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Open Loop Servo Motor Static Characteristics

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the various mechanical and electrical components of a brush-type permanent-magnet dc servo motor system. You will know how to analyze the steady state behavior of the dc servo motor in open loop mode. You will be able to calculate and develop the relationship between the dc voltage applied to the servo motor and the motor speed.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction to the functioning of the Digital Servo
- Components and variables of a servo motor
- Open loop control vs. closed loop control
- Steady state analysis of a dc servo motor
- Calculating the motor steady state speed constant

DISCUSSION

Introduction to the functioning of the Digital Servo

The Digital Servo system uses a brush-type permanent-magnet dc motor. As with conventional dc motors that employ a field winding, permanent-magnet dc motors create mechanical energy by the interaction between the magnetic field created by current flowing through the armature windings and the magnetic field created by the permanent magnet (typically made from ceramic or rare-earth/cobalt alloys).

The interaction between these two magnetic fields produces a force (called the **torque**) that causes the rotor/armature to rotate. The connections to the armature windings are made through brushes, which commutate or switch the current to the armature winding loops in order to produce a torque that causes the rotor/armature assembly to rotate continuously. Reversing the polarity of the dc power supply to the armature results in a current flow to the armature windings that produces a torque causing the rotor/armature to rotate in the opposite direction.

The use of a permanent magnet instead of field coils reduces the amount of energy consumed by the motor, the heat load created by wound field coils, and the frame size. Permanent-magnet dc motors also have a lower armature **inductance**, which results in a quicker response to changes in the armature current.

Components and variables of a servo motor

For the purposes of analysis, a dc motor can be simplified into the model shown below:

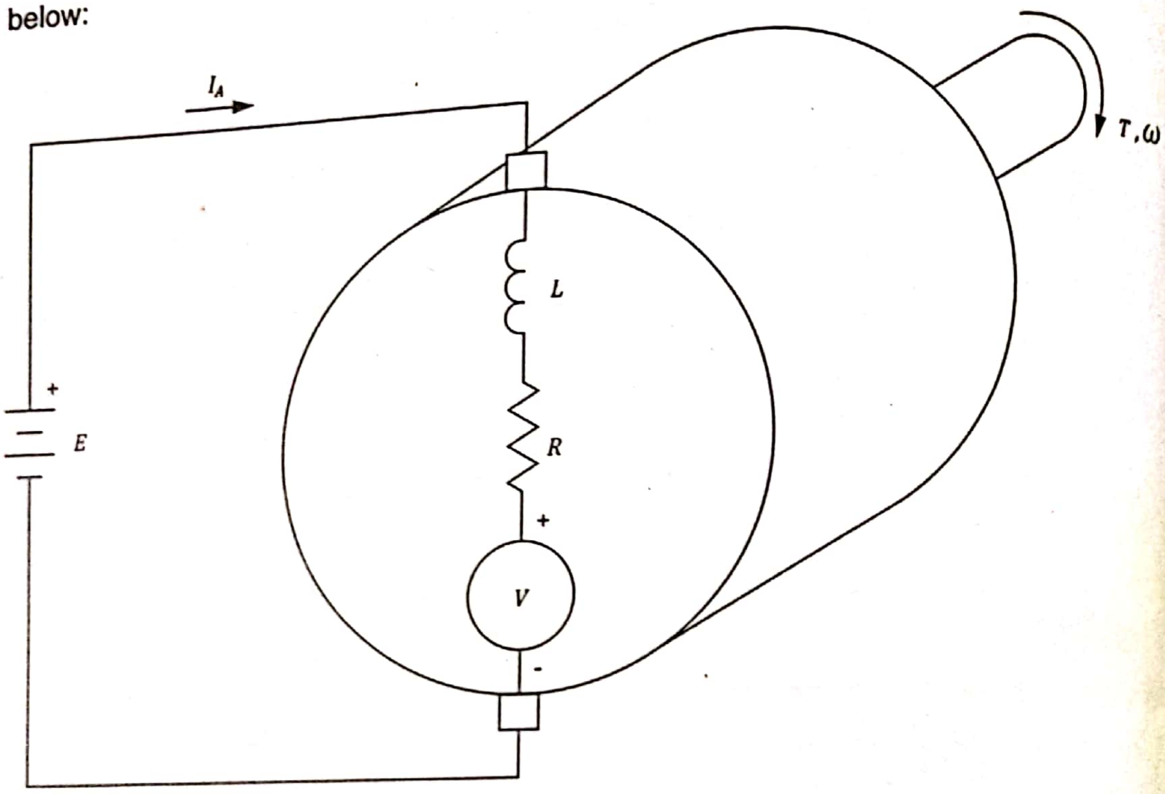

Figure 18. DC motor electromechanical model.

The following variables will be used in this manual to identify the various forces interacting in a dc motor:

- The **supply voltage** E (V)
- The **motor current** I_A (A)
- The armature winding inductance L (mH)
- The armature winding and brush **resistance** R (Ω)
- The counter-**EMF** voltage V (V)
- The motor output torque T (N·m)
- The motor speed ω (rad/s)

The counter or back EMF (Electro Motive Force) V is the voltage induced in the armature due to the relative motion of the armature windings through the magnetic field created by the permanent magnet. This voltage is proportional to the motor speed ω.

The motor input power is the product of the supply voltage E by the armature current I_A.

The motor output power is the product of the torque T and the motor speed ω.

It is important that you have a good understanding of these motor parameters and their relations with each other before going further in this manual.

The following motor parameters are important for the study of a servo motor system and are generally supplied by the motor manufacturer:

- The inductance L (mH)
- The resistance R (Ω)
- The **torque constant** K_T (N·m/A)
- The **voltage constant** K_E [V/(rad/s)]
- The motor **inertia** J_M (kg·m^2)

The following motor parameters are determined experimentally:

- The **starting friction torque** T_f (N·m)
- The **dynamic friction torque** T_d (N·m)
- The **viscous friction coefficient** B [N·m/(rad/s)]

The torque T developed by the motor is the product of the torque constant K_T and the armature current I_A.

The counter EMF voltage V developed by the motor is the product of the voltage constant K_E by the motor speed ω.

The dynamic friction torque T_d is determined by measuring the motor current when no load is applied and multiplying this value by the torque constant K_T at a given motor speed ω.

The viscous friction coefficient B is found by dividing the dynamic friction torque T_d by the motor speed ω.

The starting friction torque T_f is determined by multiplying the minimum current required to cause continuous rotation by the torque constant K_T.

Open loop control vs. closed loop control

In Exercise 2 and Exercise 3, we will concentrate on the Digital Servo operation in **open loop** control, which means that the controller computes its input into the system using only the system current state and its own model of the system without taking into account any exterior feedback. Exercise 4 and Exercise 5 will concentrate on the Digital Servo behavior in **closed loop** control, which means that the controller uses environmental feedbacks to control the states or the outputs of a dynamical system through various means (**integral** and **derivative** action for example). These means are discussed in Exercise 9.

To better understand the distinction between these two control systems, consider a car cruise control system. In an open loop control system, the cruise control controller locks the vehicle speed at the desired gas entry value for a certain speed. This, however, does not take into account any **disturbance** that might affect the vehicle speed, e.g., downhill or uphill terrain, weather, vehicle load, etc.

The vehicle speed will thus fluctuate depending on the driving conditions. In a closed loop control system, on the other hand, the controller takes into account such feedback in computing its output and tries through various means to compensate for it, which greatly reduces the output error, i.e., the difference between the desired speed and the actual speed.

Steady state analysis of a dc servo motor

To do the steady state analysis, we will ignore the motor inductance L and the motor inertia J_M. Using the basic equations for a dc motor operating in a steady state, we can develop the steady state characteristics and find the following equations:

$$E = I_A R + V \tag{1}$$

where E is the supply voltage (V)
I_A is the armature current (A)
R is the armature winding and brush resistance (Ω)
V is the counter-EMF voltage (V)

$$V = K_E \omega \tag{2}$$

where V is the counter-EMF voltage (V)
K_E is the motor voltage constant [V/(rad/s)]
ω is the motor speed (rad/s)

$$T = K_T I_A \tag{3}$$

where T is the motor output torque (N·m)
K_T is the motor torque constant (N·m/A)
I_A is the motor current (A)

$$T = B\omega \tag{4}$$

where T is the motor output torque (N·m)
B is the motor viscous friction coefficient [N·m/(rad/s)]
ω is the motor speed (rad/s)

Using Equation (1), Equation (2), Equation (3), and Equation (4), the motor steady state speed ω_{SS}, usually expressed in rad/s, can be shown to be equal to:

$$\omega_{SS} = \frac{K_T}{RB + K_E K_T} E \tag{5}$$

where ω_{SS} is the motor steady state speed (rad/s)

In Exercise 2 we will only deal with the motor's steady state characteristics. Exercise 3 will deal with the transient behavior of the dc motor, i.e., its behavior before it reaches its steady state.

Calculating the motor steady state speed constant

From Equation (5), we can define the relationship between the motor steady state speed ω and the dc voltage E applied to the motor as the steady state speed constant K_S. The equation for K_S is shown below:

$$K_S = \frac{K_T}{RB + K_E K_T} \tag{6}$$

where K_S is the motor steady state speed constant [(rad/s)/V]

The development of this equation is given in Appendix B.

The motor steady state speed constant K_S determines the steady state speed of the dc servo motor. That is, the motor steady state speed ω_{SS} is equal to the product of K_S and the supply voltage E or:

$$\omega_{SS} = K_S E \tag{7}$$

where ω_{SS} is the motor steady state speed (rad/s)

Example

Table 2 shows various characteristics of a brush-type permanent-magnet dc motor. Using these, it is possible to find the value of the motor steady state speed constant K_S.

Table 2. Brush-type permanent-magnet dc motor characteristics.

Parameter	Unit	Value
Torque constant K_T	N·m/A	0.105
Voltage constant K_E	V/(rad/s)	0.105
Resistance R	Ω	2.03
Viscous friction coefficient B	N·m/(rad/s)	0.0000708

Substituting the values shown in Table 2 into Equation (6), we obtain a K_S value of:

$$K_S = \frac{0.105}{2.03 \times 0.0000708 + 0.105 \times 0.105} = 9.4 \text{ (rad/s)/V}$$

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Viscous friction coefficient
- Steady state speed constant

PROCEDURE

Setup and connections

In this section, you will setup the Digital Servo for measuring the motor steady state speed constant K_S.

Table 3 shows the motor parameters of the Digital Servo.

Table 3. Motor parameters from the manufacturer's data sheet.

Parameter	Unit	Value
Rated speed ω	rpm	3400
Resistance R	Ω	2.23
Torque constant K_T	N·m/A	0.121
Voltage constant K_E	V/(rad/s)	0.121

1. Make the following settings on the Digital Servo system:

   - Setup the servo system for speed control, i.e., disengage the platform.
   - Set the belt tension to allow the belt to be lifted of the pulley connected to the motor shaft and slipped on the two pins to the rear of the pulley, allowing the shaft to run uncoupled from the belt.
   - Secure the flywheel to the shaft using the appropriate hex key.

2. Run LVServo, and click on the **Device Controlled** button in the **Speed Loop** menu. Make sure the settings are initially as shown in Table 4:

Table 4. Settings for measuring the viscous friction coefficient B.

Function Generator		**Trend Recorder**	
Signal Type	*Constant*	Reference	*Unchecked*
Frequency	*0 Hz*	Speed	*Unchecked*
Amplitude	*0%*	Current	*Checked*
Offset	*100%*	Voltage	*Checked*
Power	*Off*	Error	*Unchecked*
PID Controller		K_p x Error	*Unchecked*
Gain (K_p)	*1*	Error Sum / t_i	*Unchecked*
Integral Time (t_i)	*0.05*	t_d x Delta Error	*Unchecked*
Derivative Time on E (t_d (E))	*0*	PID Output	*Unchecked*
Derivative Time on PV (t_d (PV))	*0*	Display Type	*Sweep*
Timebase	*10 ms*	Show and Record Data	*On*
Anti-Reset Windup	*On*	Measured Gain (rpm)	*3000*
Upper Limit	*100%*	Measured Gain (A)	*7*
Lower Limit	*-100%*	Measured Gain (V)	*48*
Open or Closed Loop	*Open*		
PV Speed Scaling			
100% Value	*3000 rpm*		

3. Set the function generator **Power** switch to ON.

4. When the motor attains its steady state (this should take about one second) execute the procedure seen in the previous exercise to capture a few seconds of operation, then stop the recorder and export the data to a spread sheet.

5. Set the function generator **Power** switch to OFF, to turn off the motor.

Viscous friction coefficient

In the next steps, you will determine the viscous friction coefficient B by multiplying the armature current I_A by the torque constant K_T at a supply voltage of 48 V dc, and then dividing the dynamic friction torque T_d by the motor speed ω (rad/s).

6. Using the exported data, determine the armature current I_A (A) by taking the current reading in percentage and multiplying it by the measured current gain value. This value should be of 7 A if the default value has not been changed.

   $I_A =$ _______ A

7. Determine the dynamic friction torque T_d by multiplying the armature current I_A by the torque constant K_T (use the K_T given in Table 3, i.e., 0.121 N·m/A). The resulting equation is:

$$T_d = K_T I_A \tag{8}$$

where T_d is the dynamic friction torque (N·m)

   $T_d =$ _______ N·m

8. Determine the motor speed ω (rad/s) using Equation (9). To find the motor speed in rpm ω_{RPM}, multiply the speed value in percentage by the measured speed gain. This value should be of 3000 rpm if the default value has not been changed:

$$\omega = \omega_{RPM} \times \frac{2\pi}{60} \tag{9}$$

where ω_{RPM} is the motor speed in rpm

   $\omega =$ _______ rad/s

9. Determine the viscous friction coefficient B by dividing the dynamic friction torque T_d by the motor speed ω, as shown in Equation (10):

$$B = \frac{T_d}{\omega} \tag{10}$$

   $B =$ _______ N·m/(rad/s)

Steady state speed constant

In this section, you will calculate the motor steady state speed constant K_S. You will then determine K_S experimentally by plotting a motor speed versus voltage curve from the data obtained by running the servo motor. The resulting plot slope corresponds to the measured steady state speed constant.

10. Calculate the theoretical value of the steady state speed constant K_S using Equation (6). You will need to use your calculated viscous friction coefficient B along with the K_E, K_T, and R values supplied by the motor manufacturer (see Table 2). The theoretical value of K_S is thus:

K_S = ______ (rad/s)/V

11. Run LVServo, and click on the **Device Controlled** button in the **Speed Loop** menu. Make sure the settings are initially as shown in Table 5:

Table 5.Settings for measuring the motor K_S value.

Function Generator		**Trend Recorder**	
Signal Type	*Triangle*	Reference	*Checked*
Frequency	*0.01 Hz*	Speed	*Checked*
Amplitude	*100%*	Current	*Unchecked*
Offset	*0%*	Voltage	*Checked*
Power	*Off*	Error	*Unchecked*
PID Controller		K_p x Error	*Unchecked*
Gain (K_p)	*1*	Error Sum / t_i	*Unchecked*
Integral Time (t_i)	*0.05*	t_d x Delta Error	*Unchecked*
Derivative Time on E (t_d (E))	*0*	PID Output	*Unchecked*
Derivative Time on PV (t_d (PV))	*0*	Display Type	*Sweep*
Timebase	*999 ms*	Show and Record Data	*On*
Anti-Reset Windup	*On*	Measured Gain (rpm)	*3000*
Upper Limit	*100%*	Measured Gain (A)	*7*
Lower Limit	*-100%*	Measured Gain (V)	*48*
Open or Closed Loop	*Open*		
PV Speed Scaling			
100% Value	*3000 rpm*		

12. Set the time base to a very slow time of 999 ms. This will allow the motor to reach its steady state speed during each sample. You will thus acquire a series of motor speeds generated by a very low frequency triangle wave over a range from minimum voltage to maximum voltage.

13. Set the function generator **Power** switch to ON.

14. Capture a complete period (starting with the minimum value) and export it to a spreadsheet.

The speed provided in the exported data is in percentage of 3000 rpm. To convert to rad/s, multiply the speed in rpm (%) by π. Note also that the voltage in the exported data is a percentage of 48 V dc.

15. Use a spread sheet or similar mathematical tool to plot the motor steady state speed ω_{SS} in rad/s versus supply voltage E. Your plot should look similar to the one shown in Figure 19.

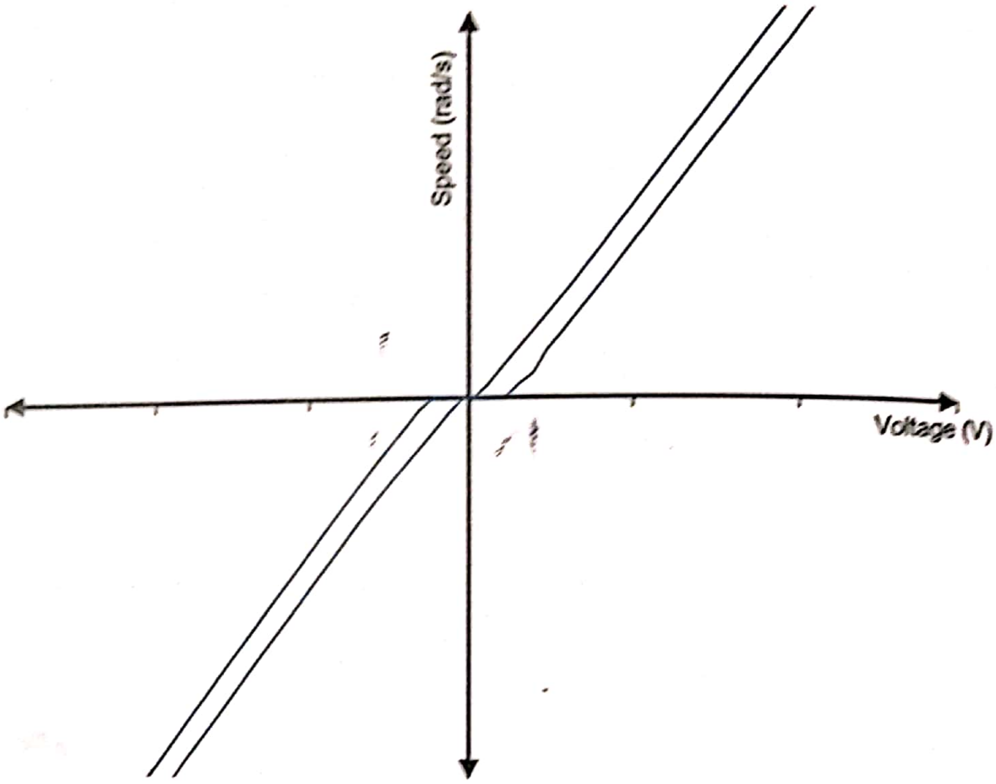

Figure 19. Steady state motor speed ω_{SS} vs supply voltage E example.

The flat portion of the curve is due to the static friction that the motor torque must overcome before the motor begins to rotate. This motor rotation occurs at the voltage that provides the required current and consequently the motor torque necessary to overcome the static friction. If the motor was ideal and static friction 0, the relationship between the steady state speed ω_{SS} and the supply voltage E would simply be: $\omega_{SS} = K_S E$.

16. Using your plot, calculate the slope and develop the equation that relates steady state motor speed ω_{SS} vs dc supply voltage E for the servo motor. Use the slope X intercept form of the straight line equation:

$Y = m(X - X_1)$

Slope m = ______ (rad/s)/V

X_1 intercept = ______ V

ω_{SS} = ______

17. Complete Table 6 below by entering the calculated and measured values of K_S:

Table 6. Calculated and measured motor steady state constant K_S values.

Parameter	Calculated	Measured
K_S [(rad/s)/V]		

CONCLUSION

In this exercise, you were introduced to the various components that make up a brush-type permanent-magnet servo motor. You analyzed the steady state characteristics of the servo motor system operating under open loop control. From experimental measurements, you were able to determine the steady state speed constant K_S of a servo motor and compare it with the value calculated using the manufacturer's data.

REVIEW QUESTIONS

1. How is the steady state speed ω_{SS} affected by a decrease in dc supply voltage E?

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2. If the motor is loaded in such a way that the viscous friction coefficient B increases, how is the steady state speed ω_{SS} affected?

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3. In the steady state speed vs. supply voltage plot (Figure 19), explain why there is a "flat" or horizontal region in the middle of the curve.

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4. Explain the difference between open loop and closed loop control systems.

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