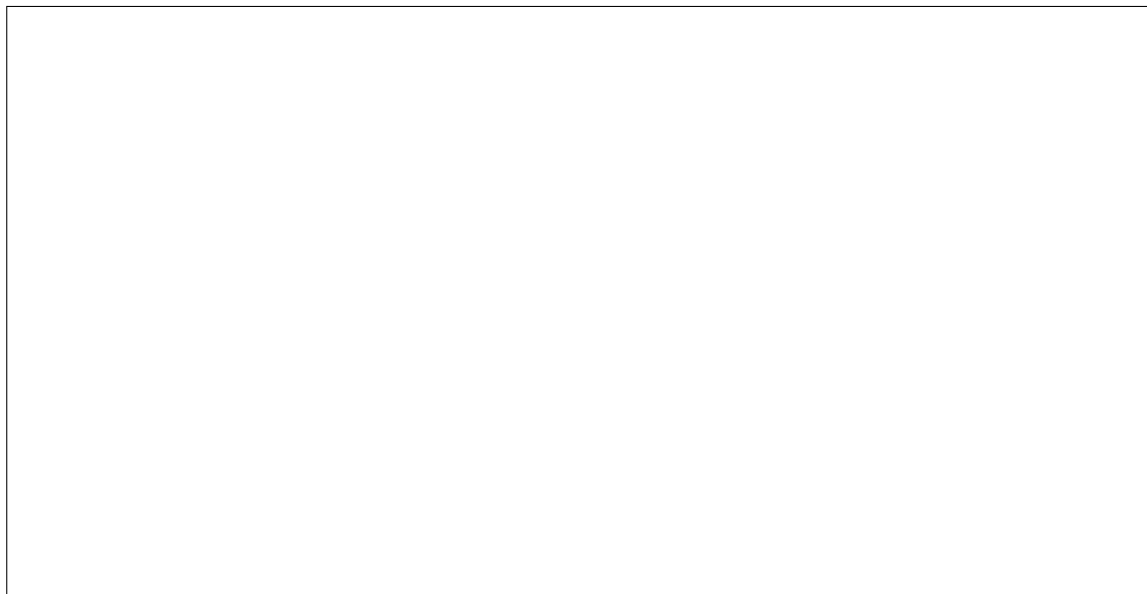
$$v_b = K_v \Omega$$

To estimate K_v spin the motor by hand, so that it acts as a generator, and measure (1) the open-circuit voltage across the motor leads, $v_m(t)$, and (2) the angular velocity of the motor, $\Omega_m(t)$. Note that because there is very little current flowing from the generator, there is no voltage drop across the internal motor resistance.



The procedure for doing this is as follows:

- Remove all damping magnets.
- Set up the Chart Recorder VI to measure two inputs, the motor voltage and the tachometer voltage.
- Spin the copper disk (and motor),
- Record the two voltages during the spin-down, and save to a MATLAB or Excel file.
- Using the tachometer constant K_t and the gear ratio, determine the angular velocity of the motor, $\Omega_m(t)$, and make a cross-plot of the two data records. From the slope of the resulting graph estimate the “back-emf constant”, K_v . Make sure you include the effect of the gear train in your calculations.



Summary:

Summarize your measured values of the lab equipment parameters below (with units):

Amplifier Gain Constant (K_a):

Tachometer Gain Constant (K_t):

Motor Torque Constant (K_m):

Motor Back-emf Constant (K_v):

Demonstrate that your motor constants obey power conservation:

ETACH2

High Speed Encoder to Analog Tachometer

Description:

The **ETACH2** is a high performance analog tachometer that converts incremental encoder signals into a stable analog voltage. The **ETACH2** is fast enough to be used in a velocity or servo control loop typically requiring a tachometer generator. The **ETACH2** has a wide frequency range (programmable full scale) and does not suffer from the low speed droop and ripple typically found with traditional analog tachometer generators. Incremental quadrature encoder signals are digitally converted to provide either positive or negative voltages; positive output voltages are provided when the signals are rotated in a positive direction, and negative voltages are provided when the direction is reversed. The output can also be selected to provide zero to maximum positive voltage output. A TTL digital direction bit is provided.

The **ETACH2** is programmed by an array of DIP switches that determine the operating frequency range and mode of operation. Two encoder connectors are provided in parallel to make it convenient to loop the encoder signals through the **ETACH2**. This allows the signals to be easily applied elsewhere in a control loop. An isolated SPDT relay output, accessed through a 5-pin pluggable screw terminal, provides a speed switch output that will be activated if the input frequency reaches an over speed limit programmed by the DIP switches. The minimum on time for the relay is 0.5 seconds even if the output is momentarily triggered.

An internal switching regulator provides internal power and supplies 5VDC to the external encoder. Analog output voltage, TTL direction bit and ground are accessed on a 10-pin pluggable screw terminal. The terminal also provides an alternate way of powering the **ETACH2**, as opposed to using the mini power jack.

DIP Switches:

The **ETACH2** is configured by an array of DIP switches. These switches are numbered from right to left. Complete explanations and switch definitions can be found on the next page.

- > Switches 1 through 10 set the frequency range.
- > Switches 11 through 13 set the operation mode.
- > Switch 14 is not used.
- > Switches 15 and 16 set the relay output as a function of % of full range speed.

Features:

- > 0 to 4.095V and 0 to 10V or $\pm 4.095V$ and $\pm 10V$ output
- > Wide full scale range DC to 0.03Hz (minimum) through DC to 12.7MHz (maximum)
- > 7kHz update rate
- > Isolated SPDT relay output for overspeed or underspeed
- > Droop free
- > No cogging or ripple at low speeds 12 bit analog resolution
- > Digital encoder direction bit output
- > Programmable input frequency ranges, frequency limits and output ranges
- > DIN rail mounting available
- > 0 to +70°C operating temperature
- > US Digital warrants its products against defects in materials and workmanship for two years. See complete warranty for details.



Electrical Specifications:

> Unless otherwise specified, all accuracy measurements assume 100kHz and within temperature range 0 to 70°C.

Parameter	Min.	Typ.	Max.	Units	Notes
Quadrature Cycle Input Frequency	0	-	2.5M	Hz	1 quadrature cycle = 4 quadrature states.
Quadrature State Input Frequency	0	-	10M	Hz	1 quadrature cycle = 4 quadrature states.
Non-quadrature Input Frequency	0	-	8.0M	Hz	
Input Supply Voltage	11	12	18	Volts	Through J6 or J1 pin-8.
	14	24	30	Volts	Through J1 pin-10.
Supply Current - 12V Input	-	75	-	mA	No encoder load.
	-	200	-	mA	250mA encoder load.
Supply Current - 24V Input	-	46	-	mA	No encoder load.
	-	103	-	mA	250mA encoder load.
Relay Contact Rating	-	-	3.0	A	24VDC / 125VAC
Relay Dielectric Strength	500	-	-	VAC	Open contact.
	500	-	-	VAC	Contact to coil.
Relay Contact Resistance	-	-	100	uOhms	Contact resistance.
Direction Output Bit - Logic Low	-	-	0.4	Volts	8mA (sinking current).
Direction Output Bit - Logic High	2.4	-	-	Volts	-4mA (sourcing current).
Full Scale Output Error	-0.5	0	0.5	% full scale	For 4.095V output mode.
	-1.5	± 0.25	1.5	% full scale	For 10V output mode.
Integral Non-linearity Error	-3.0	± 1.0	3.0	mV	For 4.095V output mode.
	-8.0	± 3.0	8.0	mV	For 10V output mode.
Offset Error	-6.0	± 1.0	6.0	mV	For 4.095V output mode.
	-8.0	± 3.0	8.0	mV	For 10V output mode.
Analog Output Load Impedance	680	-	-	Ohms	
Voltage Out to Encoder	4.8	5.0	5.2	Volts	Under 100mA load.
Encoder Current	-	-	250	mA	+5V power for external encoder.
Quadrature Encoder Inputs - Logic Low*	0	0.4	0.8	Volts	
Quadrature Encoder Inputs - Logic High*	2.0	5.0	5.75	Volts	

* Diode clamped to ground and +5V, 10K pullup to +5V.



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Frequency Range (SW1 - SW10):

DIP switches 1 through 7 set the base frequency range in Hz or quadrature cycles per second as a binary representation of the switches. DIP switches 8, 9 and 10 provide a decimal scaling factor to the value of switches 1 and 7.

Setting the frequency range DIP switches:

The frequency of the encoder output signal that is required to reach the full scale voltage of the ETACH2 is determined by the following equation.

Please note: 1 = Up Position = Switch Off, 0 = Down Position = Switch On.

$$BF * SF = \text{Encoder Frequency.}$$

BF (Base Frequency) is determined by setting switches SW1 through SW7 (see table 1 below). The sum of the values assigned to the switches should be between 3 and 127. To maximize the resolution of the ETACH2 choose the largest possible value of BF that will satisfy your configuration operating requirements.

SF (Scale Factor) is determined by setting switches SW8 through SW10. Scale factors can be selected with ranges from 0.01 to 100,000 (see table 2 below).

Example 1: Encoder Frequency = 100kHz

Set BF to 100 (100 = 64 + 32 + 4; switches 7, 6 and 3 should be set to 1). Set SF to 1000 (SW10=1, SW9=0 and SW8=1).

$$BF * SF = \text{Encoder Frequency}$$

$$100 * 1000 = 100 \text{ KHz.}$$

Example 2: Encoder Frequency = 200 kHz

Set BF to 20 (20 = 16 + 4; switches 5, 3 should be set to 1). Set SF to 10000 (SW10=1, SW9=0 and SW8=1).

$$BF * SF = \text{Encoder Frequency}$$

$$20 * 10000 = 200 \text{ kHz}$$

Operation Mode (SW11 - SW13):

Mode 0: Quadrature encoder input. Output voltage range is Zero Volts to +Maximum Volts.

Output is independent of direction of encoder rotation.

- > Zero Volts represents zero encoder frequency.
- > +Maximum Volts represents maximum encoder frequency.

Mode 1: Quadrature encoder input. Output voltage range is -Maximum Volts to +Maximum Volts.

Output is independent of direction of encoder rotation.

- > -Maximum Volts represents zero encoder frequency.
- > Zero Volts represents middle encoder frequency.
- > +Maximum Volts represents maximum encoder frequency.

Mode 2: Quadrature encoder input. Output voltage range is -Maximum Volts to +Maximum Volts.

Output is dependent upon direction of encoder rotation.

- > -Maximum Volts represents maximum encoder frequency in one direction.
- > Zero Volts represents zero encoder frequency.
- > +Maximum Volts represents maximum encoder frequency in the opposite direction.

Mode 3: Quadrature encoder input. Output voltage range is Zero Volts to +Maximum Volts.

Output is dependent upon direction of encoder rotation.

- > Zero Volts represents maximum encoder frequency in one direction.
- > ½ Volts range is zero encoder frequency.
- > +Maximum Volts represents maximum encoder frequency in the opposite direction.

Mode 4: Single channel non-quadrature frequency input.

Output voltage range is Zero Volts to +Maximum Volts.

- > Zero Volts represents zero frequency input.
- > +Maximum Volts represents maximum frequency input.

Mode 5: Single channel non-quadrature frequency input.

Output voltage range is -Maximum Volts to +Maximum Volts.

- > -Maximum Volts represents zero frequency input.
- > Zero Volts represents ½ maximum frequency input.
- > +Maximum Volts represents maximum frequency input.

Mode 6: Not used. If switch is configured to this mode, ETACH2 operation defaults to Mode 4.

Mode 7: Not used. If switch is configured to this mode, ETACH2 operation defaults to Mode 4.

Relay Output (SW15 - SW16):

DIP switches 15 and 16 are used to program the desired percent of full scale frequency. The ETACH2 has an isolated SPDT relay output contact closure that may be configured as an over speed limit switch. The relay closure may be configured as a percentage of the maximum full-scale frequency. The relay will activate at or above the programmed frequency. Once triggered, the relay will stay on for at least 0.5 seconds even if the frequency drops below the threshold.

Table 1 - Base Frequency (SW1 - SW7):

Switch	Binary Value
SW1	1
SW2	2
SW3	4
SW4	8
SW5	16
SW6	32
SW7	64

Table 2 - Scaling Factor (SW8 - SW10):

SW10	SW9	SW8	= Scaling Value
↓	↓	↓	= 0.01
↓	↓	↑	= 0.10
↓	↑	↓	= 1.00
↓	↑	↑	= 10
↑	↓	↓	= 100
↑	↓	↑	= 1000
↑	↑	↓	= 10,000
↑	↑	↑	= 100,000

Table 3 - Operation Mode (SW11 - SW13):

Mode	SW13	SW12	SW11
0	↓	↓	↓
1	↓	↓	↑
2	↓	↑	↓
3	↓	↑	↑
4	↑	↓	↓
5	↑	↓	↑

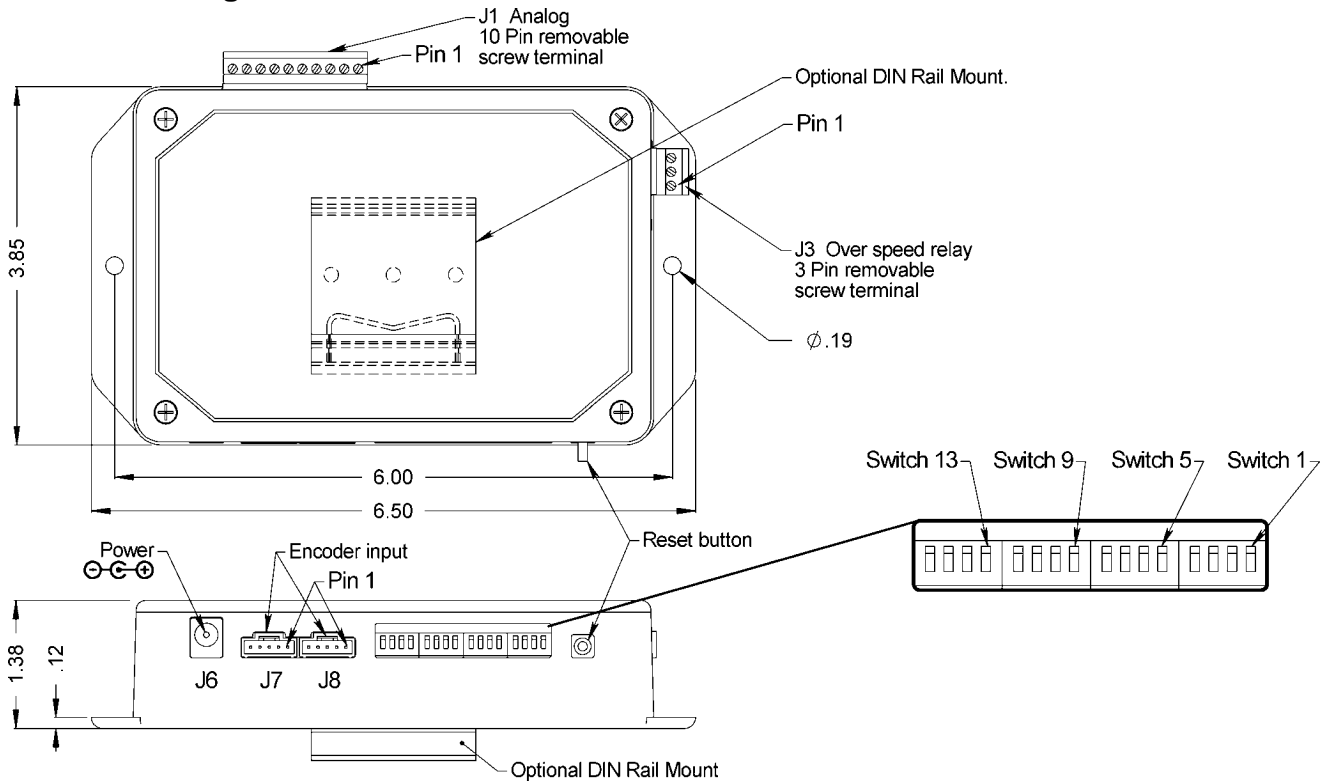
Table 4 - Relay Output (SW15 - SW16):

SW16	SW15	% of Full Scale
↓	↓	10%
↓	↑	50%
↑	↓	90%
↑	↑	100%

ETACH2

High Speed Encoder to Analog Tachometer

Mechanical Drawing:



Analog Input / Output Connector Pin-out:

Pin	Description
1	Ground
2	Output signal (0 to +10VDC) or (± 10 VDC)
3	Output signal (0 to +4.095VDC) or (± 4.095 VDC)
4	Ground
5	+5VDC power out
6	Encoder direction out
7	Ground
8	+12VDC in* (+11 to +18)
9	Ground
10	+24VDC in* (+14 to +30)

* Connect only one power source.

Relay Contacts Connector Pin-out:

Pin	Description
1	Common
2	Normally closed
3	Normally open

Encoder Input Connector Pin-out:

Pin	Description
1	Ground
2	Index
3	A channel
4	+5VDC power out
5	B channel

Compatible Cables & Connectors:

Pluggable Screw Terminals (included) for J1 / J3:
Quantity 1 of each: 3-position and 10-position

5-pin Finger-latching (not included and optional) for J7 / J8:
CON-FC5* Connector

CA-3133-1FT Connector on one end with 4 12" wires

CA-3132-1FT Connector on one end with 5 12" wires

CA-3131-6FT Connector on one end with a 6' shielded round cable

CA-3620-6FT Connectors on both ends of a 6' shielded round cable

* 22 AWG is standard. 24, 26 and 28 AWG are also available.

Attention:

- > Specify cable length when ordering.
- > Custom cable lengths are available. See the **Cables / Connectors** data sheet for more information.

Ordering Information:

Price:

\$173.25 / 1
\$155.40 / 10
\$141.75 / 50
\$129.15 / 100

Part #:

ETACH2 -

R = DIN rail (35mm wide) mounting.
NP = No power supply.

Cost Modifiers:

- > Add \$10 for **R**-option.
- > Subtract \$7 for **NP**-option (no PS-12).

Includes:

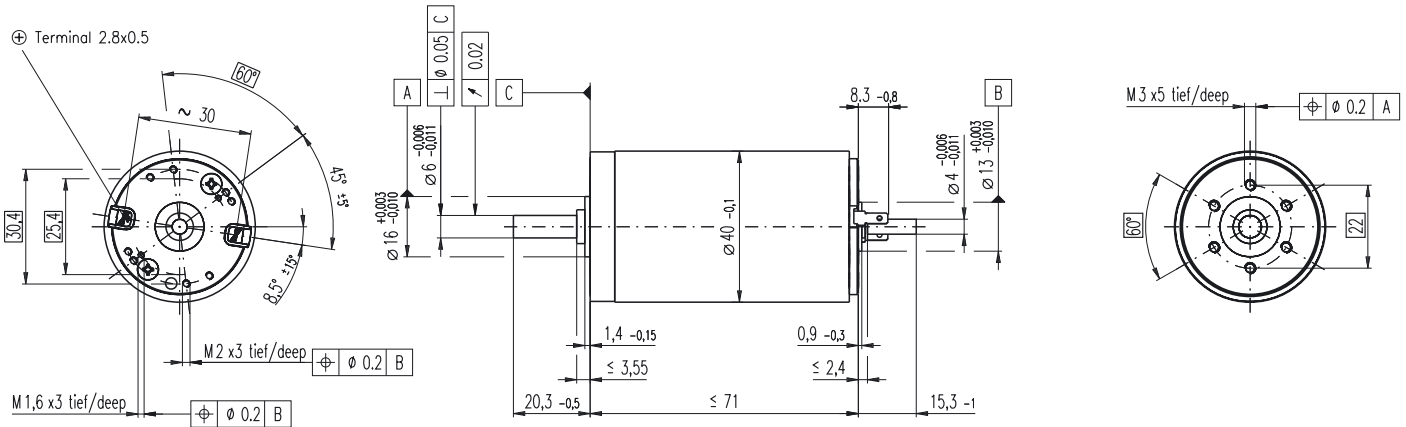
- > PS-12 (power supply).
- > 2 pluggable screw terminals (3-position and 10-position).

Technical Data, Rev. 10.25.06, October 2006
All information subject to change without notice.



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RE 40 Ø40 mm, Graphite Brushes, 150 Watt



M 1:2

- Stock program
- Standard program
- Special program (on request!)

Order Number

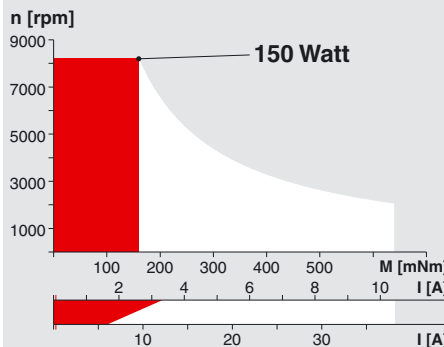
Industrial version	148866	148867	148877	218008	218009	218010	218011	218012	218013	218014	218015
	263065	263066	263067	263068	263069	263070	263071	263072	263073	263074	263075

Motor Data		148866	148867	148877	218008	218009	218010	218011	218012	218013	218014	218015
1 Assigned power rating	W	150	150	150	150	150	150	150	150	150	150	150
2 Nominal voltage	Volt	12.0	24.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0
3 No load speed	rpm	6920	7580	7580	6420	5560	3330	2690	2130	1710	1420	987
4 Stall torque	mNm	1690	2290	2500	1990	1580	996	796	641	512	415	289
5 Speed / torque gradient	rpm / mNm	4.11	3.32	3.04	3.23	3.53	3.36	3.39	3.35	3.37	3.44	3.45
6 No load current	mA	241	137	69	54	44	22	17	13	10	8	5
7 Starting current	A	103	75.9	41.4	28.0	19.2	7.26	4.69	3.00	1.92	1.29	0.627
8 Terminal resistance	Ohm	0.117	0.316	1.16	1.72	2.50	6.61	10.2	16.0	24.9	37.1	76.6
9 Max. permissible speed	rpm	8200	8200	8200	8200	8200	8200	8200	8200	8200	8200	8200
10 Max. continuous current	A	6.00	6.00	3.33	2.75	2.41	1.41	1.13	0.904	0.725	0.594	0.414
11 Max. continuous torque	mNm	98.7	181	201	196	198	193	192	193	193	191	190
12 Max. power output at nominal voltage	W	285	440	491	332	255	86.5	55.7	35.6	22.9	15.3	7.40
13 Max. efficiency	%	88	91	92	91	91	89	88	87	86	85	83
14 Torque constant	mNm / A	16.4	30.2	60.3	71.3	82.2	137	170	214	266	321	461
15 Speed constant	rpm / V	581	317	158	134	116	69.7	56.2	44.7	35.9	29.8	20.7
16 Mechanical time constant	ms	6	5	4	4	4	4	4	4	4	4	4
17 Rotor inertia	gcm ²	135	134	134	125	127	118	117	118	117	114	114
18 Terminal inductance	mH	0.02	0.08	0.33	0.46	0.61	1.70	2.62	4.14	6.40	9.31	19.20
19 Thermal resistance housing-ambient	K / W	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
20 Thermal resistance rotor-housing	K / W	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
21 Thermal time constant winding	s	41	40	40	38	38	36	35	35	35	34	34

Specifications

- Axial play 0.05 - 0.15 mm
- Max. **ball bearing** loads
 - axial (dynamic) 5.6 N
 - not preloaded 2.4 N
 - preloaded 28 N
 - radial (5 mm from flange) 110 N
 - Force for press fits (static) 1200 N
- Radial play **ball bearing** 0.025 mm
- Ambient temperature range -20 ... +100°C
- Max. rotor temperature +155°C
- Number of commutator segments 13
- Weight of motor 480 g
- 2 pole permanent magnet
- Values listed in the table are nominal. For applicable tolerances see page 43. For additional details please use the maxon selection program on the enclosed CD-ROM.

Operating Range

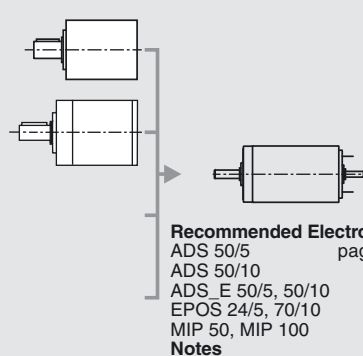


Comments

- Recommended operating range**
- Continuous operation**
In observation of above listed thermal resistances (lines 19 and 20) the maximum permissible rotor temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.
- Short term operation**
The motor may be briefly overloaded (recurring).
- 148877** Motor with high resistance winding
- 148866** Motor with low resistance winding

maxon Modular System

- Planetary Gearhead**
Ø42 mm
3 - 15 Nm
Details page 224
- Planetary Gearhead**
Ø52 mm
4 - 30 Nm
Details page 227



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- Encoder MR**
256 - 1024 CPT,
3 channels
Details page 239
- Encoder HED_5540**
500 CPT, 3 channels
Details page 242 / 244
- Brake AB**
Ø40 mm,
24 VDC, 0.4 Nm
Details page 279
- Industrial version Encoder HEDL 9140**
Details page 247
- Brake AB**
Details page 280

- Recommended Electronics:**
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- ADS 50/5 259
 - ADS 50/10 259
 - ADS_E 50/5, 50/10 260
 - EPOS 24/5, 70/10 271
 - MIP 50, MIP 100 273
- Notes**
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