

Teaching Experimental Structural Dynamics Applications

Peter Avitabile, University of Massachusetts Lowell, Lowell, Massachusetts

Educating engineers in aspects of structural dynamics with an experimental component in a university curriculum requires different teaching methodologies. The normal textbook theoretical material must be complemented with practical, realistic problems for the students to “think outside the box.” Canned homework problems and deterministic projects make the student believe that real engineering problems are just like those in the textbooks. The reality is that engineering problems are often far different from the textbook ones. In order to better prepare engineers to work in this demanding environment, several courses have been modified to include projects requiring experimental aspects of dynamic systems. This article summarizes some of the projects that have been incorporated into the course Mechanical Laboratory, Dynamic Systems and Vibrations at the undergraduate level to better prepare students for the practical reality of real engineering problems in the workplace.

In order to be effective in teaching engineering related course material, the 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. 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. Hands-on projects and problems with practical purpose tend to help students learn best.

In the UMASS Lowell Mechanical Engineering curriculum, there are many projects that provide the students with practical hands-on application of theory presented in lectures. These projects generally are contained in the individual courses related to the particular subject matter. However, in the area of structural dynamics, dynamic systems and mechanical engineering laboratory, there is a “thread” that runs through related material and the students are exposed to various tools and techniques for solving problems that have a common theme.

In this article, these mini-projects, exercises and problems are described to illustrate some of the practical aspects that have been part of the curriculum that help the students better and more deeply understand these critical tools for solving structural dynamic problems. These have been interspersed in the Mechanical Engineering Laboratory courses, in the Numerical Methods course, in the Dynamic Systems course and in the Vibrations course here at UMASS Lowell – the particular projects can easily be implemented in any curriculum which does not have to have the same course structure as that used at UMASS Lowell.

Typical Projects

There are several different projects that have been used and are described in the following sections. They are presented in somewhat of a chronological order as the students will face each problem (although the problems are scattered through several different courses in the curriculum). Of course, this is sometimes frustrating to the student because they perceive all the material to be only contained in one course and, once complete, there is no reason for them to use earlier material – nor should they be expected to do so – at least from the student’s perspective. (In fact, over the years I have often heard background comments like “he expected me to remember material from a course two semesters ago” or “I shouldn’t be required to use material learned in the course last year because this is a different course” and many more humorous statements, as well as some very pointed, “colorful” comments, could be cited.)

Some of the projects identified have been intentionally designed

to highlight problems that generally exist in a variety of different dynamic measurements typically made. The use of less than optimal acquisition configurations or instrumentation is specifically done to help the student clearly understand some of the important issues that may need to be addressed. While at times this may appear to be easily rectified with appropriate equipment, the measurement system must not be pristine. Otherwise the student gets the impression that the experiment is well behaved just like all the analytical problems from the textbook. It is important for the student to deal with uncertainty and unknown parameters in the development of solutions to common problems that they will face.

Numerical Processing of Contaminated Measurements

Many times, structural dynamic measurements may involve displacement or acceleration or both. One experiment in ME Lab uses a simple mass, spring, dashpot arrangement with an LVDT and accelerometer to make measurements. On the surface, differentiation and integration of these signals should be a straightforward process. Of course, in the numerical methods course, the approaches to accomplish this were presented and the students have mastered the basic rudimentary numerical processing concepts. But all of their data always contained very pristine data sets because the thrust of that effort was to understand the numerical process with the effects of different algorithms and time step considerations.

Unfortunately, real-world data is always contaminated with outside effects. Some are noise but others are related to the instrumentation used to acquire the data. In an effort to drill home some of these critical issues, a set of data is collected in less than optimal conditions. A measurement system is set up with a typical set of instrumentation devices (LVDT, accelerometer, signal conditioners, digital data acquisition system).

The system is to be measured using an LVDT for displacement and using an accelerometer for acceleration. (The devices must first be calibrated to determine the overall sensitivities and then digitally recorded using a PC digital data acquisition system.) An older National Instruments 12 bit ADC board is used with LabVIEW to acquire data. Once the data is collected, the acceleration data is to be integrated for comparison to the displacement measured data AND the displacement data is to be differentiated for comparison to the measured acceleration; the calculations are done using spreadsheet programs without the aid of canned algorithms. While the project seems fairly innocent, there are many technical hurdles to overcome. The issues relate to drift, bias, offset, sensitivity, ADC dynamic range/ resolution, and others. The students struggle with acceleration data that has very little signal strength and utilizes the fixed 10V ADC range very poorly – the accelerometer signal is at best 40 to 50 mV max. While the LVDT signal is much stronger at 1 to 2 V, the signal is contaminated with noise that is difficult to see without further interrogation.

A typical accelerometer measurement suffering from quantization error along with its companion LVDT signal is shown in Figure 1 for reference (top two plots). Upon initial processing of the data, the students believe that they can just apply the formulas they have learned earlier to just “plug and chug” to get the assignment completed. Of course, they are widely surprised when they see that the results do not initially compare. A typical initial differentiation of the LVDT signal is shown in Figure 1 (middle left plot) and a typical initial integration of the accelerometer is shown in Figure 1 (lower left plot). It then takes the students some time to sort through everything to start to realize that they really have to think about how to tame some of the contaminants that exist on the data they have obtained. With some work, generally most students reduce

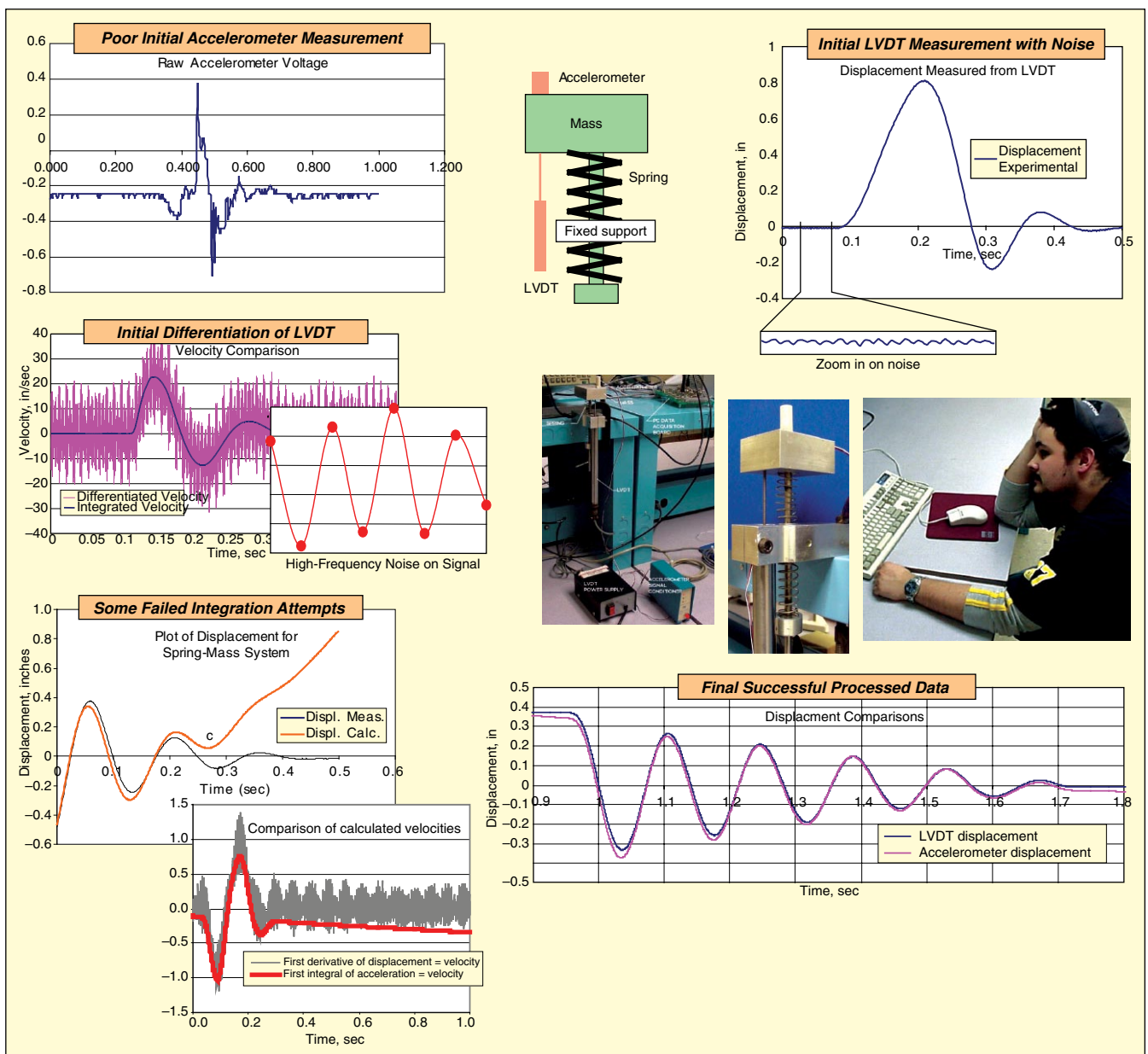


Figure 1. Overview of various aspects of the numerical difficulties project.

most of the measurement effects that are not really part of what they need to evaluate and generally provide acceptable results. But then there are always a set of students that persist until they achieve very good results. Some of the processing shows that the students clearly have taken ownership of the problem and often very novel approaches are utilized to address the contamination issues. A typical success story is shown in the lower right plot of Figure 1. More details on this project are available Reference 1.

Fourier Series using LabVIEW

Lecturing on mathematical topics related to Fourier Series, Fourier Integrals and the FFT can put anyone to sleep. The only one who really relishes this material is the professor as he develops each equation in excruciating detail. However, this mathematical tool is extremely important to the student in a wide variety of applications. In order to instill these concepts and techniques into the student's collection of tools, an innovative approach has been used to introduce the students to these concepts. Following a detailed LabVIEW project (described next), the students are exposed to the mathematical development with a practical understanding of the concepts involved. The LabVIEW project involves the study of the Fourier Series process, effects of harmonics and filtering of signals using a LabVIEW Virtual Instrument

The LabVIEW project basically involves the development of a

simple sine wave that is characterized in the time as well as the frequency domain – appropriate amplitude and frequency controls are implemented to change/control the signal. The signal is then contaminated with harmonic frequencies to show this important effect. This is then followed by the introduction of a square wave signal AND a representation of that square wave by summing up a series of sine waves. The students develop their own interface, identify frequencies of interest to form the square wave approximation and also apply some low pass filtering to change some of the frequency characteristics. Along the way, the students realize that the amplitude and frequency of their set of sine waves will approximate the square wave reasonably well when the Fourier Series coefficients are used for their amplitude and frequency control parameters. Thus in the project, the students see a first hand development of the Fourier series coefficients using their own LabVIEW GUI interface. A typical LabVIEW GUI diagram is shown in Figure 2 along with a front panel interface. This project has shown significant improvements over the previous laboratory exercises that utilized older FFT analyzers that proved cumbersome to use from the student's perspective – the exercises generally resulting in button pushing operations with minimal understanding of the material at hand.

In addition to the assignment and general lecture material, there

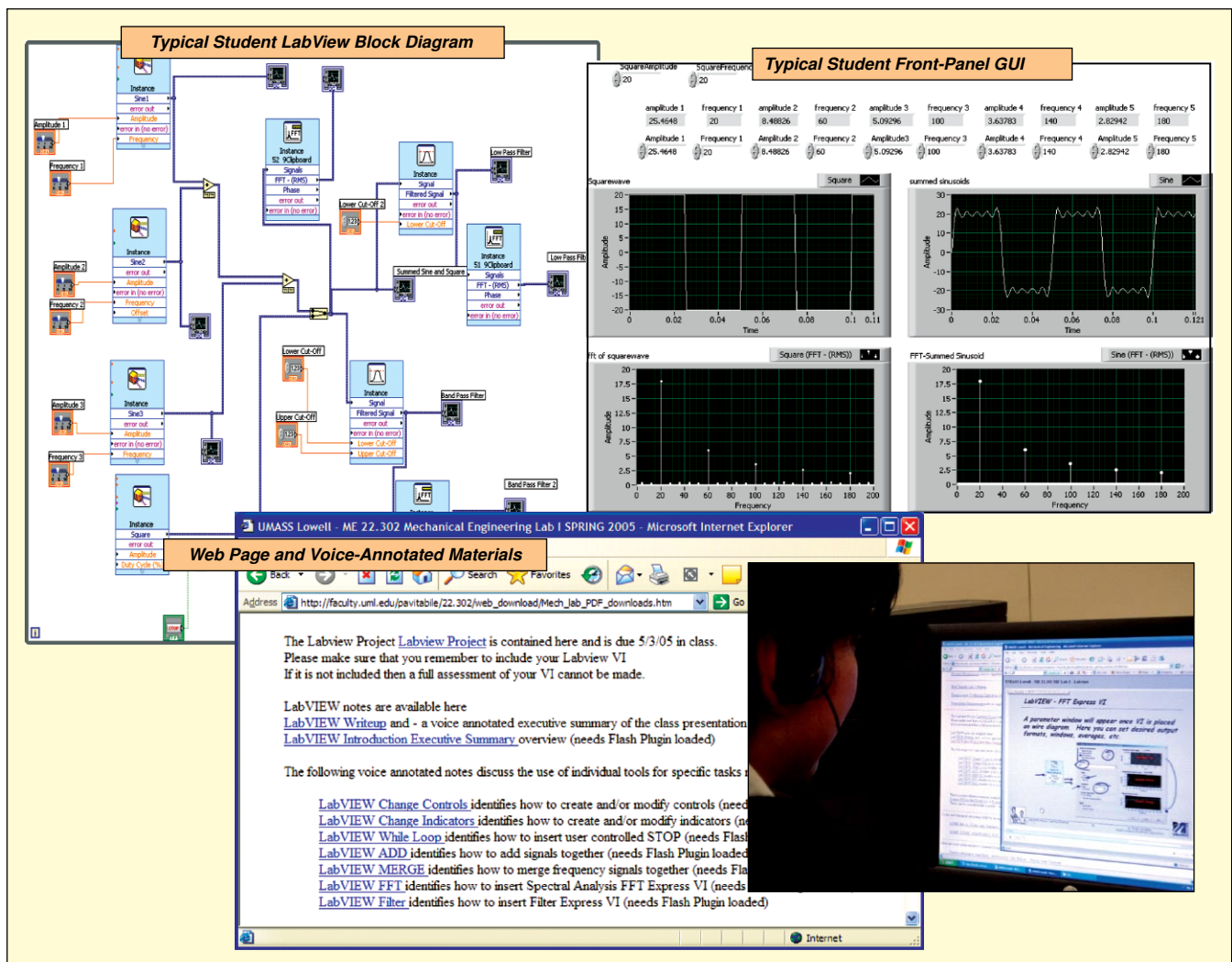


Figure 2. Overview of various aspects of the Fourier series project.

is also a set of voice annotated notes overviewing the project as well as describing all the LabVIEW tools required to develop the GUI. A segment of the online webpage covering the material is shown in Figure 2. The complete project is described in much more detail in Reference 2. The online tools are available in Reference 3.

Spectral Processing using an FFT Analyzer

Once the LabVIEW Fourier Series is complete, the students are now better prepared to tackle real measurements in the laboratory with dedicated FFT analyzers. One particular lab exercise is intended to expose the students to measuring real signals in the presence of noise, harmonics and other contaminants. Using a DACTRON Photon II FFT analyzer, the students make a series of measurements involving discrete sine waves to explore the use of window functions to minimize leakage, to measure sinusoidal signals that have noise and harmonics, to identify a filter response characteristic with broadband excitation as well as discrete sinusoidal excitation. The first two exercises reinforce the time to frequency transformations and the common problems of leakage which can be minimized by windows along with noise and harmonic signals; in addition, the students become familiar with the operation of the DACTRON Photon analyzer. The characterization of the filter using broadband and discrete frequency excitations reinforces the advantages of the frequency domain for characterization of the commonly used low pass filter by evaluating magnitude and phase relationships with closed form analytical formulations. A typical set of measurements for the various parts of the lab exercise are shown in Figure 3.

Impact Testing to Identify Structural Characteristics

The need to identify structural dynamic characteristics from

measured data is invaluable. A separate lab exercise is used to identify the common impact measurement techniques to identify structural frequencies and compare those to a closed form solution for a simple beam structure. (This measurement is performed as a prelude for the next balancing exercise where the structure to be balanced also has structural resonances which must be identified in order to balance the system. Because the system is so complicated a simple analytical model is not easy to develop and confidence in the impact testing technique to identify frequencies is obtained from this exercise).

The students use the impact technique to identify resonant frequencies of a beam system. They are required to calculate beam frequencies from closed form solutions and to identify frequency range of interest as well as identify optimal measurement locations (to avoid node points). Aspects of force/exponential windows are utilized in the identification of lightly damped beams. Frequency response and coherence are presented and discussed in order to identify measurement quality. Again the DACTRON Photon II FFT analyzer is used to make measurements required. The upper portion of Figure 4 shows a typical measurement along with general setup for impact testing.

Following the introduction to the Fourier concepts, dedicated FFT analyzer measurements and impact testing, the students are to balance a rotor kit system after identifying structural resonances of the system. The DACTRON Photon II FFT analyzer is used for the impact measurements to identify structural resonances with an impact measurement technique and then perform a balance procedure using either the DACTRON Photon analyzer or the National Instruments LabVIEW acquisition system to make measurements with eddy current probes to perform the balance of the system. Some of the typical balancing setups are shown in the lower half

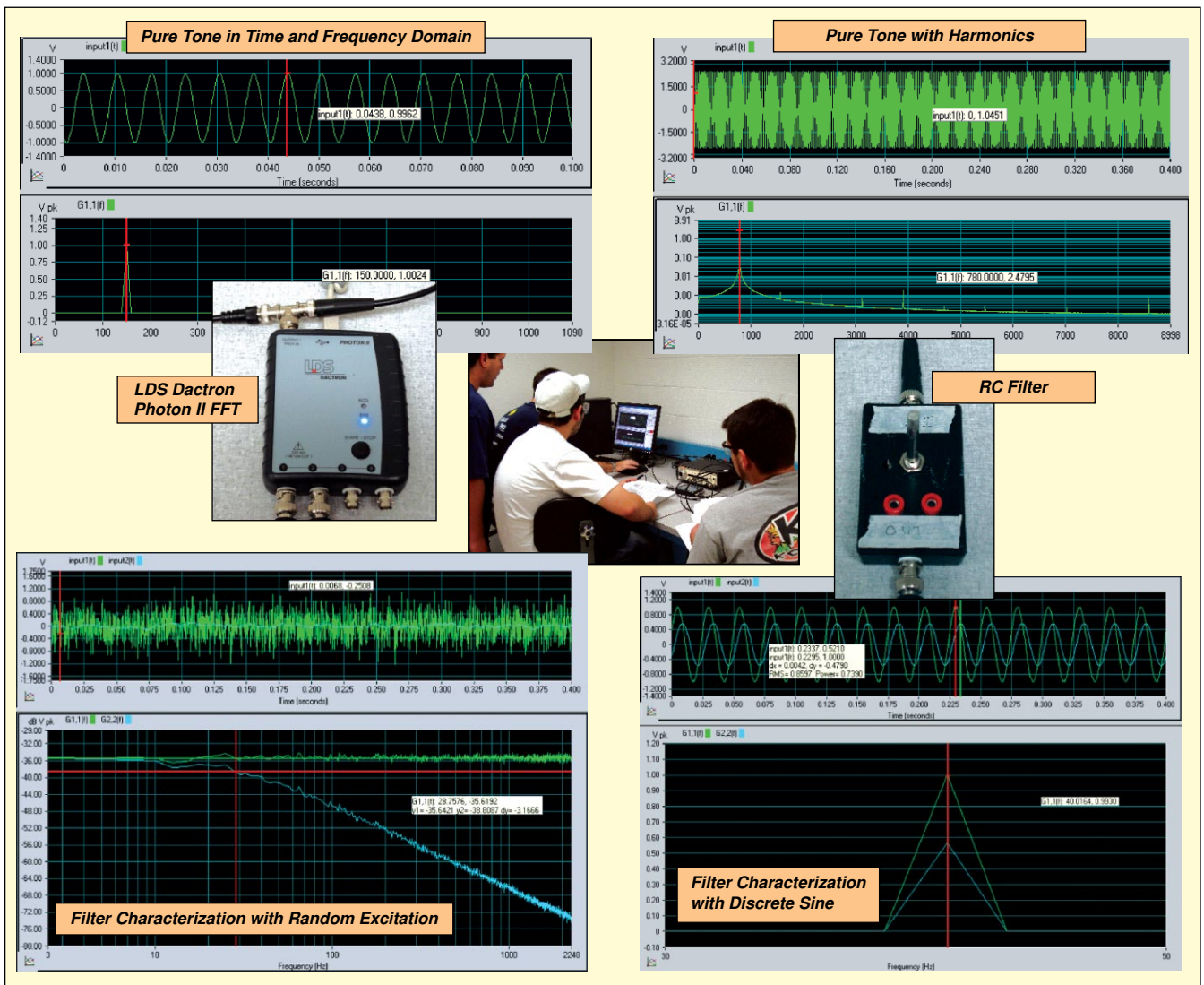


Figure 3. Overview of various aspects of the spectral measurements project.

of Figure 4. (The spectral waterfall map was produced using LMS Cada-X to illustrate the concepts of structural resonances and their relation to a typical runup sweep for a rotating system)

Design of a Measurement System – Dynamic System

A Mechanical Engineering Lab five week mini-project is implemented at the end of the two semester lab sequence. With the previous skills in hand, the task is to design a measurement system for the dynamic response of a beam system. This project has been used for many years now and the details of the project are summarized. The problem is posed as a measurement system to determine the tip response of a disk drive armature unit due to arbitrary loadings; the disk drive armature is considered to be approximated as a simple cantilevered structure. The students are to make measurements on a cantilevered beam structure shown in Figure 5 (which is a conceptual representation of the disk drive armature). The students are given general guidelines regarding the measurement system to be developed. The students are required to select three non-collocated different measurement devices from several possible transducers such as LVDT, accelerometer, laser, eddy current probes, and strain gages. They must determine suitable locations for the transducers, identify digital data acquisition (DAQ) requirements, etc. to determine the “best” method to address the problem. Ultimately, they are to predict the dynamic response at the tip of the beam.

Measurements from all three devices must be compared to each other which require spatial adjustment as well as integration/differentiation of displacement, velocity and acceleration measurements. The use of dynamic system models to determine actual response

due to arbitrary loading is required (using MATLAB and/or SIMULINK). The optimization of the parameters (signal type, location, transducer sensitivity, etc) is required to provide the “maximum” signal for the ADC specified for the data acquisition system.

The students proceed with typical procedural steps to finalize the measurement system once the initial shock of the scope of the project wears off. Procedures for calibration of equipment are developed and performed. Since an analytical model was developed for the “design” of the measurement system, some validation of the model is necessary. Students often use frequency response measurements to assure that the dynamic characteristics of the beam are correctly modeled. Other issues (noise, drift, bias, etc.) are also addressed in the process of designing the measurement system.

The goal is to obtain the displacement and acceleration at the tip of the cantilever. The transducers are not located at the same position or at the end of the beam. The measurements may be displacement, velocity and/or acceleration. The real effort lies in the spatial adjustment and integration/differentiation of the measurements taken. A significant effort is needed to achieve this. The students must use materials learned from the laboratory courses as well as related courses such as Numerical Methods, Strength of Materials, etc.

At the conclusion of the project, the groups present their models, assessments and results which predict the tip displacement and acceleration of cantilever beam. A typical “success” story is shown in Figure 5 which shows the overlay of data from a laser, strain gage and accelerometer used at three different non-collocated locations to predict the tip displacement response. All the issues previous faced in earlier lab sessions must now be pulled together to design

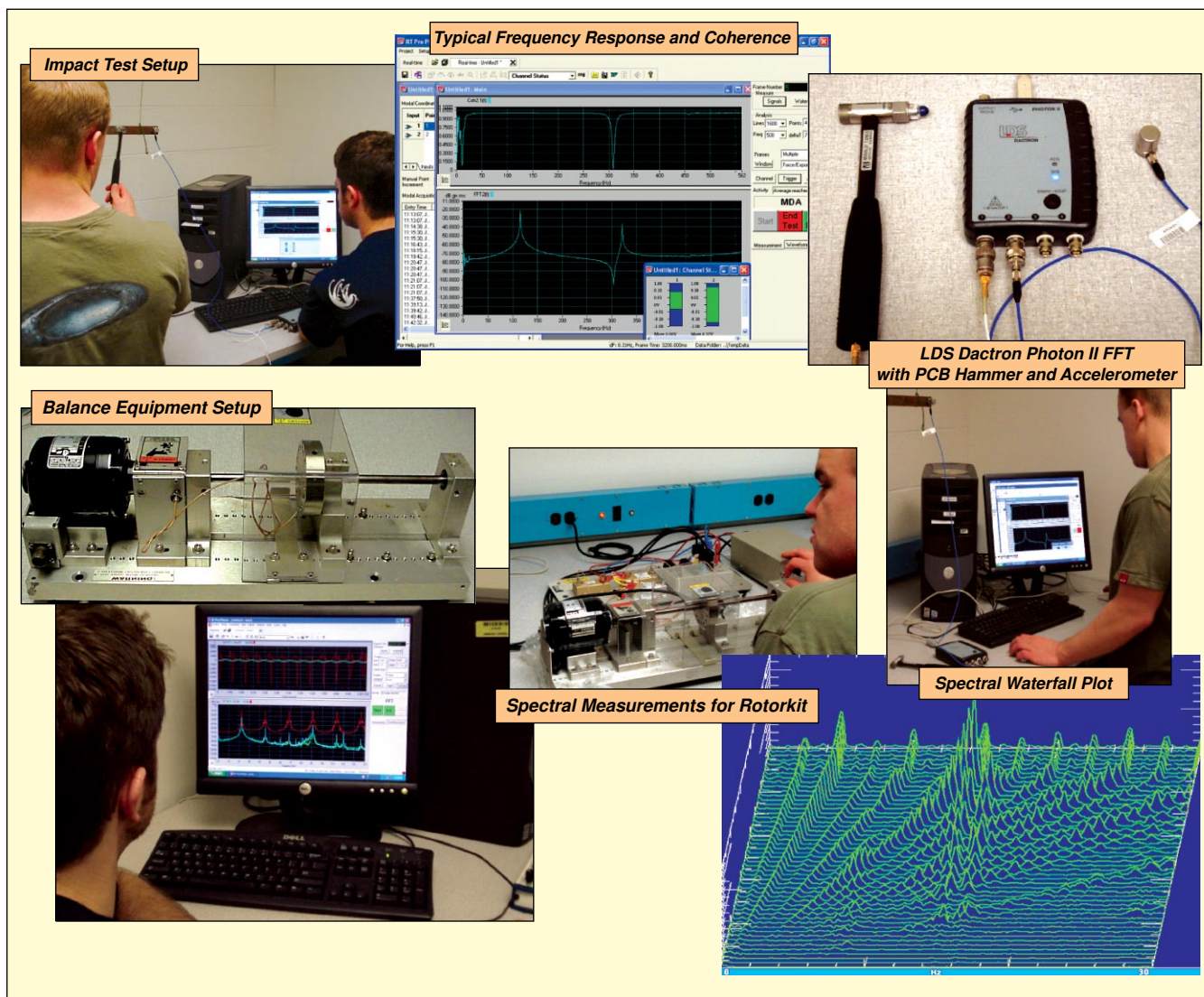


Figure 4. Overview of various aspects of the impact and balancing project.

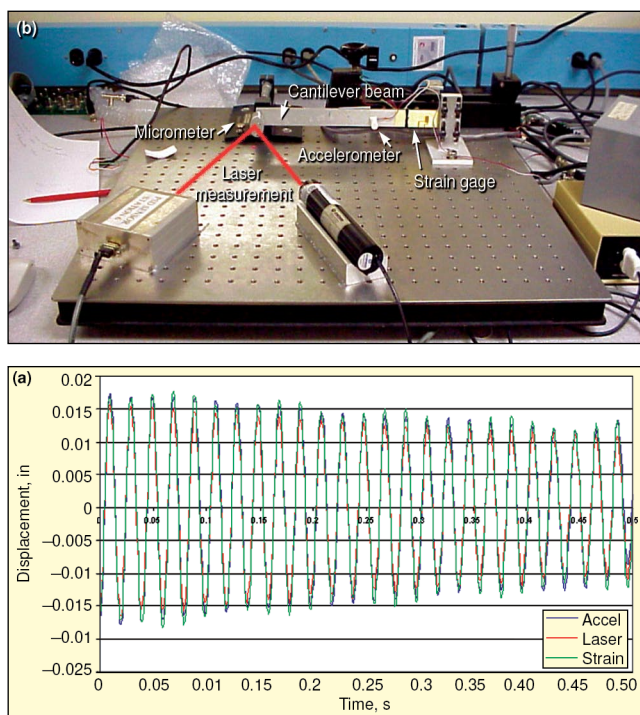


Figure 5. Comparison of non-collocated accelerometer, laser and strain gage approximations to the tip displacement of the cantilever.

this measurement system. While the students struggle to complete the project, they have indicated that the pain is well worth the rewards of better understanding the material. This Mechanical Engineering course has been taught in this manner for over 10 years now and the student comments have been very positive as to their experiences learned in developing a measurement system. More details on this project are documented in Reference 4.

Characterization of a 2nd Order Dynamic System

The Dynamic Systems course includes the typical array of first and second order system characteristics for mechanical, electrical, electro-mechanical, thermal-fluid systems, etc. presented from an analytical standpoint. However, this material is augmented in the class with several hands-on projects. Two such projects have been implemented – one is an analytical project and the other experimental project is discussed next. The response of a second order mechanical system with variable characteristics is used for the identification of system parameters. The system referred to as RUBE (Response Under Basic Excitation) is shown schematically in Figure 6. The main focus of the project is to identify characteristics where the system mass, damping and stiffness values are not vaguely known. The impulse response and displacement initial condition response are the only known measured parameters. The system has variable mass and stiffness characteristics that have a variation of 15 to 20% which results in system parameters that vary approximately 10 to 15% overall.

Because the system changes upon each execution of the measurement, the system parameters are constantly changing. This causes the students to struggle with uncertainty in the extracted

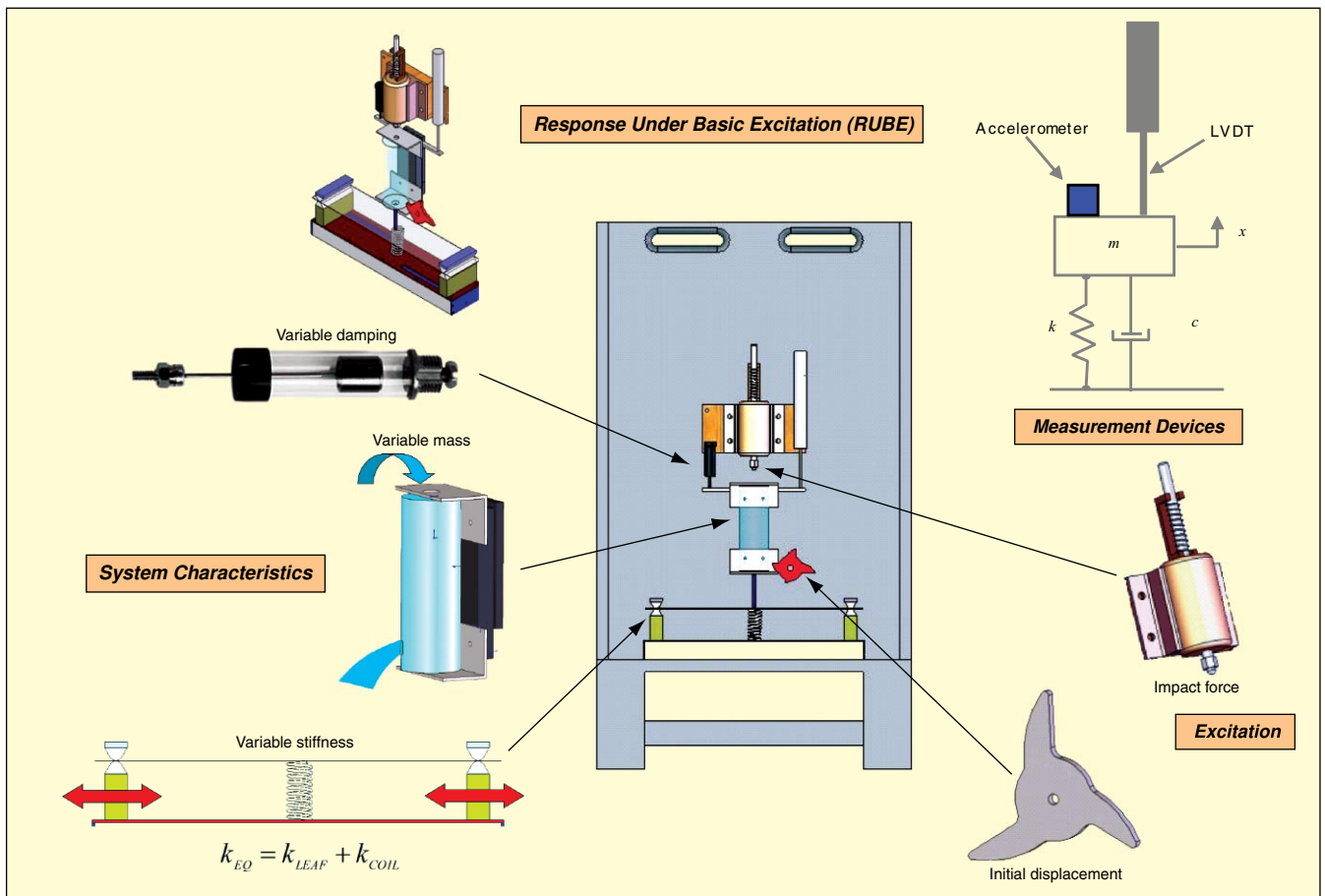


Figure 6. RUBE online measurement system.

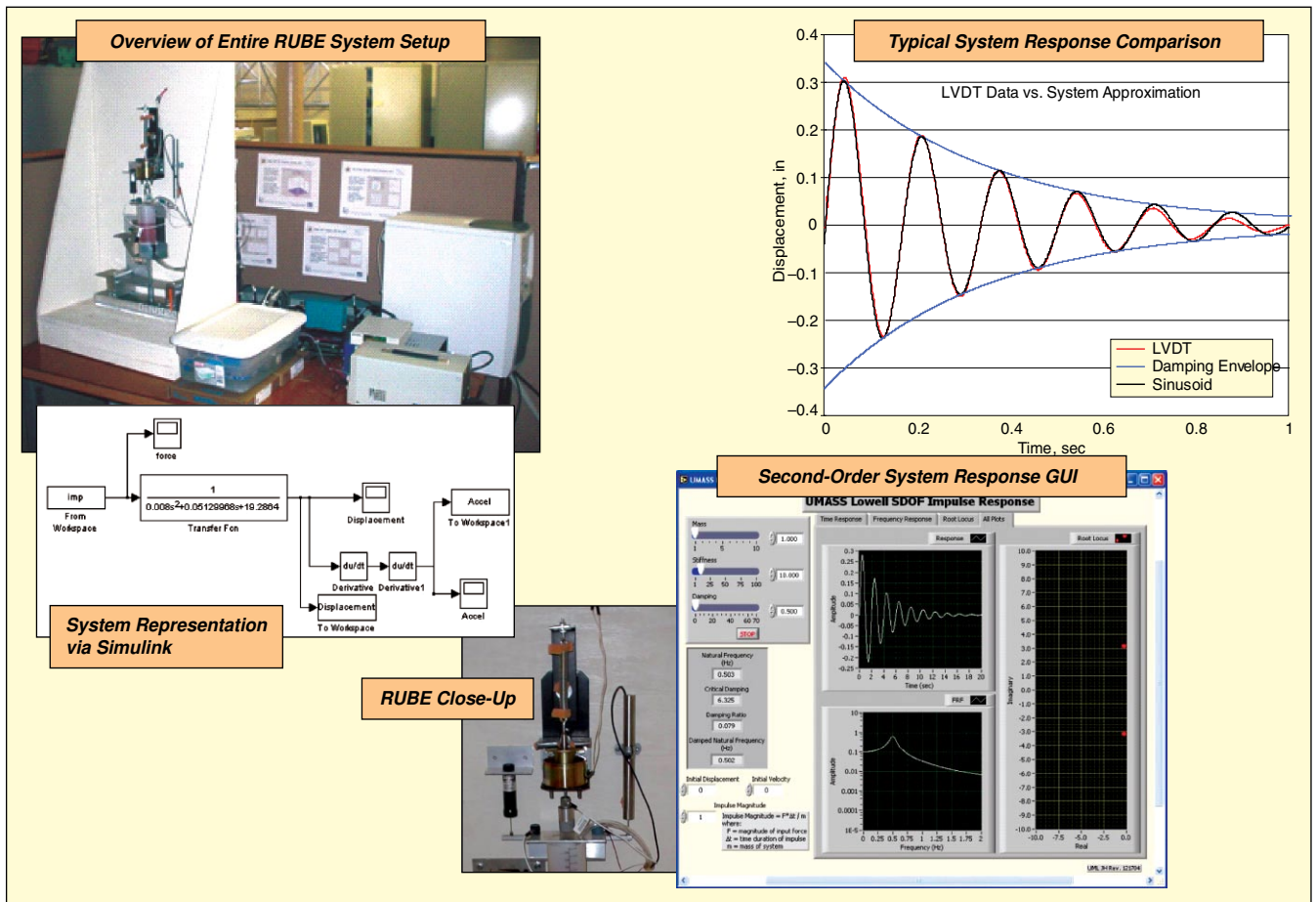


Figure 7. RUBE online measurement system and typical student results.

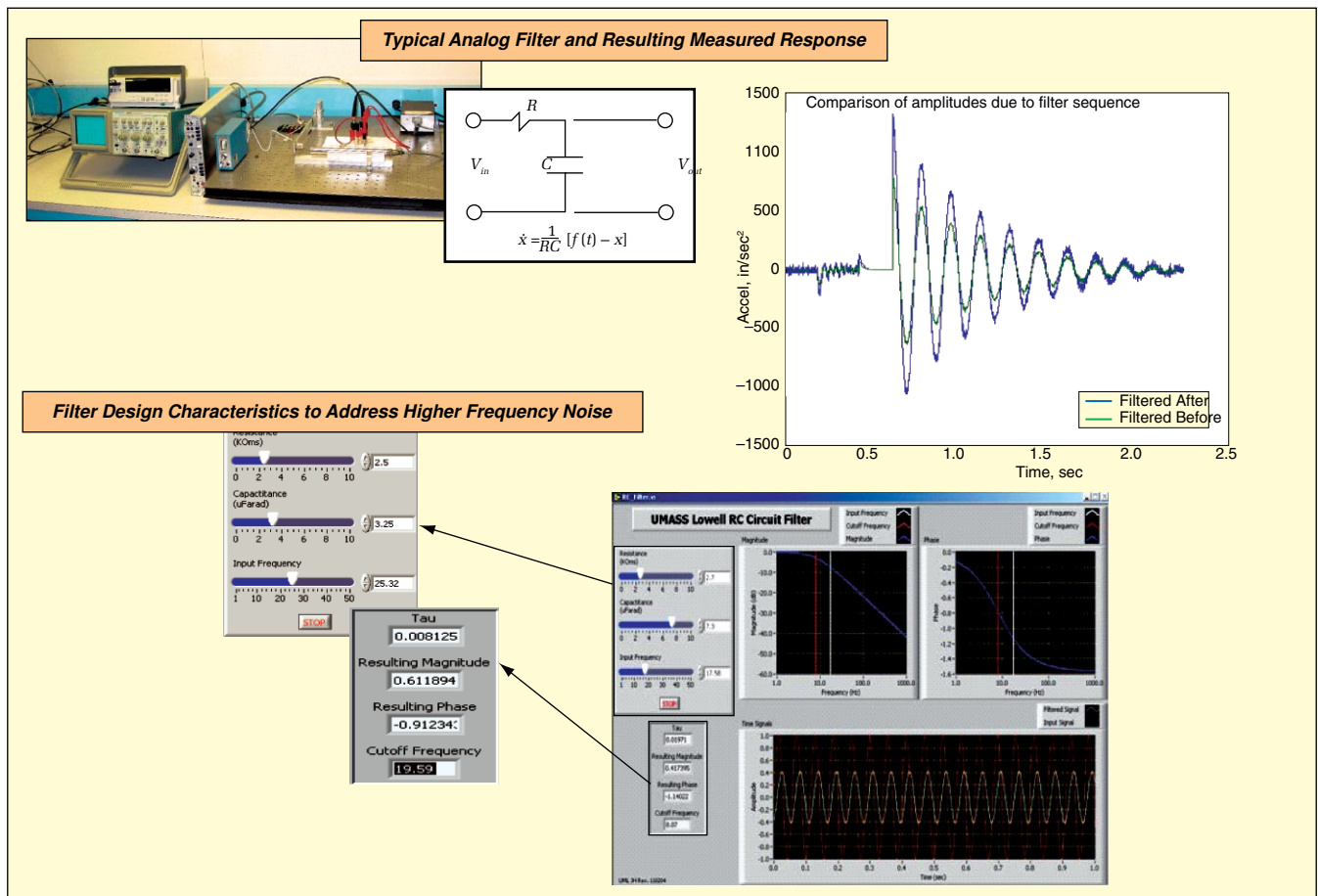


Figure 8. Analog and analytical filter design and implementation.

parameters. The main advantage of this project is that students start to really appreciate all the theoretical equations presented from a very practical standpoint. Each group of students must extract a set of system parameters and can do so from a variety of different approaches. These may include a combination of analytical and experimental approaches. The assumed “known” parameters can be used to predict system response and then verify that the parameters selected make physical sense by altering the assumptions to restart the estimation process. The students must also verify their system characteristics by using another measured excitation/response (that was not used to develop the model) and compare it to their analytical predictions. The response obtained with typical models is shown in Figure 7.

This project as well as the description of the RUBE online measurement system is the subject of Reference 5 and 6.

This set of projects has been used for many years now and has proved to be very beneficial from a student learning perspective. The concluding projects for the Dynamic Systems course vary from year to year and have included some variations of the theme of the first two projects. One particular project has included the design of a first order filter (both analytical and physical RC circuit design) to address some of the higher frequency noise that contaminates the signals (seen in earlier courses and projects). This enables the student to address the problems that have plagued earlier measurements. A typical setup along with some results is shown in Figure 8. (Note that the Dynamic Systems course has been supplemented with materials that were partially developed under an NSF Engineering education grant. The materials from this effort have been included in the material listed under Reference 7.)

Dynamic Modeling of Structural Configurations

The Vibrations course includes the typical assortment of classical theoretical problems seen in most vibration courses. However, in the UMASS Lowell course, there is an assortment of projects that are both analytical and experimental that expands beyond the classical theory to give the students a hands-on exposure to

analytical modeling including finite element modeling techniques using MATLAB. These projects include typical response studies of multiple degree of freedom systems (some of which use the underlying single degree of freedom concepts for forced and free response, base excitation, force transmission, tuned absorbers, shock response and seismic applications). In addition to analytical projects, there is an assortment of experimental projects to help give substantiation to the theory developed.

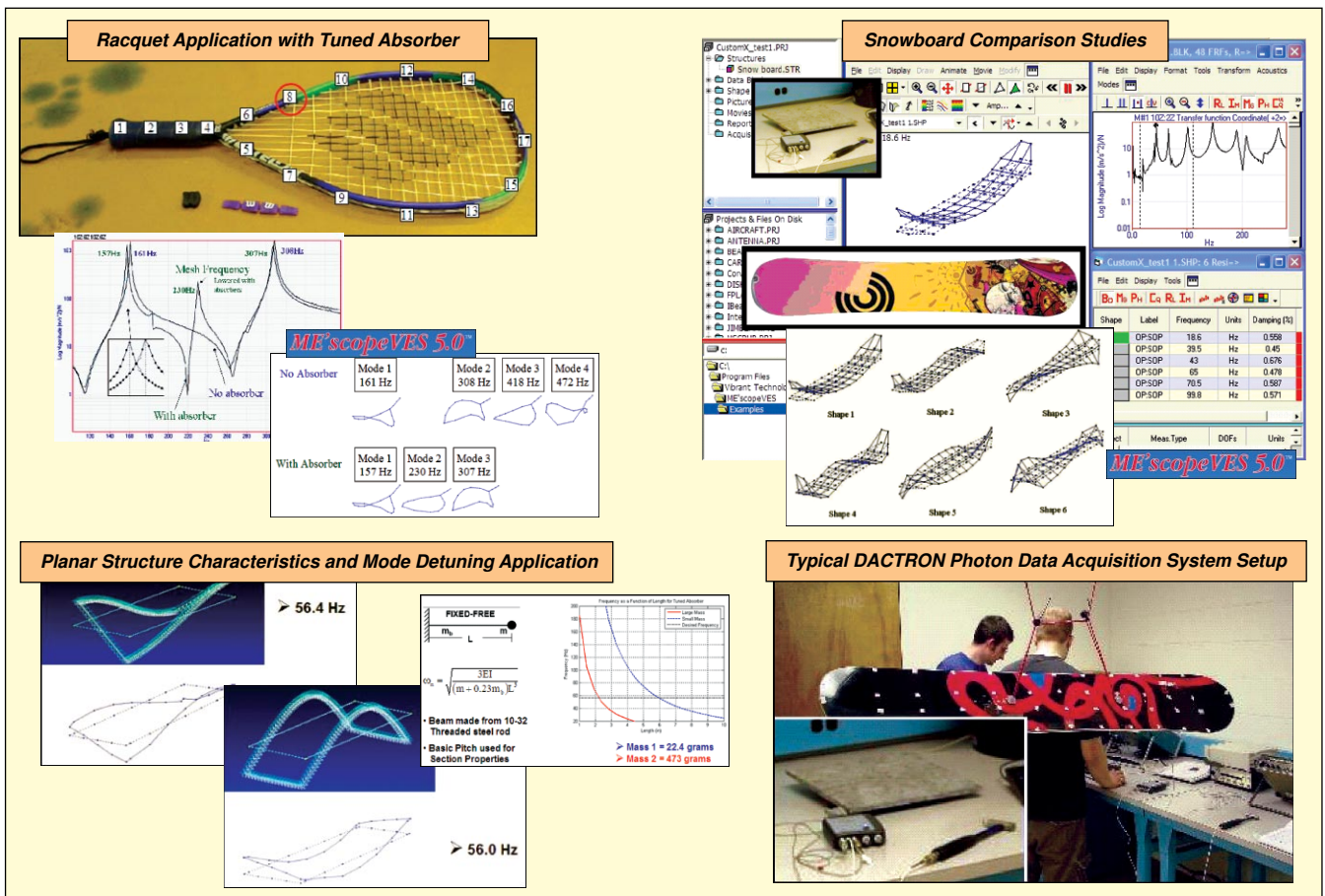
Projects involve experimental modal testing, dynamic characterization of sporting good equipment, tuned absorber applications, comparison to analytical models, to name a few of the typical experimental tests that have been incorporated into the course. These projects have had a significant impact on the overall students learning and comprehension of topics that would otherwise remain as a series of theoretical presentations without meaningful realistic application. Figure 9 shows some typical results obtained from the experimental tests included in the course for a few of the projects that have been used. The majority of the measurements are obtained using the DACTRON Photon FFT analyzer in conjunction with MScope for the reduction of the FRF data acquired.

Concluding Remarks

The Mechanical Engineering curriculum at the University of Massachusetts Lowell has included a wide assortment of hands-on experimentally based projects that form a strong part of the course curriculum in teaching structural dynamic modeling applications. These projects span across the several courses including the Mechanical Laboratory course sequence, the Dynamic Systems Course as well as the Vibrations course. These hands-on based projects and lab exercises have been shown to help reinforce and strongly instill these general concepts for deeper student learning and comprehension of the material.

References

1. “Numerical Evaluation of Displacement and Acceleration for a Mass, Spring, Dashpot System”, P. Avitabile, J. Hodgkins, 2004 ASEE Conference, Salt Lake, UT, June 2004.



- "Innovative Teaching of Fourier Series Using LabVIEW," P. Avitabile, J. Hodgkins, T. Van Zandt, A. Butland, D. Nicgorski, 2006 ASEE Conference, Chicago, IL, June 2006.
- Specific Course Webpage Tags to PDF File and Voice-Annotated Streamed Flash Files:
http://faculty.uml.edu/pavitabile/22.302/web_download/LabVIEW_getting_started022805.pdf
http://faculty.uml.edu/pavitabile/22.302/web_download/flash/LabVIEW_getting_started_031805.htm
http://faculty.uml.edu/pavitabile/22.302/web_download/flash/LabVIEW_FFT.htm
http://faculty.uml.edu/pavitabile/22.302/web_download/flash/LabVIEW_Filter.htm
http://faculty.uml.edu/pavitabile/22.302/web_download/flash/LabVIEW_ADD.htm
http://faculty.uml.edu/pavitabile/22.302/web_download/flash/LabVIEW_Merge.htm
http://faculty.uml.edu/pavitabile/22.302/web_download/flash/LabVIEW_Input_Change_Controls.htm
http://faculty.uml.edu/pavitabile/22.302/web_download/flash/LabVIEW_Input_Change_Indicators.htm
http://faculty.uml.edu/pavitabile/22.302/web_download/flash/LabVIEW_While_Loop.htm

- "Dynamic Systems Teaching Enhancement using a Laboratory-Based, Hands-On Project," P. Avitabile, C. Goodman, J. Hodgkins, K. Stevens, T. V. Zandt, G. StHilaire, N. Wirkkala, T. Johnson, 2004 ASEE Conference, Salt Lake City, UT, June 2004.
- "Dynamic Systems Teaching Enhancement Using a Laboratory Based Project (R.U.B.E)," P. Avitabile, T. Van Zandt, J. Hodgkins, N. Wirkkala, 2006 ASEE Conference, Chicago, IL, June 2006.
- "Second Order Mechanical Online Acquisition System (R.U.B.E)," P. Avitabile, T. Van Zandt, J. Hodgkins, N. Wirkkala, 2006 ASEE Conference, Chicago, IL, June 2006 – DELOS Best Paper.
- The Dynamic Systems Website, <http://dynsys.uml.edu/>, with assorted tutorials, graphical user tools and online data acquisition system:
<http://dynsys.uml.edu/tutorials.htm>
http://dynsys.uml.edu/Acquisition_system/onlineacquisition.htm
<http://dynsys.uml.edu/downloads.htm>
- LabVIEW, National Instruments.
- Dactron Photon II FFT Analyzer, LDS Dactron.
- ME'scopeVES Modal Analysis software, Vibrant Technology.
- LMS CADA-X, LMS International.



The author may be reached at: peter_avitabile@uml.edu.