DYNAMIC SYSTEMS TEACHING ENHANCEMENT USING A LABORATORY BASED HANDS-ON PROJECT

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Abstract

An undergraduate course in dynamic systems involves basic material in previous undergraduate courses that are critical building blocks for course execution. Differential Equations, Mathematical Methods for Engineers, Dynamics, etc. are all basic underlying material that is critical to the material covered in an undergraduate course. Material taught in those prerequisite courses is often considered irrelevant to the student since there is no practical application to firmly instill these basic STEM (Science, Technology, Engineering, Mathematics) concepts. A traditional Dynamic Systems course, with traditional class lecture/homework/test scenario is destined to the same fate as these earlier courses, if taught in the same manner.

A new variation of this Dynamic Systems course has been implemented, which has individual projects which address various analytical approaches using closed-form analytical solutions with MATLAB and SIMULINK computer software to completely address 1st and 2nd order systems. In addition, a laboratory based component is added to collect measured data for these systems to be used to further develop the analytical representation of these systems. Students work in groups and collect data to develop these models and prepare detailed reports summarizing their efforts. Each project is anonymously peer reviewed by another team to provide a detailed evaluation of the report and data evaluation. As a result of this peer review, the students further appreciate the need to analyze and report findings in an accurate manner.

The project is described along with laboratory experiments performed. Student comments regarding the project are presented. Assessments at the end of the first deployment of the project clearly indicate that the students enjoyed the hands-on based project and clearly felt that they understood the material in much greater depth as a result of the project.

I. Problem

Many students do not understand the need for basic STEM (Science, Technology, Engineering, Mathematics) material that is critical to the solution of engineering problems. Many times this occurs since there is no practical relevance of the material presented – as far as the student is concerned. Unfortunately, all of these underlying courses and related material become very critical as upper level course material is addressed in the final semesters of a student's undergraduate educational studies. Often the students feel that they do not command the subject matter well enough and sometimes feel that it is too late to catch up and review what they now realize they should have already known from previous courses. Figure 1 shows a cartoon expressing the student's eventual realization as they approach the latter part of the undergraduate educational career.

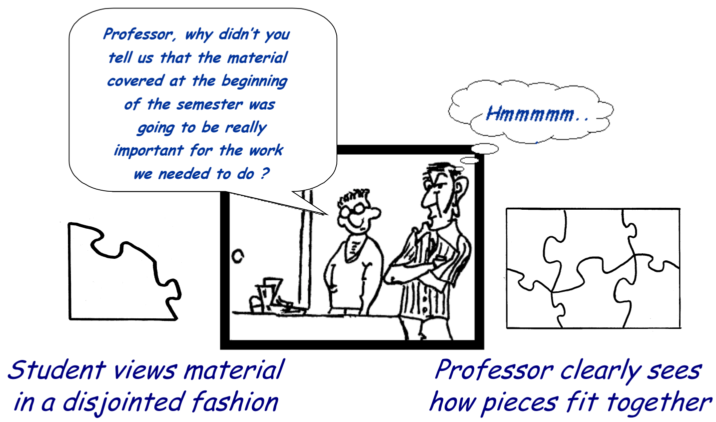


Figure 1 – Professor vs. Student View of Material Presented

This is especially true in a senior level Dynamic Systems course where previous material in Differential Equations, Mathematical Methods for Engineers, Dynamics, Solid Mechanics, Electrical Circuits, Thermal-Fluid Systems, etc. all have relevance to the understanding of the dynamic response of any system.

II. Introduction

The mission for all instructors is to educate their students in the most efficient manner possible. Teaching techniques should challenge, educate and promote innovative thinking from students. The lecture-based format of teaching which predominates in engineering education may not be the most effective manner to achieve these goals [1,2]. Constructivist learning theory asserts that knowledge is not simply transmitted from teacher to student, but is actively constructed by the mind of the learner through experiences. [3,4].

Students learn best with hands-on projects and problems with practical purpose [5]. Laboratory based, experimental problems are very good for demonstrating many aspects of engineering problem solving. Unfortunately, many laboratory environments are set up as "exercises" which typically have very clear, predetermined outcomes. This is done to reinforce lecture material that is presented in related courses [6]. The students are exposed to "canned" lab experiments and therefore, the lab becomes fairly well-defined and moderately deterministic. This forces the results to follow a fairly well-defined path. Experiments of this type are very good for demonstrating basic inherent skills that the students need to know. Many professors are comfortable with this approach since the outcomes of the lab experiment are well defined and can be assessed and evaluated with very clear guidelines.

However, this does not exploit the laboratory experience to its fullest. Students get the impression that the experimental environment is very similar to the classroom environment where homework problems and tests have very explicit answers given the problem statement. Unfortunately most, if not all, engineering problems do not follow this cookbook approach. Students must be afforded the experience of problems that require them to formulate solutions to problems with no specific straight-line structure to the solution – they must learn how to "think outside the box" [7].

The laboratory environment is an excellent opportunity to force the students to "think on their own". Real-world laboratory exercises and experimental approaches clearly show that there is not always an "answer at the back of the book". While students at times become frustrated by this, they learn that they need to employ many of their STEM skills in order to solve even the simple problems. Industry advisors have clearly identified the need for students to be exposed to a real-world laboratory environment where modern instrumentation and computers interface in performing data acquisition and data reduction [9, 10, 11].

Experiments play a very critical role in validating analytical models and hypotheses. Students must feel comfortable in a laboratory environment and must not feel foreign to lab equipment, instrumentation, etc. Students must also feel comfortable formulating solutions to real engineering problems using all of the STEM tools available to them. The STEM must become an integral part of their learning process throughout their entire educational and professional careers – the students must, in essence, "live the material" every day and in every course. The disjointed presentation of the material must cease to exist if this is to happen.

"After two weeks, people generally remember 10% of what they read, 20% of what they hear, 30% of what they see, 50% of what they hear and see, 70% of what they say, and 90% of what they say and do."[8] Clearly, the students need to drive the need for learning STEM related material. Once they have been able to clearly identify the need to learn and understand these basic STEM principles, then their ability to utilize the concepts and principles in solving real-world engineering problems will be enhanced. Students need to take ownership of the STEM material that is critical to solving engineering problems early in their educational career.
Real engineering problems are rarely solved by "looking up answers at the back of the book". Yet many engineering courses are taught this way and students feel that they can push the "reset button" after each class since they do not see the integration of all the material until late in their undergraduate career through the capstone experience. This is too late for them to realize the importance of earlier course material.

A Dynamic Systems laboratory-based, hands-on project has been implemented which attempts to address many of the issues identified above. This series of projects is described in the following sections.

III Description of the Set of Dynamic Systems Projects Developed

A set of dynamic system projects has been developed to task the students, working either individually or in teams, to address several dynamic system characteristics. The first project is an individual effort to force the student to develop the necessary skills to solve systems described by differential equations, Laplace transforms and numerical techniques; this project is a hands-on based analytical project. The second project is a group effort and involves the identification of the mass, damping and stiffness characteristics of a simple second order mechanical system; this laboratory based project clearly helps the students develop intuitive skills necessary to address real world problems. The third project is a group effort to identify the time and frequency response characteristics of a first order RC circuit that can be used as a low pass filter to address some of the measurement problems identified in the second project. Each project is discussed in more detail in the following paragraphs.

III.1 Analytical Modeling Tools for Identification of a Second Order MCK System

The students are instructed to develop generic models to address the response of a second order mass, spring, dashpot system using analytical closed form solutions by both ordinary differential equations and Laplace transformation techniques; these solutions are to be compared to the solutions obtained from both MATLAB and SIMULINK. The response of the simple single degree of freedom mechanical mass, spring, dashpot system due to external forces and/or initial conditions of displacement and velocity are to be evaluated.

Obviously, the students should have the ability to develop these models with no problems. However, since all the material needed to develop the theoretical solutions may be a little "rusty", the students struggle to varying degrees depending on their individual level of "rustiness". Now it is well known that students work together to develop these solutions and in some respects it is valuable to have students helping each other. This reinforces their ability to understand the material by taking ownership of the process. Of course, the closed form analytical solutions can be compared to the MATLAB and SIMULINK solutions so that the student have, in essence, "the answer at the back of the book".

Now comes the monkey wrench in the project! Each student is given his/her own individual MCK parameters and individual initial conditions of displacement and velocity. In this manner, each student has a different solution. This forces each student to "take ownership" of the solution to his/her problem. (The student can work with other students, but ultimately each must provide their own solution to their own particular system.)

The parameters of each model are very easily handled with private information of each student. The student's social security number (xxx-yy-zzzz) is used to define the mass, damping and stiffness and birth month and day are used for the initial displacement and velocity, respectively, according to Table 1. Note that the birth month is divided by 10 to provide displacements that are reasonable. Also, note that the SS numbers are rounded up for confidentiality.

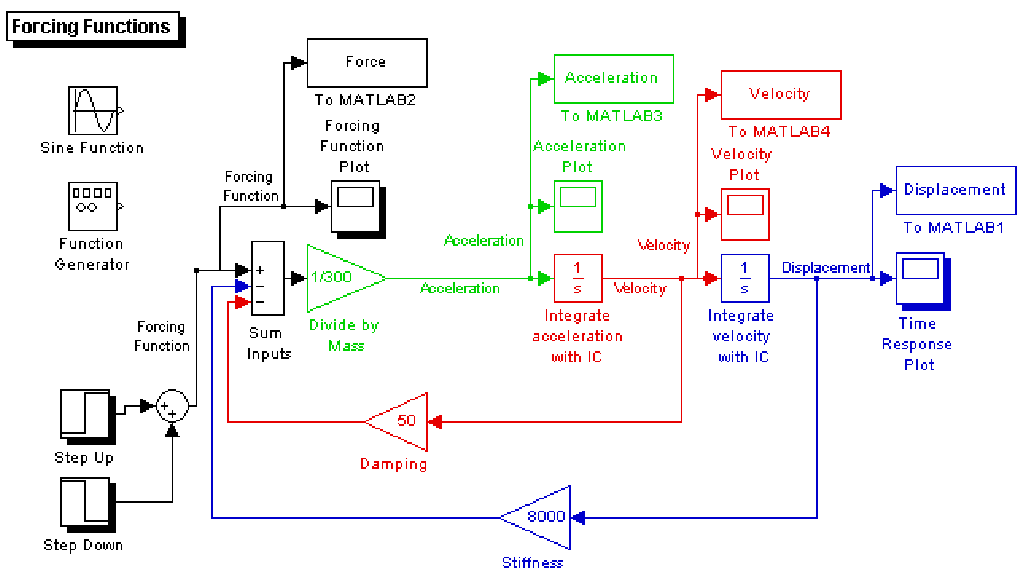
Table 1 – Parameters for Single Degree of Freedom Model

Social Security Number	***xxx***	***yy***	***zzzz***
System Characteristics	Mass	Damping	Stiffness
Birth month and birthday	***month***	***day***	
Initial displacement	month/10		
Initial velocity		day	

For example, SS 123-45-6789 with birthday of Feb 29th results in a model of

$$200\ddot{x} + 50\dot{x} + 7000x = f(t) \quad ; \quad x(0) = 0.2 \text{ inch and } \dot{x}(0) = 29\text{in/sec}$$

Working individually, the students reinforce their skills in basic mathematical techniques learned in earlier courses. In addition, new skills are developed to assemble both MATLAB and SIMULINK models to address any type of first and second order model. The students develop SIMULINK models that are useful for the solution of many dynamic system responses due to various loading situations as seen in Figure 2.



Simulink model block diagram for single degree of freedom mass, spring, dashpot system with unit impulse input.

Figure 2 – Typical Generic SIMULINK Model Developed

III.2 Evaluation of a Single DOF System and Cantilever Beam

The second project utilizes the tools developed in the first project. The students work in groups of three or four members and address the measured response of two simple mechanical systems. The first is a simple single DOF mass, spring dashpot system and the second is a cantilevered beam. The students are asked to measure the response of both systems due to impulsive or displacement inputs and then develop analytical models to characterize each system. Measurements are made using an assortment of different devices including strain gage, LVDT, eddy-current probe, laser, accelerometer, etc. These are all devices that have been used in assorted lab experiments from their Mechanical Engineering Laboratory courses. Therefore, the students are generally familiar with most, if not all, of these measuring devices. However, each of these measuring devices has its own personality (sensitivity to noise, drift, bias, and other measurement problems). In addition, the mechanical system to be measured has many of its own personality issues (some of which are not easy to address). Both mechanical systems are defined by some unknown physical characteristics. The simple single DOF system will be discussed first followed by the cantilever beam.

III.2.a Single DOF System

The simple mass, spring, dashpot system poses many hurdles in the development of the dynamic model of the system. The system is shown in a photo as well as schematically drawn in Figure 3. The moving mass characteristics must be determined. The exact materials are not given so the students have various mechanisms to determine the weight – the most obvious is to weigh the parts.

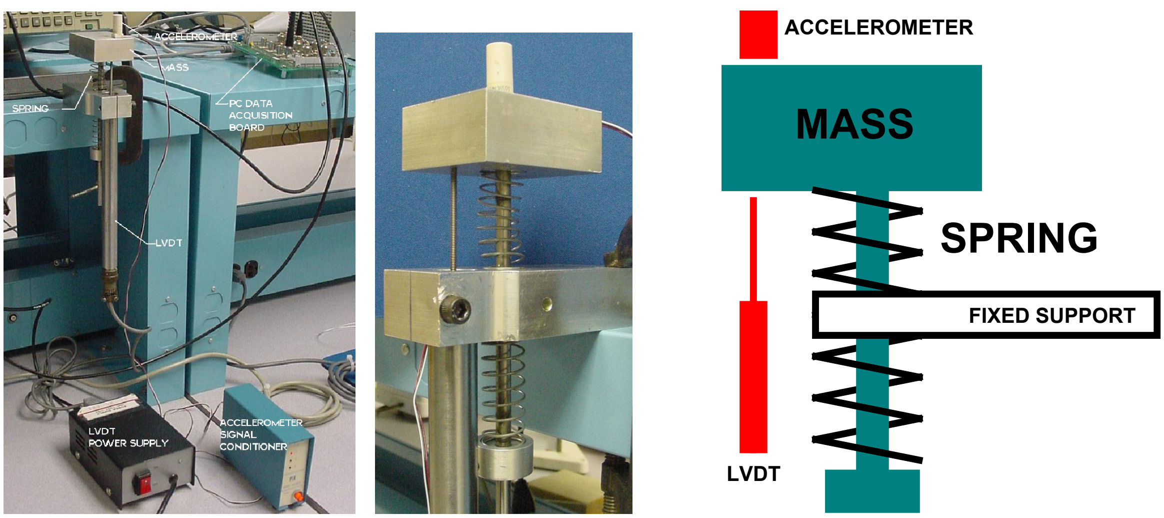


Figure 3 – Photo of MCK System along with Schematic of Configuration

However, many students do not recognize, at first, what is the actual moving mass of the system. They forget that the rod, collar, spring are part of the moving mass of the big block and also fail to recognize that the attached instrumentation has mass associated with the motion of the system! The spring stiffness can easily be determined in various ways but the students must decide on how to accomplish this. Last, but certainly not least, the students need to determine the damping effects of the bearing arrangement.

Up to this point, all of their analytical models have addressed very simplistic viscous damping. However, depending on the degree of lubrication in the bearing, some combination of viscous and frictional damping exists. At first assessment of the data, many students struggle with this reality. Generally, the professor is contacted (sometimes by email in the middle of the night) with questions of concern with the odd characteristic response. A sample of a response plot is shown in Figure 4 (email excerpts are not included due to some of the candid/colorful comments that come along with the plot). Of course, the role of the professor at this point is to further discuss/describe the physical phenomena observed. The data shown in Figure 4 also contains some obvious noise effects that later affect the numerical processing of the data.

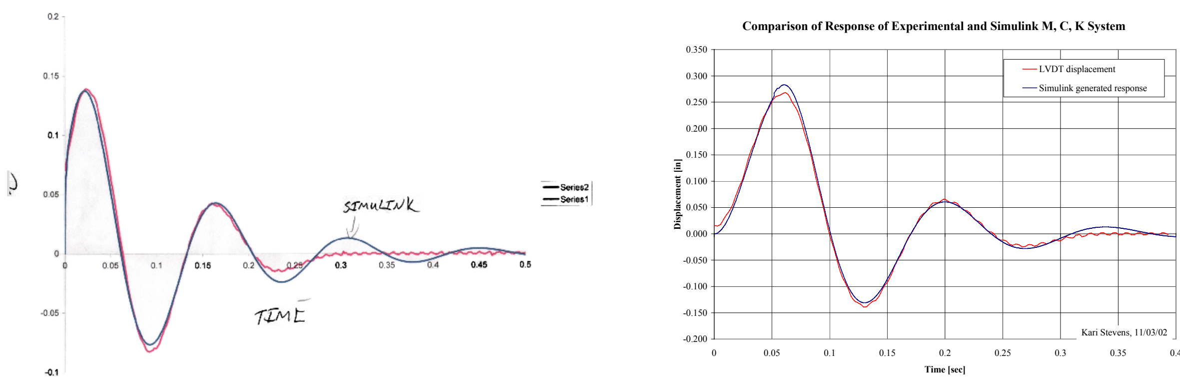


Figure 4 – Typical Plot of Response of the System

The students work with their data and make several different evaluations and try various approaches to describe the system based on different assumptions and starting points. (For instance, they could assume the mass is known/calculated, measure the frequency and calculate the stiffness.) The students often only take the minimum number of steps to find a solution. However, many forget to proceed further to check to make sure that the solution obtained is reasonable (is the assumed mass reasonable?). While the results of the natural frequency may compare, the physical characteristics of the system may not be believable.

III.2.b Cantilever Beam

The cantilever beam is actually much simpler than the single DOF system. The system is shown in a photo as well as schematically drawn in Figure 5. The moving mass characteristics must be determined. The exact materials are not given so the students need to determine both mass and stiffness characteristics. As in the single DOF system, many fail to recognize that the instrumentation mass has a significant effect in this case. The spring stiffness can be determined various ways - analytically or experimentally (but the students need to be reminded that they have already determined this characteristic experimentally as part of their Mechanical Engineering Laboratory courses). While damping is not a difficult item to determine in this case, many students are at times confused by the beam response which may be the result of more than just one mode of the system. (While the higher frequency is a small effect and not activated significantly, the students, at times, incorrectly identifies it as noise.)

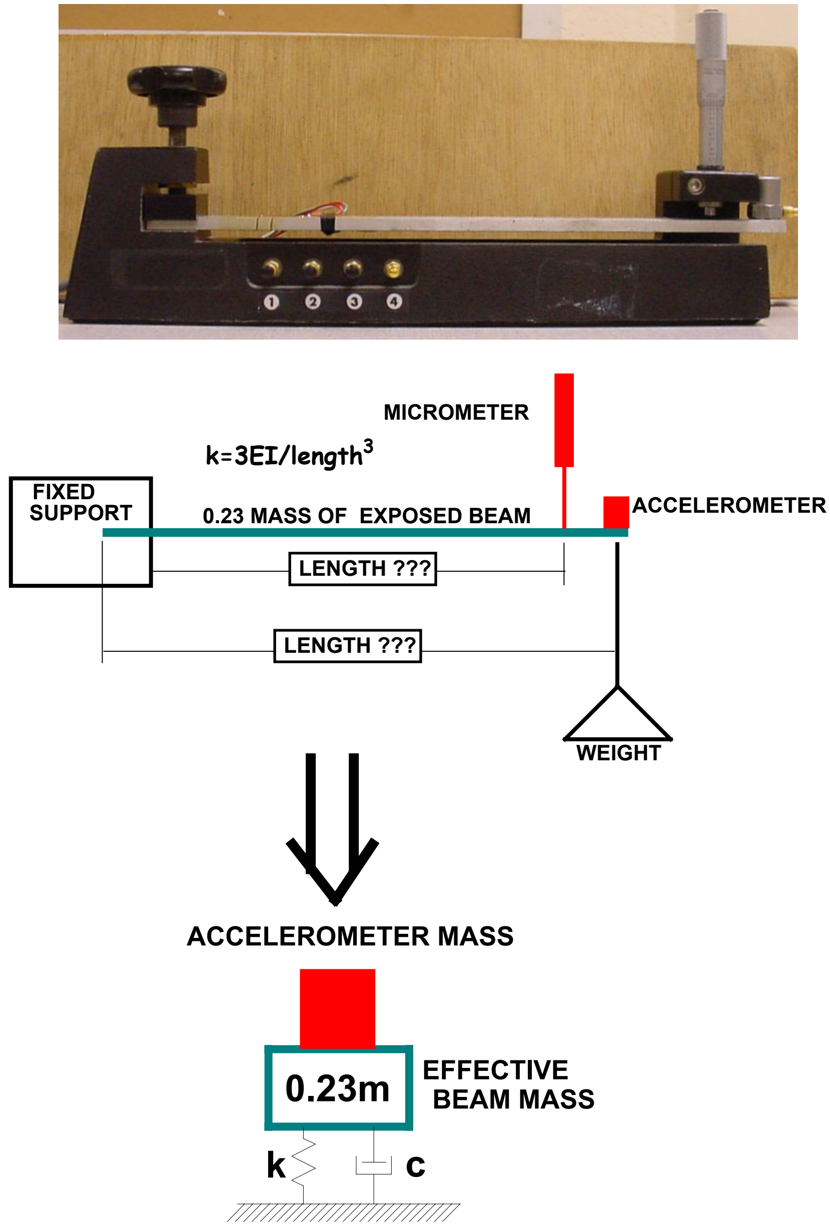


Figure 5 – Photo of Beam System along with Schematic of Configuration

A sample of a response plot is shown in Figure 6. The data shown in Figure 6 also contains some obvious effects of other modes of the system which can affect the numerical processing.

Again, the students make different attempts to identify the system characteristics and various approaches are utilized to completely describe the system from several different assumptions /starting points, then the system characteristics can be obtained. As before, the students often only take the minimum number of steps to find a solution. Many forget to proceed further to check to make sure that the solution obtained is reasonable. Again the results of the natural frequency may compare, the physical characteristics of the system may not be realizable.

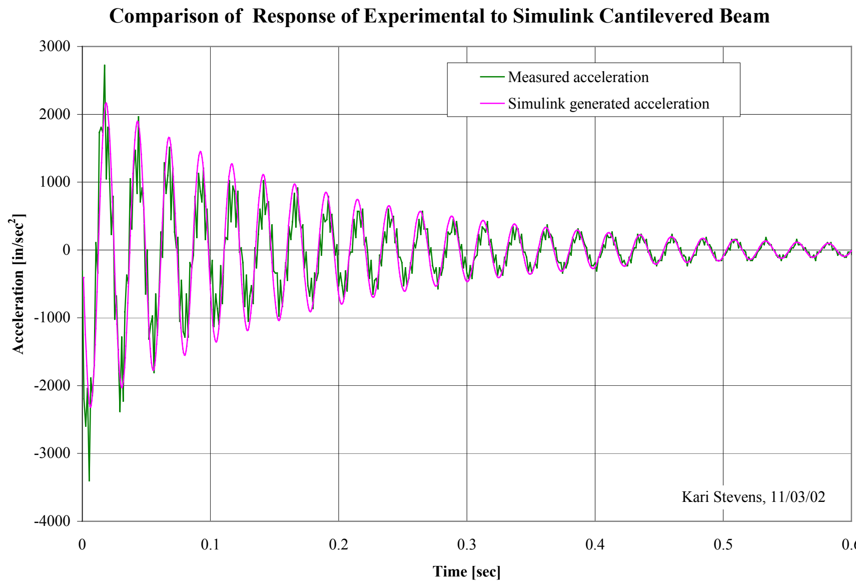


Figure 6 – Typical Plot of Response of the System

III.2.c Report Evaluation

Once the teams develop their group reports, the next step is evaluation of the reports. However, instead of the professor reviewing the reports, another twist is thrown into the process. Each report is anonymously given to another team to review. Each team must give a sincere, hard evaluation of the report assigned to them. Written comments are then orally discussed with the group. This effort is multi-fold and has numerous benefits.

The students get first hand experience in reviewing reports and determining adequacy of the report and material presented. Since each team has just evaluated the two systems, they are well equipped to critique the report assigned. Since all groups may not have necessarily used identical approaches for assessment of their systems, the groups learn alternate technical mechanisms for evaluation of the systems. Each group learns from the experience of this review process. Generally, the group evaluation is very candid and EXTREMELY critical of every mistake – no matter how important each mistake may be to the overall assessment of the system. Generally, the students all start to quickly realize how hard it is to write a report, how hard it is to review a report when material is not well organized, and how deficient each of their own reports may have been.

This review process has been found to be extremely useful for the student learning process as well as a reminder of how important it is to be clear, concise, accurate and to the point in generating technical reports. (This review process also serves as an aid to the professor since many errors are pointed out by the review teams in the preliminary evaluations.)

III.3 Evaluation of a First Order RC Circuit (Low Pass/High Pass Filters)

This project centers around the evaluation of a first order RC circuit. Excitations are applied to a variable resistance - capacitor circuit. The input-output time response is measured for evaluation. A SIMULINK model of the configuration is shown in Figure 7.

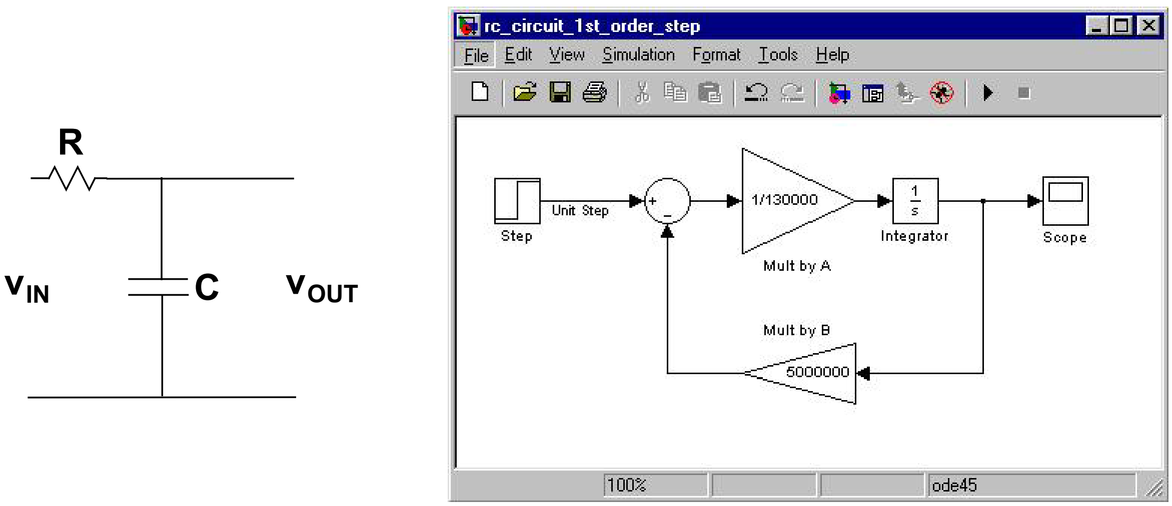
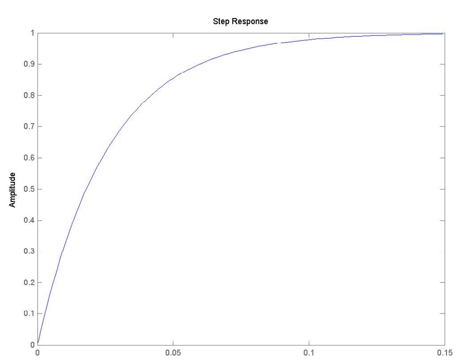
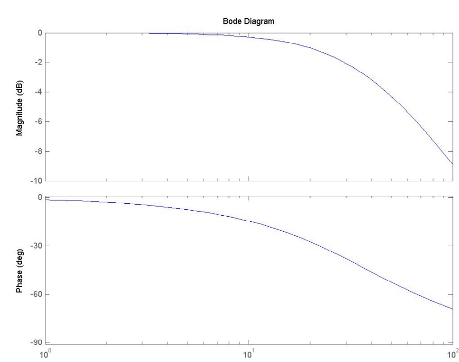


Figure 7 –RC Circuit and SIMULINK Model

The students collect time response data in order to estimate the time constant of the system. The system is exposed to a square wave step function to determine the response time of the system. This data is used to generate a SIMULINK model. At the same time that the system response time is measured, the students subject the circuit to a random excitation and record both the input and output signals. This data is then used with the FFT to compute the frequency response function. This measured response function is then compared to the MATLAB/SIMULINK model. Some typical time response and Bode plots are shown in Figure 8.



Time Response



Bode Plot

Figure 8 – MATLAB Time Response and Bode Plot for Variable RC Circuit

At this point the students realize that the RC circuit is nothing more than a low pass filter. The balance of the project is aimed at determining the filter characteristics. The cutoff frequency is identified. The students are then required to analytically identify the effects of the filter on various sine waves which are both above and below the cutoff frequency of the RC circuit low pass filter.

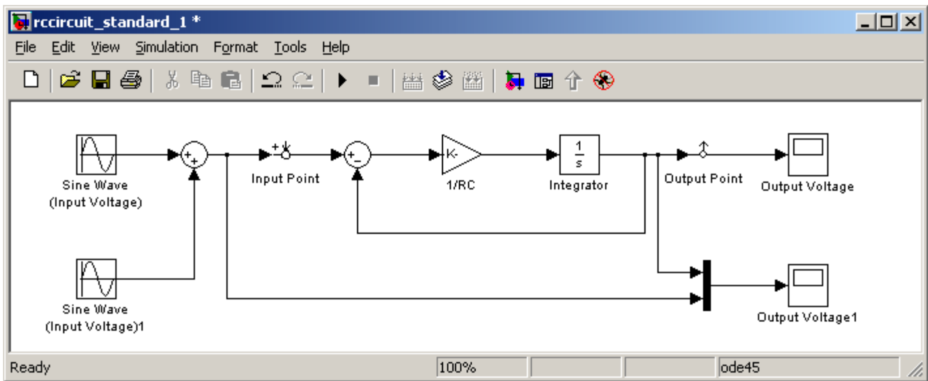


Figure 9 – SIMULINK Filter Effects on Sine Waves using the Variable RC Circuit

The RC circuit parameters are requested to assist in the filtering of the LVDT measurements made on the single DOF system which was contaminated with noise (such as 60 Hz noise). In addition, filter specifications are requested to design a high pass filter to remove any low frequency drift and bias errors that existed on either the single DOF system or on the cantilever beam. This project helps to close the loop on many issued identified in previous Mechanical Engineering Laboratory experimental that were plagued with noise, bias, drift, and other errors observed.

IV Student Observations and Candid Assessments

Several student observations along with candid student assessments of the overall project validate the overall goals of the integrated hands-on, project based assignments included as part of the Dynamic Systems course. These student comments are contained in this section.

Student #1 (Junior level status during course) – "As a recent transfer to the UMASS Lowell Mechanical Engineering program, my exposure to this type of hands on project was limited. Prior to this course, the important concepts of a particular subject did not necessarily "click" in the same semester in which I was taking the course. Many times I grasped the concepts in the following class which built upon the class I had just completed; this always left me feeling a semester behind. However, my experience in this Dynamic Systems course was different. In this course, the projects not only reinforced the material covered in lecture, but also went a few steps further by forcing us to think about which variables can affect the response of the systems we studied. These variables were not always intuitive and in order to obtain the correct response, they had to be addressed. The projects did not have simple solutions and involved interpretation of data, application of concepts discussed in lecture, and understanding of the physical system in the lab. Although I often struggled through each project, after obtaining the solution I had a much firmer understanding of the behavior of each of these systems. In addition, the opportunity to review the work of my peers was extremely valuable as it provided insights into their method of solution." -TJ

Student #2 (Junior level status during course) - "I almost always learn more completely when I do something as opposed to when someone instructs me. I believe relevant hands-on experience is much more effective than theory by itself. Struggling with a project makes me think harder and pursue other possible approaches to solving the problem. Project work forces me to learn the material to complete the assignment. This is not necessarily the case with homework problems taken from a book. When pressed for time, it is easy to copy the steps from examples and finish the assignment without understanding the problems. As a student, the ultimate goal is to learn the material so I can apply it once I graduate. These projects helped me understand the characteristics of a system and methods used to characterize dynamic systems. The group dynamics in project work are beneficial, as well. When members of our group disagreed, we were forced to dig deeper into what we were doing to find out who was right." - NW

Student #3 (Senior level status during course) - "This class has taken an approach to material presentation that is unlike any previous class. The theory and materials are presented in the class periods, and are driven home during project preparation. The projects have forced the students to indeed "think outside the box". This course curriculum has undoubtedly tied many ideas and previously learned material together. As a student that learns through hands on experience, as most students in this field are, I can say with conviction that due to the lab work associated with this class, I now understand the practical application of differential equations. As a part time student, it is common for there to be several semesters, sometimes years, separating Dynamic Systems from Differential Equations from Mechanical Engineering Laboratory. I have needed to spend time reviewing past material and I am now seeing this material in a new light. It is very fortunate that a class such as this is offered." - GSH

Student #4 (Senior level status during course) - "Admittedly, the Dynamic System course required more work and time than many other courses I had taken before it. However, the hands-on approach and struggling through the projects is exactly the process by which the information was absorbed – by not only learning, but really understanding. Very few engineering courses are successful at integrating information from previous semesters into a logical path to a problem solution. Granted, many of the previously covered skills had to be reviewed, and possibly relearned in some instances. However, after having used these skills in solving more realistic engineering problems, hopefully relearning will not be needed in the future. The only other courses that have left me feeling as in control of the information learned were the Mechanical Engineering Laboratories, in which use of transducers and measurement equipment became second nature. Understandably, this is for the same reasons as the Dynamic Systems course. Logical assumptions, trial and error, and asking one's self 'does this make sense' seem to be instinctive on the surface, however accepting that these are essential parts of engineering solutions and knowing how to use them wisely can only be developed in this type of realistic project setting. Likewise, working in groups of varying levels of understanding is required of professional engineers. One benefit of this course was that I learned that group members bring different qualities to the table. For example, while one member may not claim differential equations as a strong suit, that same member will notice the simplest, yet not the most obvious, method to determining the spring stiffness. This aspect of different points of view is also beneficial in the peer review process. Sometimes students find one solution to the problem and believe that it is the only solution. However, the during the peer reviews you find yourself thinking 'why didn't I think of that?'. In all, the time consumption and hard work paid off in not only learning the required information, but in understanding the engineering problem solving process much better." -KW

<u>Student #5</u> (Senior level status during course) - "With regards to previous course material (such as differential equations), it was very helpful to actually be forced to use earlier course material - I had to find my differential equations notebook and review some material before completing the first project. I feel that differential equations in particular is taught and then never used again, so that its significance is not clear until needed in this Dynamic Systems course."

"The development of both Matlab and Simulink to confirm analytical results was very useful. While the professor 'strongly suggested' that it would be helpful to use these models to study variation of parameters and types of inputs, I feel that it would have been helpful to have homework assignments requiring this to be performed; as all the students are very busy, it is 'put off' this important but 'not required' task."

"In terms of laboratory work requiring collection of data, this definitely helped me understand that these problems are not as simple as they might seem! In homework assignments, specific physical values are assigned to problems but when we actually have to find these values ourselves based on physical measurements of the system, and compare analytical models to measured results, we have a greater understanding of how imprecise this can be. For example, all of the calculations performed assume viscous damping, and in the mass-spring-dashpot system part of the damping is actually friction. We don't have a clear understanding of the error that can be caused by this assumption until we actually see the results. We also become aware that there are multiple ways to determine the system characteristics of a physical system, and the importance of using multiple methods and comparing the results. Problems that seem easy when you do the homework at the end of a chapter in the text actually turn out to be much more complicated in practice – you are forced to really think about the material and how it all fits together"

"The peer review of other group project reports actually was quite enlightening. This should be done about three years earlier in our curriculum! I definitely think that more time should be spent on technical report writing. It was helpful look for mistakes in other students' papers to understand the importance of clear writing, as well as to see other ways of approaching the problem solution. I do think that it would have been useful to actually read the comments written by the group that reviewed our paper. This would 'close the loop' on the review process." -TVZ

V Professor Observations and Assessments Made

Several items can clearly be identified in terms of student overall performance from the professor's standpoint. As the students work on the projects assigned, questions arise to which they seek guidance from the professor. The questions generally tend to be well posed. As the students work on the project, they begin to take ownership of the project. The project is no longer a homework assignment of unrelated material. The students tend to assemble knowledge related to the problem at hand. Students query aspects of the problem with confidence. They rattle off equations related to the problem with true understanding – not just memorization of disjointed pieces of information. This knowledge results from an intimate understanding of the data collected and desire to solve the problem.

While all of the students "moan and groan" relative to the amount of work required for the project, they work hard and devote well-spent time to solve the problem as best as they can. But ALL of the students agree that the project is a critical part of the course and they would not learn as much if the project were not included.

From the student perspective, ad hoc discussions indicate that they feel that it is imperative that the first project must remain an individual effort. The reasoning is that this way every student comes to the second project with all the skills and tools necessary to work on subsequent pieces of the various projects. In this way, each member of the team is assured to be able to provide equal support to the team overall. The following projects require more effort and a team effort is considered necessary by the students. But with all the skills in place resulting from the first project, each team member is guaranteed to be able to provide reasonable support to tackle the latter projects.

While ad hoc assessments are invaluable, several more formal assessments have been conducted for the overall redefinition of the Dynamic Systems class and newly introduced project based assignments to supplement the course. Formal assessments have been given to the students that have taken the newly revised Dynamic Systems course. In terms of understanding Ordinary Differential Equations after completing that course, 48% felt that they had a vague understanding on the material overall and 45% felt they understood the material well. Upon completing the Dynamic Systems course (which instituted the new hands-on, laboratory-based open-ended project with a substantial review of ODE, Laplace, etc), more than 75% stated that they understood the basic ODE, Laplace, etc. well and the remaining 25% stated that they understood the material very well. When asked if the project were not included how well would they understand the material, over 45% responded that they would probably only vaguely understand how to solve a dynamic system problem. When asked if the project challenged them, 85% felt that the problem was significant and pushed them to be creative in solving the problem. Over 75% of the students felt that the physical measurement tremendously enhanced their understanding of the problem. And when asked if the project should remain as part of the course, 85% felt that it was a critical part of the course and is necessary in order to firmly instill the underlying STEM concepts (even though 100% of the students stated that it was a significant burden in terms of workload).

VI Summary

A new hands-on, laboratory-based project has been added as a supplement to a traditional senior level Dynamic Systems course. The students tend to better understand the material as evidenced from overall capabilities and student comments regarding how they feel with respect to their overall understanding of the material. The discussion and presentation of the material needed for a Dynamic Systems course is still presented in a traditional classroom environment. However, the hands-on, laboratory-based project helps the students to better understand the basic core STEM material necessary for solving these types of problems. The students appear to better understand the material overall through "living the material" rather than learning/memorizing equations that do not appear to have any practical relevance. Student comments relative to inclusion of the project were overwhelming positive. The students feel that the project is a critical part of the course that helped them to better understand all the material presented in the Dynamic Systems course as well as material in related courses.

VII Acknowledgement

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