

Experiment 3: Model Identification and Transient Response of a DC Servo Motor System

1 OBJECTIVES:

- To model and identify some of the parameters of a DC servo motor system.
- To illustrate the basic idea of closed-loop feedback control.
- To illustrate the transient response of a second order system to a step input and find the relationship between the parameters of the transient response and the parameters of the closed-loop DC motor system.

2 BASIC KNOWLEDGE

In this experiment we introduce mathematical models for a DC servomechanism and basic identification methods.

A block diagram for a typical servomechanism is shown in Fig. 1. The action of the servomechanism is to track a desired position (or speed) despite the presence of disturbance inputs to the process and despite errors in the sensor data.

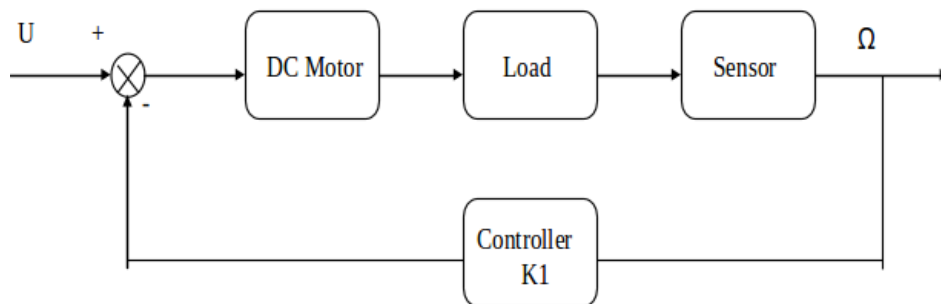


Figure 1: Servomechanism block diagram

2.1 Model Development

We begin by developing a simplified linear model of an armature controlled DC servo motor and load. Fig. 2 shows the schematic diagram of the motor

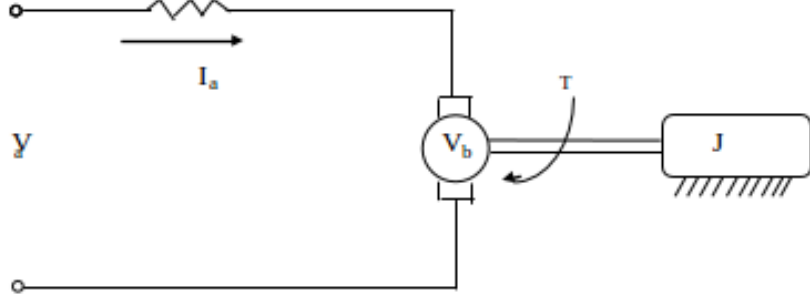


Figure 2: schematic diagram of the DC servo motor

and load.

Neglecting the inductance of the armature circuit, the armature voltage V_a produces a current I_a as given by:

$$I_a = \frac{V_a - V_b}{R_a} \quad (1)$$

Here V_b denotes the back emf of the motor and R_a is the armature resistance.

The motor torque T is proportional to I_a :

$$T = K_T I_a \quad (2)$$

But from Newton's law, assuming an inertia load:

$$T = J\ddot{\theta} \quad (3)$$

combining equations 1, 2, and 3 we obtain:

$$K_T \left[\frac{V_a - V_b}{R_a} \right] = J\ddot{\theta} \quad (4)$$

Using the relationship $V_b = K_b \dot{\theta}$ and, letting $V_a = U$ (input signal), we have:

$$\frac{K_T}{R_a} [U - K_b \dot{\theta}] = J\ddot{\theta} \quad (5)$$

$$\frac{JR_a}{K_T} \ddot{\theta} + K_b \dot{\theta} = U \quad (6)$$

$$\ddot{\theta} + \frac{K_b K_T}{JR_a} \dot{\theta} = \frac{K_T}{JR_a} U \quad (7)$$

or letting $\omega = \dot{\theta}$, and

$$\dot{\omega} + \frac{K_b K_T}{J R_a} \omega = \frac{K_T}{J R_a} U \quad (8)$$

Equations 7 and 8 are the differential equations for the DC motor.

Let $\frac{K_b K_T}{J R_a} = \frac{1}{\tau}$, $\frac{K_T}{J R_a} = \frac{K_{0s}}{\tau}$. Here, K_{0s} is the static gain and τ is the time constant of the system from input voltage to output speed. From D.E. 7 we can have the following transfer function:

$$\frac{\theta(s)}{U(s)} = \frac{K_{0s}}{s(\tau s + 1)} \quad (9)$$

And from D.E. 8 we obtain the transfer function of the DC motor from U to $\dot{\theta} = \omega$:

$$\frac{\omega(s)}{U(s)} = \frac{K_{0s}}{(\tau s + 1)} \quad (10)$$

Considering the measurements of speed and position, the system can be depicted as in Fig. 3

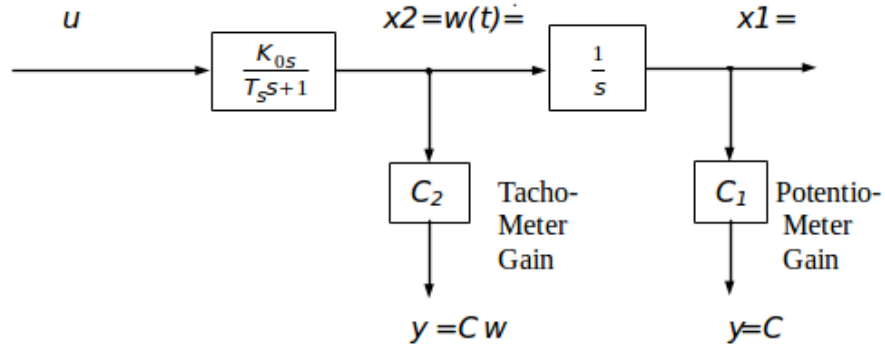


Figure 3: schematic of the DC motor system with measurements

Then, the second order D.E. of the DC motor can be rewritten in the state-space format:

$$\dot{x} = A x + B u \quad y = C x$$

$$\text{where, } x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \quad u = u, \quad y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}, \quad \text{and } A = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{1}{\tau} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ \frac{K_s}{\tau} \end{bmatrix},$$

$$C = \begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix}$$

Further, the input/output transfer function of the DC motor is:

$$G(s) = \frac{Y(s)}{U(s)} = \begin{bmatrix} G_1(s) \\ G_2(s) \end{bmatrix} = \begin{bmatrix} \frac{C_1 K_{0x}}{s(\tau s + 1)} \\ \frac{C_2 K_{0s}}{\tau s + 1} \end{bmatrix} = \begin{bmatrix} \left(\frac{C_1}{C_2}\right) * C_2 K_{0s} \\ \frac{s(\tau s + 1)}{\frac{C_2 K_{0s}}{\tau s + 1}} \end{bmatrix} \quad (11)$$

Define: $C_s = C_1/C_2$ and $K_s = C_2 K_{0s}$, then

$$G(s) = \frac{Y(s)}{U(s)} = \begin{bmatrix} G_1(s) \\ G_2(s) \end{bmatrix} = \begin{bmatrix} \frac{C_s K_s}{s(\tau s + 1)} \\ \frac{K_s}{\tau s + 1} \end{bmatrix} \quad (12)$$

The model has one pole at the origin and one pole on the negative real axis. The problem is to identify parameters K_s, τ and C_s . From 12, the transfer function from input u to output y_2 is:

$$\frac{Y_2(s)}{U(s)} = \frac{K_s}{\tau s + 1} \quad (13)$$

The step response of the first order system is shown in Fig. 4:

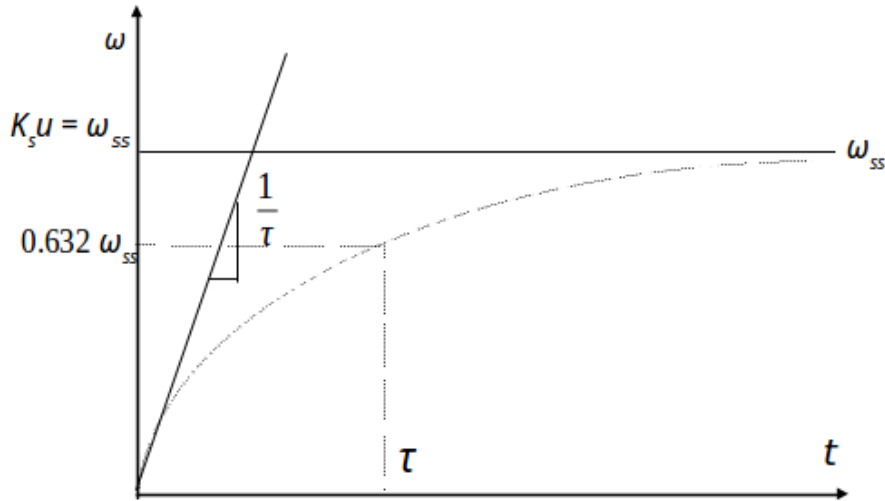


Figure 4: step response of the DC servo motor

From this diagram, we can determine that the time constant of the motor, τ , is the time it takes y_2 to reach 63.2% of its steady state value y_{2ss} . We can also obtain the steady-state gain $K_s = \frac{y_{2ss}}{U_{ss}}$.

In addition, notice that regarding C_s there is a conformity that has to be satisfied:

$$C_s = \frac{\frac{dy_1}{dt}}{y_2} \quad (14)$$

This gives the way to identify C_s .

2.2 Closed Loop Control for a DC servomechanism

The block diagram of Fig. 1 for the servomechanism can be simplified into the block diagram given in Fig. 5.

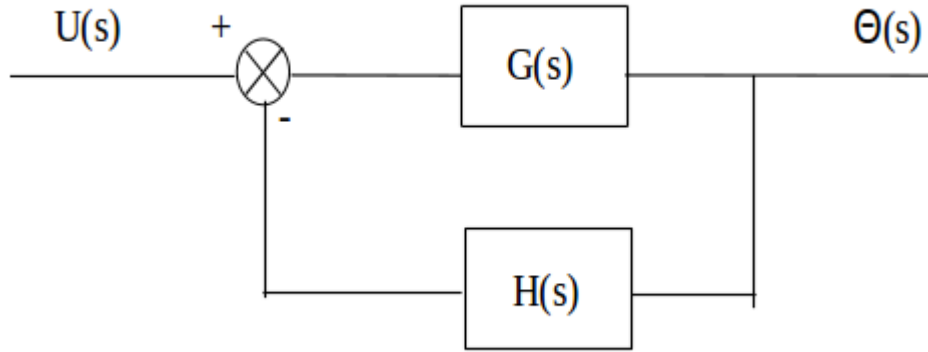


Figure 5: simplified block diagram

This configuration is referred to as a negative feedback closed loop configuration where $G(s)$ is the forward loop transfer function and $H(s)$ is the feedback loop transfer function. The equivalent transfer function between the input $r(t)$ and the output $y(t)$ as shown in Fig. 4 can be represented as the transfer function $G'(s)$ shown in Fig. 6.

$$G'(s) = \frac{Y(s)}{U(s)} = \frac{G(s)}{1 + G(s)H(s)} \quad (15)$$

Considering the servomechanism transfer function:

From Eq. 9: $G(s) = \frac{C_s K_s}{s(\tau s + 1)}$,

$H(s) = K_1$ (Output feedback controller gain),

$$G'(s) = \frac{\frac{C_s K_s}{s(\tau s + 1)}}{1 + \frac{C_s K_s}{s(\tau s + 1)} K_1} \quad (16)$$

We observe that the transfer function of the closed-loop system, $G'(s)$ is a second order system with one free controller parameter K_1 . Changing the gain K_1 can be used to alter the transient dynamics of the second order system.

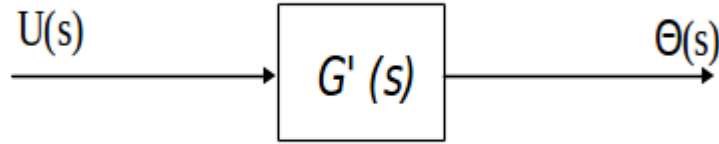


Figure 6: equivalent closed-loop transfer function

3 EXPERIMENTAL PROCEDURES:

3.1 Model Identification:

1. Run **MATLAB** and open the model **Lab3_identification.slx**. The *DC servo* block contains a masked model of a DC servo motor. Run the model. A unit step input is applied to the motor winding at $t = 1$ s. Open the scope and look at the angular velocity trace. Determine the steady-state speed of the motor. This is the value of K_s , the steady-state gain. Determine the time at which the speed reaches 63.2% of its final value. Find the elapsed time since the step function was applied. This value is the time constant τ .
2. Open the model **Lab3_Comparison.slx**. Update the servo transfer function block to match the parameters you determined above. Compare the behavior of your model transfer function to that of the DC Servo block. See if you can more closely match the DC Servo block by making small changes in your transfer function parameters.

3.2 Transient Response:

In this part the closed loop servomechanism system for position control is being implemented as explained in section 2.2. The main goal is to change the controller gain K_1 , observe the characteristics of the transient response and relate these to the parameters of the closed-loop system and the parameters which define the transient response. The following objectives should be met:

1. Understanding the relationship between the system parameters: damping ratio (ζ) and natural frequency (ω_n), the transient response parameters: %overshoot (M_p), settling time ($T_{settling}$), peak time (T_p), rise time (T_r), and the closed-loop poles, with the gain K_1 .

2. Understanding the qualitative effect of the controller gain K_1 on the transient response of the servomechanism.
3. Obtaining a basic understanding of computer control for the DC-servo system.

Procedure:

1. Open the model **Lab3_Transient.slx** and run it. Save the theta trajectories associated with each of the different values of K_1 . You will need this data for an exercise.

3.3 System Type and Tracking Error

In this portion of the procedure, we explore the effect of system type on our ability to track reference signals of various types. The Simulink model used in this portion includes five different cases. First, we have position feedback used to track a step, ramp, and parabolic reference. The remaining two cases use speed feedback with step and ramp references.

Procedure:

1. Open the model **Lab_SystemType.slx** and run it. For each case, observe the following: Does the system state track the reference? If not, characterize the error (is the error constant, increasingly linearly, increasing quadratically, etc.). How does the system's ability to track the same signal differ depending on whether speed or position is being tracked?
2. If a reference signal is not being tracked, adjust the gain for that case. What happens to the error? Is it possible to eliminate the error?

4 EXERCISES:

1. Fill in the following table for each case.

Gain	Poles	%overshoot	ζ	ω_n	$T_{settling}$	T_{peak}	T_r

2. Using the table from exercise 1, plot the following:
 - (a) Poles in the s plane for all values of gain constant K_1 .
 - (b) The damping ratio vs. K_1 .
 - (c) % overshoot vs. ζ .

- (d) settling time, $T_{settling}$ vs. ζ .
- 3. Using the graphs from exercise 2, try to explain (qualitatively) the effect of changing K_1 on:
 - (a) Poles of the closed-loop system
 - (b) Overshoot of the closed-loop system
 - (c) Settling time of the closed-loop system
- 4. Explain the tracking errors observed in the System Type and Tracking Error in terms of the Final Value Theorem.