MASSACHUSETTS INSTITUTE OF TECHNOLOGY

DEPARTMENT OF MECHANICAL ENGINEERING

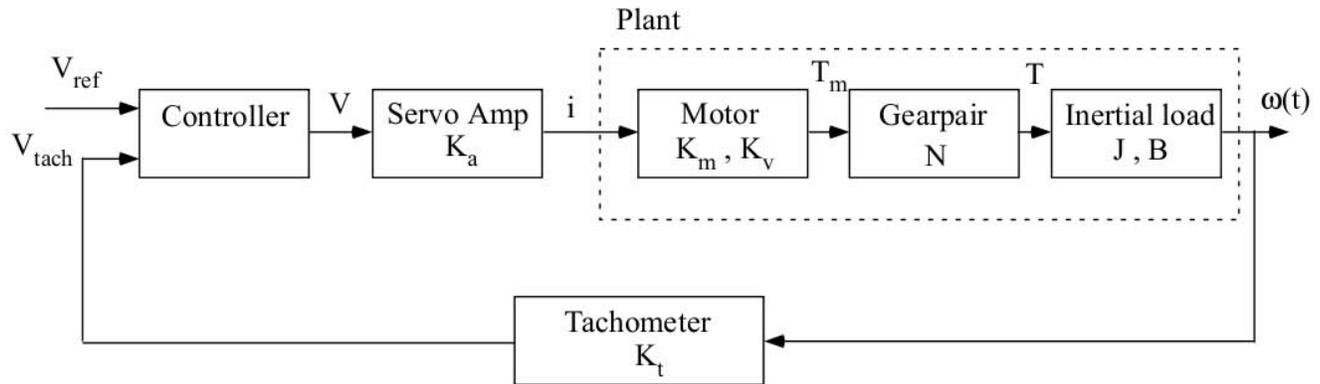## 2.004 System Dynamics and Control
Fall Term 2007

Lab 2: Characterization of Lab System Components

OBJECTIVES

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 measured the mechanical properties J and B of the rotational plant. In this session your goal is make measurements on the other system components and to determine their parameters. The specific objectives are to:

1. measure the gain of the servo-amplifier, K_a .

2. measure the tachometer gain constant K_t .

3. measure the motor back-emf constant K_v .

4. measure the motor torque constant K_m .

5. demonstrate that the DC electric motor obeys power conservation.

PROCEDURE

1. Measure Amplifier Gain Constant, K_a :

The servo-amplifier is a voltage-controlled current-source, i.e. 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 plus or minus 40 volts). Within the linear range the input/output relationship is

$$i(t) = K_a V(t)$$

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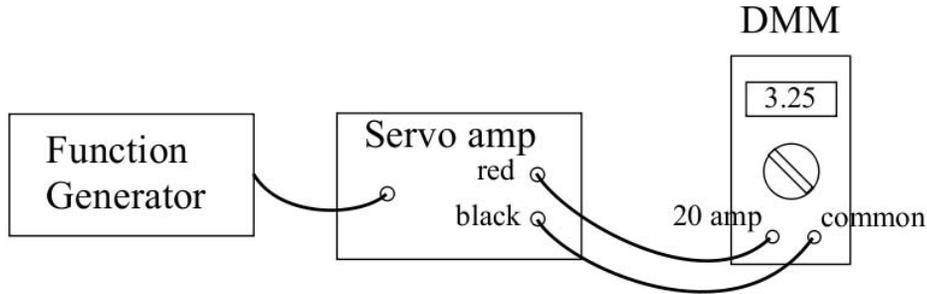
Note: The black terminal on the servo amp is not ground (0v DC). You must NEVER connect a grounded connection from an instrument, such as an oscilloscope, to this terminal. Serious damage to the instrument and the servo amp could result. The digital multi-meter (DMM) is not grounded, and is therefore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

Procedure 1:

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 on 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 .

2. Measure Tachometer Gain Constant, K_t :

The tachometer serves as the angular velocity sensor for closed-loop control. The US Digital ETACH 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 of the disk (i.e. flywheel), ω_d ,

$$v_t(t) = K_t \omega_d(t)$$

The task is to measure the constant K_t for your tachometer. The ETACH data sheet is attached. The tachometer should already be set up for a gain constant $K_t = 16$ mv/rpm, (0.016 volt/rpm), with a maximum angular velocity of $\pm$ 256 rpm, and an output voltage range of $\pm$ 4.095 volts. Your task is to verify this value of K_t.
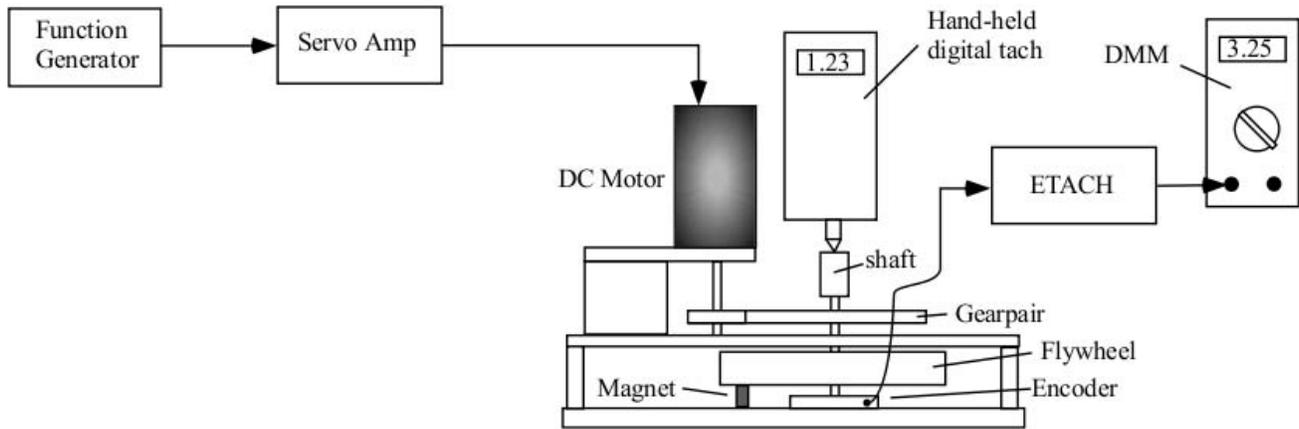
Procedure 2

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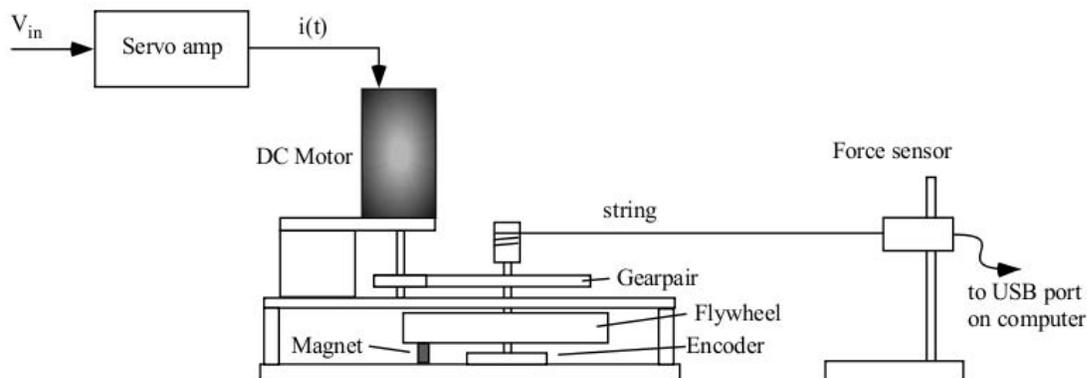
Note: The lab has only two portable digital tachometers, and it will be necessary to share them between groups.

3. Measure 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 3

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 cross-plotting your data points you will determine the torque constant K_m (N.m/amp). The geometry of the set-up is shown below:
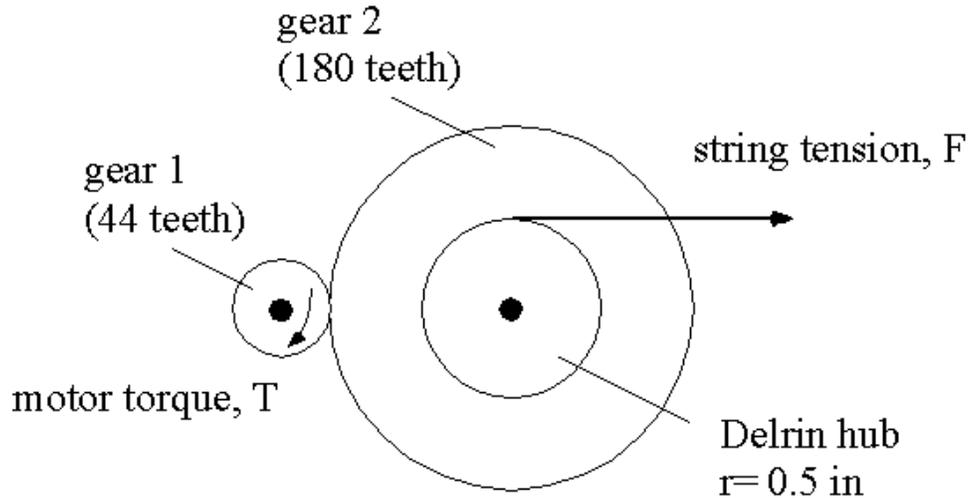
You must first derive an expression to relate the tension in the string, F, to the motor torque T. Note that the figure above is not to scale. In fact,

$$r_{hub} = 0.5in$$

$$\frac{n_1}{n_2} = \frac{44}{180}$$

The procedure for measuring F is as follows.

- Set the function generator to produce a DC voltage. Make sure that the 50 Ω terminator resistor is connected to the output. 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.

4. Measure the Motor Back-emf Constant

The back-emf voltage, v_m, is generated whenever the motor spins, and is proportional to the motor's rotational speed, ω_m , that is

$$v_m(t) = K_v \omega_m(t)$$

To estimate K_v, spin the motor by hand so that it acts as a generator, and measure the open-circuit voltage across the motor leads, $v_m(t)$, and 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.
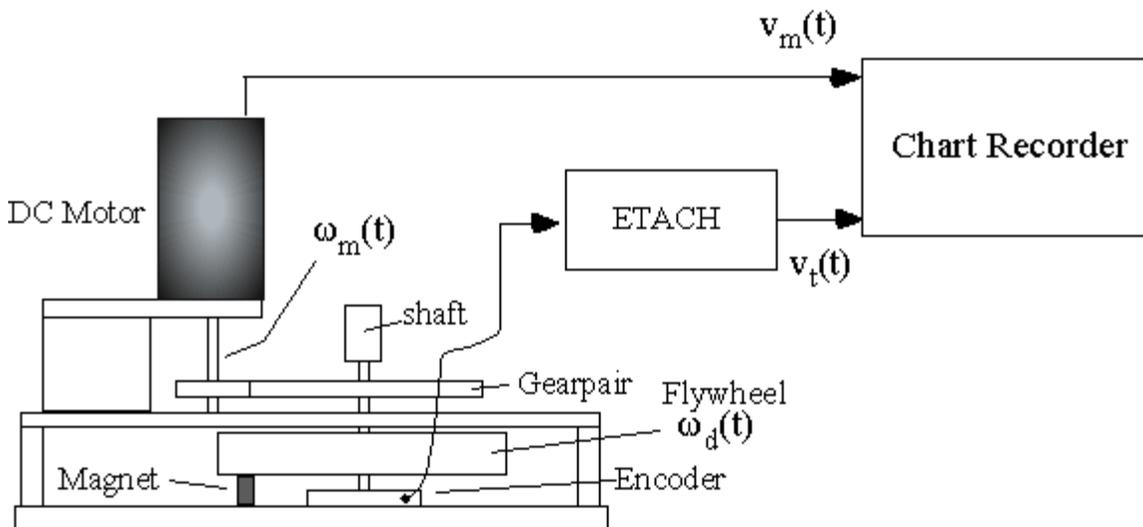
Procedure 4

- 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, N, 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.**

5. Demonstrate that your motor constants obey power conservation:

In the *electromechanical transduction* element of an ideal D.C. Motor, the electrical and the mechanical power variables are related by the following equations:

$$T = K_m i \qquad\qquad v = K_v \omega$$

(a) Assuming that the transduction element is lossless, i.e. $Power_{in} = Power_{out}$, show how K_m and K_v must be related.

(b) The motor used in the lab is the Maxon model 148867. The data sheet is attached. The data for the 148867 is contained in the **second column.** Lines 12 and 13 specify the torque constant and back-emf constants. By converting to a consistent set of units, show that the transduction is lossless for this motor.