2006-734: AN INTERWOVEN MULTISEMESTER DYNAMIC SYSTEMS PROJECT TO INTEGRATE STEM MATERIAL

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AN INTERWOVEN MULTISEMESTER DYNAMIC SYSTEMS PROJECT TO INTEGRATE STEM MATERIAL

Abstract

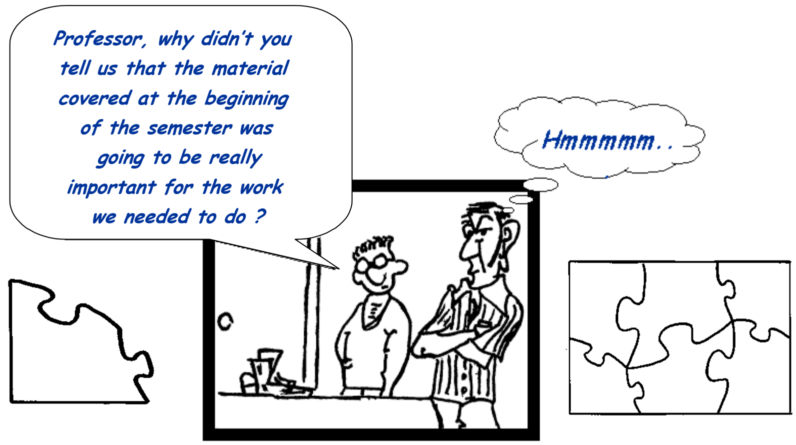
Students generally do not understand how basic math and science material fits into all of their engineering courses. Because they have no clear-cut reason to embrace these concepts, the students hit the "reset button" after each and every course. This often comes back to haunt the students in subsequent upper level classes which require a firm understanding of this material.

A new multisemester interwoven dynamic systems project has been initiated to better integrate the material from differential equations, mathematical methods, laboratory measurements and dynamic systems across several semesters/courses so that the students can better understand the relationship of basic math and engineering material to an ongoing problem. This is emphasized with tutorial materials using graphical user interface (GUI) modules to instill concepts. Several experimental systems (including first and second order response) are used to illustrate many of these concepts in an interwoven fashion.

These materials have been implemented in the Mechanical Engineering curriculum at UMASS Lowell for the Mathematical Methods course, two Mechanical Engineering Laboratory courses and a Dynamic Systems course. The materials have also been extended and implemented in both the Mathematics Department and Chemical Engineering Department at UMASS Lowell. Also, the materials have been adapted and implemented in three courses at Michigan Technological University in the Mechanical Engineering Department. This paper highlights the overall concept underlying the new approach. A description of the project and modules (analytical and experimental) under development is presented.

Introduction (or Motivation)

Many students do not understand the need for basic STEM (Science, Technology, Engineering and Mathematics) material that is critical to the solution of engineering problems. Closely related material may be spread out over several courses. By the nature of the structure of semesters (or quarters), material is grouped together into logical units to allow for material to be deployed in a controlled fashion with specific timetable that integrates the material in the student's academic career. Unfortunately, students don't understand this. As far as they are concerned, the material does not appear to have any connection to other material from previous courses. This then makes the material appear to be unimportant. Students naturally tend to hit the "reset button" after each and every course since there is no apparent reason to want to actively retain the information. All professors encounter this problem as depicted in Figure 1.



Student views material in a disjointed fashion

Professor clearly sees how pieces fit together

Figure 1 – Professor vs. Student View of Material Presented

In order for STEM material to become an integral part of the student's knowledge base throughout their entire educational and professional careers, the students must, in essence, "live the material" every day and in every course [1-5]. To foster this approach, material must be presented in a more cohesive fashion.

Basic Concepts (or Goals and Objectives)

Different approaches (i.e., ODE, Laplace, Fourier, Numerical Methods, etc) can be used to solve the same problem. Unfortunately, these are covered in different courses and often the inter-relationship is not emphasized. What typically happens is that the students don't see the connections between these methods because each technique is applied to a different problem [2]. In order to help the students understand the application of each technique, the same generic problem needs to be incorporated into each course. By showing the application of each technique to the same problem, the resulting similarities and differences can be seen. The basic underlying concept of this effort is to present material in a more cohesive fashion with integration of materials and concepts interwoven between related courses. This fosters student comprehension so they can better grasp the inter-relationship of the basic STEM material. In order to accomplish this, simple first and second order systems are used. These are generic to all engineering problems. From these two simple systems, an array of inter-related concepts can be deployed. A concept schematic showing various pieces of interrelated material is presented in Figure 2. The figure shows various aspects of different approaches to solve the dynamic response of a simple cantilever beam. All the material shown is important for solving dynamic system problems.

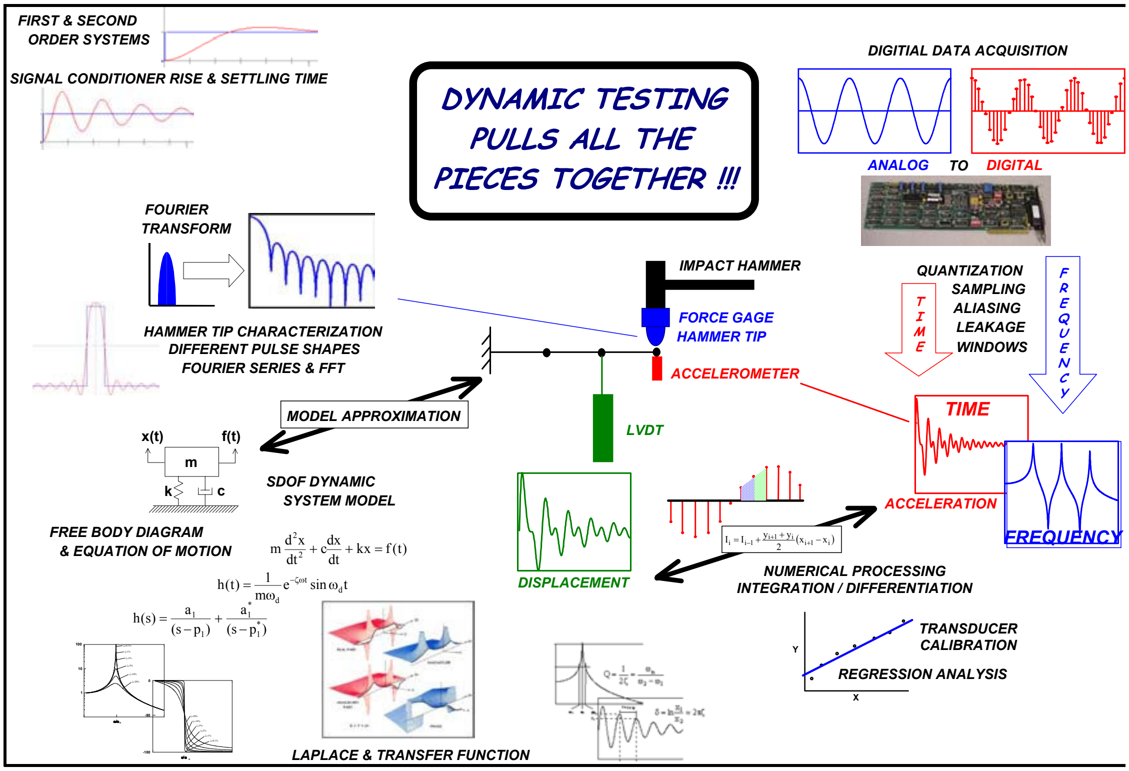


Figure 2 – Concept Schematic of Interwoven Material

Structured and designed correctly, the interwoven, multi-semester problem has numerous features of differential equations, Fourier/Laplace transforms, and numerical processing of both time and frequency data (which can consist of both simulated analytical data and actual measured experimental data). The lab component of this problem can introduce instrumentation/signal conditioning, calibration, analog and digital data acquisition systems, time and frequency data (FFT), impulse response/frequency response, rise time and settling time in both instrumentation and actual structural systems, as well as considerations of transducer design to measure the desired characteristics of a dynamic system.

Generally, a well-behaved analytical model can provide very useful “virtual” data for the students to understand and comprehend data. This “well-behaved” data is extremely useful since the model used to develop the data can be perturbed and modified to simulate a variety of different effects that can typically be observed in real data. Note that real data can always be obtained but generally has many contaminants that are simultaneously applied and therefore the student may not be able to interpret the data easily with many effects superimposed.

While the evaluation of “well-behaved” analytical data is the cornerstone of the student’s understanding of how to process data and develop analytical models, experimental issues pertaining to “real” data quickly illustrate the need to employ all the STEM tools [6].

The efforts of this work are directed towards the development of a new, creative approach to address student understanding of related material in different courses through the use of a multi-semester interwoven project to reinforce basic STEM material which is critical to solving dynamic systems problems. A strong laboratory component with multimedia and hands-on application of STEM material will reinforce theoretical concepts. These are broken down into analytical related topics presented first followed by experimental topics.

Analytical Materials Developed

In order to develop the multisemester integrated approach, a series of inter-related tutorials covering a variety of pertinent materials were created to address first and second order systems. These materials are intended to address mechanical systems from an analytical standpoint as well as the measurement of those analytical systems which then introduce electrical signal conditioning/measurement issues that also involve first and second order systems. These materials can be roughly broken down as:

Theoretical Aspects of First and Second Order Systems
First Order Systems
- Modeling Step Response with ODE and Block Diagram

Second Order Systems
- Modeling Step, Impulse, and Initial Condition with ODE and Block Diagrams

Mathematical Modeling Considerations
- Fourier Series, Integration/Differentiation, Regression Analysis

Miscellaneous Materials
- Simulink and MATLAB Primer Materials
- LabVIEW Tutorial Materials
- Virtual Measurement Modeling Simulations
- Integration/Differentiation Considerations with Contaminated Data Sets

Many of the tutorials are supplemented with MATLAB and Simulink scripts as well as LabVIEW modules. Both MATLAB and LabVIEW have been used to generate Graphical User Interfaces (GUI). A GUI allows for the easy adjustment of parameters so that the student can explore various system parameters and the effects on system response. A brief description of each of the tutorials and GUIs is presented below.

Theoretical Aspects of First and Second Order Systems – This covers a basic overview of the underlying information regarding the classical treatment of this material.

First Order Systems – Modeling Step Response with ODE and Block Diagrams

Response of First Order Systems – Step Response – Covers basic development of a model for a first order system. A MATLAB script with variable parameter selection via a GUI allows the user to explore parameters. A companion LabVIEW GUI model is also available.

Block Diagram Modeling of First Order Systems – Covers basic development of a first order block diagram model. A block diagram using Simulink is the end result of this tutorial. The user can vary parameters in Simulink to explore the effects of parameter variation.

Filtering using RC Circuits – Covers basic development of a first order system using the frequency domain rather than the time domain response approach. Concepts of time response, cutoff frequency, and roll-off are described and the filter effect on simple sine wave is introduced. A MATLAB script with variable parameter selection via a GUI is available. A companion LabVIEW GUI model is also available.

Second Order Systems – Modeling Step, Impulse, and Initial Condition Responses with ODE and Block Diagrams

Response of Second Order Systems – Step, Impulse and Initial Conditions - Covers basic development of a model for a second order system. A MATLAB script with variable parameter selection via a GUI allows the user to explore parameters. A companion LabVIEW GUI model is also available.

Block Diagram Modeling of Second Order Systems – Covers basic development of a second order block model. A block diagram using Simulink is the end result of this tutorial. A MATLAB script with variable parameter selection via a GUI allows the user to explore parameters.

Mathematical Modeling Considerations

Fourier Series Tutorial – Covers basic concepts of generating a set of Fourier series terms to approximate general waveforms. A Simulink script with variable Fourier series term selection via a MATLAB GUI allows the user to explore the generation of arbitrary waveforms in addition to the specific values used in the tutorial.

Numerical Integration/Differentiation Tutorial – Covers basic concepts of general integration and differentiation of second order system response of displacement, velocity and acceleration. A MATLAB/Simulink GUI is available which also explores the effect of noise, bias, and drift in numerical processing.

Regression Analysis Tutorial – Covers basic concepts of generation of least squares error fit of a set of data fitting multiple curves over different regimes of the data considered. A

MATLAB GUI allows the user to easily select different data sets, and model order, and select/deselect points to view the effect on the computed analytical model.

Miscellaneous Materials

Virtual Measurement System – Covers basic concepts of measurements that can be obtained from second order systems; provides a MATLAB/Simulink GUI that allows the user to specify the second order analytical model and then introduce common measurement errors such as noise, bias error, drift, and offset on the analytical data for both acceleration and displacement measurements (commonly made with an accelerometer and LVDT, respectively). This tutorial pulls together all the pieces of the other tutorials and provides a virtual representation of an actual measurement system as encountered in the laboratory. This enables the students to provide some control on how "experimental parameters" contaminate their analytical model output and allows them to study the basic underlying effects in a very controlled fashion.

Numerical Integration and Differentiation Comparison – Allows for the comparison of differentiated or integrated signals that are contaminated by noise, drift, bias and other measurement problems. A MATLAB GUI allows the user to vary many of the contaminating parameters that are added to the analytical model. The GUI allows the user to differentiate or integrate both the pure analytical and the "contaminated" signal to see the effects of distortion when processing data.

S-Plane 3D Frequency Response Function – Allows the user to explore the S-Plane through a GUI interface to see the effects of parameters on the system characteristics. A MATLAB GUI allows the user to explore the complex frequency response function (Re, Im, Mg, Ph) to see the effects of parameters on the system characteristics.

Simulink and MATLAB Primer Materials –
- Basic Tutorial on the Use of Simulink
- Importing and Exporting Data from MATLAB and Simulink to Excel
- Using State Space and Transfer Function Blocks in Simulink
- Modeling an Impulse in Simulink
- Use of the LTI Viewer and MUX Blocks in Simulink

LabVIEW Tutorial Materials –
- Basic LabVIEW model development
- Tutorial material on LabVIEW features for Fourier Series project development

Several of the MATLAB and Simulink GUI scripts are presented to illustrate some of the features available to assist the student in understanding the problems faced when actual measurements are acquired; LabVIEW GUIs are also presented. The other tutorials also have either MATLAB or Simulink GUI scripts to allow the student to further explore the material in the tutorial.

Sample MATLAB and Simulink GUI Scripts

Several different MATLAB and Simulink GUI script files that are associated with the tutorial material are presented below; in addition, several similar LabVIEW modules also exist.

Single DOF Complex Frequency Response Function (FRF) Plot

The definition of a complex frequency response function requires students to clearly understand complex numbers as represented in the frequency domain. Sometimes there is confusion regarding this in the student's mind. Representation in terms of magnitude/phase vs. real/imaginary are easy once a student becomes accustomed to this notation. A MATLAB GUI is provided that allows the students to specify the mass, damping and stiffness values of a single degree of freedom mechanical system; the values can be easily adjusted via keyboard entry or scroll bar. The frequency and damping of the system are reported along with complex frequency response plots. The MATLAB GUI is shown in Figure 3.

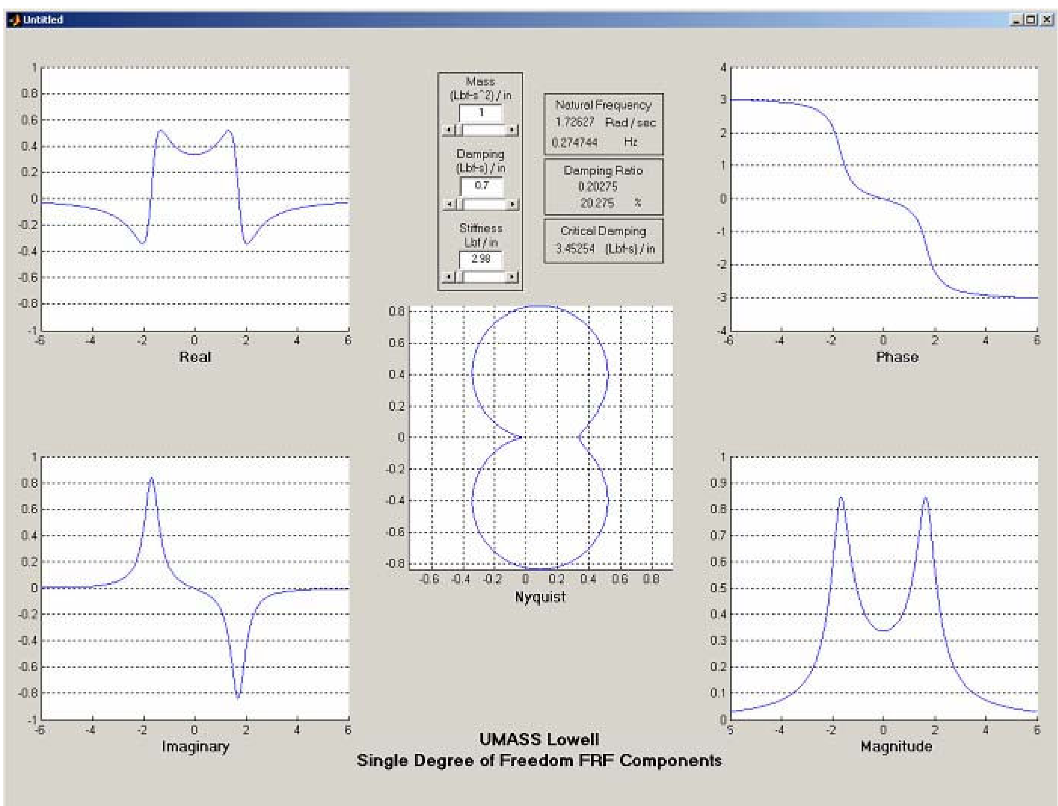


Figure 3 - Single DOF Complex FRF Plot GUI

Fourier Series Signal Generator

Fourier series are an important concept in the processing of time and frequency data. This mathematical concept is taught but the application is often not understood by students until an upper level course or practical example presents itself. A Simulink GUI is provided which allows the student to specify the terms of the Fourier series and see the resulting time signal. The user enters frequency, amplitude and phase components of a user defined signal to display the resulting signal; the values can be easily adjusted via keyboard entry or scroll bar. The user can also select sample signals such as square, triangle, etc and the pre-determined Fourier coefficients are applied to the user-defined signal. The time signal as well as the corresponding frequency component are displayed. The Simulink GUI is shown in Figure 4.

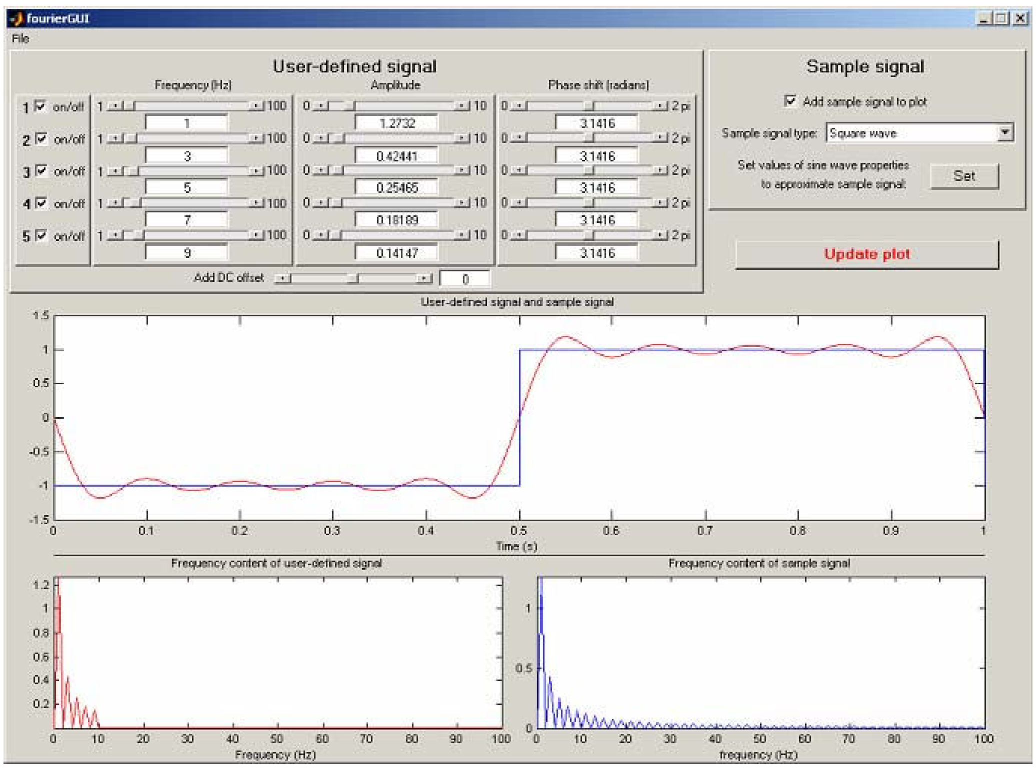


Figure 4 - Fourier Series Signal Generation GUI

In addition to the MATLAB/Simulink GUI, a companion LabVIEW GUI on Fourier Series is also available for student use. A LabVIEW tutorial is also available to guide the students to develop their own LabVIEW FFT GUI. This enables the students to comprehend the entire process of the time to frequency transformation process. The tutorial has the students develop a single sine wave and its FFT to clearly identify important aspects of this transformation process. The tutorial then leads the students through the addition of harmonic distortion components to the primary sine wave. This then becomes the prelude to the development of a square wave from the summation of Fourier coefficients. While the ultimate goal is to understand the time-frequency relationships and the FFT process, the tutorial reinforces these important concepts by having the students “doing” rather than “listening” [6] which has been shown to provide deeper learning and understanding of material.

First Order Low Pass Filter

The definition of a 1st order system is fairly straightforward. However, the frequency filter characteristics are not so obvious from a traditional time constant representation. Students (and sometimes engineers in industry) will remark that they didn't really realize just how much attenuation and phase shift really occurs in the low pass filter – 3 dB sounds very innocent until the actual plot characteristics are displayed. A very simple MATLAB GUI is provided that allows the students to specify the time constant of the filter and the excitation/source sinusoidal frequency; the values can be easily adjusted via keyboard entry or scroll bar values. The Bode plot (magnitude/phase) is displayed (with the cutoff frequency) along with the original and filtered time signal. A similar LabVIEW GUI is also available. The MATLAB GUI and LabVIEW GUI are shown in Figure 5.

Second Order System Step Response

The step response of a simple second order mass-spring-dashpot system is studied with the MATLAB GUI shown in Figure 6. A companion LabVIEW GUI is also available and is shown in Figure 6 also. The students specify the mass, damping and stiffness values of a single degree of freedom mechanical system; the values can be easily adjusted via keyboard entry or scroll bar. The frequency, damping, critical damping, etc. of the system are reported along with plots of the time response, frequency response and the root locus plot. As values are changed the plots update and the location of the poles in the s-plane is easily observed.

Virtual Measurement System GUI

The interpretation of an actual measurement can be an overpowering experience to a novice student. There are numerous measurement issues that contaminate the expected response of the system that are related to instrumentation and transducer considerations. In order to assist the student in deciphering the data, an analytical model is developed and then "controlled" contamination signals are added to the known analytical response. Both acceleration and displacement measurements are included in this evaluation. These are typical measurements that are collected in the field and are often contaminated by various factors. Since controlled effects are included in the simulation, the distortion is more easily identified and understood. In this way, the students gain first hand experience interpreting the information collected and gain a better understanding as to how to process the data.

The virtual representation of an actual measurement system is accomplished with the Simulink GUI shown in Figure 7. The students specify the mass, damping and stiffness values of a single degree of freedom mechanical system; the values can be easily adjusted via keyboard entry or scroll bar. The sensitivity of a displacement measuring device and an accelerometer are included along with possible contamination of the measured signals due to noise, bias, drift and other problems. The contaminated displacement and acceleration signals can then be saved/plotted and compared to other virtual measurements. This virtual measurement system is a complete representation of the entire measurement process and contains features from the other tutorials and simulations that are presented individually.

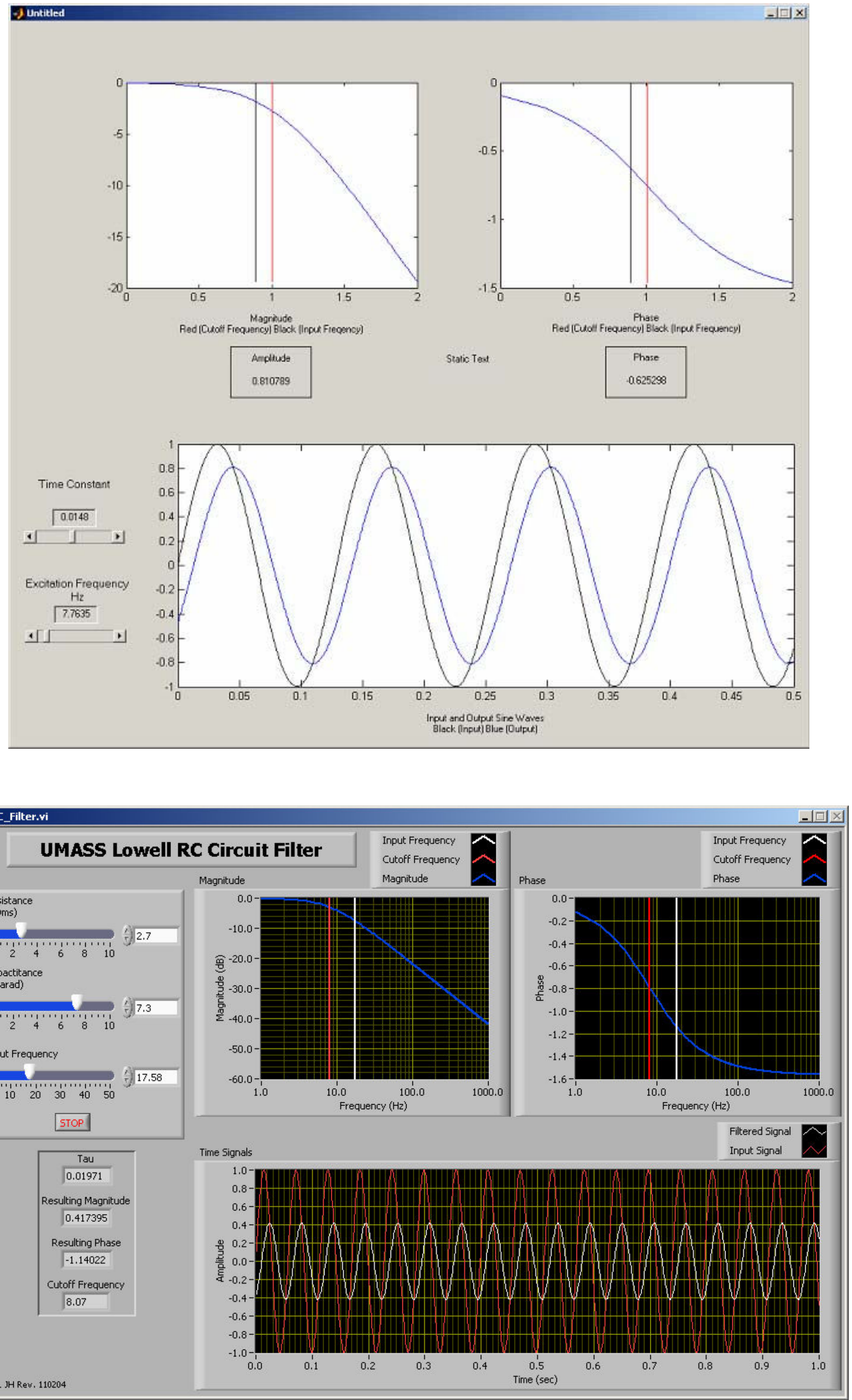


Figure 5 - First Order Low Pass Filter GUI - MATLAB (top) and LabVIEW (bottom)

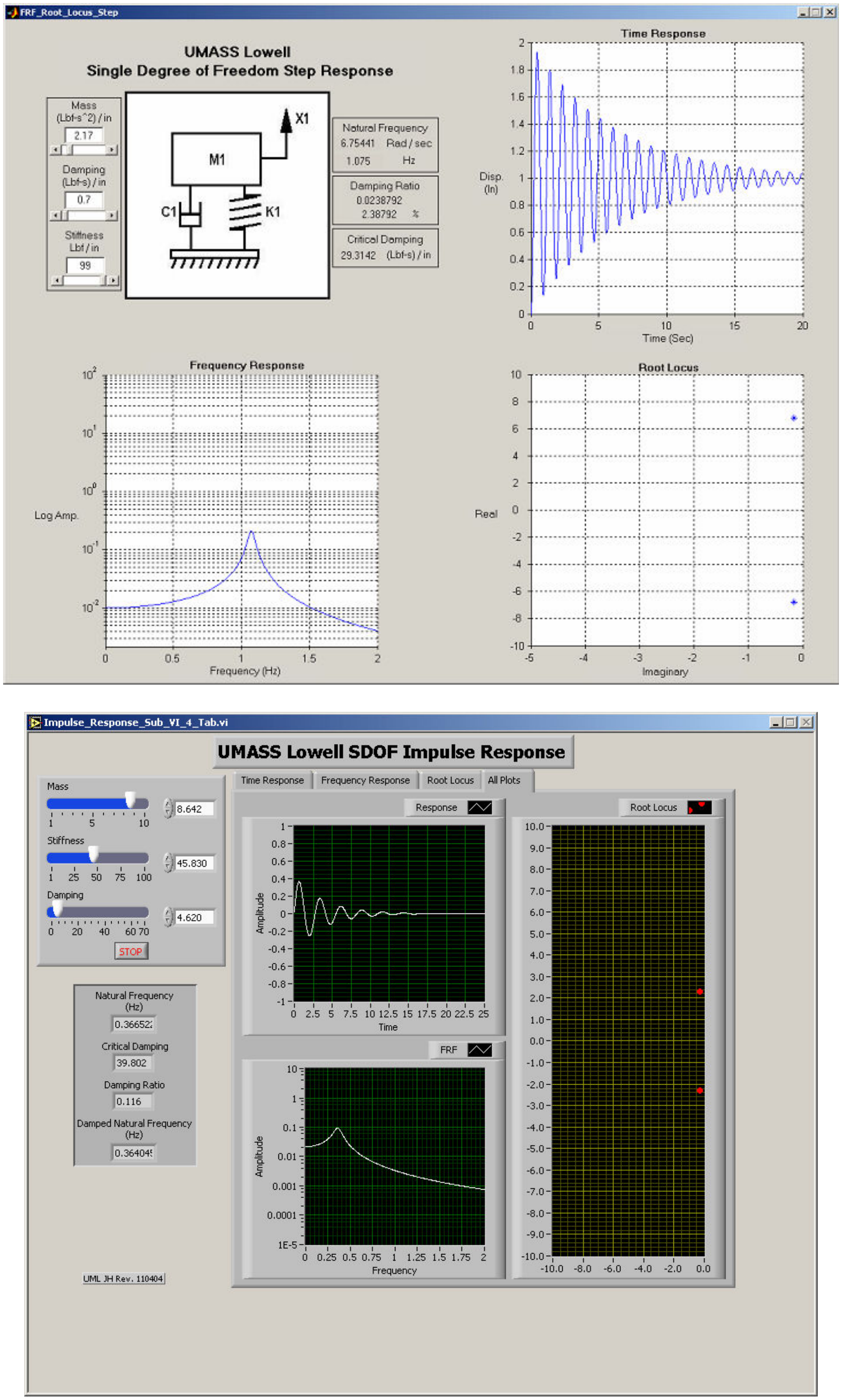


Figure 6 - Second Order System Step Response GUI - MATLAB (top) and LabVIEW (bottom)

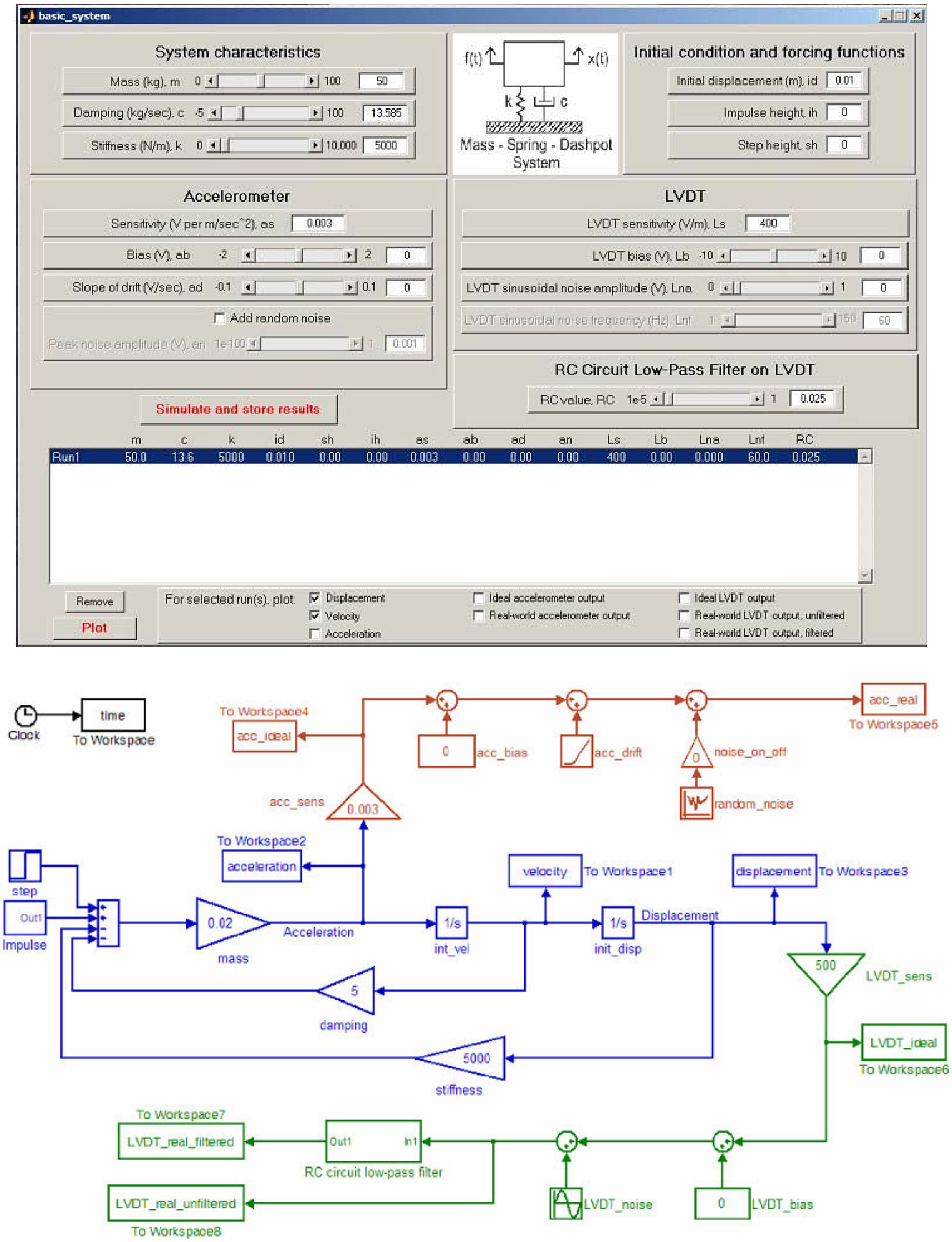


Figure 7 - Virtual Representation of an Actual Measurement System GUI

Numerical Integration and Differentiation GUI

The processing of measured data can seem overwhelming, especially when measured data is contaminated by real world measurement problems. There are numerous measurement issues that contaminate the actual response of the system which are related to instrumentation and transducer considerations as well as noise. In order to assist the student in deciphering the data, analytical data is used as a baseline and measurement effects typically observed are added to "contaminate" the actual signal. The types of "controlled" contaminations that can be added to the signal are bias, drift, random noise, and sinusoidal noise. The actual signal and "contaminated" signal are displayed in an overlay plot and then the differentiated or integrated signal are displayed in a separate overlay plot. Since the effects added to the measurement are known, the student can easily see how the data is affected by any distortion in the processed data.

The processing is accomplished with the MATLAB GUI shown in Figure 8. The students specify the amount of distortion to contaminate their signals via keyboard entry or a scroll bar.

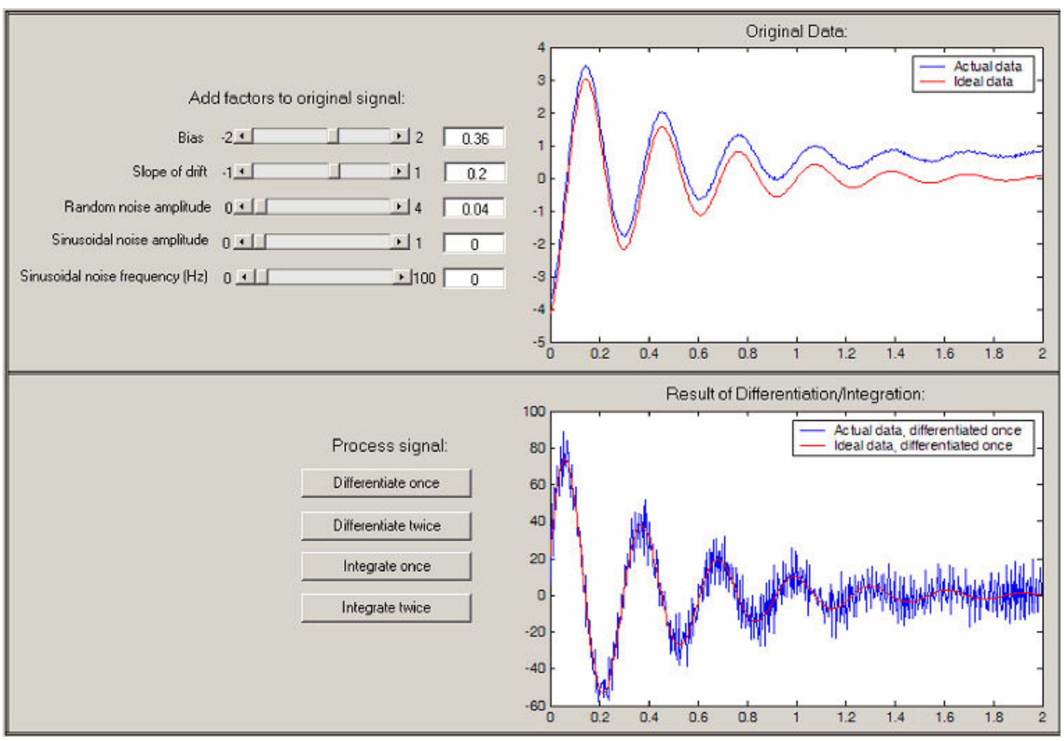


Figure 8 - Virtual Representation of an Actual Measurement System GUI

Experimental Online Measurement System Developed

To complement the analytical tools developed and to provide access to data for further exploration of first and second order systems, an online data acquisition system was developed. The system consists of a simple mass-spring-dashpot system that is instrumented to measure its response due to initial conditions or an impulsive force.

The online data acquisition system has been designed to have several unique features in terms of its overall performance. The system is designed to have both variable mass and variable stiffness characteristics which change every time the system is started by a remote user. This guarantees that the system is not known and can be used time and time again by the same student. The student can then utilize all of their knowledge and skills to determine the system characteristics and deal with the issues related to data which is not always perfect and is contaminated by a variety of features inherent in transducers, their signal conditioners and noise. A diagram of the basic system, RUBE (Response Under Basic Excitation), is shown in Figure 9. The system is available as an online experiment. Students have access to the experiment over the internet using a LabVIEW Web-based Interface. A photo and sketch of the system and a screen capture of the LabVIEW Interface are shown in Figure 10.

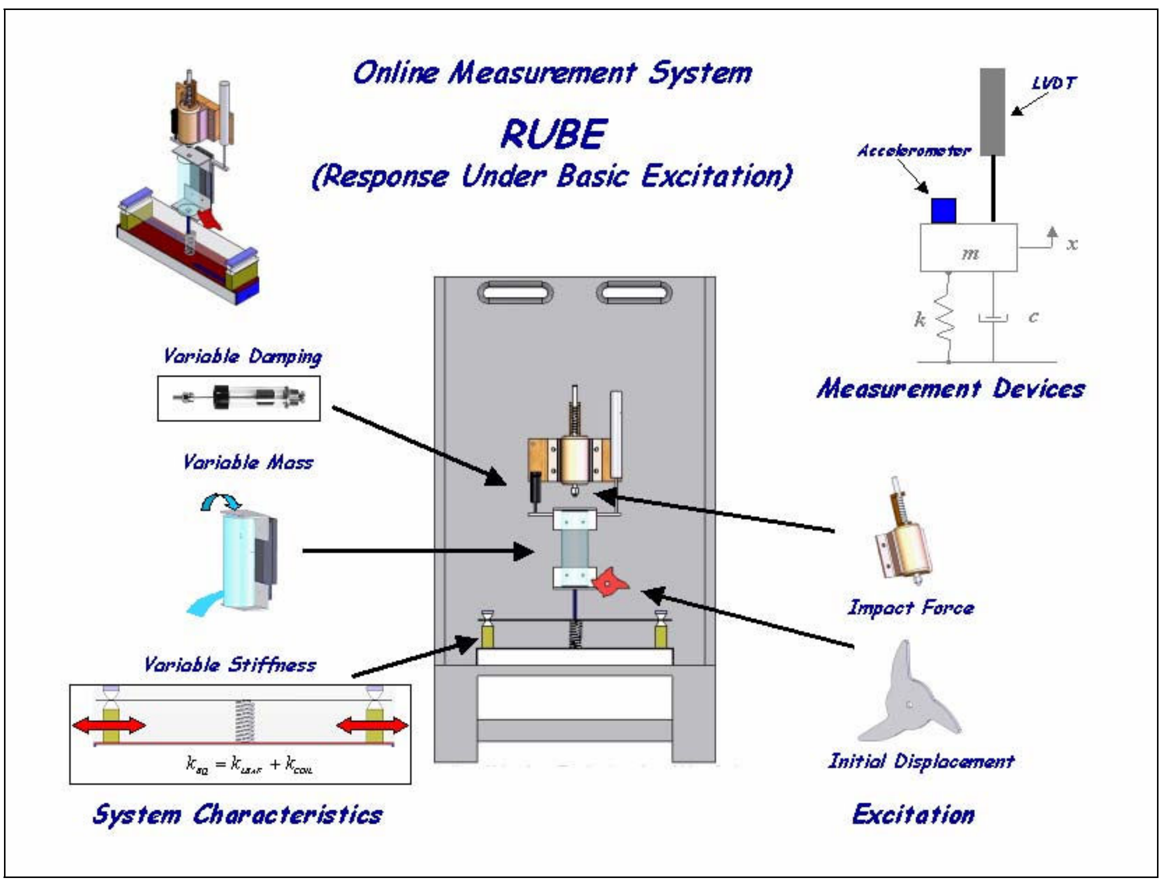


Figure 9 – Schematic of the Various Components of the Online Measurement System

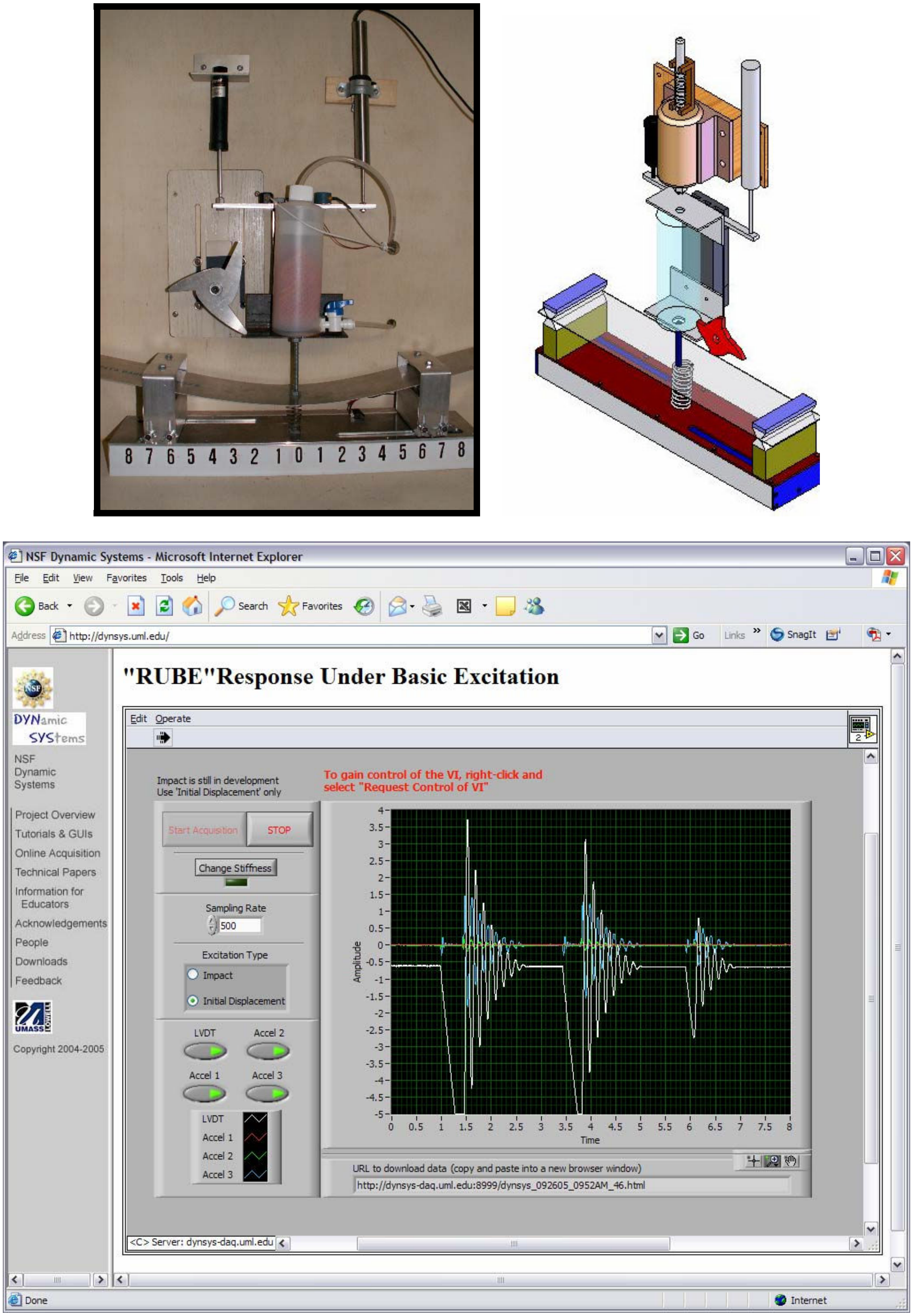
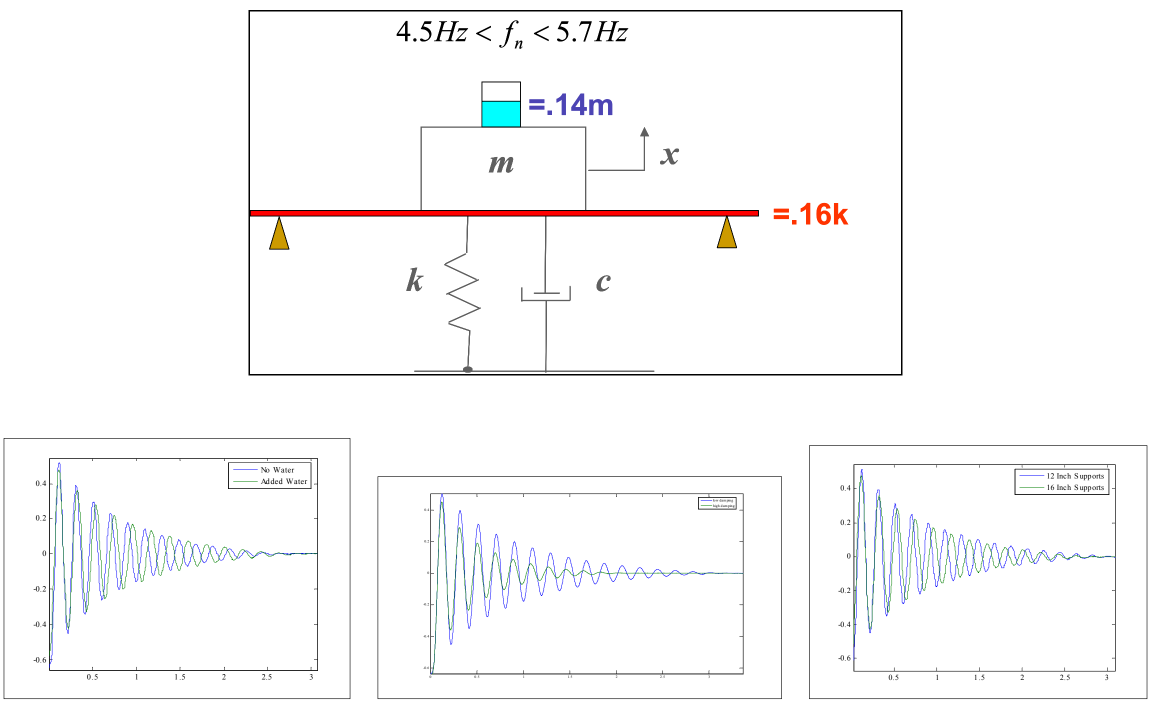


Figure 10 – Photo and Sketch of MCK System along with LabVIEW Interface

Several important features need to be mentioned regarding the RUBE system. Every time the system is accessed, the system parameters are changed. First, the mass of the system is constantly changing due to a slowly varying water level controlled by a float/pump system. In addition, the stiffness of the leaf spring support system changes each time the system is run – the spacing of the support location changes. In this way, every student receives a set of data which is slightly different than any other set of data collected by other students. The excitation of the system is obtained by a variable impact force or one of three different input displacements from a motor driven cam system.

The RUBE system is designed to have mass, damping, stiffness and natural frequency that typically has 15 to 20% variation in values due to the changing parameters of the system. In this way, students have a different set of characteristics every time the system is run. An overview schematic of the system characteristics and effect on system parameters is shown in Figure 11. The RUBE system is described in much more detail in References 7 and 8.

Specific information regarding the system is presented to the students in a set of documents. This forces the students to think about "what IS the actual mass, damping and stiffness of the system?" – rather than being spoon-fed the specific values. The students then work through many different scenarios to determine the best set of system characteristics to describe the overall system.



(Variation in response due to the design variables are in order of mass, damping, and stiffness, respectively)
(Specific values are not intended to be read in plots – only a conceptual overview of the range of values is intended)

Figure 11 – Schematic of RUBE Range of System Parameters and Effect on Response

Implementation of Materials

The materials described above are being implemented in several programs in the Fall 2005 and Spring 2006 semesters.

- Mechanical Engineering curriculum at University of Massachusetts Lowell
- Mechanical Engineering curriculum at Michigan Technological University
- Chemical Engineering curriculum at University of Massachusetts Lowell

The description below identifies areas where the material is being implemented. However, specific material regarding assessment of the material is not available as of this writing; this will be available in future writings on this work.

Mechanical Engineering - University of Massachusetts Lowell

During the Fall semester, these materials are being implemented in the Mechanical Engineering curriculum and feeder courses to the Dynamic Systems course.

This material will be adapted/implemented starting in the Ordinary Differential Equations course (92.236) taught by the Mathematics Department. This is intended to provide the students with exposure to real measurements in a real application to firmly instill the need for this material for mechanical engineering applications.

The Mechanical Engineering Numerical Methods course (22.361) will include a variety of the modules developed related to integration/differentiation and regression analyses which are typically addressed in this course. Processing of data that is tainted with measurement contamination will be addressed in a virtual measuring environment; known contaminants allows the students to better understand the effects.

The Mechanical Engineering Laboratory I & II (22.302 & 22.403) will provide extensions of the Numerical Methods material but using real data that is contaminated with unknown parameters. This material will extend what the students have learned as they move on to more difficult data. In addition, a five week project on the design of a measurement system in the second lab course is expected to utilize all of these materials in a significant fashion.

The Dynamic Systems course (22.451) will be the focal point of all of the material developed in terms of implementation/adaptation. This will involve the integration of previous course materials throughout the curriculum. This course uses both the analytical materials developed as well as the online data acquisition system.

Mechanical Engineering - Michigan Technological University (MTU)

The program at MTU offers some distinct advantages. Originally, the material was anticipated to be implemented mainly in the mechanical laboratory sequence (MEEM3000) with some material implemented in the vibrations courses (MEEM3700). Currently, the Mechanical

Engineering program is modifying part of its curriculum related to its Dynamic Systems sequence.

The laboratory course emphasizes three aspects of the mechanical experience using Dynamic Systems, Heat Transfer and Mechanic of Materials. Adaptation of the existing materials will be implemented into this course.

The current Vibrations course (MEEM37000) is being modified to be more of a System Dynamics course with a heavy MATLAB and numerical solution of Ordinary Differential Equations using Simulink. This also works well with the materials developed related to numerical methods and dynamic systems.

The materials developed can also be adapted for the Experimental Structural Dynamics course (MEEM4701) as well as for the Controls course (MEEM4700). The other advantage of the MTU curriculum is that each course is offered every semester so that a larger exposure to the material will be available for assessment purposes.

Chemical Engineering - University of Massachusetts Lowell

In the Chemical Engineering curriculum, there are three primary courses where the material will be implemented/adapted and two secondary laboratory courses as described below.

As in the Mechanical Engineering curriculum, there will be some implementation in the Differential Equations course (92.236). Applications of 1st and 2nd order systems to fluid flow in single and multiple tank configurations will be provided for the students. This will help to provide an application basis to help student retention of material.

In the Fluid Mechanics course (10.303), applications of fluids systems (tanks in particular) will be addressed. Issues related to the filling and/or draining of tanks with constant or varying cross-sectional area, or with different size exit flow areas, or even different piping arrangements at the exit to offer different flow resistances. These models then become a precursor to the numerical methods and laboratory courses.

In the Applied Problem Solving Course with MATLAB (10.317), typical numerical processing issues are investigated. Numerical issued identified in the earlier courses can be addressed with material in this course.

The Unit Operations Lab I (10.315) and the Processes and Controls Lab (10.415) courses are laboratory related courses that have experiments related to fluid flow in a variety of storage tank configurations. The previously developed materials on mechanical systems will be implemented/adapted for this course. In addition, the existing theory and MATLAB tutorials will be tailored, as needed, to serve as additional learning resources for the junior and senior Chemical Engineering students taking these two lab courses.

Conclusion

Modular material related to Dynamic Systems has been developed. This material can be deployed into various courses which constitute pre-requisite material for the solution of dynamic systems. This includes both analytical related material (tutorial and graphical user interfaces) and an experimental online measurement system, RUBE (Response Under Basic Excitation).

The intent of the project is to allow for the interweaving of material in a multisemester dynamic systems project. The salient feature of the project is that material from various courses (such as differential equations, mathematical methods, laboratory measurements and dynamic systems) is integrated in a fashion that helps the students understand the need for basic STEM (Science, Technology, Engineering and Mathematics) material.

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