



Creating an Experimental Structural Dynamics Laboratory on a Shoe-string Budget

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Introduction

Educating architectural engineers in aspects of structural dynamics is essential. When architectural engineering students graduate and enter the workforce they will be faced with analyzing and designing a variety of structural systems. Oftentimes in the workplace, sophisticated analytical models are created to model the dynamic response of buildings subjected to dynamic loading. Commonly, these models rely on the modal superposition method resulting in natural frequencies and modes shapes. The objective of the course is to enhance student learning with student-led experimentation that complements the normal theoretical textbook material and homework.

When designing a new course two critical elements to consider are the educational benefits to the students and the cost for the University. ‘Experimental Structural Dynamics Laboratory’ provides students with the opportunity to experiment with physical models and real life structures at a minimal cost.

This paper describes the development of a course proposal for the undergraduate senior level/graduate level course “Experimental Structural Dynamics Laboratory”. The overall objectives are (1) to reinforce dynamic structural analysis concepts relevant to engineers and (2) to visualize that those analytical concepts such as natural frequencies and mode shapes exist in real structures and (3) to foster student learning through hands-on experimentation. The basic notion that sets this laboratory apart from most existing laboratories is that the laboratory can be conducted with inexpensive equipment, such as a low capacity shake table, a linear mass shaker, simple mobile data acquisition equipment and a limited number of accelerometers. The laboratory course is intended to accompany a concurrent senior level/graduate level structural dynamics course in which the relevant theoretical concepts of structural dynamics are introduced. One possible experimental laboratory (3 hours) per week over a 10 week quarter is described in this paper.

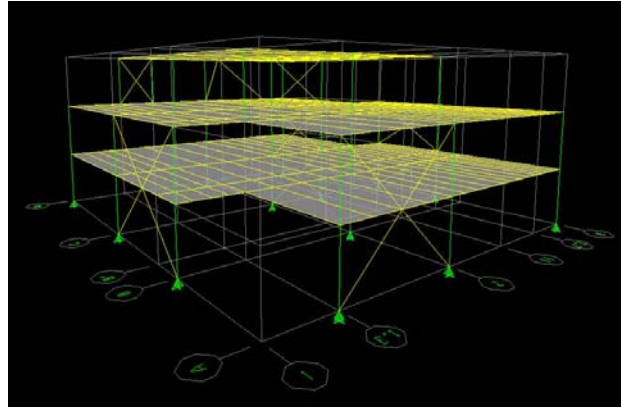
Background

A unique experimental dynamic laboratory is developed to improve students’ physical understanding of the complex principles presented in mechanical vibrations courses. There is often a disconnect in students’ minds between theoretical models and real world applications. In theoretical models, concepts such as eigenvalues and modal superposition often remain mysterious to students. Rather than relying solely on the typical small scale unidirectional model with lumped masses to illustrate important mechanical vibrations concepts, a large-scale three-dimensional structure and a real building (Figure 1(a)) are used to improve the relevance of the experiments so that students can more readily connect the results with the real world. In addition, the course will enhance the student’s ability critically assess their computer models and create more accurate computational models. The course proposal stems from previous successful efforts

to improve student learning in structural dynamics based on forced vibration testing^{1,2} of large-scale and full-scale buildings.



Figure 1-(a) Building to shake



(b) Computational model (ETABS³).

Course description

Course objectives:

- Reinforce dynamic structural analysis concepts relevant to engineers
- Visualize structural response to dynamic loading
- Demonstrate the physical existence of natural frequencies and mode shapes in real structures
- Create analytical models that accurately represent the structures being investigated
- Compare experimental quantities with analytical model quantities such as natural frequency and mode shapes
- Experimentally determine the structural damping properties of a structure
- Introduce similitude concept for model scaling
- Enhance student learning with student-led experimentation

Learning outcomes:

- Students will demonstrate a physical understanding of the equations describing the natural frequencies and mode shapes of engineered systems
- Students will demonstrate a physical understanding of damping in engineered systems
- Students will develop more accurate computational models of engineered systems
- Students will check the computational models with simplified hand calculations

Table 1 shows the 10 week course outline. It begins with an introduction to the measuring equipment and the signal processing software. A simple model is placed on the shake table and subjected to white noise. The students will operate the data acquisition system and signal processing software. The students will analyze the signals and calculate the Fourier transform and power spectrum. The aim in Week 2 is to identify natural frequencies in a two-story large scale structure purely subjected to ambient vibration. This allows the students to compare the frequencies to those from computational models. Weeks 3 and 4 focus on testing of scale models of moment and braced frames. The models will be tested on the shake table at their natural

frequencies. Natural frequency and mode shapes will be derived from acceleration measurements and compared to analytical predictions. In Week 5, the focus will be on similitude between models and real application. The implications in terms of e.g. mass, stress and time are explored. Weeks 6 and 7 are spent charting the natural frequencies, modes shapes and damping of the two-story structure. A linear shaker is the source of excitation. Several structural configurations are explored and are compared to analytical predictions. In Week 8, the students will shake a real building and determine its natural frequencies and mode shapes and to discuss damping caused by non-structural elements. Figure 1 shows an example of a building successfully shaken and the corresponding analytical model. This also presents the opportunity to compare to computer simulations. Weeks 9 and 10 are devoted to a student self-designed experiment. The experiment must explore dynamic features of a real building and must involve comparison with analytical models.

Table 1 – Course outline

Weeks	Topic	Description	Equip-ment. *	Analytical models required
1	Laboratory measurements and signal processing	- Introduction to measurement techniques for acceleration and signal processing - Use of the Fourier Transform and Power Spectrum	E1, E3, M2	
2	Ambient vibration	- Determination of natural frequencies of the two-story structure	E1, M1	Pre-test, computer model
3-4	Natural frequency, damping and mode shapes	- Exploration of natural frequency, damping and mode shapes in pre-defined SDOF and MDOF scale model structures	E1, E3, M2	Analytical models
5	Scale models and similitude	- Exploration the consequences of using scale models to predict structural behavior - Scaling of mass, stress and time	E1, E3, M2	
6-7	2-story large scale structure	- Forced vibration excitation - Determination of natural frequencies, mode shapes and damping - Multiple brace configurations.	E1, E2, M1	Post test, computer models
8	Real building behavior	- Forced vibration excitation of a real building. - Determination of natural frequencies, mode shapes and damping	E1, E2	Pre- and post-test computer models
9-10	Self-designed laboratory	- Students build and test their own models. - Models are conceived as scale models of realistic structures.	E1, E3	Predictive analytical/computer models

*) Equipment and models

E1: Accelerometers, data acquisition unit, signal processing software

E2: Linear Mass Shaker (30 lb)

E3: Low capacity unidirectional shake table

M1: Two-story large scale steel frame with concrete floors (laboratory)

M2: Scale models of frame and braced-frame buildings

Models, Excitation and Data Acquisition

Two types of structural models are used in the course. (1) Small scale models placed on a unidirectional shake table and (2) a large scale two-story frame structure. The small scale models range from single-degree-of-freedom (SDOF) 'lollipop' models to multi-degree-of-freedom (MDOF) models (Figure 2). These systems are simple to represent analytically and are used to initially demonstrate the data-acquisition system (Week 1) and to demonstrate natural frequency, mode shapes and damping (Week 3 and 4) and lastly to demonstrate similitude concepts (Week 5).

Forced vibration testing (FVT) of the small scale models is done on the low capacity unidirectional shake table shown in Figure 3. It is capable of producing white noise, harmonic excitation and arbitrary acceleration signals.



Figure 2-Small scale model



Figure 3-Shake table

The two-story large scale frame structure is shown in Figure 4(a) and consists of reinforced concrete slabs supported by a steel moment frame. The structural system can be altered by attaching additional braces in the lower and upper stories, such that moment frame and braced frame behaviors can be studied. Stiffness eccentricity can also be studied. The total height is 9 ft.,

plan dimensions are 6 ft. by 4.5 ft. and the diaphragms 18 inches thick. A computational model is shown in Figure 4(b).



(a) Photograph



(b) Computational model (ETABS³)

Figure 4-Two-story large scale structure

Dynamic response of the large scale two-story structure is recorded under ambient vibration conditions (Week 2) and when subjected to FVT (see below) (Weeks 6 and 7). FVT of this structure is driven by the 30 lb linear shaker shown in Figure 5. A function generator and an amplifier generates the shaker input. The linear shaker is also used for excitation of the real structure (Figure 1(a)). It is noted that the shaker harmonic force output produces structural accelerations several orders of magnitudes above the ambient noise at resonance in the real structure.



Figure 5-Linear mass shaker

The mobile data acquisition system shown in Figure 6(a) consists of multiple highly sensitive accelerometers connected to an analog-to-digital converter, and the laptop that records the digital signal and performs real-time signal processing. A mobile assembly of three orthogonally oriented accelerometers is shown in Figure 6(b). Table 2 indicates the approximate cost of the key data acquisition devices and shaker equipment. A package with four accelerometers, data acquisition units, shaker, amplifier and function generator (without computer and signal processing software) costs in the vicinity of \$15,000. Used equipment can often be found at less than half the cost of new equipment.



(a)



(b)

Figure 6-Data acquisition devices

Table 2-Shaker and data acquisition cost

Item	Cost
Accelerometer	~\$500
Vibration Data Acquisition System	~\$1500
Function Generator	~\$800
Shaker amplifier	~\$4500
Long Stroke Linear Shaker	~\$6000
Misc. cables	~\$300

FVT Procedure for two-story structure and real building

The general FVT procedure consists of multiple phases where 1) natural modal frequencies, 2) modal damping ratios; and 3) the mode shapes are determined. The structure's natural frequencies are identified by a FVT frequency sweep. Then the shaker frequency is varied in the vicinity of the natural frequency of interest to establish the acceleration response from which the structure modal damping can be deduced. Finally the shaker is set at the natural frequency and placed strategically to maximize its effect on a particular mode and minimize its effect on

adjacent modes. The steady state floor accelerations are then measured at selected locations throughout the model/building to establish the mode shape. Further details may be found in references^{4,5}.

Assessment

The evaluation plan for this course involves both formative and summative assessment. The criterion for success is based on the delivery of this laboratory experience that leads to improved student learning of mechanical vibrations, with reference to achieving the stated learning outcomes.

Evaluation of the learning outcomes will be based on reports turned in by the students and based on a final course evaluation. The effectiveness of the course can be related to changes in student behavior that indicate improved student learning and can be assessed through pre- and post-tests. Efforts will be made to assess improved student learning by comparing identical surveys of two sections participating in the same theoretical dynamics course, where only one section has had the laboratory experience. These sections could be simultaneous and/or could occur in different terms.

Quantitative evaluation will also be done through pre- and post-experience interviews of students by asking targeted technical questions that explore their understanding of e.g. the response of a specific building. Students' interest in the subject of mechanical vibrations can be measured using pre- and post-experience surveys. Through Likert type scale questionnaires, students will be asked targeted questions to help determine the level of interest in the subject matter covered throughout the course.

Conclusion

An experimental structural dynamics laboratory course for undergraduate senior level/graduate level students, taught concurrent with their theoretical structural dynamics course, is proposed to reinforce dynamic structural analysis concepts relevant to engineers. Analytical concepts are visualized and the existence of natural frequencies and mode shapes are demonstrated in real structures. The practical basis for the course is that the laboratory can be conducted with inexpensive equipment. One experimental lab per week is proposed. Students will conduct physical experiments and compare the result to analytical models.

Often, in students' minds, a disconnect exists between theoretical models and real world applications. Student led experimentation on models and a real building will improve the relevance of the theory, so that students can more readily connect the laboratory results with the real world. By the end of the course the students are expected to demonstrate a physical understanding of the equations describing the natural frequencies and mode shapes of engineered systems and demonstrate a physical understanding of damping properties. Also, the course is expected to enhance the student's ability assess their computer models and create more accurate

computational models. This will help to bridge the theories presented in classes with the realities in the workplace.

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