AC 2011-352: INTEGRATING SERVOMOTOR CONCEPTS INTO MECHATRONICS ENGINEERING TECHNOLOGY CURRICULUM EMPHASIZING HIGH SPEED PACKAGING MACHINERY

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Integrating Servomotor Concepts into Mechatronics Engineering Technology Curriculum Emphasizing High Speed Packaging Machinery

Abstract

Most of the driving forces in high speed packaging are obtained from three-phase induction motors and servomotors. In order to introduce them adequately to undergraduate students having the Mechatronics major, one needs to start with the relationship between electrical and mechanical aspects of either type of motor. This relationship is also important for the understanding of kinematics of high speed packaging machinery systems and their design, operation and maintenance. Concepts are conveyed through force-current and force-voltage analogies between mechanical and electrical systems and simulation of mechanical systems by using differential equations and electrical networks. These concepts are being introduced by a sequence of four courses in the Mechatronics Engineering Technology program. Mathematical modeling of a servomotor control system using Laplace transformation and software tools are essential for communicating the concepts. Sizing a three-phase induction motor - amplifier combination for a desired motion trajectory of a load and also sizing a servomotor - amplifier combination for a desired motion trajectory are an integral part of programmable logic controller (PLC) course. Mechatronics Engineering Technology is a new program in the department of Engineering Technology. The curriculum emphasizes high-speed packaging that involves motion control mainly with servomotors and induction motors. The students in this program, in addition to many other courses, take courses in basic mechanics and mechanical design, electric circuits, basic mathematics and calculus before taking four courses of the sequence of courses.

Concepts of mechanical cams (Ref: “cam definition” Merriam Webster) operation and performing an electronic cam using a servomotor control system for a given task are introduced. Writing ladder logic to perform a given cam operation for an application is also an integral part of the PLC course. A semester long project based on real life applications is assigned in each of these courses to satisfy the experiential learning component of the curriculum. Studying the performance of a given servomotor under a various load condition using models and software tools such as Simulink and LabVIEW are introduced in the PLC course.

I. Integration of Servomotor Concepts into the Curriculum

The Mechatronics Engineering Technology uses a combination of Mechanical and Electrical Technology courses. However, servo concepts, used extensively in Mechatronics systems, are not introduced in either program. To overcome this deficiency, this paper explains how the necessary concepts, missing from the traditional electrical and mechanical curriculums, are integrated into the Mechatronics program by enhancing a sequence of four courses. The student learning outcomes related to the Mechatronics concepts that have been added to the existing courses are as follows:

Students will be able to:

1. Model and analyze performance of mechanical components
2. Model and perform response analysis of mechanical systems using software tools
3. Perform Simulink analysis of the servomotor transfer function
4. Size an induction motor for a given load and motion trajectory
5. Size a servomotor for a given conveyor belt application
6. Perform time-response analysis of a Mechatronics setup by varying motor, load, gearbox parameters.
7. Model and analyze performance of a control system

In order to achieve the above student learning outcome a sequence of four courses are enhanced and material pertaining to Mechatronics, especially related to high speed packaging machinery motion control, are introduced in these courses. Also, in addition to classroom discussion, each of these courses in the sequence have at least three to four laboratory experimentation having progressive level of difficulties to fulfill the learning outcomes mentioned here. Experiment on mass-damper-spring mentioned in this paper is used in the beginning course in the sequence and servomotor modeling and response analysis experimentations, major subject matter of the paper, are used for programmable logic controller course and other higher level courses. Modeling and simulation approach to such Mechatronics laboratory activity provides a great educational value through which students can acquire a lot of understanding by changing variables and observing the response in a short period of time. In some cases it may be almost impossible to achieve such objectives in an educational laboratory environment.

Students use both Simulink and LabVIEW for these experiments. Both of these software tools are introduced quite early in the Mechatronics program. Experiments are designed for the students to learn LabVIEW and Simulink. Interested reviewers and other may contact main author regarding information about Mechatronics courses and the program.

A semester long class project is assigned in all courses in the sequence and the subject matters are especially chosen based on the courses objectives and learning outcomes.

The six general concepts added in the aforementioned courses are summarized in the following sections of this paper.

II. Introductory Concepts

In order to convey the understanding of kinematics of three phase induction motors and servomotors, the main driving force for high speed packaging machine, analogous between electrical variables and mechanical variables need to be established first. The two most common variables in electrical side are current, $\boldsymbol{i}$ and voltage, $\boldsymbol{v}$. Similarly, in the mechanical side they are force, $\boldsymbol{f}$ and velocity, $\boldsymbol{u}$.

The following table provides above electrical variable and their corresponding mechanical analogous representation:

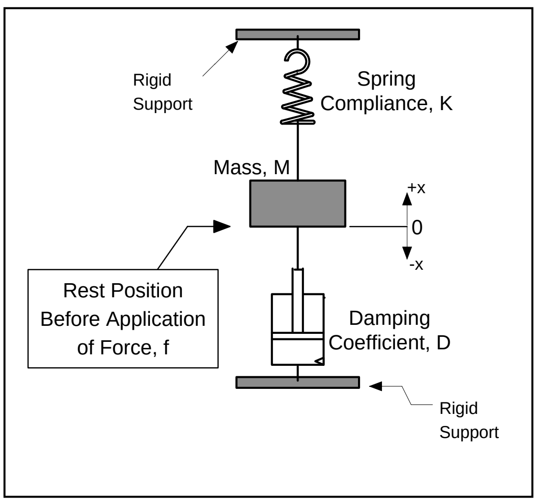
Electrical Variable	Mechanical Variable
Voltage = v	Force = f
Current = i	Velocity = u
Resistance = R	Damping Coefficient = D

Inductance = L	Mass = M
Capacitance = C	Spring Compliance = K
Charge = q	Displacement = x

Linear Motion Variables

For the purpose of modeling mechanical systems with electrical circuits it is also necessary to define the relationship among variables within each group. According to Newton's Laws of motion, when a force is applied on a mass, $\boldsymbol{M}$ it accelerates and a displacement, $\boldsymbol{x}$ takes place to the mass.

As derived in class, for a linear system, when the spring, mass, and damper are supported from two fixed supports (Figure 1), by applying D'Alembert's principle differential equation (1a) can be written:



$$f = f_M + f_D + f_K = M\frac{d^2x}{dt^2} + D\frac{dx}{dt} + Kx \quad (1a)$$

$$\frac{X(s)}{F(s)} = \frac{1}{Ms^2 + Ds + K} \quad (1b)$$

Figure 1: Virtual Mass-Spring-Damper Setup

After taking Laplace transformation of equation (1a) that result (1b), the mechanical system could be expressed in the form of a function block in Laplace's domain as follows:

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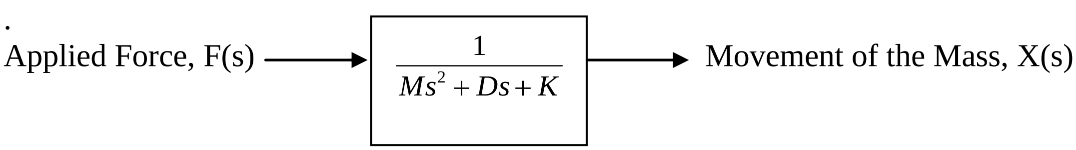


Students use this transfer function (TF) in a laboratory experiment and perform time-response analysis for various values of each item in the TF. This experiment provides the students good understanding about already known physical behavior of the components in Figure 1. After performing this experiment, students acquire a more in-depth understanding of the time-response characteristics and the mathematical analog of the system components.

Rotational Motion Variables

In rotational systems, relationships among the following variables are to be considered carefully. Rotational variables are angular measure, θ; angular speed, ω; linear speed, u; moment of inertia, J; angular acceleration, α; torque, T; and angular momentum, L. Most of the basic relationships among variables can be found in a basic mechanics or a physics book. A few of the important relationship among these variables are provided below:

$$\omega = \frac{\theta}{t} = \frac{ut}{rt} = \frac{u}{r} \quad (2)$$

$$AngularSpeed = \frac{LinearSpeed}{Radius} \quad (3)$$

Kinetic Energy of a rotational mass having angular speed, ω, is as follows:

$$KE_{rotational} = \frac{1}{2} m\omega^2 r^2 \quad (4)$$

The term $J = \sum mr^2$ is called the moment of inertia of the body. It is the rotational analog of mass. It has the same value regardless of the state of motion, because it is not a function of speed. KE of a rotational body can also be written as follows:

$$KE_{RotationaBody} = \frac{1}{2} J\omega^2 \quad (5)$$

Angular Acceleration

Relationship between tangential acceleration and angular acceleration can be expressed as follows: $\alpha = \frac{a_T}{r}$ This means

$$AngularAcceleration = \frac{TangentialAcceleration}{PathRadius} \quad (6)$$

Where $\boldsymbol{a_T}$ is the tangential acceleration and $\boldsymbol{r}$ is the path radius

Torque and Angular Acceleration

Torque is the rotational analog of force. Thus, Torque, T = (Force) (Moment Arm) = (F) (L) and the unit is Newton-Meter, Nm. Torque = (Moment of Inertia) (Angular Acceleration).
Thus, $T = J\alpha$ (7)

Work and Power of a Rotational System

If tangential force, F, applied on a shaft having radius, **r**, has turned an angle,θ, after a time , **t,** work done, $W = T\theta$. Thus rotational power or the power required by a rotational system is:
$Power_{Rotational}$ = (Torque) (Angular Speed) = $T\omega$ (8)

Angular Momentum

The magnitude of angular momentum of a body depends on its moment of inertia, ***J***, and its angular speed, ***ω***, in the same way as the linear momentum depends on its mass, ***m***, and linear speed, ***u***. Thus Angular Momentum, L = (Moment of Inertia) (Angular speed) = (J) (ω)   (9)

III. Motor Sizing for a Motion Trajectory

Before starting with the motor sizing task, students required to review fundamentals discussed in earlier section.

To qualify for a given system, the motor must successfully pass the following three tests:
a) Can the drive motor generate the peak torque?
b) Can the drive motor run at the maximum velocity?
c) Can the drive motor generate desired torque without overheating?

(a) In order to drive a load along the required motion trajectory, the motor must generate certain amount of torque, T_g. Torque depends on the moment of inertia, the total friction of the load, and required amount of acceleration for the trajectory. This torque is given by the following relationship:

$$T_g = J\alpha + T_f \qquad (10)$$

Where: J = Moment of inertia; T_f = Combined value of all frictions; α = angular acceleration. Total friction, if not given need to be calculated or estimated in Nm.

(b) In order to accomplish the required move within a specified amount of time, the motor must be able to run at the maximum velocity. The peak angular velocity of the motor can be calculated by the following equation:

$$\omega_0 = \frac{\theta}{t} = \frac{Distance(2\pi)}{\frac{1}{2}t_{accel} + t_{slew} + \frac{1}{2}t_{decel}} \qquad (11)$$

In the above equation $\frac{1}{2}t_{accel}$ and $\frac{1}{2}t_{decel}$ is the average velocity during acceleration and deceleration. Since the velocity must be reached within the specified acceleration time, the acceleration rate can be given by the following equation:

Also, Angular Acceleration,

$$\alpha = \frac{\omega_0}{t_{accel}} \qquad (12)$$

Another important equation useful for this purpose is the rate of change of speed, Δn.

$$\Delta n = \frac{30}{\pi}\frac{T_g \Delta t}{J} \quad (13)$$

Where: Δn = Change in speed in rev/min (rpm)

T_g = Torque (N.m)

Δt = Interval of time during which the torque is applied (second)

J = Moment of inertia ($Kg.m^2$)

$30/\pi \approx 9.55$, constant for the consideration of the unit

(c) Finally, the following equation can be used to calculate the required power of the motor.

$$Power, P = \frac{nT_g}{30/\pi} = \frac{nT_g}{9.55} \quad (14)$$

The overheat part of the 3rd item (c) is little bit more involved. Temperature rise of the motor is proportional to the root-mean-square value of the torque. Thus it is necessary to compute the root-mean-square value of the torque by using the following equation and compare with the rated continuous torque:

$$T_{g(rms)} = \left[\frac{1}{T}\int_0^T T_g^{\,2}\,dt\right] \quad (15)$$

Using the above theoretical concepts, students perform three experiments on induction motor and servomotor sizing. Then, in addition, they use commercial grade motor sizing software tools to verify the results. This provides a good understanding of commercial motor sizing software tools and inspires for a fruitful classroom discussion of the subject matter.

Effect of a Gear Box on Load Moment of Inertia

In many instances a gear box sits between a load and a motor. Thus studying the dynamics on both side of gear box is important for the understanding of kinematics. Gear box in a mechanical system is equivalent to a two-winding transformer in an electrical system. Thus,

$$\frac{\text{TorqueontheLoadSide}}{\text{TorqueontheMotorside}} = \frac{T_L}{T_M} = \frac{n_M}{n_L} \quad (16)$$

$$\text{GearBoxRat io} = \frac{n_M}{n_L} = \frac{\omega_M}{\omega_L} = \frac{\theta_M}{\theta_L} \quad (17)$$

Reflected inertia, $J_{\text{Reflected Motor Side}}$, which is the load and gear box inertia seen by the motor shaft, can be written as:

$$J_{ReflectedMotorSide} = \frac{J_{Load}}{\left(\frac{n_{Motor}}{n_{Load}}\right)^2} = \frac{J_{Load}}{\left(\frac{\omega_{Motor}}{\omega_{Load}}\right)^2} = \frac{J_{Load}}{(GearRatio)^2} = J_{Load}\left(\frac{n_L}{n_M}\right)^2 = J_{Load}\left(\frac{\omega_L}{\omega_M}\right)^2 \quad (18)$$

Also,

$$GearRatio = \sqrt{\left[\frac{J_L}{J_M}\right]} \quad (19)$$

The angular acceleration of the motor and that of the load at any instant of time can be written as follows:

$$\alpha = \frac{T_{Motor} - T_{Load}}{J} \frac{radian}{second^2} \quad (20)$$

Where:

T_{Motor} = Torque developed by the motor
T_{Load} = Torque dissipated by the load
J = Total moment of inertia of the motor rotor and that of the load.

In the above equation (20), if angular acceleration, ***α***, is required at the load side then the moment of inertia, ***J***, would be the total moment of inertia at the load side. On the other hand, if angular acceleration, ***α*,** of the motor shaft is desired then the moment of inertia, *J* in equation (20), would have to be the total moment of inertia seen by the motor shaft. After these discussions in class students begin to understand how a gearbox is analogous to a transformer in an electrical system.

IV. Servomotors and Motion Controls in Industry

Most of driving force having position control in a packaging machinery system comes from servomotors. Servomotor is a motor with built-in encoder made in to one unit. It is connected to a power amplifier called a drive and is controlled by a motion controller. A servomotor and its drive are almost like matched pair units. As if they are made for each. Given the complexity of the command structure for a modern servomotor-drive-controller system, it is quite difficult if not impossible to control a servomotor made by a manufacturer A by using a drive and controller made by a manufacturer B.

In most packaging machinery, system dynamics revolves around servomotor, load, and gearbox. In order to communicate the kinematic aspects of a servomotor driving packaging machinery system, a model of a dc servomotor with load and gearbox is presented in the paper. The diagram in Figure 2 is of a dc motor with a load, a gear box, an encoder, and an amplifier.

V. Transfer Functions of a DC Servomotor

To avoid confusion, variables for the servomotor model are redefined and are given as follows:

V_a = Applied Voltage to the Armature
K_t = Torque Constant
φ = Field Flux
K_g = Gear ratio
θ_m =Angular position of the motor shaft
L_a = Armature inductance
J_L = Load inertia
b_t = Rotational viscous friction damping
i_a = Armature Current
K_b = Motor Constant (volt-sec/radian)
V_b = Back emf induced in the armature
ω_m = Angular speed of the motor armature
θ_l = Angular position of the load shaft
R_a = Armature resistance
J_M = Motor inertia

After step by step derivation in class of a DC servomotor transfer function, students in programmable logic controllers' course perform two experiments using the model equations (21) and (22) and perform time-response analysis of a servomotor by varying model parameters.

Angular position, $\theta_l(s)$ and and angular speed, $\omega_m(s)$ are outputs and $V_a(s)$ is the command input to the function block that represent the servomotor, load, and the gearbox.

$$\frac{\theta_l(s)}{V_a(s)} = \frac{K_g K_t}{s[L_a J_{eq} s^2 (L_a b_t + R_a J_{eq}) s + R_a b_t + K_g^2 K_t K_b]} \tag{21}$$

$$\frac{\omega_m(s)}{V_a(s)} = \frac{K_g^2 K_t}{L_a J_{eq} s^2 + (L_a b_t + R_a J_{eq}) s + R_a b_t + K_g^2 K_t K_b} \tag{22}$$

After performing through the modeling and simulation process, students in PLC course then perform experiments with actual servomotor (Allen-Bradley MPL-A430P Series) using various cam profiles (operations). Although, limited number of variables can be altered in the laboratory setup, it provides students with information about software tools and physical experience of the cam profiles and their implications.

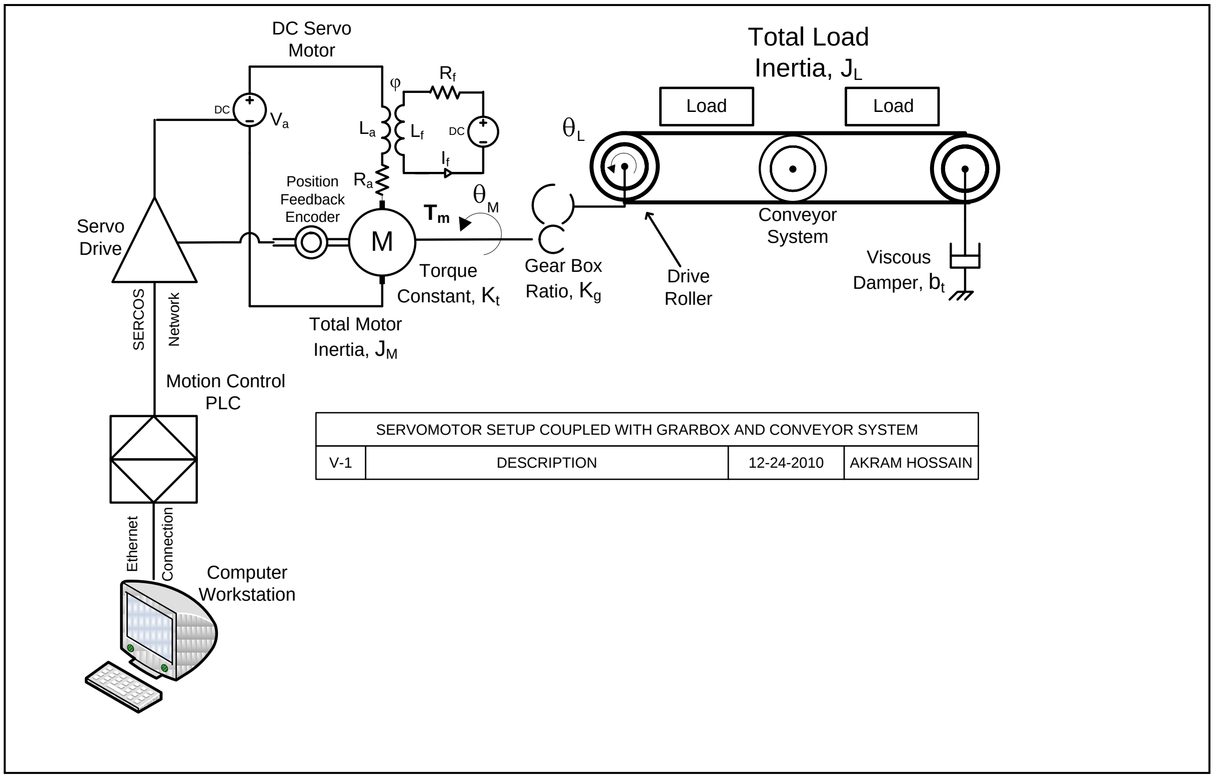


Figure 2: Servomotor Setup Coupled with Gearbox and Conveyor System in Mechatronics Laboratory

VI. Discussion and Result

The following discussion is presented here to illustrate students' activities in the laboratory and expected time-response characteristics upon transition from the model to actual servomotor. In order to test the model (equation 21 and 22) shown in Figure 2, specification of a dc servomotor was taken from a manufacturer data sheet and applied into the model equations. Using MATLAB & Simulink software tools the model was analyzed by varying inertia ratio, load and gear parameters. However, the results presented in this section of the paper are for various values of inertia ratio for a step position command and two different cam profile.

Matching inertia between servomotor and load is an important subject matter for the understanding of kinematics of servomotor positioning. Inertia mismatch between drive motor and the load can cause system instability, longer time to position the servomotor and inaccurate cam by the motor. Although, 1:1 match between load-to-motor inertia ratio can be an ideal situations, but it is costly and thus rarely used. Most cases it should not go beyond 10:1. However, going beyond 10:1 is also possible for a system knowing stiffness and linearity of the system. Because the real cause of oscillation of the load is the stiffness of the interface between motor and the load. Thus most important factor of controlling the position of a servomotor coupled with a load is the stiffness of the coupling itself. For purpose of this experimentation inertia ratio was varied from 100 to 1 and the effect are graphically presented in this section.

Figure 3 is a screenshot of the servomotor model in Simulink with step input position command. Figure 4a through Figure 4f below presents experimental results for 100:1, 50:1, 25:1, 10:1 and 1:1 load-to-motor inertia ratios. The result presented below is for a step input position command to the motor. Figure 4a through Figure 4f shows time response characteristics of the servomotor model.

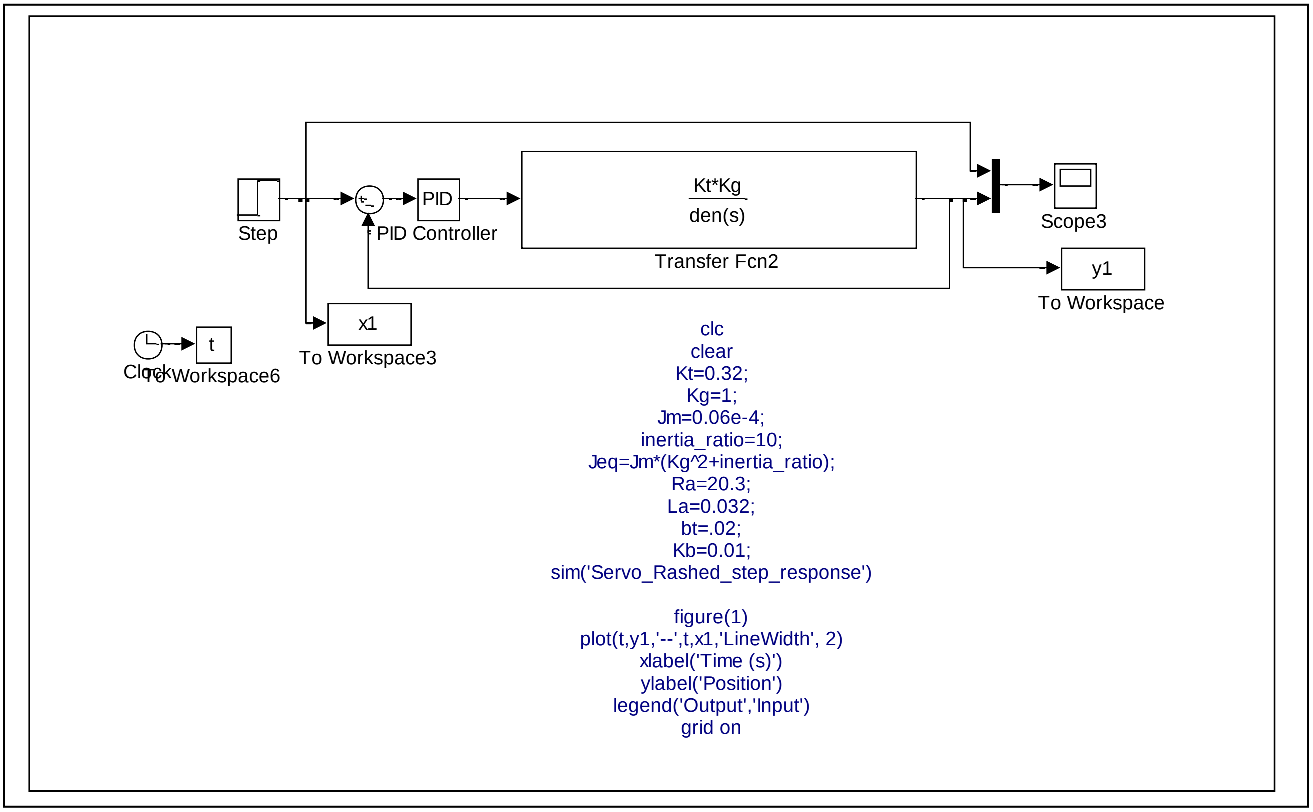


Figure 3: Screenshot of Servomotor Model in Simulink with Step Input Position Command

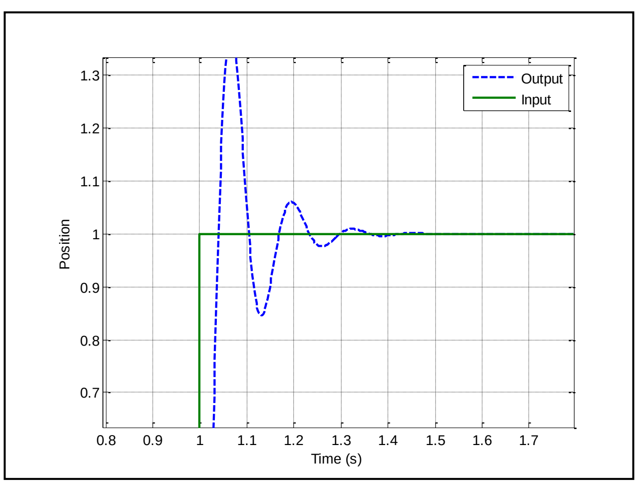


Figure 4a: Inertia ratio of 100:1and Step input

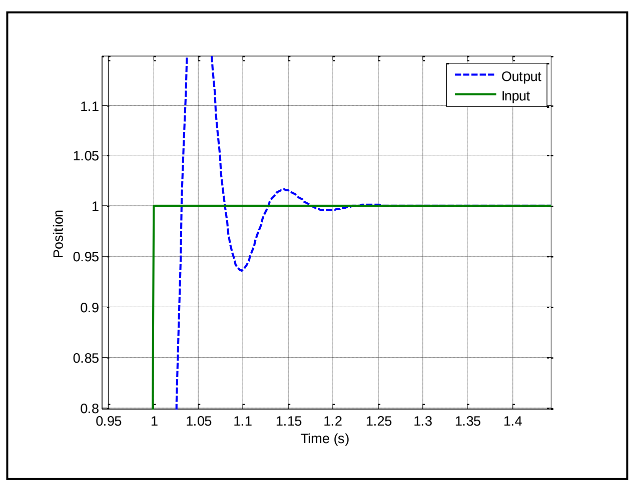
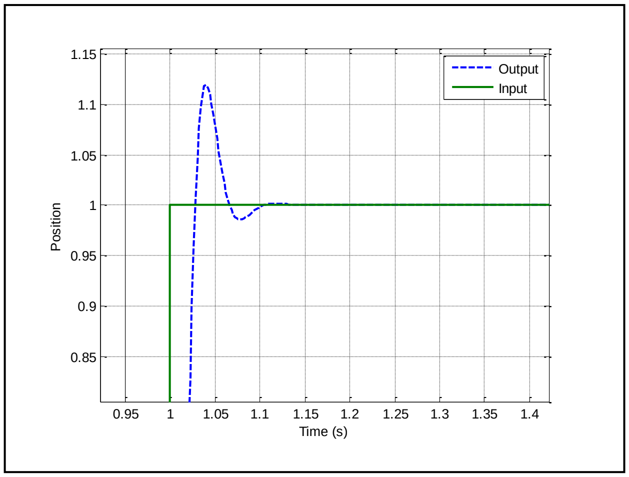


Figure 4b: Inertia ratio of 50:1 and Step input



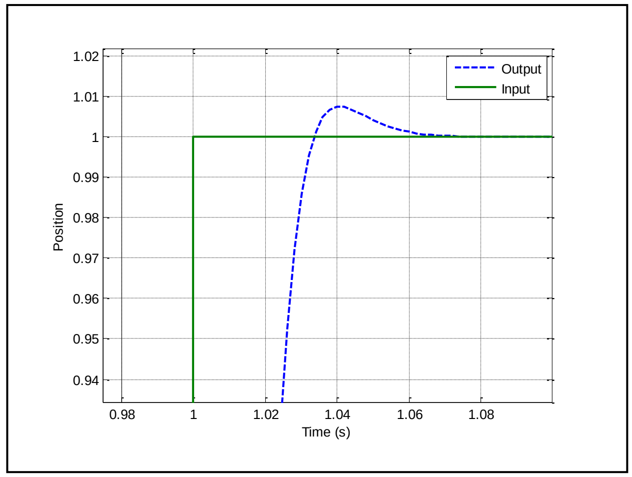
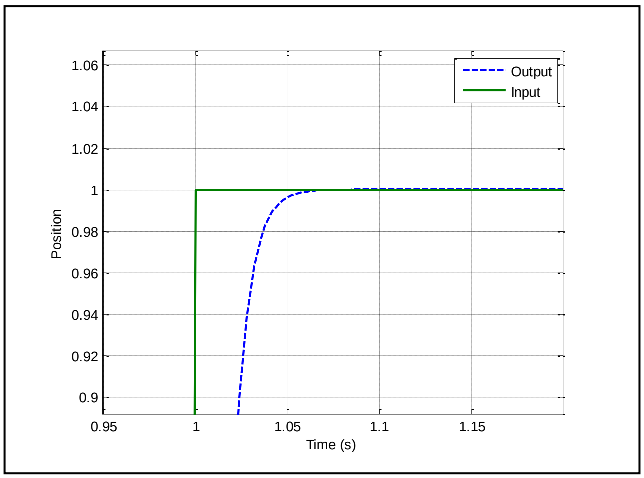


Figure 4c: Inertia Ratio 25:1 and Step input

Figure 4d: Inertia ratio of 10:1and Step input



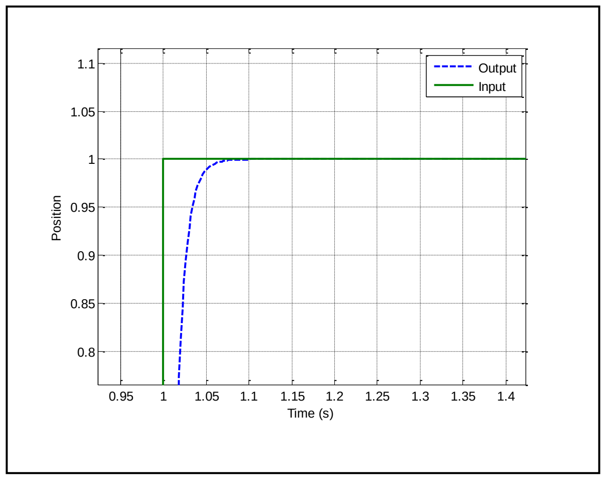


Figure 4e: Inertia ratio of 5:1 and Step input

Figure 4f: Inertia ratio of 1:1 and Step input

Load-to-motor inertia ratio of 100:1 took about 1.50 seconds to position the motor to its commanded position. Inertia ratio of 50:1 took about 1.25 seconds; inertia ratio of 25:1took about 1.15 seconds, 10:1 took about 1.07 seconds, 5:1 took about 1.06 seconds; and 1:1 took about 1.10 seconds. The inertia analysis also shows that up to 10:1 there are expected 2nd order oscillation (overshoot and under shoot) and on the other hand inertia ratio below 10:1 there are no overshoots and undershoots. Students will then understand that since this is a 1st order response (versus a second order response), it becomes a slower response.

Similar analysis was performed with various values of inertia ratio except this time it was done for given cam profile (operation). Figure 5 is a screenshot in Simulink of the servomotor model having input of three different cam profiles. Figure 6 through 8 below presents experimental results. **1st cam** is to position the load at 72º from home position then wait at the position for 0.1 second then move to a new position at 216º from home almost in no time. **2nd cam** is to position the load at 288º in 2 seconds, stay there for 6 seconds then return to home position in 2 seconds.

3rd cam is to position the load to 216º from position in 4 seconds then move to 360º in almost no time. Stay at this position for 2 seconds then to 144º in almost no time then go to home position in 4 seconds. Figure 6a and 6b shows time-response characteristics of 1st cam. Figure 6a is the time-response characteristics of the first transition and Figure 6b is the second transition. Inertia ratio of 10:1 was used for all the above cam profile. Figure 7 and Figure 8 shows the time-response characteristics of the 2nd and the 3rd cam profile described above. The time-response characteristics shows that input and output are almost overlapping. This means that servomotor model with an inertia ratio of 10:1 can perform the commanded cam profile accurately.

If the inertia ratio is changed from 10:1 to 50:1, the position versus time diagram will be different. Students in PLC course are required to do experiments with many such variations and analyze the results and write report with appropriate justifications.

There are many other variables, such as gear ratio and motor torque constant, available in the model for students to get a good understanding of servomotor operation and its performance within a short period of time. However, to perform the same experiment using real life servomotor, drive and motion controller, it would take a much longer time to do in a laboratory environment. Thus, concept is passed on easily with proper explanation, using the above process and with help of a software tool.

After time-response analysis, using the above model, students proceed experimenting with actual servomotor and associated motion controller, various types of servomotor drives, and various cam profiles.

Students perform experiments with servomotor positioning and cam profile using real world servomotor, drives and motion control PLCs. Servomotor setup shown in Figure 4 and several other similar real-life motion control systems are available in Mechatronics laboratories for experimentation. In addition, Mechatronics laboratories have setups of various manufacturers' motion controllers coupled with conveyor systems, high-speed camera vision, sensors, variable frequency drives (VFDs), and Human Machine Interface (HMI) for students to use and perform experimentations. Mechatronics laboratories have motion control setups by Allen-Bradley CompactLogix PLCs, MPL-A430P series motors, Ultra 3000, Kinetix 6000 integrated servo drives, PanelView 600 HMI units and RSLogix 5000 software tools (the entire FactoryTalk Tools set is available in the Mechatronics lab.). There are also several other setups by other venders, such as Mitsubishi, ELAU GmbH, EATON Corp. available in Mechatronics laboratories.

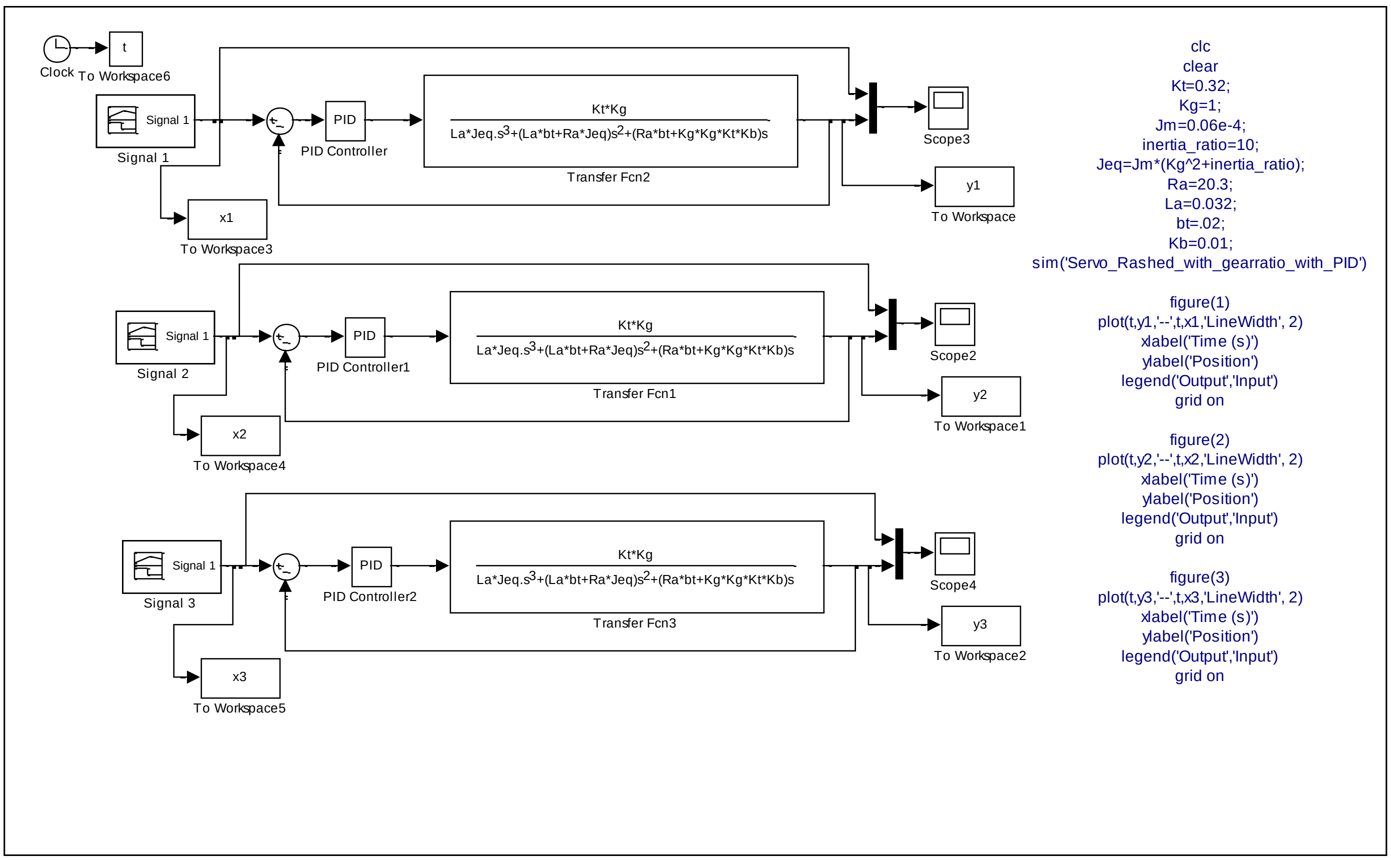


Figure 5: Screenshot of the Servomotor Model in Simulink with Three Different Types of Cam Profile Inputs

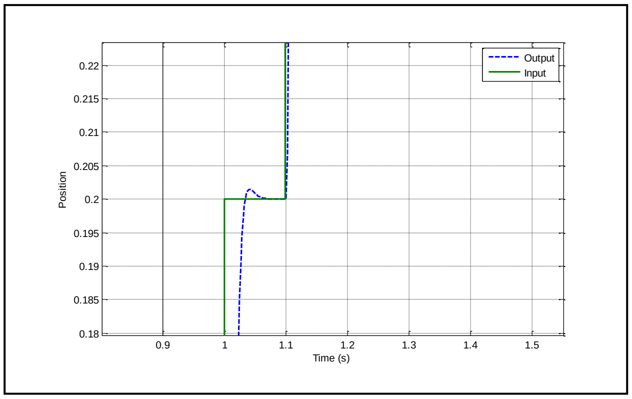


Figure 6a: 1st Transition of the 1st Cam, Inertia ratio of 10:1

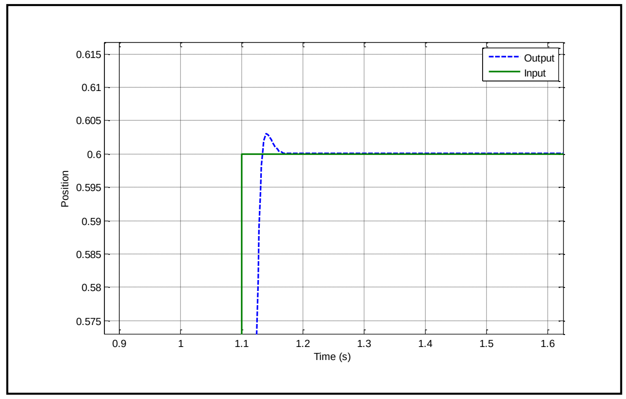


Figure 6b: 2nd Transition of the 1st Cam, Inertia ratio of 10:1

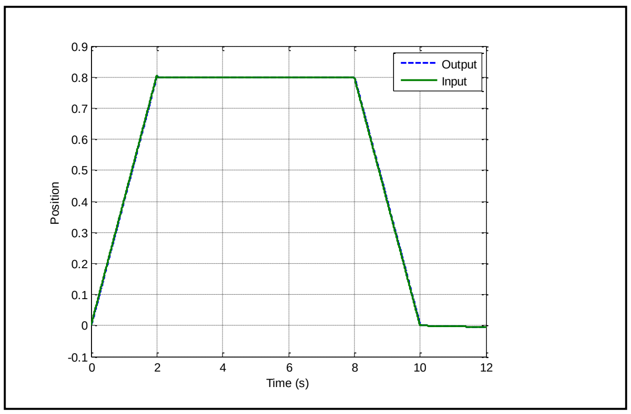


Figure 7: 2nd Cam Profile, Command-Response, Inertia ratio of 10:1

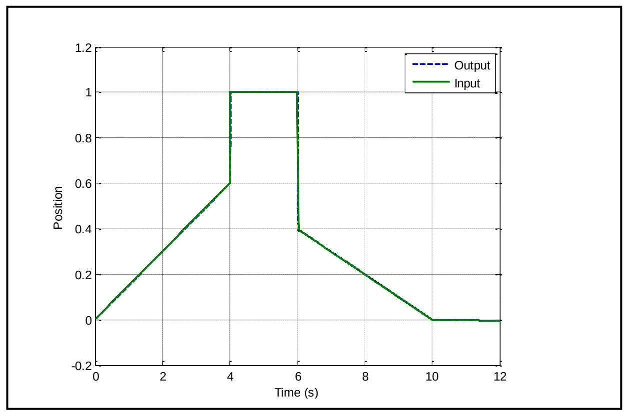


Figure 8: 3nd Cam Profile Command-Response, Inertia ratio of 10:1

VII. Conclusion

In order to achieve the student learning outcomes for a Mechatronics Engineering Technology program, as related to servomotors, a sequence of four courses are enhanced and material pertaining to high speed packaging machinery motion control, are introduced in these courses. Also, in addition to classroom discussion, each of these courses in the sequence have at least three to four laboratory experimentation having progressive level of difficulties to fulfill the learning outcomes of the program. Software tools and modeling are used to enhance student learning of the new concepts introduced in the program. These tools make it possible for students to better observe the effects of different variables in the system. Coupled with laboratory experimentations, it was expected that student learning will improve. A *course embedded assessment* has been performed in each of these four courses to measure the student achievement as related to the course objectives and student learning outcomes. This assessment uses a three prong approach to measure student understanding of the course outcomes. Initial assessment of student learning outcomes for the sequence of these courses that use concepts of modeling and simulation has shown improvement of student understanding in the area of high speed motion control, servomotors, and cam.

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