ABSTRACT

Teaching structural dynamic modeling approaches in an educational curriculum is described for the modal option in the UMASS Lowell program. The curriculum involves a well blended combination of analytical and experimental techniques with an inclusion of commercially available hardware and software. The sequence of courses involves mainly project work with several themes that build on basic rudimentary concepts that evolve into more complicated interwoven themes. The course sequence is described in this paper along with the projects that comprise the majority of the work of the courses. Themes revolving around analytical topics, experimental issues as well as integration of these are described in this paper.

INTRODUCTION

Teaching structural dynamics utilizing both analytical and experimental approaches in an undergraduate/graduate curriculum poses some unique challenges and unique opportunities. While “hard core theory” is critical to be included in all of the material delivered, there is a very important need to include experimental components to solidify the theory through practical examples. Students learn best with hands-on approaches that afford them the opportunity to see the “theory in action”. This helps to explain the theory as well as allow the students to more deeply understand and appreciate various aspects of structural dynamic modeling techniques and applications.

At the University of Massachusetts Lowell, the curriculum for structural dynamic modeling courses is broken down into several courses that are mainly graduate courses but also include introductory upper level senior elective courses. These courses include:
- Vibrations,
- Modal Analysis (Theoretical Concepts),
- Experimental Modal Analysis,
- Structural Dynamics,
- Matrix Methods for Structural Dynamic Modeling Applications

Pieces of each course are described in the following sections - a smattering of the more important topics are included along with a description of the major projects that the students must address as part of the courses.
**VIBRATIONS**

Typically, a Vibration course can be found in most programs. In order to provide undergraduate students with a diverse, broad background in the major tools needed to solve typical engineering problems involving vibrations, the traditional course was modified to include an assortment of tools that might be necessary to solve a wide assortment of typical problems encountered.

The basic core material related to single degree of freedom (SDOF), free and forced response, as well as sinusoidal excitations and arbitrary inputs are presented. Typical base excitation, isolation and force transmission are presented. The traditional multiple degree of freedom (MDOF) systems presented for two DOF is included along with modal space representations, tuned absorbers and the related material. The course then extends into very simple finite element modeling techniques with simple beam and lumped mass representations to extend the SDOF and MDOF to be able to handle more realistic modeling situations. The introduction to experimental modal analysis is the logical extension of this material to complement the finite element modeling approaches. A brief introduction into random vibrations is included to help the students be able to understand how to apply the basic SDOF and MDOF theory as a building block to understand more complicated loading scenarios. Beyond this, the introduction of base excitation of MDOF systems leads directly into structural modeling applications including seismic analysis, shock analysis and response spectrum analyses.

While the theoretical foundations are presented in class, the importance of all the theory is amplified through the use of projects to solidify many different concepts. Several of the more important projects are listed:

- **Concepts of response for SDOF and MDOF systems** are reinforced with projects that utilize MATLAB for determining the forced response of SDOF, MDOF and mode superposition to show the interrelationship of the different approaches. Also, where possible, Simulink models are utilized to form solutions to these problems along with closed form solution if available. In addition, a LabVIEW GUI allows for the easy identification of different free and forced response characteristics for a SDOF system which is used as part of class projects to help reinforce theoretical concepts. The GUI is available at [http://dynsys.uml.edu/tutorials/2nd_Order_Systems/Sys_Resp/SDOF_System_Response_LabVIEW_GUI_110805.zip](http://dynsys.uml.edu/tutorials/2nd_Order_Systems/Sys_Resp/SDOF_System_Response_LabVIEW_GUI_110805.zip)

- **Development of MDOF equations** by defining a project to build a seismic anchor to simulate a built-in condition is an “eye-opening assignment”. This forces the students to obtain a better grasp of the physical parameters needed to actually simulate such a severe constraint that typically is so easy to write analytically but extremely difficult to achieve in a real test situation.

- **A finite element modeling project** is assigned and each student is given a slightly different configuration that can be modeled with simple beams and lumped masses and simplistic support boundary conditions. A general problem is posed for the students to determine how system level response will change due to a rotating sinusoidal excitation when various parameters of the system are changed (such as mass of specific components, CG shift of certain components, support stiffness changes). The effects of number of elements, distribution of mass and other items must be addressed. In many cases, the students are asked to design tuned absorbers to de-tune a troublesome mode of the system. Every semester, the students are given configurations such as vertical pumps, muffler configurations, valve/piping systems, heat exchanges, generator turbine sets, and various other typical industrial applications. All the models are presented in class to provide some meaningful discussion of modeling scenarios deployed and alternate mechanisms to possibly model the system.

- **An experimental modal test** is performed on a variety of simpler structures including application of tuned absorbers to see the effect of mode de-tuning. Structures have included simple beams, plates, and frames but have also included aluminum baseball bats, snowboards, tennis rackets, skis and racket ball rackets (with some equipment coming from wood, aluminum, composites and other constructions to see differences in resulting characteristics). In the evaluation of snowboards, six different commercial configurations were evaluated to observe the change characteristic shapes due to different construction configurations and resulting frequency patterns.
MODAL ANALYSIS (STRUCTURAL DYNAMIC MODELING TECHNIQUES)

The Modal Analysis course has its roots in developing the major analytical tools needed to address structural dynamic modeling applications. This course presents basic finite element modeling concepts for dynamic applications. The course contains the necessary linear algebra tools needed for the majority of techniques utilized in modeling. Topics revolve around model reduction and model expansion for the development of accurate reduced models for response analysis and model correlation/model updating efforts. Structural dynamic modification (SDM) using modal based approaches are used as introductory material for follow on material related to system modeling. Component mode synthesis for free and constrained systems is discussed in detail. In addition frequency based substructuring is also included. Other important topics such as model correlation and model error when compared to test data are covered in detail; tools such as MAC, POC, CoMAC, CORTHOG and other tools are discussed. This is followed by introductory concepts in model optimization utilizing measured data; effects of reduction and expansion are important to these materials.

The theoretical concepts presented in class are explored using several projects for the evaluations of some simple structures. Several of the more important projects are listed:

- Effects of model reduction using Guyan condensation, dynamic reduction, IRS, SEREP and Hybrid techniques are all explored through the use of simplistic models with a variety of different sets of master DOF to understand the shortcomings of traditional techniques and the improvement with more recently developed techniques. Expansion techniques are also covered as part of this project.
- Structural dynamic modification is studied using free-free acquired modal data sets to clearly understand the effects of modal truncation, rigid body modes and constraint modes. Various combinations of models are studied to help the students better understand the areas of concern in using these modeling approaches.
- System models are developed using constrained, unconstrained and variations to understand common techniques employed. System models are developed using modal approaches, reduced model approaches, physical/modal approaches and also using frequency based techniques; all of the techniques are compared on an equal basis to understand that all the techniques provide the same information but displayed in completely different forms to show the similarities and differences.
- Correlation of a model to measured data (where data is provided to the students) is performed to understand the differences between vector correlation tools such as MAC and POC and DOF correlation tools such as CoMAC, ECoMAC, CORTHOG, FRAC and others. The correlation is performed and students are required to explore various aspects of development of the model to see its effect on the results obtained.
- Model improvement using measured data is also performed to update the analytical model and also as a tool to help identify damage in structural configurations; discrepancies are identified using data provided for these studies.

EXPERIMENTAL MODAL ANALYSIS

The Experimental Modal Analysis course presents a complete overview of all the techniques commonly used for the development of experimental models. The general overview of theory related to experimental modal analysis is covered including signal processing, FRF development, noise considerations, measurement techniques (impact, shaker, MIMO), and the reduction of measured data to extract modal parameters using time and frequency domain approaches (including use of all tools for mode identification). An assortment of other topics such as operating data (output only techniques), force estimation, forced response simulation and others are presented. Testing on several different structures is performed by all students either working individually or in small teams of 2 to 3 people. Classical approaches developed over the past several decades as well as recent trends are presented in the course and compared using actual data and simulations to clearly identify the issues of concern when using many of the alternate variations that exist for describing systems.

Class lecture material is complemented with several projects that are interwoven together throughout the entire semester and build on previous results in many cases. Several of the more important projects are listed:

- The basic underlying experimental equations that relate poles, residues to analytical model parameters are studied. Simple peak pick techniques are applied to some analytically supplied data for a two DOF
system. The next piece of this project provides the mass, damping and stiffness matrices for two systems and the system transfer equations, poles and residues must be computed by hand and the FRFs must be generated and compared to the results from the previous piece of the project. These FRFs are then ultimately transferred into the major experimental modal packages (such as STAR, MEscope, LMS CADA-X) and the data is used for modal parameter estimation studies (curvefitting) to extract properties. Because the data comes from a known analytical source, the resulting extracted parameters can be evaluated since the answers are known. One model is characterized as a simple 2DOF system with well separated, well behaved modes and the other model is not as simple and has some difficult features that the students struggle with.

- A simple structure mounted to a relative large mass is provided for impact testing (but has an auxiliary appendage which intended to cause complications). The structure has features of rigid body motion, dynamic interaction between components as well as base-support structure having its own dynamic characteristics – this is all layered on top of a structure that is susceptible to double impacts and causes the test to have many problems often encountered in many test scenarios. The students are asked to develop an initial model to attempt to identify the generic characteristics of the system prior to conducting any testing; the goal of the test is to validate the basic model developed. Often many features of the model and test are missed but these are generally better understood since the results are all orally discussed in a one-on-one presentation to the instructor. This project appears to be very simple on the surface but the students learn a tremendous amount of respect for modeling and testing even simple structures after the completion of this project.

- A more complicated structure is tested using MRIT and SISO/MIMO techniques where consideration must be given to the effects of boundary conditions, mass loading from instrumentation and shaker loading effects which all cause differences to result in the models generated.

- Operating data is collected for a structure for comparison to a full MIMO modal test performed on the same structure. Aspects relating to the scaling of operating data to provide fully scaled modal data from operating data must be addressed. Aspects of structural dynamic modification are employed to investigate the mass loading effects and sensitivity based approaches for scaling operating data.

- Generally a modal test is performed on a general structure (but fairly simplistic in configuration) so that correlation and model updating studies can be performed to study this important area of modeling. Often times known modeling discrepancies are introduced into the analytical model for comparison to the measured test data or known experimental perturbations are introduced into the test configuration for study with correlation and model updating approaches. Correlation and model updating techniques are utilized for assessment of the test and model data.

- Structural dynamic modification studies and system modeling studies are continued in this course but using experimentally derived components where the rigid body modes or truncation effects cause difficulties along with the lack of rotational DOF for any further modeling studies. Expansion techniques are applied for estimation of RDOF and analytical representations of rigid body modes and higher frequency modes are included – these mode sets must be subjected to general normalization and scaling procedures to assure that a consistent data set is available for further modeling studies.

- Other studies such as force estimation are also included to allow for additional data processing.
STRUCTURAL DYNAMICS, MATRIX METHODS, ADVANCED TOPICS

These courses are described together and generally follow the core courses previously described. These courses are not offered with the same frequency as the other courses discussed previously due to the specialty nature of some of the material presented. Topics for these courses round out previously covered materials. Issues pertaining to development of system models, damping estimation, forced response, and numerical analysis approaches are all discussed. Coupled with the numerical methods course, techniques of numerical integration (such as central difference, Wilson θ, Newmark and others) are developed and programmed in MATLAB to compare response analysis approaches using commonly used techniques in commercial codes. Mathematical methods for root finding and solutions typically used such as LU decomposition (Crout, Choleski, etc), eigen solutions (Jacobi, Lanczos, Householder QR, etc) are programmed and compared to understand different approaches. Additional work, extending system model development in much more detail, is performed in these courses. Mathematical methods of root finding, LU decomposition and eigenvalue problems are developed and programmed using MATLAB. Detailed course projects are not detailed but follow the same concepts as the other courses. These courses generally extend the student knowledge and comprehension of material used in earlier courses.

OBSERVATIONS

Over the past 20 or more years, these courses have been taught with the same basic philosophy – present basic material and drill home concepts and techniques through project based work. These projects are, in cases of the more critical concepts and ideas, orally presented so that an open discussion can evolve where the students have to justify their approach, technique and results obtained. This forces a much greater student understanding of all the material presented. (Tests are rarely given in any of these classes.) Student comments have always been very positive as to their overall understanding and comprehension of material presented – but the majority have always stated that the workload is significant in all of these classes. While at times some oral presentations have appeared as if a student is in front of a firing squad (from their perspective), the dialogue greatly assists the students to further query areas where they still feel not as strongly in understanding the material as they may have liked to. The dialogue also helps in the overall evaluation of the student performance.

CONCLUSIONS

The curriculum in the Modal Analysis and Controls Laboratory in the Mechanical Engineering Department at the University of Massachusetts Lowell is heavily complemented with hands on projects to foster deeper student learning and comprehension. This paper describes some of the concepts introduced and integrated into the curriculum with a heavy project based format.
PROJECT ASSIGNMENTS

This section identifies the Project Assignments for the semester.

The experimental modal project is identified for each group as follows:

- **Group A**: to do testing of granite tiles
- **Group B**: to do testing of beam and design tuned absorber
- **Group C**: to do testing of beam and design tuned absorber
- **Group D**: to do testing of racket ball racket with and without vibration absorbers
- **Group E**: to do testing of blue frame and design tuned absorber
- **Group F**: to do testing of several different snowboards

The finite element modeling project is identified for each person:

- **Cunniff**
- **Egan**
- **Hidalgo**
- **Guidetti**
- **Dallas**
- **Beauregard**
- **Hall**
- **Tavilla**
- **Vigneault**
- **Butland**
- **Chipman**
- **Nicgorski**
- **Williams**
- **Carney**
- **Gibson**
- **Ismail**
- **Kremer**
- **Marden**
- **Ouellet**

**Project #1**: development of equations for a three DOF system and the development of boundary conditions.

**Project #2**: development of equations for a two DOF system and the response of the system due to applied loads.

These are non-printable PDF files of class notes:

- **Chapter 1**: Introduction - lecture notes used in class
- **Chapter 2**: Free Vibration - lecture notes used in class
- **Chapter 3**: Forced Vibration - lecture notes used in class
- **Chapter 4**: Transient Vibration - lecture notes used in class
- **Chapter 5**: MDOF Systems - lecture notes used in class
- **Chapter 6**: MDOF Systems - lecture notes used in class
- **Chapter 8**: Solution Techniques - lecture notes used in class
- **Chapter 10**: Finite Element Methods - lecture notes used in class
- **Chapter 13**: Random Vibrations - lecture notes used in class
- **Experimental Modal Analysis**: lecture notes used in class
- **Base Excitation/Seismic**: lecture notes used in class

**Voice Annotated PowerPoint Notes Narrated by Peter Avitabile**

- **Introduction**: Overview of Course
- **Chapter 1**: Oscillatory Motion
- **Chapter 2**: Free Vibration
- **Chapter 3**: Harmonically Excited Vibrations
- **Chapter 4**: Transient Vibration
- **Chapter 5**: Systems with Two or More Degrees of Freedom
- **Chapter 6**: Properties of Vibrating Systems
- **Chapter 8**: Computational Methods
- **Chapter 10**: Introduction to the Finite Element Method
- **Modal Overview**: Introduction to Experimental Modal Analysis
- **Chapter 13**: Random Vibrations
- **Miscellaneous Topics**: Base Excitation and Seismic Applications

**Plate Response**: explanation of plate response

**Animations**: some animations of structural systems
HOMEWORK ASSIGNMENTS
Make sure you look at the Modal Space articles so you have an idea of what subject matter is discussed in each article.
Make sure you read the article on Experimental Modal Analysis - A Simple Non-Mathematical Overview

PROJECT ASSIGNMENTS
This section identifies the Project Assignments for the semester.
Project 1 is intended to get you started with the development of modeling techniques.
Project 2 is a treatment of model reduction and model expansion.
Project 3 is a treatment of structural dynamic modification.
Project 4 is a treatment of system models with reduced physical components.
Project 5 is a treatment of correlation of analytical and experimental data. The experimental data is located here.

These are non-printable PDF files of class notes
SDOF Review lecture notes used in class
MDOF Review lecture notes used in class
Solid Mechanics lecture notes used in class
FEM Review lecture notes used in class
Linear Algebra Review lecture notes used in class
Model Reduction lecture notes used in class
Modal Expansion lecture notes used in class
Overview Structural Dynamic Modification lecture notes used in class
SDM Theory lecture notes used in class
Understanding SDM Truncation lecture notes used in class
Frequency Based Substructuring Theory lecture notes used in class
Frequency Based Substructuring Application lecture notes used in class
Comparison of System Modeling Techniques lecture notes used in class
System Modeling Concepts lecture notes used in class
Correlation lecture notes used in class
Model Updating lecture notes used in class
Vector Scaling lecture notes used in class
PROJECT ASSIGNMENTS

Project 1 employs peak pick technique to identify modal characteristics
Project 2 requires hand calculations to determine modal characteristics
Project 3 impact measurements on a plate like structure
Project 4 Project 4 (and Project 6) concern Modal Parameter Estimation
Project 5 Project 6 (and Project 4) concern Modal Parameter Estimation
Project 5 is an extension to Project 3 to show system characteristics.

Student Group A - Project 7 experimental modal tests
Student Group B - Project 7 experimental modal tests and advanced data manipulation
Student Group C - Project 7 experimental modal tests and advanced data manipulation

The class notes were distributed on CD