

# Teaching Vibration and Control courses using Animation, Simulation, and Experimentation

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## Abstract

*Vibration and control theories are both subjects that encompass almost all fields of engineering applications. Understanding the theory of vibration is essential to understanding of control theory for undergraduate engineering students. The traditional treatment in teaching both theories tend to be highly theoretical and mathematically complex and may not be beneficial for some undergraduate students who can be classified as sensing, or visual learners. Modern computation tools equipped with simulation and visual capability can ease explanation of topics in vibration and control theories in the classroom and laboratory. Through the use of these modern visualization and simulation tools, it is possible to teach “mathematically advanced concepts in vibration and control courses in engineering” more efficiently and make it more interesting for them to understand.*

*This paper describes teaching vibration and automatic control courses in the Mechanical and Electrical Engineering departments at the West Virginia University Institute of Technology. Experiments are designed to give student thorough understanding of basic concepts in vibration and control theories using animation, simulation, and experimentation. A series of lab sessions are introduced to the class to complement the lecture materials and to guide the students to understand vibration and control theory together and explore different important parameters that exist in both theories.*

## I. Introduction

Vibration and Control is highly multidisciplinary branch of engineering. In fact, vibration and control system engineering is a part of many branches of engineering that needs to be taken very seriously among our graduating undergraduate engineers who will be involved in design and analysis of complex systems soon after they graduate. Teaching vibration and control system can be both conceptual and experimental. Vibration and Control system experimentation, however, is not an established discipline, and there are many fundamental issues that are worthy

of deep and careful consideration. The student needs to understand and “feel” the vibration and control theories parameters before starting to design the system that needs to be controlled. Both vibration and control theories tend to be mathematical and the traditional treatment in teaching both theories tends to be highly complex.

Basic animation and simulation can significantly improve the instructional process relative to the traditional blackboard approach. Advances in digital computers have made it possible for teachers to develop optimum learning tools through 3-D visualization of concepts in almost every science. What is so called a “PC” has evolved in a serious computational and design tool for students in engineering. With the availability of fast computers and software available for every subject, it is now possible to teach students much more than what we could in the past using the traditional tools. We believe that using these computational tools, instruction of so called “difficult” topics in vibration and control will be easily achieved. Through the use of these tools one can help students to develop intuition and judgment for problems, which could not been possible through traditional chalk and board techniques. Instead of presenting computational techniques in the classroom, it is now possible for the professor to focus on both fundamental and advanced concepts and let the software packages do the computation and simulation. Finally, these tools can make student who is “weak” analytically to get involved in undergraduate research and be motivated and achieve his/her highest goals. The new instructional technology is at the heart of what today’s entering college students are familiar and comfortable<sup>[1,2]</sup>.

West Virginia University Institute of Technology (WVU Tech) is the only institute of technology in the State of West Virginia and is one of only two institutes offering a variety of engineering and engineering technology programs in the State. The Leonard C. Nelson College of Engineering (LCNCOE) at WVU Tech offers degree programs in chemical, civil, computer, electrical and mechanical engineering, master of science in Control System Engineering as well as computer science areas. WVU Tech also offers through its Community and Technical College (CTC) a variety of two and four year engineering technology programs. WVU Tech has changed significantly over its 106-year history in trying to meet the demands of higher education in West Virginia. Through a major portion of this period, WVU Tech offered degree programs in engineering, engineering technologies, sciences, business, and health professions. The decade of the 80’s and the first half of the 90’s brought changes in the service region, including changes in the mix of business and industry employing graduates and major changes in the technology, mainly in computer technologies found in the workplace. As a relatively small state-assisted institution with an open admission policy, WVU Tech provides access to higher education for the citizens of the nation, state and its local region who seek careers in engineering, engineering technologies, sciences, business, general education and health professions. Graduates, particularly in engineering have been very successful in their careers and the alumni support is very strong and widespread. The rigorous curricula and the dedicated faculty at WVU Tech help graduates receive a quality higher education presenting unlimited employment opportunities.

LNC College of Engineering’s goals include involving faculty and undergraduate students in the creation of computer-based instructional technology on topics spanning the complete range of technical disciplines<sup>[3]</sup>. The key to success for this instructional approach depend on:

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1. Employing fast computers capable of manipulating massive amounts of image data required for visualization and 3-D animation.
2. The creativity of the faculty in implementing new teaching methods, along with the outstanding skills of our undergraduate students.

This paper is an integration of many recommendations on enhancing the undergraduate vibration and control education<sup>[4,5]</sup>. Educational laboratory exercises can be in general from programming highly structured tasks to unstructured tasks<sup>[6,7]</sup>. This paper draws attention to unstructured experimentation in vibration and control. These ideas are implemented within the Automatic Control Laboratory course offers by ECE Dept at WVU Tech.

## **II. Interactive vibration and pre-control simulation laboratory**

There are many general-purpose computational tools such as MATLAB, SIMULINK already in use for computational purposes in higher education. Most of these software tools are becoming more user-friendly and interactive to use on the computer screen. In this paper two different software packages are used to demonstrate the effectiveness of Simulation and Animation in instructing engineering experiments in vibration and control.

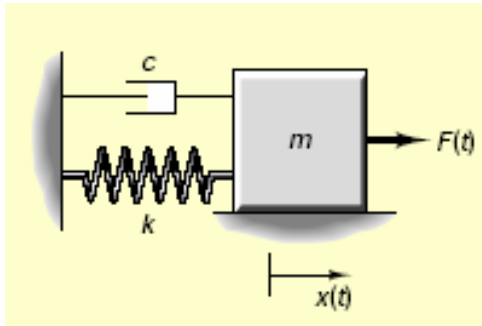
1. Working Model, which is a general purpose Simulation/ Animation package.
2. MathCAD , which is a comprehensive design environment that enables one to combine formulas, text and interactive graphics in a single worksheet.

These simulation demonstrations will prepare the students to understand and better visualize the vibration and control aspects of such systems.

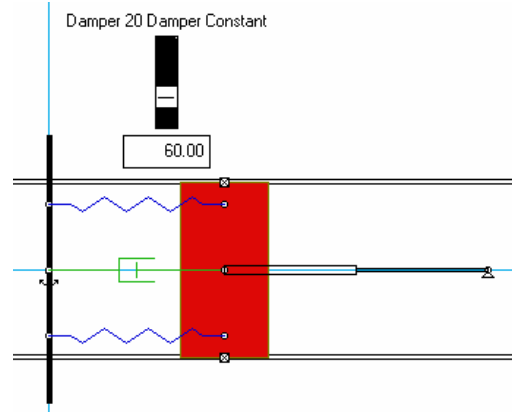
### ***i. Teaching Concepts in Vibration and Control using the interactive simulation tools***

In this section a few concepts in engineering have been chosen to apply and prove the effectiveness of simulation and animation in improve teaching effectiveness during vibration and control laboratory. The classes that these tools are used are mostly upper level engineering courses where the theoretical concepts are more difficult to understand by the students. The class sizes where these methods are applied range from 15 to 23 students.

Vibration of a single degree freedom system, a spring-mass system, with damping in theory of vibration is a fundamental concept to teach to students in theory of vibration. It is also very important for engineers since many machines and devices in real-life applications do experience vibratory phenomenon. For application engineers it is most important to visualize the behavior of these machines with lack of enough damping produces undesired vibration. A schematic of such single degree freedom system with damping with mass  $m$  is given in Figure 1. The simulated model in Working Model is shown in Figure 2. Both models have exactly the same parameters and material constants.



**Figure 1.** Spring mass system with damping



**Figure 2.** Model created in Working Model 2D for Simulation

These models represent a single degree freedom system with harmonic excitation and its governing differential equation of motion is given by

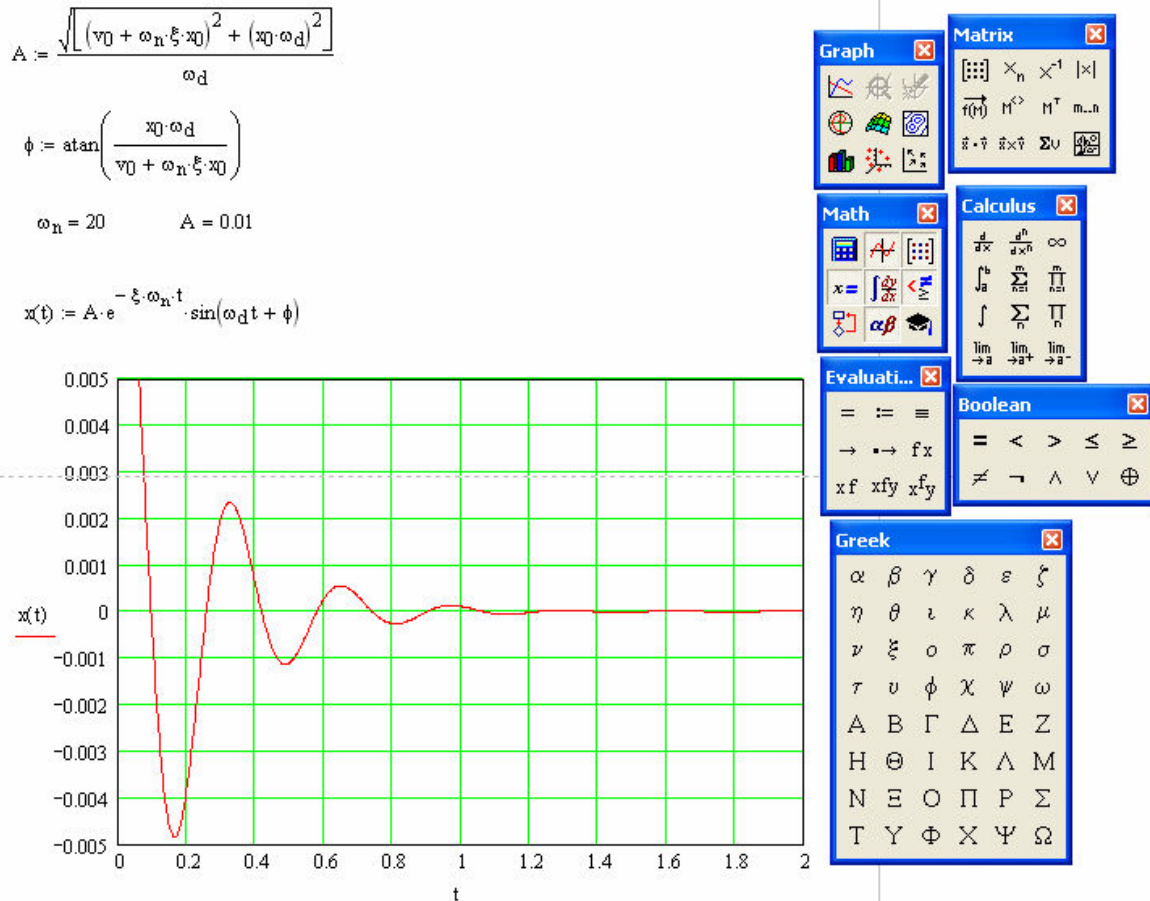
$$m \ddot{x} + c \dot{x} + kx = F_0 \sin \omega t$$

The total solution to the above equation is given by:

$$x(t) = A \sin(\omega_d t + \phi) + \frac{F_0 / k}{\sqrt{(1 - r^2)^2 + (2\zeta r)^2}} \sin(\omega t - \tan^{-1}(2\zeta r / (1 - r^2))) \quad (1)$$

Where  $\omega_d$  is the damped natural frequency,  $r$  is the frequency ratio,  $\zeta$  is the damping factor of the system and  $A$  and  $\phi$  are determined from the initial conditions for the system. The exciting force is a harmonic excitation.

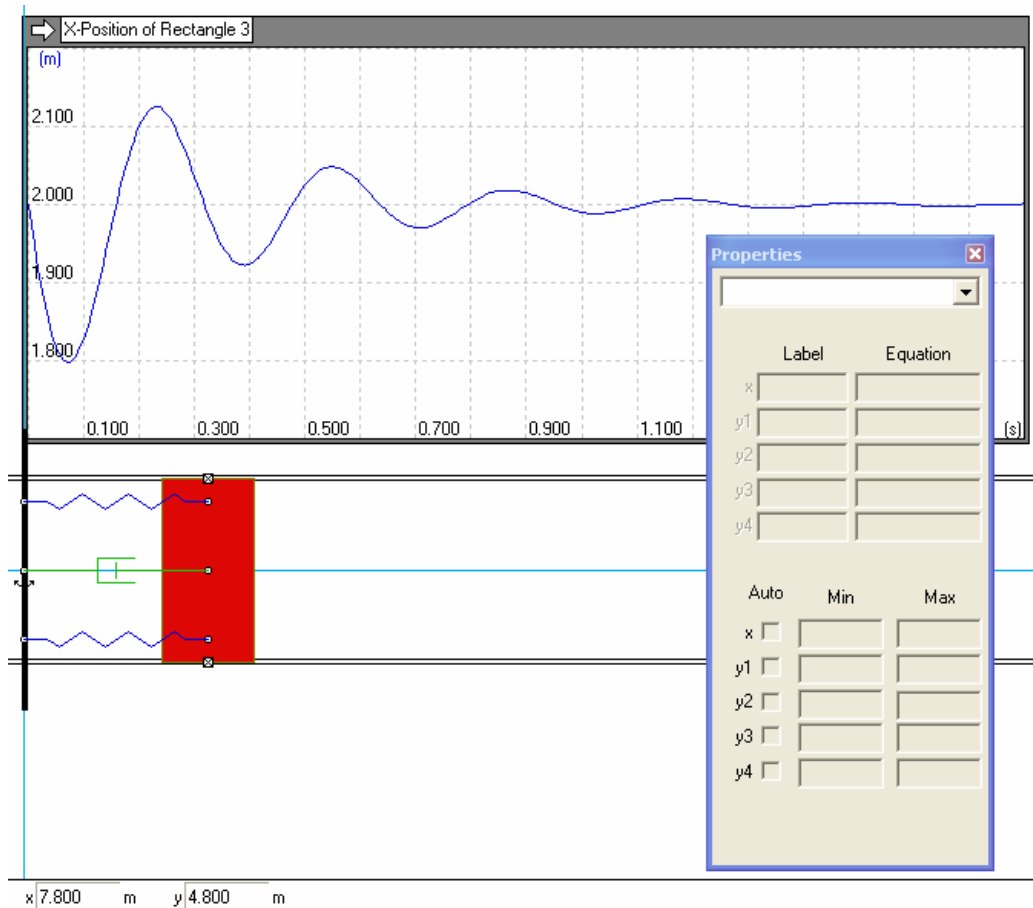
To understand the behavior of this system, one needs to perform parametric studies by obtaining solutions to equation (1) for different values of system's parameters. One way is to create the physical model and obtain experimental data and produce graphs of the data to demonstrate the solution to students. The physical model of this system is available at the control laboratory which will be demonstrated to the students later. MathCAD will produce graphical results of equation (1) for different inputs of the parameters of the system and allow the user to obtain the solution for different values of the system's parameters. These parameters will be important in understanding the control action of a controller like the damper. The results are produced graphically which can be used in the classroom for presentations. The results of inputs into MathCAD have produced graphs shown in Figure 3. Using such software, students' understanding of problems such as the spring mass system can be improved considerably. A survey obtained in engineering vibration course and a class size of 23 students showed improvement in scores students on topics which computational software was used during instructions.



**Figure 3.** MathCAD output for a simple parametric studies of spring-mass with damping

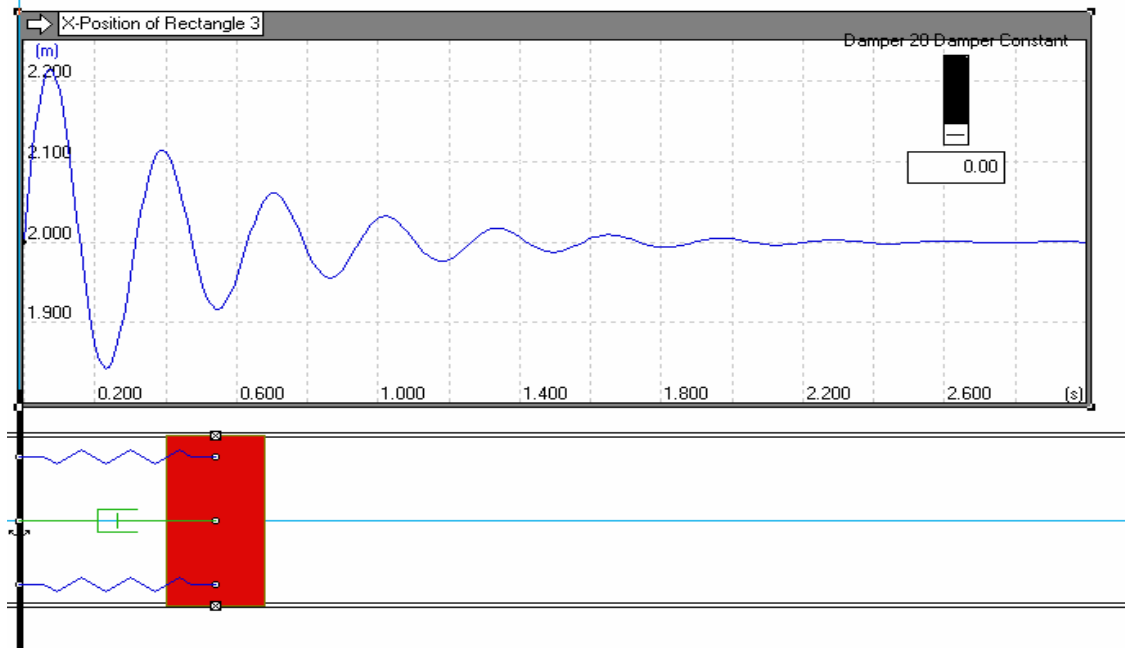
The investigation also revealed that using computational software such as MathCAD will only help those students that already have a good mathematical understanding of the problem being discussed in class. Combining mathematical computational tools with simulation tools in class to introduce problems such as the spring mass system will help to improve teaching effectiveness more than just using the computational tools. One of these simulation software that can be successfully used during class is Working Model. Working Model is an advanced motion simulation package with sophisticated editing capabilities. The program makes it possible to build and analyze dynamic mechanical systems with essentially no programming or mathematical understanding about the dynamics of the problem. The software allows one to design and test without building a physical model for the problem or system. The windows interface is intuitive and easy to learn. The dynamics engine is physics-based and enables the program to accurately calculate the behavior of even highly complex models. Figure 4 shows the model created for spring mass problem and the results of the motion for its free vibration due to a step input to the system. This simulation model allows the user to change the system's parameters on the screen and the results are shown to match perfectly with those results obtained from the computation software tools or by experiments. The step input will be experimented in one of the laboratory experiments in the Control Laboratory using the ECP Model 210 (Rectilinear Control System). By introducing the concept in the vibrations class, students will be able to understand more readily the purpose of controlling the physical spring mass system. The

authors experience in using such motion simulation model during the class is that it helps students to become interested and help them to understand the mathematics involved in motion and control of such structures.

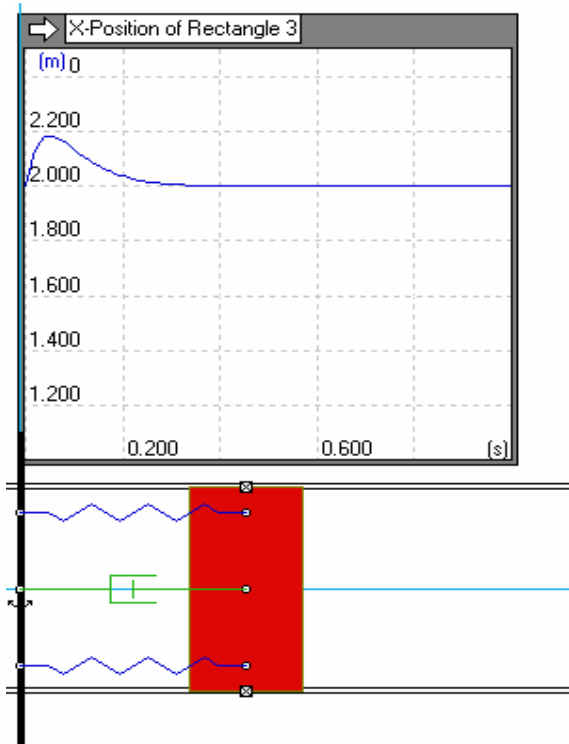


**Figure 4.** Simulation model created in Working Model for the SDF spring mass system

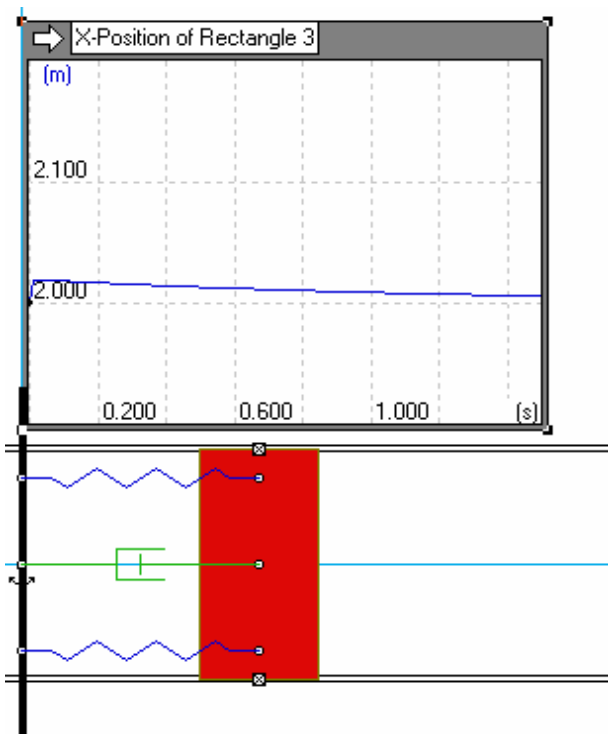
Figures 5 represent simulation of under damped, critically damped, and over damped cases, respectively for the motion of the spring mass system. These are demonstrated during the lecture portion of vibrations course.



**Figure 5 i.** Under damped SDF system



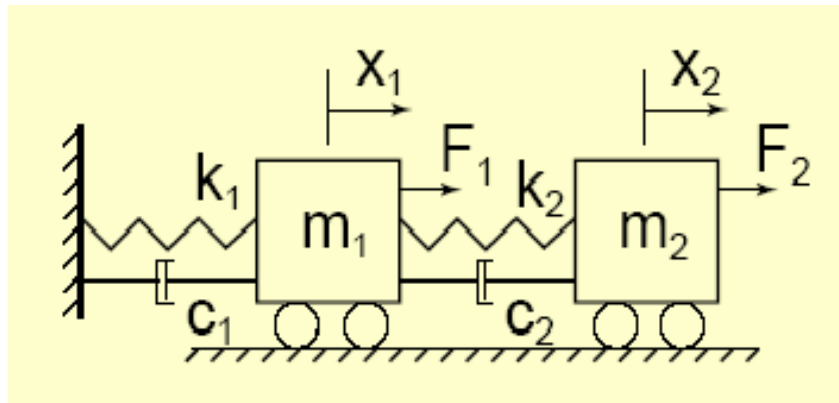
**Figure 5 ii** Critically Damped system



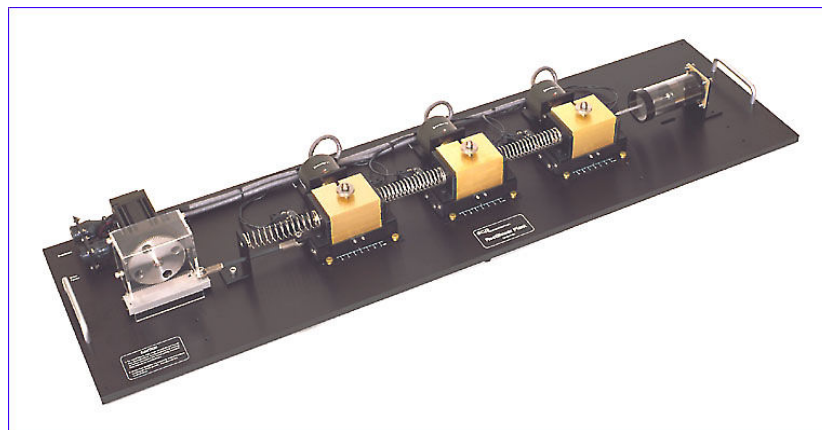
**Figure 5 iii** Over damped system

Figure 6 shows a typical two degree of freedom spring mass system with damping. The system is under excitation of two forcing functions. These forcing functions could have different forms such as step, sinusoidal, triangular, etc. The task is to demonstrate to the students affect of all of the parameters for each component during the vibration of this system and later be able to use the

experimental model, Model 210 Rectilinear plant shown in Figure 7, to demonstrate the control aspect involved in the system. This classical system appears commonly in dynamics and controls text books and serves as a benchmark for vibration and control method evaluation.



**Figure 6.** Two degree of freedom spring mass system with damping



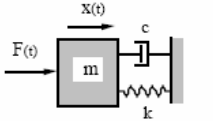
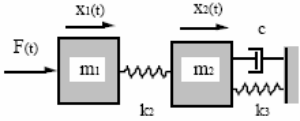
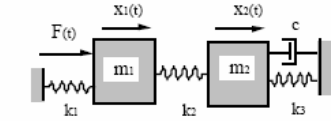
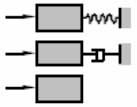
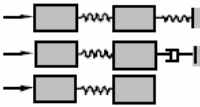
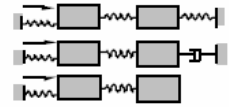
**Figure 7.** Model 210 Rectilinear plant used in Control Laboratory

The Rectilinear plant shown in Figure 7 provides vivid demonstrations of elementary topics such as rigid body PID control, lead/lag compensators, phase and gain margin, trajectory tracking, and regulation - as well as advanced high order collocated and noncollocated system control. This apparatus also clearly demonstrate salient properties of flexible systems such as mode shapes, natural frequencies, and characteristic transient and frequency responses. An optional secondary drive may be positioned at any output (mass carriage) to create a MIMO plant (requires Executive USR™ software) and provide for the study of disturbance rejection. This versatile mechanism is readily transformed into the variety of configurations shown in Figure 8. It serves to vividly demonstrate both lumped parameter dynamics and generic vibrations issues. This system appears commonly in dynamics and vibrations text books and provides excellent demonstrations of classical theory of vibration and control. The mechanism features adjustable masses, interchangeable springs and adjustable air damping. The system is furnished with a comprehensive set of dynamics and vibrations experiments that provide an excellent introduction to one degree of freedom systems and continue through higher order flexible structure dynamics.



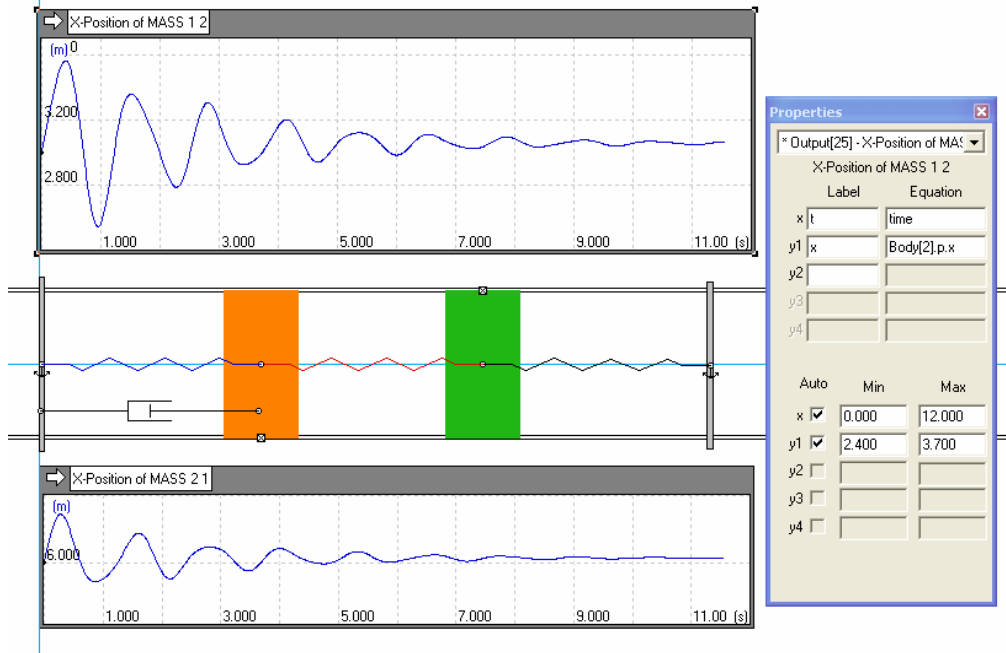
All of these plants can easily be simulated in Working Model software during the class in vibrations course in order to prepare students for the control laboratory session.

**Easily Transforms to Twelve Distinct Plants**  
(sixteen plants with optional third mass)

<b>Plant Models</b>	 <p style="text-align: center;"><i>Spring / mass / damper</i></p>	 <p style="text-align: center;"><i>Free - constrained, 2 DOF</i></p>	 <p style="text-align: center;"><i>Constrained - constrained, 2 DOF</i></p>
<b>Additional Configurations</b>			
<b>Time Domain Equations*</b>	$m\ddot{x}(t) + c\dot{x} + kx(t) = F(t)$	$m_1\ddot{x}_1(t) + k_2x_1(t) - k_2x_2(t) = F(t)$ $m_2\ddot{x}_2(t) + c\dot{x}_2(t) - k_2x_1(t) + (k_2 + k_3)x_2(t) = 0$	$m_1\ddot{x}_1(t) + (k_1 + k_2)x_1(t) - k_2x_2(t) = F(t)$ $m_2\ddot{x}_2(t) + c\dot{x}_2(t) - k_2x_1(t) + (k_2 + k_3)x_2(t) = 0$
<b>S-Domain Equations*</b>	$\frac{x(s)}{F(s)} = \frac{1}{ms^2 + cs + k}$	$\frac{x_1(s)}{F(s)} = \frac{m_2s^2 + cs + k_2 + k_3}{D(s)}, \quad \frac{x_2(s)}{F(s)} = \frac{k_2}{D(s)}$ $D(s) = (m_1s^2 + k_2)(m_2s^2 + cs + k_2 + k_3) - k_2^2$	$\frac{x_1(s)}{F(s)} = \frac{m_2s^2 + cs + k_2 + k_3}{D(s)}, \quad \frac{x_2(s)}{F(s)} = \frac{k_2}{D(s)}$ $D(s) = (m_1s^2 + k_1 + k_2)(m_2s^2 + cs + k_2 + k_3) - k_2^2$
<b>Characteristics</b>	<ul style="list-style-type: none"> <li>• Classic damped oscillator.</li> <li>• Pole excess = 2.</li> <li>• Configurable to type 0, 1, or 2 system.</li> </ul>	<ul style="list-style-type: none"> <li>• Two damped modes.</li> <li>• <math>x_1/F</math>: "Damped" zero, pole excess = 2.</li> <li>• <math>x_2/F</math>: "no zeros, pole excess = 4.</li> <li>• Configurable to type 0, 1, or 2 system.</li> </ul>	<ul style="list-style-type: none"> <li>• Two damped modes.</li> <li>• <math>x_1/F</math>: "Damped" zero, pole excess = 2.</li> <li>• <math>x_2/F</math>: "no zeros, pole excess = 4.</li> <li>• All configurations type 0.</li> </ul>

**Figure 8.** Model 210 Rectilinear plant and its different distinct plants

Figure 9 represents simulation of one of the plants shown in Figure 8. The response of the system is obtained for a step input and the motion of each mass is simulated by the software during the vibrations class. Different values of input as well as different damping coefficient is tried and the output motion is demonstrated to class.



**Figure 9** Simulation for one of the plants of Rectilinear system created in Working Model for the 2DF spring mass with damping system

### III. Automatic Control Laboratory

The topics introduced in the course ELCE 424 Automatic control such as Introduction to control systems, Time domain analysis, Control system characteristics and performance of feedback control, complement the vibrations course. The course, entitled "Automatic Control Laboratory," is organized around consideration of principles of control systems. There are many aspects of a Control System problem that can be investigated. For example, formulation of a mathematical model for the 'Plant,' or the system to be controlled, and identification of values of the parameters of this mathematical model is seldom given much attention. The emphasis in the Laboratory exercises is on plant identification, open-loop & closed loop characteristics, effect of damping and design & implementation of PID control schemes. There are numerous aspects of control system that present difficulties in the laboratory not apparent from classroom analysis. It is the intent of the laboratory to allow the students to investigate such problems experimentally after they have been demonstrated some of its important aspects in the vibrations course through simulation. This will give them an opportunity to solve such practical problems of vibration and control system engineering. The Laboratory experiments are designed to provide insight into the vibration control system principles through theoretical as well as practical demonstration and experimentation. The laboratory experiments are designed in such a way that the theoretical principles can be demonstrated.

#### *i. Structure of the laboratory*

The four vital Educational Control tools used extensively are: ECP Model 210 (Rectilinear

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Control System)<sup>[8]</sup>, ECP Model 205 (Torsional Control System)<sup>[9]</sup>, SFT154 (educational Servo Trainer)<sup>[20]</sup>, and ES151 (Educational Servo)<sup>[21]</sup>. These systems are designed to provide insight to control system principles through hands-on demonstration and experimentation. The electromechanical plant has a full complement of control hardware and software. The user interface to the system is via a friendly, versatile, PC window environment which supports a broad range of controller specification, trajectory generation, data acquisition, and plotting features. The systems are designed to accompany introductory through advanced level controls courses and support either high level usage (i.e. direct controller specification and execution) or detailed user-written algorithms<sup>[9, 10]</sup>.

The electromechanical apparatus may be transformed into a variety of dynamic configurations, previously demonstrated through simulation, which represent important classes of "real life" systems. The ECP Model 205 (Torsional Control System) and ECP Model 210 (Rectilinear Control System) apparatus represents many such physical plants including rigid bodies; flexibility in linear drives, gearing and belts; and coupled discrete vibration with actuator at the drive input and sensor collocated or at flexibly coupled output (non collocated). Thus the plant models may range from a simple double integrator to a fourth order case with two lightly damped poles and either two or no zeros.

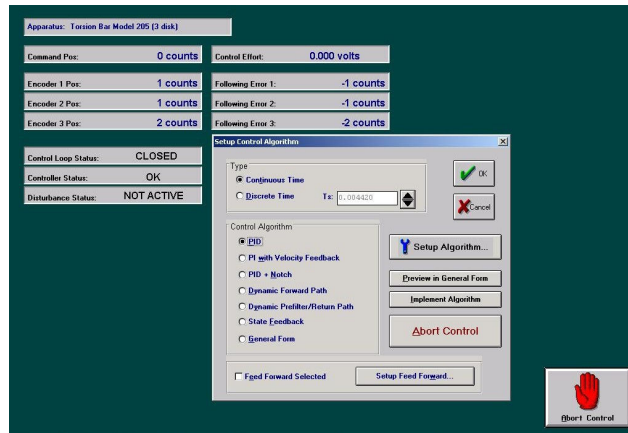
The experimental control system is comprised of the three subsystems. The first of these is the electromechanical plant which consists of the spring/mass mechanism, its actuator and sensors. The design features a brushless DC servo motor, high resolution encoders, adjustable masses, and reconfigurable plant type. The second subsystem is the real-time controller unit which contains the digital signal processor (DSP) based real-time controller, servo/actuator interfaces, servo amplifier, and auxiliary power supplies. The DSP is capable of executing control laws at high sampling rates allowing the implementation to be modeled as being continuous or discrete in time. The controller also interprets trajectory commands and supports such functions as data acquisition, trajectory generation, and system health and safety checks. A logic gate array performs motor commutation and encoder pulse decoding. Two optional auxiliary digital-to-analog converters (DAC's) provide for real-time analog signal measurement. This controller is representative of modern industrial control implementation. The third subsystem is the executive program which runs on a PC under the DOS or Windows operating system. The ECP Executive program is the user's interface to the system. It is a menu driven / window environment that the user will find is intuitively familiar and quickly learned. This software runs on a PC and communicates with ECP's digital signal processor (DSP) based real-time controller. Its primary functions are supporting the downloading of various control algorithm parameters (gains), specifying command trajectories, selecting data to be acquired, and specifying how data should be plotted. In addition, various utility functions ranging from saving the current configuration of the Executive to specifying analog outputs on the optional auxiliary DAC's are included as menu items.

The **User Units** dialog box provides the user with various choices of angular or linear units. For ECP Model 205 the choices are *counts*, *degrees* and *radians*. There are 16000 counts, 360 degrees and  $2\pi$  radians per revolution of both the load and drive inertia disks. And for ECP Model 210 the choices are *counts*, *centimeters* and *inches*. There are 1604 counts, per centimeter

travel of the mass carriages. By clicking on the desired radio button the units are changed automatically for trajectory inputs as well as the Background Screen displays, plotting and jogging activities.

**Setup Control Algorithm** allows the entry of various control structures and control parameter values to the real-time controller, Figure 10. In addition to feed forward which will be described later, the currently available feedback options are:

- PID
- PI With Velocity Feedback
- PID+Notch
- Dynamic Forward Path
- Dynamic Prefilter/Return Path
- State Feedback
- General Form



**Figure 10** Set Up Control Algorithm Dialog Box

The **Feedback ES151 Educational Servo System** is a high quality electro-mechanical servomechanism. The system has two basic subsystems,

- The Actuator Unit, and
- The Educational Servo.

### The Actuator Unit

The Actuator Unit has the following components

- A **24V dc electric motor** whose nominal full speed is 3000 r/min.
- A **tachogenerator** is a device which generates a voltage related to speed.
- The **gearbox**. A worm and wheel is used to drive an output shaft, the speed of which is only 1/30th of that of the motor shaft and at right angles to it. Full output speed is about 100 r/min.
- The **output disc** and **potentiometer**. This disc is calibrated to indicate output shaft position (angular) and has stroboscope tracks that can be used to determine certain speeds. In front of the disc is a **SENSOR** or **TRANSDUCER** called a **POTENTIOMETER** which will give a voltage output that is related to the shaft

position.

- A **Loading Unit**. This is used in conjunction with the large thin aluminum disc supplied in the accessory pack.

In use, the disc is mounted on the motor shaft and then runs between the magnets that can be positioned, using the lever, to cover a large or small area of the disc. This position is calibrated 0 to 10 on a scale at the side of the unit.

When the disc rotates between the magnets a torque is generated, due to what are called Eddy Currents, which tries to slow the motor. The braking effect depends on the motor speed and the amount of magnet overlap on the disc.

### **The Educational Servo**

The single 'control box' actually contains several units, the details of which will be considered later. To emphasize the main I function of this item it will be, in future, referred to in the text as the Control Unit. It contains all the necessary power supplies for the system to operate and must be coupled to an I electrical power source of 100-240V ac as required. The unit is fused and if necessary the fuse can be replaced by pressing and turning the fuse holder.

The **SFT154 Servo Fundamentals Trainer** is intended to provide students with a sound introduction to the principles of servomechanisms, and by extension to those of closed-loop systems more generally. It has facilities for examining a system based entirely on analogue signals and also a system which is almost entirely digital. The SFT154 Servo Fundamentals Trainer consists of 3 units:

- Analogue Unit AU 154A,
- Digital Unit DU1548, and
- Mechanical Unit MU 154C.

The Analogue Unit and the Digital Unit are separate, allowing a purely analogue system to be converted into a analogue and digital system.

### **Analogue Unit**

The Analogue Unit connects to the Mechanical Unit through a 34-way ribbon cable which carries all power supplies and signals enabling the normal circuit interconnections to be made on the Analogue Unit using the 2mm patching leads provided. The unit enables a basic system to be configured and contains facilities to introduce compensation to investigate improvement in overall system performance.

### **Digital Unit**

The Digital Unit connects to the Mechanical Unit through a 34-way ribbon cable carrying all power supplies and signals enabling the normal circuit interconnections to be made on the unit using the 2mm patching leads provided.

The unit contains an A/D converter to enable continuous input or error signals to be digitized for computer input. The computer input can also be obtained directly from the output transducer or bi-phase speed tracks. The computer output can be converted to a continuous motor drive signal through a D/A in the unit or to a Pulse Width Modulation (PWM) switching signals for motor drive.

### **Mechanical Unit**

The Mechanical Unit contains a power amplifier to drive the motor from an analogue or switched input. The motor drives the output shaft through a 32:1 belt reduction. The motor shaft also carries a magnetic brake disc and an analogue speed transducer (tachogenerator). A two-

phase pulse train for digital speed and direction sensing is also derived from tracks on the brake disc.

The output shaft carries analogue (potentiometer) and digital (64 location Gray code) angle transducers. The unit contains a simple signal generator to provide low frequency test signals, square and triangular waves, and requires an external power supply providing: +15V, 0, -15V at 1.5A, +5V, 0, at 0.5A, The Feedback PS 446 is suitable.

## *ii. Classification of experiments*

This section describes the experiments that reinforce the principles of analyzing a simple control system. The experiments are

- Motor characteristics
- Open loop and closed loop analysis
- System identification
- Effect of damping
- Effect of Proportional, Integral and Derivative action on a given system.
- Project

The first two experiments are structured, wherein students are given step by step instructions. The objective of the first laboratory exercise is to learn the steady state characteristics of the system and observe the changes in the output of the system with changing load conditions, as it was demonstrated in vibrations course. The second exercise demonstrates the significance of feedback in a control system. An Open loop system is a system in which the output is neither measured nor fed back for comparison with the input. Thus, to each reference input corresponds to a fixed operating condition; as a result, the accuracy of the system depends on calibration. Closed loop system maintains a prescribed relationship between the output and the reference input by comparing them and difference as a means of control. The aim of the experiment is to control the position of the output potentiometer.

The next experiment outlines instructions for mathematical modeling of a simple second order system. After completing the exercises the students will:

- Be familiar operating the ECP system operation
- Be able to recognize the hardware/software settings
- Be able to calculate the hardware gains and develop a transfer function by measuring plant parameters i.e., spring and damping constants.

This exercise gives a procedure for identifying the plant parameters. The approach will be to use certain fundamental properties of lightly damped second order system to indirectly measure the inertia, spring and damping constants of the plant by making measurements of the plant while setup in a pair of classical spring-mass configuration.

The progressive decay of the response of the system with time in the amplitude of the free oscillations of the system may be termed as the damping of the system. The next exercise outlines instructions to investigate the damping in a second order system.

After completing the exercise the students will:

- Understand the differences between under damped, critically damped, and over damped systems, as it was demonstrated through simulations during vibration course.
- Investigate the effect of changing inertia, stiffness of the spring on the damping of a

second order spring-mass-damper system.

- Understand various ways of applying as well as changing the damping of a given system.
- In the next exercise the effect of Proportional, Integral and Derivatives actions on the system performance are investigated. These exercises should give the students a thorough understanding of the three term (PID) controller.

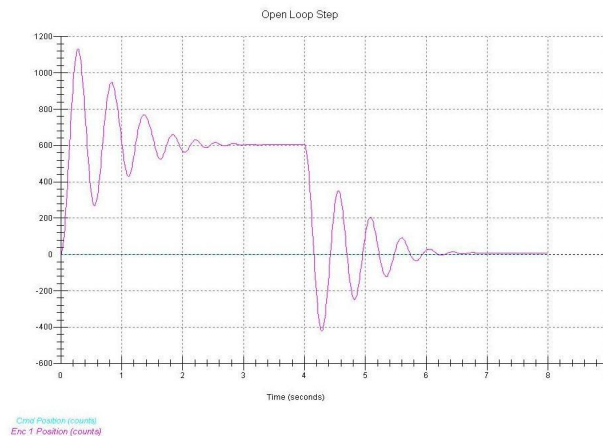
After completing the exercises the students will be able:

- To investigate the effects of Proportional, Integral and Derivative control action on the system performance
- To analyze the advantages and disadvantages of each of the control actions.

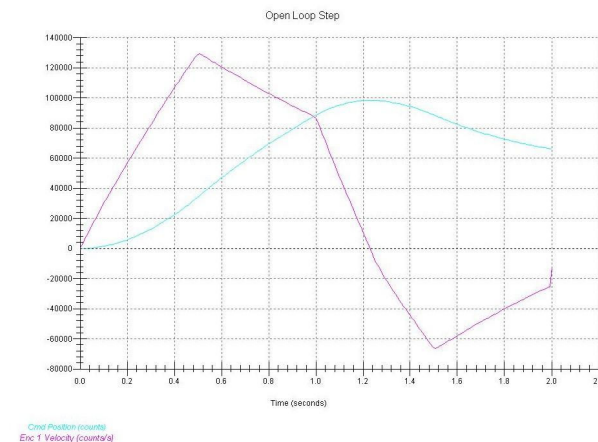
The last exercises are projects given to the students to demonstrate their ability to analyze a given system and design as well as implement a PID control scheme. Students should be able comment on the stability of the system (Open loop response) and which control scheme is best suitable for the given system.

### iii. Experimental results

This section illustrates some of the experimental results obtained by the students. The results are compared by simulating the same experiment in Working Model software by students during the laboratory. All of the results correlate successfully.



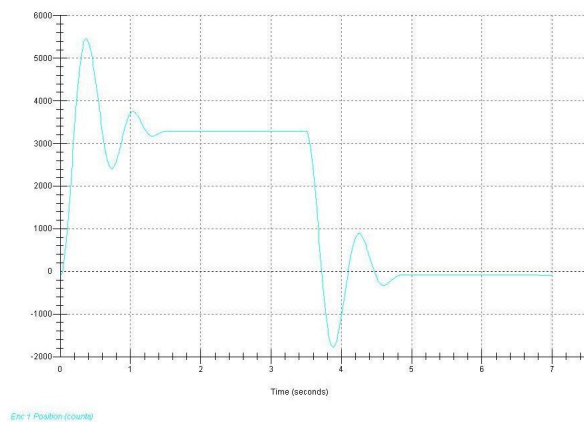
**Figure 11** Open Loop Response on ECP Model 205 Torsion System



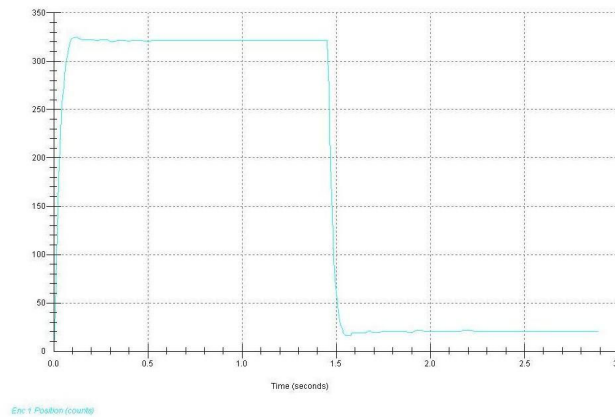
**Figure 12** Open Loop Velocity profile of the base disk

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The objective of this laboratory exercise is to identify the plant parameters. The approach will be to use certain fundamental properties of lightly damped second order system to indirectly measure the inertia, spring and damping constants of the plant by making measurements of the plant while setup in a pair of classical spring-mass configuration. This experiment will be carried out concurrently with a demonstration of the simulation of the plant in the Working Model software. Figure 11 shows the oscillation of the system with the masses attached to the disk. The amplitude of oscillation helps in calculating the natural frequency and damped natural frequency of the system. The frequencies are estimated by logarithmic decrement of the oscillations. A number of trials can be performed in each of the cases to get consistent values. Figure12 shows the velocity profile of the disk, which is useful in measuring the acceleration and deceleration of the system. These values are measured in turn to calculate the hardware gain of the system.

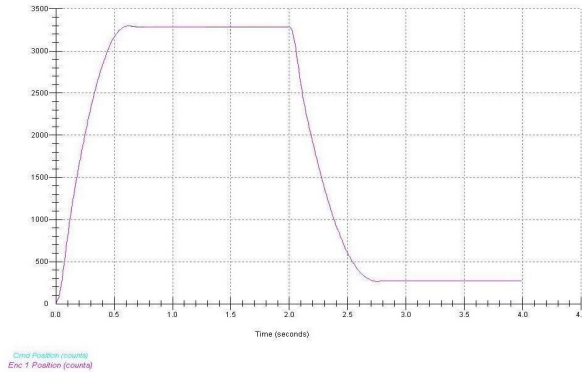


**Figure 13** Under-damped system ECP Model 210



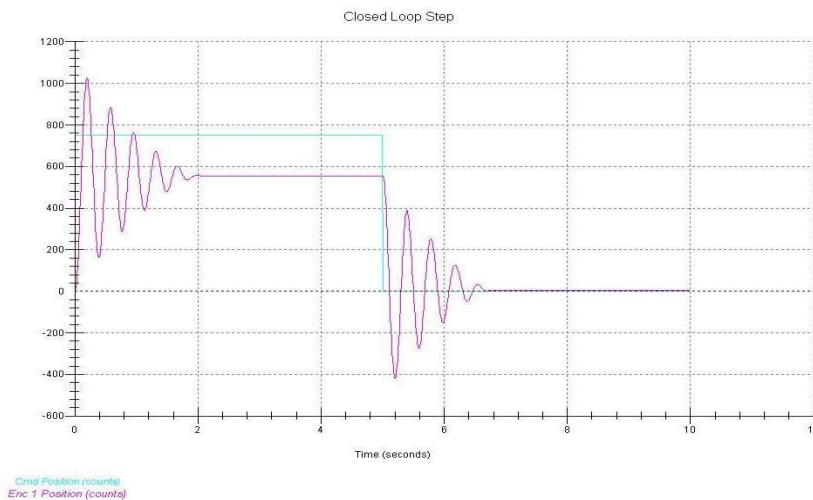
**Figure 14** Critically-damped system ECP Model 210



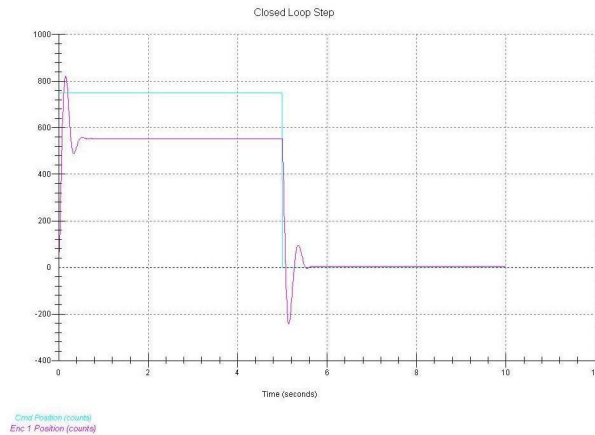


**Figure 15** Over-damped system ECP Model 210

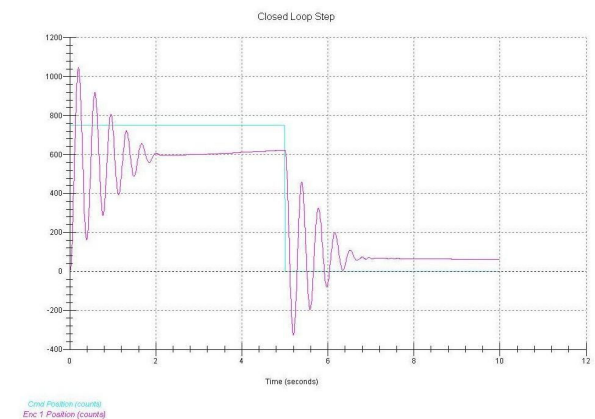
The objective of this exercise is to investigate the effect of changing inertia, stiffness, and damping on the response of a second order spring-mass-damper system and understand the differences between under damped, critically damped, and over damped systems, as it was demonstrated by simulating the motion if the same model during vibrations course. The damping of the system is changed with the help of the air damper. In the first case an under damped system is illustrated with no mass on the carriage and damping adjustment knob open. There are many factors affecting the damping of the system such as the masses, stiffness of the spring and the position of the damping adjustment knob. Figures 13, 14, 15 illustrate general cases of under damped, critically damped and over damped system respectively. The students have identified the different cases of damping as well as are able to identify the various factors affecting the damping of a given system. The simulated models demonstrated during the vibration course, Figure(s) 5, revealed the same results<sup>[22-23]</sup>



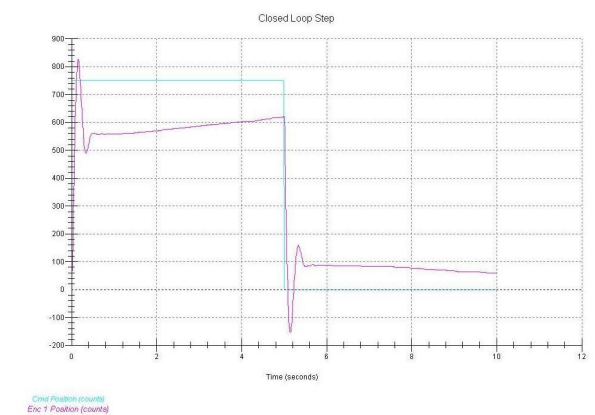
**Figure 16** Closed Loop Response- Proportional Control action



**Figure 17** Closed Loop Response- Proportional and Derivative Control Action



**Fig 18** Closed Loop Response- Proportional and Integral Control Action



**Figure 19** Closed Loop Response-Proportional, Integral and Derivative Control Action

The objective of this exercise is to observe the effects of Proportional, Integral, Derivative actions individually as well as combination of two components on the system. A proportional controller ( $K_p$ ) will have the effect of reducing the rise time, but difficult to eliminate the steady-state error. An integral control ( $K_i$ ) will have the effect of eliminating the steady-state error, but

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it may make the transient response worse. A derivative control ( $K_d$ ) will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response. The nominal cases of these control action is shown in the Figures 16, 17, 18, 19.

## Conclusion

The Automatic Control Laboratory has been developed in such a way that both the undergraduate as well as the graduate students will benefited by the laboratory. Most part of the work is concentrated on improving the under-graduate laboratory course in vibration and control. The method of presentation of the topics in both vibrations and control undergraduate courses in both ECE and ME departments have been very successful. The laboratory exercises have coincided with the class materials in both vibrations and control, providing a visual aid for the lecture concepts. With unstructured instructions students have improved their retention capabilities and problem solving skills.

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