Development of dynamic simulators using Pasco models equipped with LabVIEW

A Major Qualifying Project Report completed as required of Bachelor of Science degree at Worcester Polytechnic Institute

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By

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Abstract

This paper proposes a systematic integration of PASCO scientific models, National Instruments hardware, LabVIEW, sensors and analysis software to simulate and analyze earthquake signal using in structural dynamics and structural health monitoring education. This reconfigurable software-hardware platform is a novel approach because even though it has been done before by other research groups, very few could overcome the drawbacks of high price and un-customizable control system, which are the keys for education purpose applications. In this project, the limit in initial design of PASCO scientific models was redesigned to greatly reduce the price and make it adaptable to National Instruments (NI) data acquisition system, including NI hardware, sensors and LabVIEW software as the control system. Frequency response analyses are also demonstrated in the proposed laboratory activities to confirm the precision, stability and flexibility of this toolbox. Based on the frequency analysis, features of natural frequencies are extracted to determine the structure condition. A structural dynamics course with detailed syllabus combining theory and experiment aspects was designed to familiarize students with this innovative tool. With further study, this toolbox will become a cost-effective solution for educational purpose of structural dynamics and structural health monitoring.

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1. Introduction

1.1 Smart Structures and Structural Health Monitoring in engineering practice and education

With current technology, every structural dynamics experiment for education purpose can be simulated using computer programs, but it cannot replace real experiment. In engineering education, even though real hands-on experiments have effects such as measurement errors that can be programmed, experience gained from real activities does not come from simulation laboratories (Goodwin and Medioli et al., 2011). Laboratories experiments help student assimilate complex theoretical concepts in an easier and more interesting way and provide them experience working with laboratory instruments and equipment that they will work with in the future (Torrey, 1994). Therefore, the best solution to link between theory and practice for engineering education is to combine simulation with real laboratories (Froyd and Wankat et al., 2012).

Some major recent concepts to civil engineering field of high-rise buildings including vibration control (SVC), system identification (SI), and structural health monitoring (SHM) were introduced in the society of civil engineering in 1970 but these ideas have only recently gained worldwide recognition in the academic arena (Hurlebaus and Stocks et al., 2012). In general, in high-rise buildings, large-scale excitations like earthquakes, hurricances, and blasts apply external engery on structures and this source of energy is then transformed into both kinetic and potential energy. It is essential to mitigate the hazardous effect of earthquakes by distributing input energy within the structure. To mitigate the effect, a damper system must be installed to absorb the energy, preventing structure from collapsing. Technique that controls performance of these dampers is called SVC (Constantinou, 1994). Another crucial process that is involved in this approach is SI and SHM, which is the process of implementing a damage detection strategy for aerospace, civil, and mechanical engineering infrastructure (Sohn and Farrar et al., 2004).

Although these revolutionary concepts are attracting attentions from researchers, engineers, property owners and decision makers, educatiors still cannot make them popular to students to make them aware of the importance of the technology (Zhang and Lu, 2008). The reason for this is that these technologies mostly require not only substantial background

on actuators, sensors, data acquisition systems, and various computational models but also great amount of investments. This costly investment is mostly spent on laboratory facility, consisting of specialized equipment, which are essential for the educational as well as research purposes in small scale (Albu and Holbert et al., 2004). Thus, to design a simpler, cheaper simulator which does not require such extensive knowledge on the subject but still produces good results is one of the solutions for undergraduate level of structural dynamics and SHM education.

1.2 Recent developments of educational shake table projects in the United States

In the United States, many colleges have been researching on educational tools of this simulator for structural dynamics and earthquake engineering using shake table. A vast majority of these tables are used to test scaled structures of new concepts and techniques before their real-life implementation. Despite their effectivenesess, they still have different drawbacks that prevent their project to become a major intrument for educational purpose. (Turner and Shaw et al., 2011).

One of the most well-known is Purdue University Consortium on Instructional Shake Tables (UCIST) project which concentrates on the emerging technology of tele-operation capability. Following the fifth major shift in current engineering education which includes Remote Laboratories (Froyd and Wankat et al., 2012), this feature makes it possible to a broader set of students at institutions to access by remotely controlling the structure and collecting the data, recording video in real-time via internet (Dyke and Christenson et al., 2007). This solution also allows a community share expensive equipment and reduce the equipment downtime. Although remote labs will probably become a major component in engineering education (Orduna and Garcia-Zubia et al., 2012), whether or not it could replace in-person labs is still questionable (Froyd and Wankat et al., 2012). Another major drawback of tele-participation capability of this projects and others similar ones from Lehigh Unversity and University of California at San Diego is that it is difficult to demonstrate independent experiments that require modifying the structure. Also, price of the whole system, which is $10,000-$25,000, is much higher than other products (Dyke and Christenson et al., 2007) (Elgamal and Fraser et al., 2005) (Zhang and Lu, 2008).

The second well-known project is Colorado University- Network for Earthquake Engineering Simulation (CU-NEES) Instructional Shaking Table. It is also designed for educational outreach purpose with tele-operation potential. The control software is LabVIEW environment, which can maximize the flexibility of the control system for a variety of research purposes. On the other hand, the drawback of this project is due to weight of structure, the actuators need to be strong to provide enough force for moving the shake table at desired amplitude and frequency. As a result, the price of actuator devices and the structure is still high for a non-comercial product (Wallen and Larson, 2007).

Last but not least, large-scale high-performance shake tables at other universities such as University of California, San Diego; University of California, Berkeley; University at Buffalo, The State University of New York are not suitable for our small-scale model study and research purposes (Nees.ucsd.edu, 2014) (Nees.ubuffalo.edu, 2014) (Peer.berkeley.edu, 2014) .

1.3 Proposed solution and current project

As a result, currently there is no solution that comprises of all factors including cost-efficiency, functionality, flexibility, stability and precision for educational purposes. The most noticable drawbracks of the present commercial products is the high price of model and control system. The most well-known equipment provided by Quanser has price of at least $10,000 (Dyke and Christenson et al., 2007). To solve this problem, a new system must have low-price actuators but still need to provde enough capacity to shake a structure at desired amplitude and frequency. Therefore, the solution would be to design a system that integrates both structure and shake table to maximize the potential of both components. In this paper, a simple, small-scale 4-story structure is examined to serve a purpose of testing the integration of PASCO and LabVIEW. The set includes PASCO Scientific Structural model, PASCO Mechanical Driver and National Instruments devices and LABVIEW software for data acquisition and analysis. The two major notable factors of our structure are the creative design of soil model, and flexible and customizable LabVIEW controller.

First of all, including sensors, the total mass of our plastic structure is only 2.6 lbs. (1.2 kg) so a high-capacity and expensive mechanical driver is unnecessary. After various designs and modifications, the final solution of the soil model using PASCO model was accepted. This model has enough capacity to move the structure smoothly on 2 long PASCO axles. This soil

model using PASCO is not originated from PASCO. It is innovatively yet simply designed by altering the connection between the first floor and the mounting bars. More details of this design will be provided in section 2.5.

Second, LabVIEW environment was chosen as the computational tool for the control program due to it advantages of being able to be programmed to serve any purpose. Despite this feature of a graphical programming language, the final product is a customizable and flexible user interface that could help students perform all of the work easily. Also, some of its other advantages include: it is a language developed for use in lab applications such as this one; it has a rich set of user interface options for controlling experiments an processes; there was already a body of work done which acquired and displayed sensor data; it is a graphical programming language that is easier for non-computer scientists to modify while performing further experiments and it was already integrated with the National Instruments input and output devices. (Karstaedt and Lauer et al., Year).

The final result of this solution is expected to be able to perform funadamental structural dynamics laboratory and also study of SHM. As mentioned above, although the concept of SHM is not new, it is not popular among undergraduate study due to various constraints of laboratory equipment including both softwares and hardwares, instruments. Using this toolbox, instructors are able to perform SHM as a laboratory activities, helping students gain hands-on experience on this concept. The proposed approach is to use the change in structural paramenters to acknowledge the change in structural health.

2. Physical models

2.1 Pasco high-rise building

The structure was built using PASCO ME-6992 Advanced Structures set. This set included plastic beams, flat beams (used as columns) and corner connectors. Due to the plastic material, any component of the model could be altered or redesigned to extend the research purposes such as changing the stiffness of the columns, adding mass to each floor, adding a pendulum functioning as a damper. Every component has a precise dimensions and the same material properties: Young's modulus of the material is 2.29 GPA (424 ksi), cross section of the beam is in the pictures below. The flat members have nominal cross section dimensions

of 0.4 in x 0.1 in (Pasco.com, 2014). From this, the users could create a mathematics model of this structure.
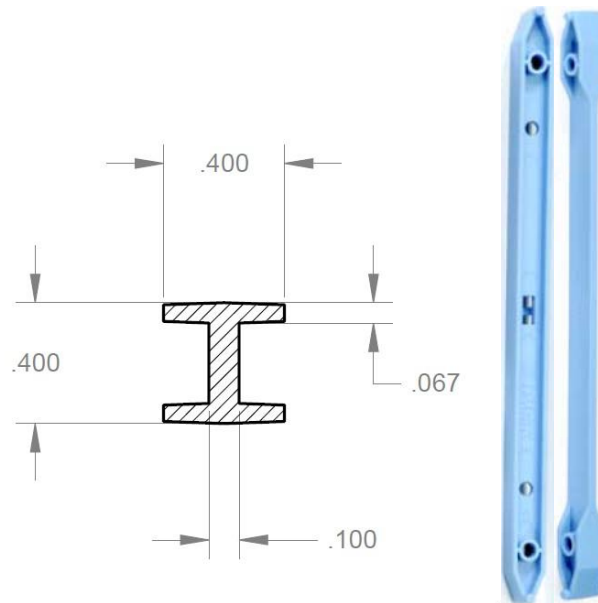

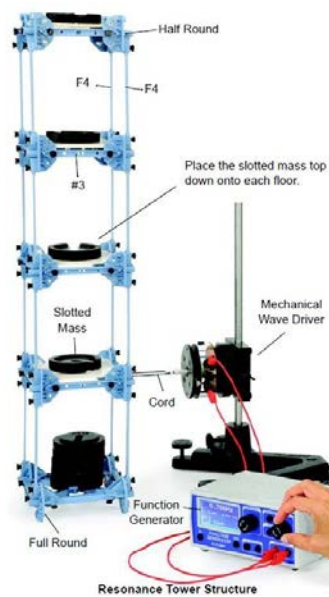Figure 1: Dimension of PASCO beam members (Pasco.com, 2014)

Figure 2: PASCO 4-story structure and original design (Pasco.com, 2014)

2.2 Pasco bridge structure

PASCO ME-6991 Bridge included beams, brackets, screws, cord tensioning clamps, a Mini-car, and a flexible road bed for building various trusses and bridges. Dynamics tracks could

also be constructed to study motion. In addition, rollercoaster design could be studied (Pasco.com, 2014). By combining ME-6991 and ME-6992, users could extend the scale of structures using truss and beam elements of the Advance Structures set (Pasco.com, 2014). Nonetheless, for the purpose of this project, this set was only utilized to build the structure frame.
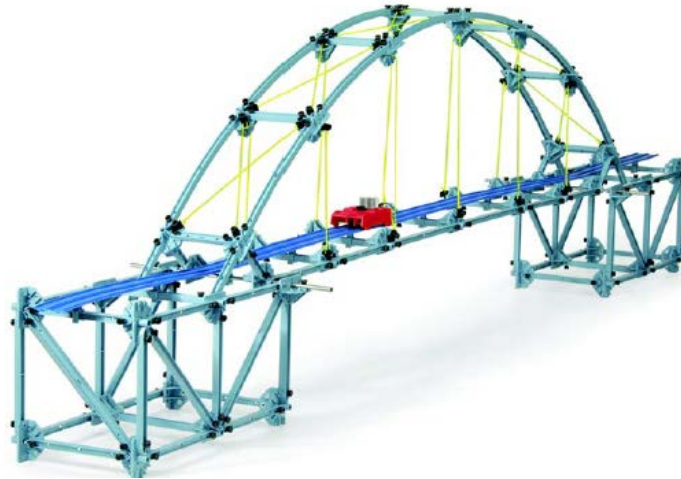
Figure 3: PASCO Bridge structure (Pasco.com, 2014)

2.2 Actuators

Our actuator is the PASCO Mechanical driver SF-9324. This is a device for driving waves with high accuracy. Basically, it is a strong, long-throw speaker attached to the drive arm. The speaker is able to vibrate in the range of 0.1Hz to 5kHz with maximum amplitude of 7 mm at 1Hz . It can generate any kind of wave provided sufficient voltage information is given (Pasco.com, 2014). Conversely, to maintain acceptable amplitude as well as not to blow out the speaker and prevent aliasing, the driving frequency should be limited to less than 50 Hz and the input voltage should be less than 6 V.
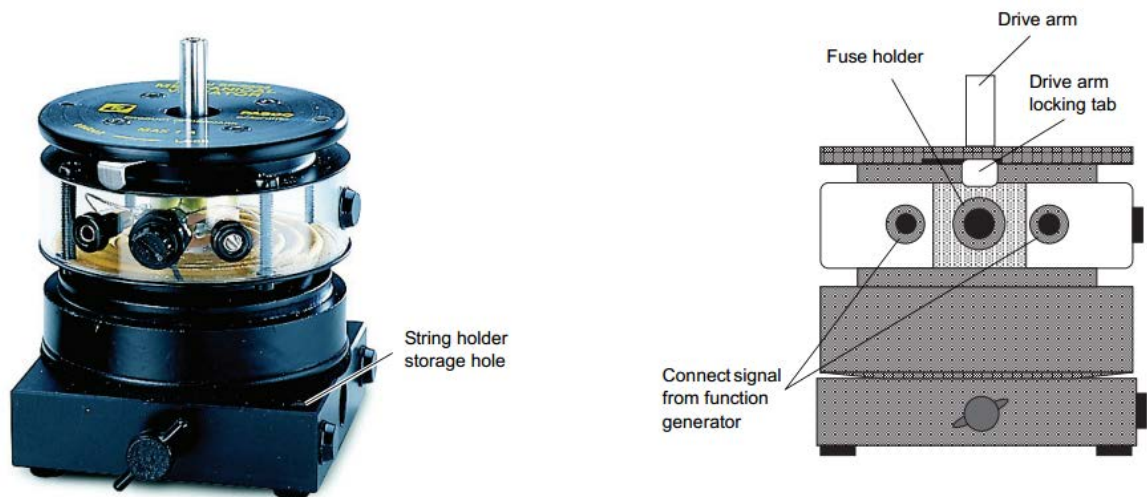
Figure 4: Mechanical Wave Driver SF-9324 (Pasco.com, 2014)

Table 1: Specification of Mechanical driver SF-9324 (Pasco.com, 2014)

Property	Specification
Frequency Range	0.1 Hz to 5.0 kHz
Amplitude (peak-to-peak)	7 mm at 1Hz
Input Impedance	8 ohms
Maximum Current	1 ampere (fuse limited)
Nominal Current Required	<0.25 A
Maximum Input	6 V at 0.8 A

In addition, PASCO provided an acturator mounting rod with diameter of 0.5 inch, which was not a good choice for the substantial vibration frequency and amplitude. A new mounting bar was designed using light-weight fiber reinforced material. This bar was then fixed to the vibration-isolated table, functioning as a damper, diminishing most of the potential reaction force and vibration from the structure that might cause noise in the output signal.

2.4 Sensors

Four accelerometers including two PCB 302A and two Wilcoxon Research models 780C were the sensors used for measuring accelerations of 4 floors of the structure. PCB 302A has

sensitivity of 10mV/g and it can measure up to frequency of 10 kHz in the range +/- 500 g (pcb.com, 2014). This is a high performance accelerometer so it is over-qualified for our purpose. The other two accelerometers, which are Wilcoxon Reaseach models 780C are more economical. This model has sensitivity of 100mV/g, frequency range of 1-7000 Hz and acceleration range of +/- 80g (wilcoxon.com, 2014). If more sensors are required for this project in the future, the second model would be preferred due to its acceptable range of frequencies and sensitivity as well as the lower cost. In addition, to minimize the effect of these accelerometers on the structure movement, they were attached to the middle of each floor beam and their masses were added to total floor mass for mathematical model analysis.

Figure 5: Accelerometers: Left - Wilcoxon Research models 780C (wilcoxon.com, 2014); Right - PCB 302A (pcb.com, 2014)

PASCO also provides other types of sensors (motion sensor and load cell) that are used to be considered for our project. The motion sensor is an electrostatic transducer in the face of the Motion Sensor transmits a burst of 16 ultrasonic pulses with a frequency of about 49 kHz. The ultrasonic pulses reflect off a target and return to the face of the sensor. The target indicator flashes when the transducer detects an echo. This sensor measures time between the trigger rising edge and the echo rising edge to calculate the distance to the object. To determine velocity, the consecutive position measurements can be used to calculate the rate of change of position. Similarly, the acceleration can be determined by using the consecutive velocity measurements (Pasco.com, 2014). The load cell could be used with Load Cell Amplifier to measure compression and tension forces. The reasons explaining why they were not used are discussed in part 3.1.
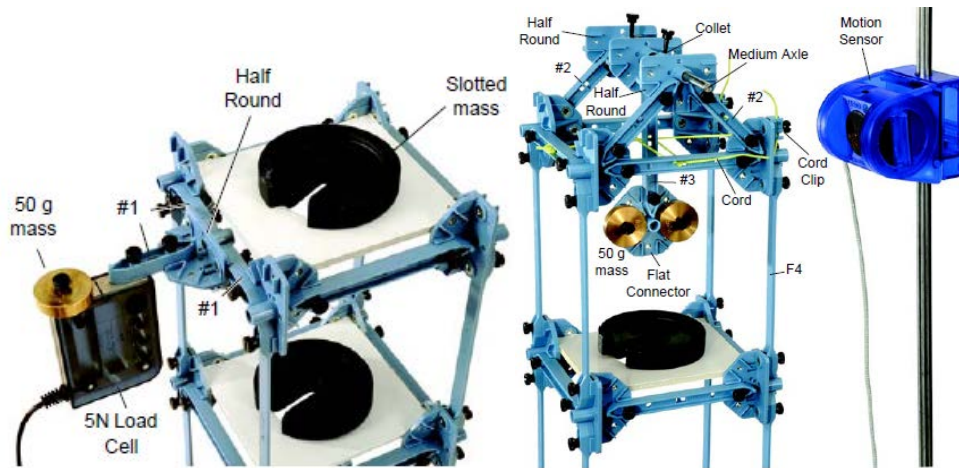
Figure 6: Load cell and Motion Censor and their applications (Pasco.com, 2014)

2.5 Soil Model – Mini shake table

As indicated above, one of the most notable features of our tool-box is the design innovative mini shake table built by PASCO model. This table is smaller than a regular bench-scale shake table and it is also more mobile than one. The main components are two force structures brackets, two axles and the soil model pad assembled similar to other floors of the structure. The modifications include:

- Drill holes in force structures brackets to attach it to the table

- When building the soil model pad, instead of attaching the #3 I-beams outside, attach them inside, allowing two axles to go through the half-round connector.

- A banana plug was used to extend the length of the mechanical driver connector. To attach this connector to the base, cut the bridging piece in the middle of the beam and screw through the hole.

The mini shake table was tested both with and without the structure attached to the base. Input signals of sine wave and Gaussian white noise were sent from computer to the mechanical driver, shaking the base and everything attached to it. In both cases, the motions were smooth with minimal friction. Although this model is still limited in term of capacity (less than 4 lbs.) and amplitude (7 mm), it is the best that one can get from using the material directly from PASCO structure set and it fully serves all of the desired functions.
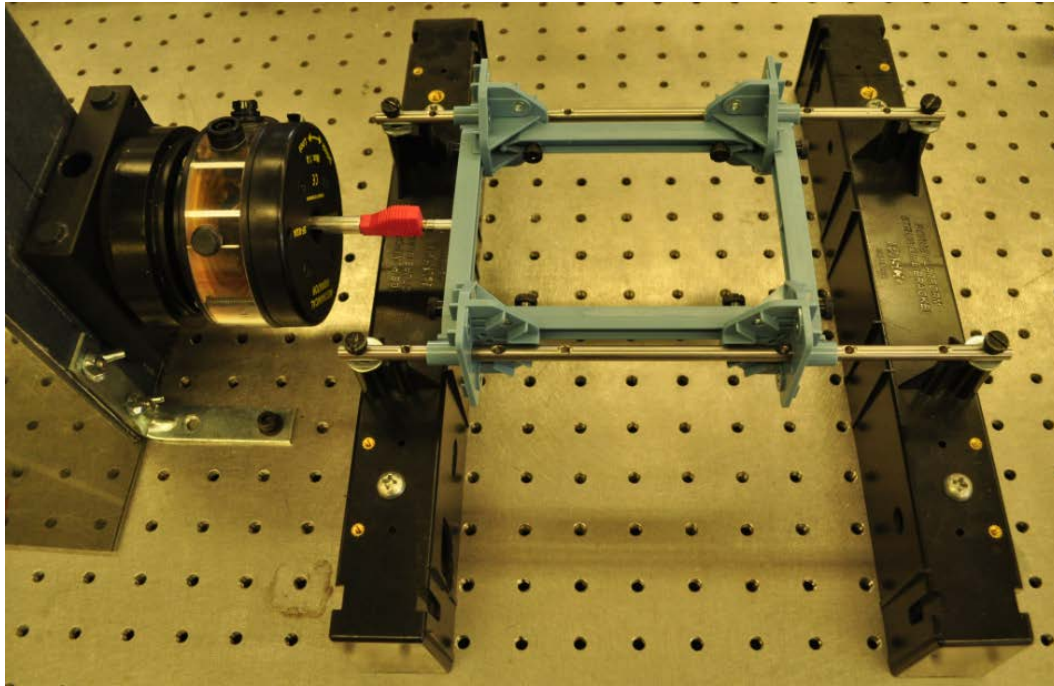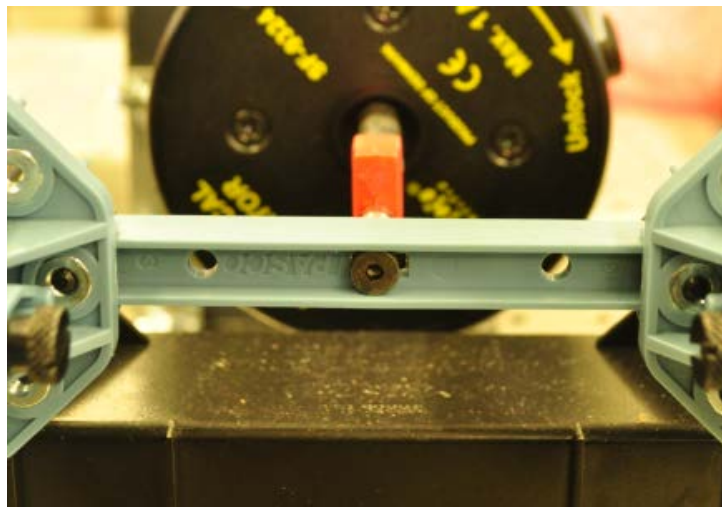
Figure 7: Design of mini shake-table

Figure 8: Connection between mechanical driver and structure base/soil model

3. Function Generator, Data acquisition and analysis system

3.1 Function Generator

Although it is recommended by PASCO to send signal to the machincal driver using a PASCO function generator (Pasco.com, 2014), this option was disregarded due to the inability

to produce vibration signals with different patterns other than just basic signal patterns. Therefore, the solution for function generator was to use LabVIEW and National Instruments device to send voltage signals. This option provided more options, including all of the desired signals, not just limited to the basic signals. Also, the most notable advantage of this option is the capability of generating simulated earthquake signals using input data from MATLAB. As a result, this virtual instrument can produce any earthquake signal, both periodic and aperiodic, which is a helpful function for both studying and researching.

3.1 Pasco hardware and software

For the data acquisition system software, PASCO sensors were our first option (with the capacity of measuring load, displacement, acceleration and velocity) because of the time capability to demonstrate output signal. Despite this potential, it has a low sampling rate and inability to customize. More detailed reasons are listed as the advantages and disadvantages of the system below:

Table 2: Advantages and disadvantages of PASCO system

Advantages of PASCO	+ Mechanical Driver can excite the model at desiable amplitude (+/- 7mm) and desirable range of frequency (0-5kHz) for cheap price
Disadvantages of PASCO	+ Acceleration and velocity measurements are derived from differentiations of displacement, causing noisy data. + The laboratory operator cannot customize the control and data acquisition software to do more advanced functions. + Function Generator PI-8127 cannot generate random or more complex waveforms. It only generates sine, square, triangle, positive ramp, and negative ramp with a frequency range of 0.001 Hz to 100 kHz (Pasco.com, 2014). + The laboratory operator must manually start the function generator and data acquisition system simultaneously because it is impossible to integrate PASCO function generator and labVIEW data aquisition system. As a result, the input and output data would not perfectly match in time-domain.

3.2 National Instruments hardware and LabVIEW software

A better and more practical solution for data acquisition devices and controlling software was necessary, and National Instruments devices and LabVIEW software were used instead of PASCO software. By doing this, it was possible to customize our own virtual instruments, maximizing the potential of the PASCO model as well as making use of high sampling rate of the sensors, producing valuable information. National Instruments LabVIEW software originally did not support doing SHM for the building/bridge model but it can be programmed to function as a data acquisition and analysis system. Thus, National Instruments and labVIEW were chosen to be our solution for data acquisition system despite the lack of capability to demonstrate data in real-time due to hardware limit. More details behind this choice are listed below.

Table 3: Advantages and disadvantages of National Instruments

Advantages of National	+ Compatible with labVIEW and other devices including PASCO mechanical driver. + Make use of the high sampling rate of accelerometers and PASCO mechanical driver.
Disadvantages of National	+ Requires using of GLX Power Amplifier PS-2006 to connect the mechanical driver of PASCO to NI 9269 for signal/Function generating + Cannot analyze data in real-time due to hardware limitation (Karstaedt and Lauer et al., Year)

The National Instruments hardware system was specified as: Input and output was handled by data acquisition and generation hardware from National Instruments. The sensors received information from control program via a National Instrument SCXI-1000 data acquisition module. From the LabVIEW control program, signal was converted from digital to analog by a NI-9174 and a NI-9269. These two devices National Instruments (NI) cDAQ-9174 USB Chassis and NI-9269 Analog Output module work in conjunction to receive a signal from the computer and send out an analog voltage signal." (Karstaedt and Lauer et al., Year).

In this project, the data acquisition virtual instrument was designed by a group of Professors and Students at Worcester Polytechnic Institute (WPI). The main purpose of this program was to test and implement control models for experimenting with using MRDs in structures to modulate the effect of impact loads. The requirements for this program were based around the needs of researchers with little or no programming ability. (Karstaedt and Lauer et al., Year). Therefore, besides its funtionality, it is also a good choice because of user-friendly interface of LabVIEW.

3.3 Matlab-based analysis software

Although LabVIEW could provide our virtual instrument with built-in functions to analyze the data collected from data acquisition system, in this project, the final analyzing objective is still being developed so the LabVIEW virtual instrument has not been finalized to include all of the desired functions and features. Therefore, for this developing process, Matlab-based analysis was used. The main purpose was to collect raw data from LabVIEW, cleanse, normalize and convert data and finally is to plot the data. In addition to data analysis, Matlab was also used to do model analysis of the structure to identify structural parameters to compare between experimental and theoretical approaches. One of the main advantages of using Matlab to analyze data is that it provides students with opportunities to work on their own computer or develop their own analysis functions once they collect all necessary data. This approach stimulates their creativity as they could think of different methods to meet the laboratory objectives.

4. Project descriptions

A similar project using integration of PASCO Scientific model, National Instrument and Labview to perform small scale study of Structural Dynamics and SHM was done by the corporation of National Instruments and Rice University (Huang and Vemuru et al., 2010). Our project had the same objectives but focused on the designing aspect of the building structure, and using frequency response analysis as a tool to confirm the stability and precision of the model. It also suggested using this model for SHM in educational purpose by a short demonstration of the effectiveness of this structure in a SHM course project.
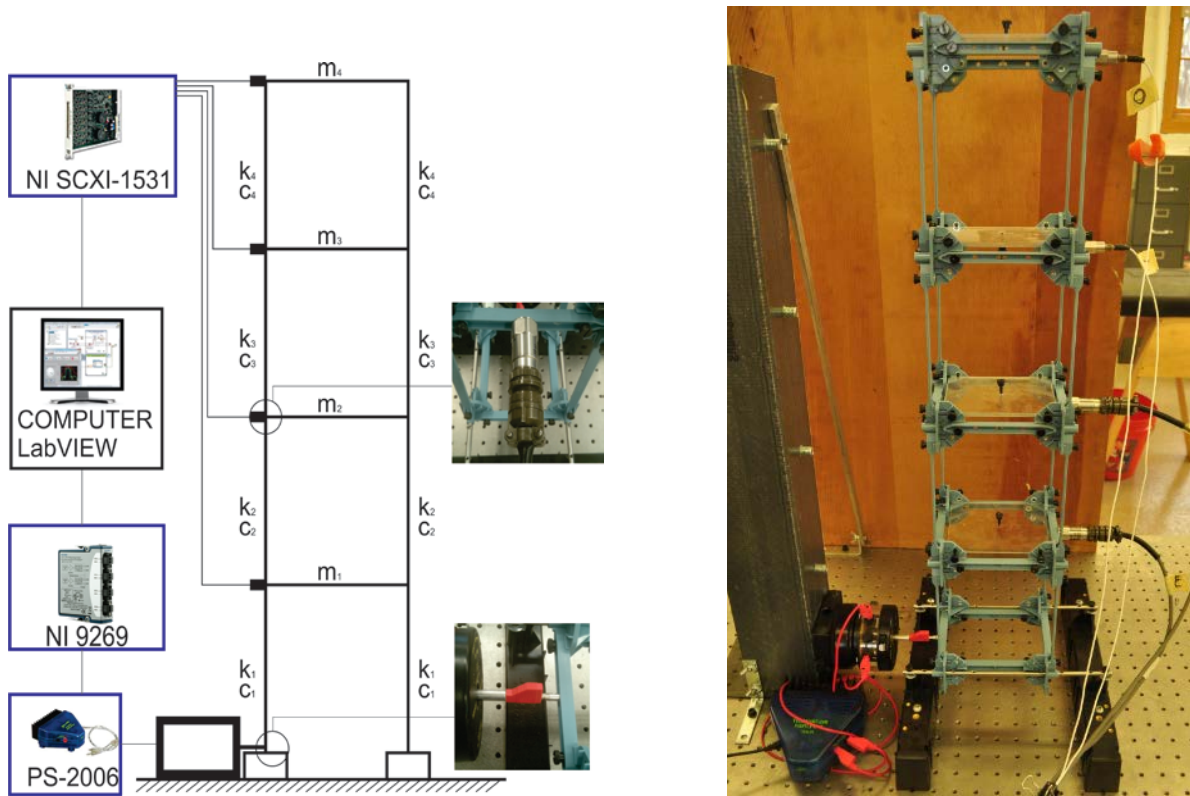
Figure 2: Project setup

4.1 Frequency response analysis

In this paper, frequency response analysis was a major tool used in the proposed projects to prove the qualities of the model. The dynamic characteristics of a structure (eigenfequencies and corresponding loss factors) can be obtained using the results of frequency reponse analysis. However, the scope of this paper was limited to demonstrating the potential of this project based on frequency response analysis. Therefore, our method considered the change in frequency response of the structure a proof of change in structure properties without analyzing of the finite element model.The main tool used to do frequency response analysis was Fast Fourier Transform. This is the method that transforms the signal from one domain to another domain in which many characteristics of the signals are revealed. The domain of the original signal is usually the time or spatial while the transformed domain is the spectral or frequency. The data collected from the accelerometers were initially in time domain, then were applied Fourier Transform to convert frequency domain for further studies.

Various methods including modal analysis and applying Gaussian white noise ground motion to measure natural frequencies were applied to confirm the precision and stability of the model.

4.2 Structural health monitoring

SHM was demonstrated based on frequency response analysis to present the potential of this toolbox in education. Two conditions of the structure including healthy and modifed (or damaged) were investigated. First, the case of a healthy structure was developed for reference. Such a case represented the response of the structure without any structural modification. This was established by using frequency response analysis to determine the natural frequencies of a un-damaged structure. After that, all possible cases of damage at different locations causing damage severity ranging from 8% to 25% stiffness reduction were simulated. Any change would help detecting and evaluating the location and severity of damages. The damages were simulated by loosening the bolts in the connection between columns and beam, assuming that these connections carried no force or moment.

5. Proposed course experimental activities

After the structure and its testing system were built, they were tested. It is demonstrated from both testing and its analysis that the proposed testing framework is useful in teaching undergraduate students.

5.1 Proposed course description and syllabus

The theoretical concepts of a Structural Dynamics course are proposed in Table 4. The concepts are very similar to the outline of the book Dynamics of Structures by Anil K Chopra (Chopra, 2011). Every course and laboratory activity must have clear learning objectives, which are essential in designing an efficient learning system and also in applying an effective system of assessment (Feisel and Rosa, 2005). The major intended objectives that students should achieve at the end of each lab as well as at the end of the course include:

1) Instrumentation: Know how to use sensors, National Instruments data acquisition system and LabVIEW virtual instrument for each experimental purpose.

2) Models: Identify the difference between a theoretical and real model; be able to create a numerical model in Matlab or Simulink using material properties, section properties and other structures properties to do computer simulation and mathematical modal analysis.

3) Data analysis: Demonstrate the ability to collect, analyze and interpret data for each experimental purpose.

4) Design: Be able to build and assemble the 4-story structure model, develop a simulation system that could simulate structure response of various input scenario.

5) Basic understanding of structural dynamics, sensor technology and structural health monitoring.

Table 4: Proposed course syllabus

Theory	Experiments
1. Equation of Motion, Problem Statement, and Solution Methods	- Introduction to data acquisition and analyzing system
2. Single Degree of Freedom - Free vibration of undamped system - Free vibration of damped system - Free vibration test	- Develop a numerical model of structural in MATLAB to calculate structure features and compare with later experiment results - Free vibration of damped system experiment
3. Single Degree of Freedom - Forced vibration of undamped system - Forced vibration of damped system - Resonance analysis	- Forced vibration of damped system experiment (Using Impact Hammer connected to LabVIEW data acquisition system)
4. Multi Degree of Freedom - Free vibration of damped system - Free vibration of undamped system	- Computer simulation – Simulink of damped and undamped systems - Develop a numerical model of structural in MATLAB to calculate structure features and compare with later experiment results

	- Free vibration of damped system experiment
5. Multi Degree of Freedom - Forced vibration	- Computer simulation of Earthquake response of structure - Test structure under the same earthquake signal
6. Modal Analysis	- Fourier Analysis using Matlab or LabVIEW - Transform time-domain data to frequency-domain data
7. Additional topic: Structural Health Monitoring	- Structural Health Monitoring and Assessing using frequency response analysis.

Examples of the laboratory activities using this toolbox is presented below. Some of them require using of additional devices such as impact hammer, or PASCO load cells and motion sensors (to measure force, acceleration, velocity and deflection under sine wave vibration input). All of the laboratories are closely tied to course projects and the final project to help students keep track and be responsible for their work to achieve the final objective of the whole course. This approach enhances their interest in laboratory activities because they would have fewer, clearer and more interesting but also more demanding goals for the whole course. The final project for the course is similar to the SHM example below, in which students will have an opportunity to design and test a complete case study of SHM, using everything they have learnt from the course. Before starting this final project, students should be familiar with the course materials, lab equipment and the other experiment procedure and results. By then they could fulfill all of the proposed objectives of this course, such as: be able to use sensors, data acquisitions and analyzing systems; be able to create a numerical model using computer simulation and observe the difference between simulated and real experiments; be able to analyze data to assess the structure condition.
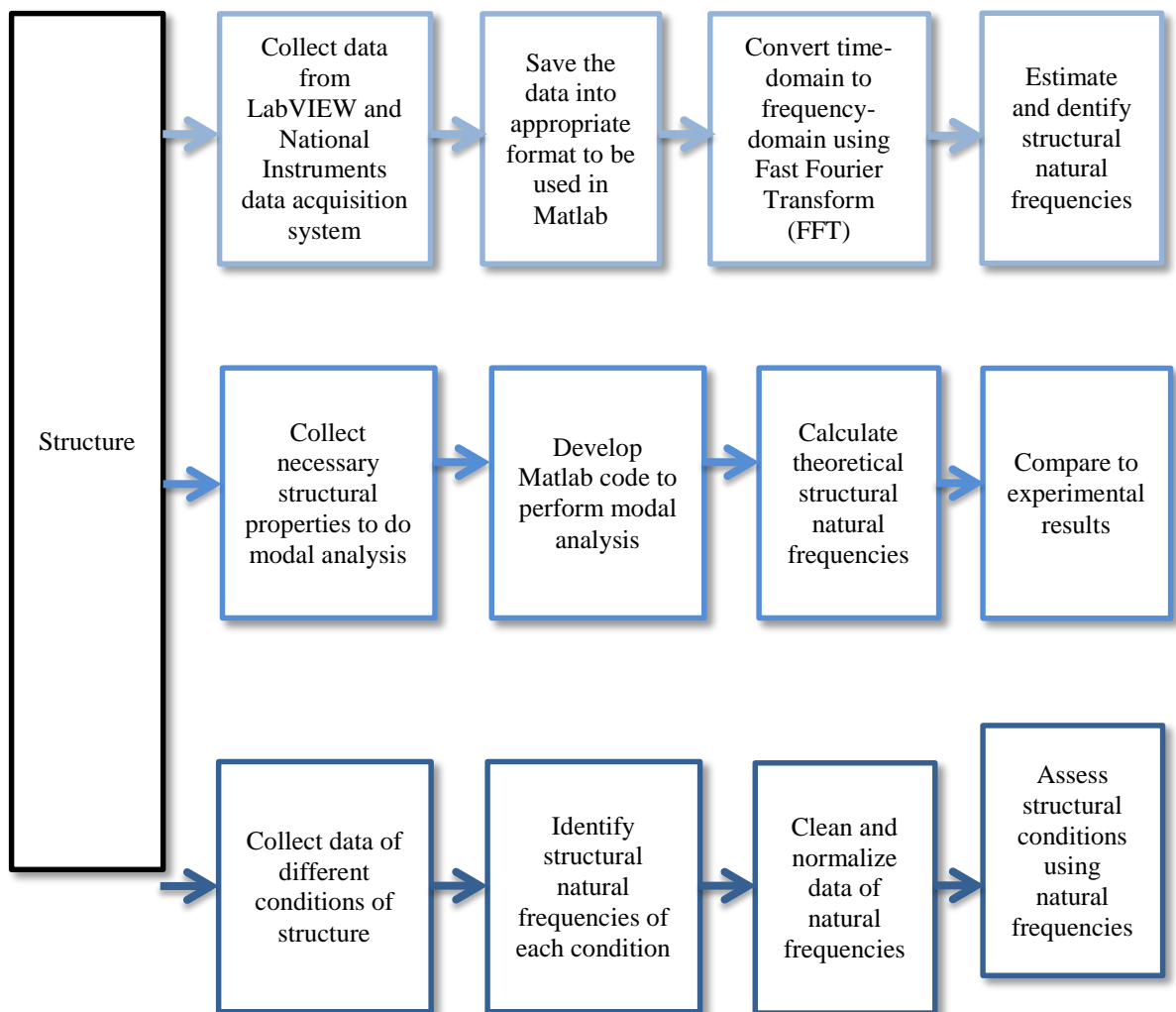
Structure

Row 1:
Collect data from LabVIEW and National Instruments data acquisition system → Save the data into appropriate format to be used in Matlab → Convert time-domain to frequency-domain using Fast Fourier Transform (FFT) → Estimate and dentify structural natural frequencies

Row 2:
Collect necessary structural properties to do modal analysis → Develop Matlab code to perform modal analysis → Calculate theoretical structural natural frequencies → Compare to experimental results

Row 3:
Collect data of different conditions of structure → Identify structural natural frequencies of each condition → Clean and normalize data of natural frequencies → Assess structural conditions using natural frequencies

Figure 9: Proposed course laboratory activities

5.2 Time domain response – MDOF Structure testing under applied ground motion

Before this laboratory, students should be familiar with equipment, LabVIEW virtual instrument user interface and data acquisition system. This activity serves as an introduction to MDOF and the objective is to produce a time history of acceleration data under random ground motion. Motion sensors could be used to observe structure motion at a certain floor.

Figure 5 represents the time-domain responses of the structure excited by the random Gaussian white noise signals. The data from 4 accelerometers are collected and stored simultaneously. As seen, however, it is difficult to extract valuable information from the time history responses due to the fact that the input vibration signal was random, which means each experiment with the same condition has a distinctive data set, producing different structure response outputs each time student runs the system. Due to this factor, no structural features could be extracted directly from the time-domain response. To address this issue, the time history responses are transformed into frequency responses.
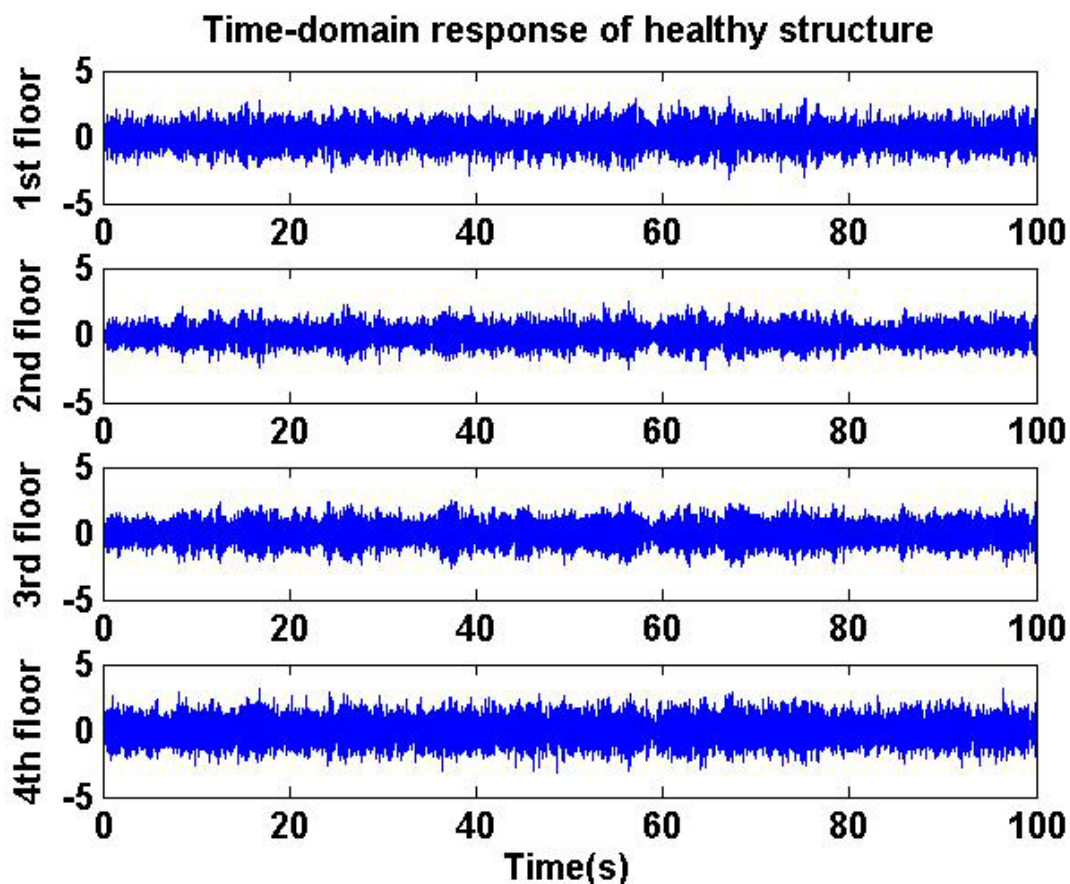

Figure 10: Time history of acceleration data

5.2 Frequency domain response – Fourier Analysis Using Matlab

This laboratory introduces students to analyzing/transforming data using Matlab. Before this activity, students should understand the basic concepts of Discrete Fourier Transform, frequency domain, sampling rate, aliasing and the algorithm of Fast Fourier Transform. Matlab interface and simple functions are also designed in the theory part prepared for this course.

To achieve the objective of this laboratory, students should have a fundamental background in Matlab or any programming language or be able to learn in a short time. Most of the Matlab functions are provided by the instructor but students still need to understand the given codes to develop new ones by themselves to do their final project. The main steps of the provided Matlab analysis are shown below:
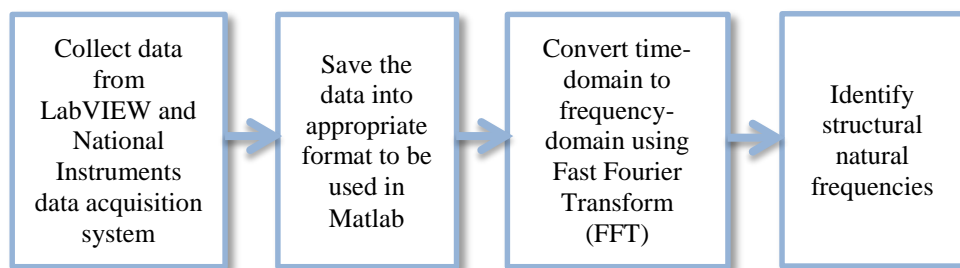

Figure 11: Frequency domain response laboratory

Figure 12 shows the frequency responses obtained using Fast Fourier Transform. Due to resonance, the structure had a tendency to respond with greater amplitude to the input frequencies that matched its four natural frequencies. Thus, when all of the frequency and amplitude of responses were added up together in frequency domain, only the peaks at natural frequencies of the structure were noticeable and useful for determining the condition of structure. By transforming the original data into another domain, more useful and precise decisions to determine the condition of structure could be made. After doing this, 4 natural frequencies of this structure were estimated to be 2.548 Hz, 8.058 Hz, 13.139 Hz and 16.769 Hz.
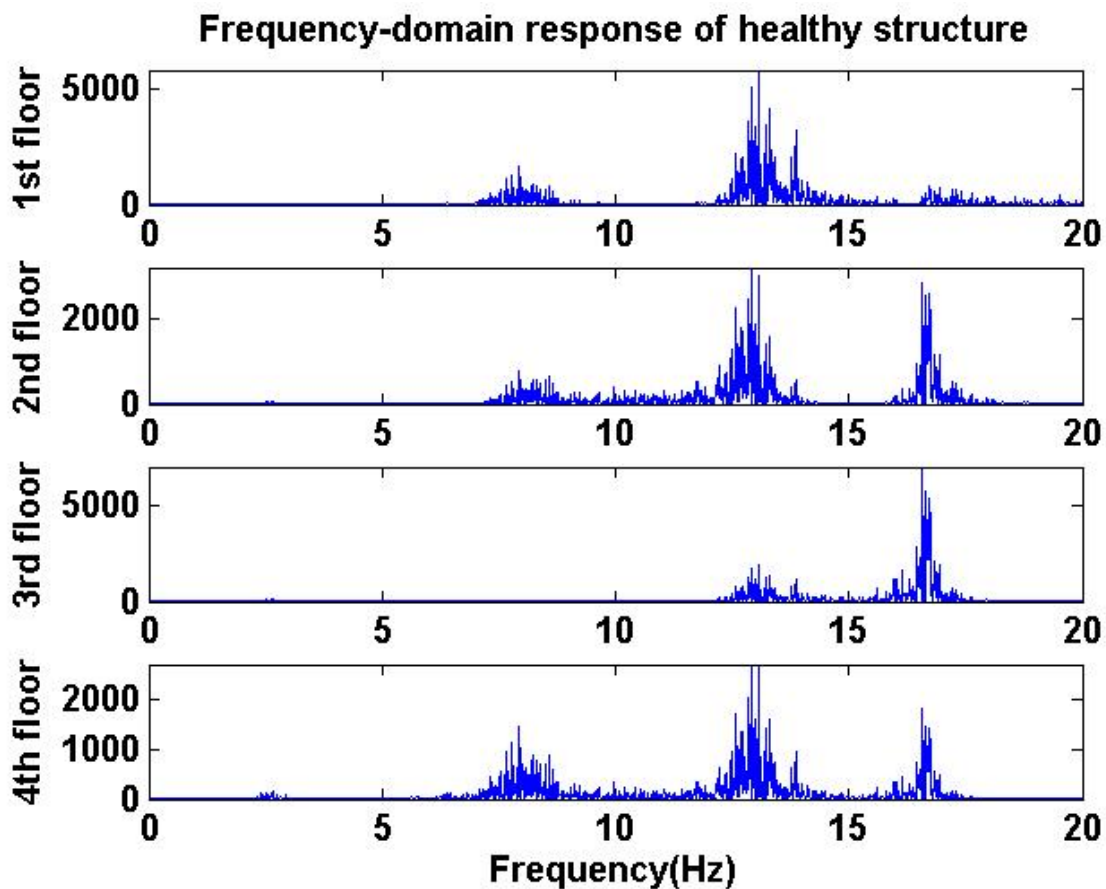
Figure 12: Output data of acceleration in frequency domain

5.3 Modal analysis - Development of numerical model of structural in Matlab

After getting familiar with Matlab, students approach this laboratory in a more advanced level, which requires knowledge of both MDOF structure dynamics analysis and Matlab programing. They need to measure and calculate structure properties to get values for inputting in their Matlab code to do modal analysis of the structure.
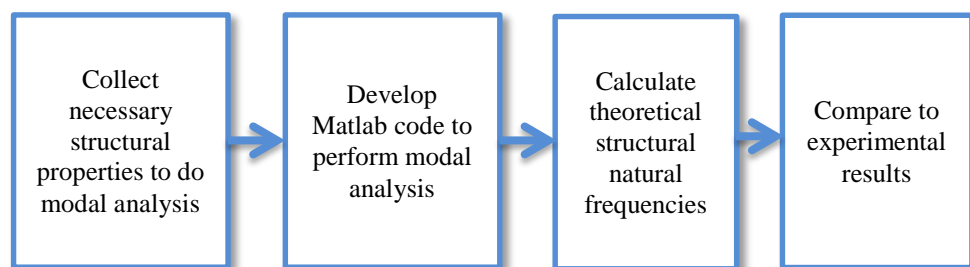

Figure 13: Modal analysis laboratory

The result of modal analysis of structure was calculated to compare to the experimental result to confirm the precision of this structure. The PASCO structure was modeled as a 4-story 2-dimensional structure. Every property of this structure is calculated and measured from the real case or from PASCO manual and recorded in table 5.

Table 5: Structure properties

	Mass (lb.s^2/in)	Stiffness (lb./in)	Damping
1st floor	0.590	4.184	0.504
2nd floor	0.590	4.184	0.504
3rd floor	0.618	4.184	0.518
4th floor	0.588	4.184	0.503

Although only mass and stiffness contributed to natural frequencies calculation in frequency response analysis, the damping was still approximated using Rayleigh damping with coefficients of 0.5 and 0.05. The eigenfrequencies of the equations were calculated and compared to the result of the experimental approach:

Table 6: Natural frequencies from experimental approach and analytical approach

	Experimental Method	Analytical approach
1st natural frequency (Hz)	2.548	2.814
2nd natural frequency (Hz)	8.058	7.894
3rd natural frequency (Hz)	13.139	12.142
4th natural frequency (Hz)	16.769	14.840

5.4 Structural Health Monitoring – Final Project

Basically, this laboratory activity is a review of all previous experiments, in which the final objective is to understand the basic concept of SHM using what students have learnt in the whole course. Additionally, new concepts that are introduced in this final project include SHM, data cleansing, data normalization and structure condition assessment using collected data.
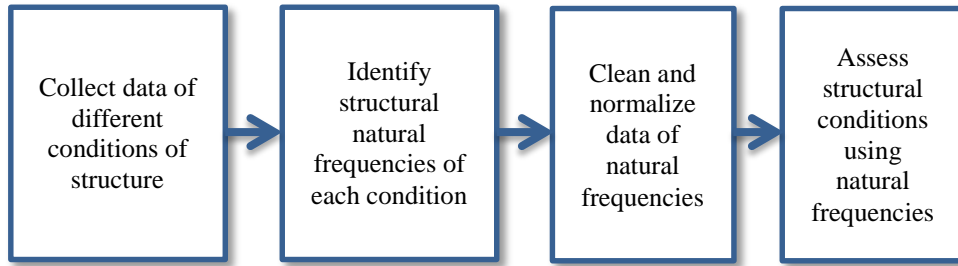
Figure 14: Final Project

There were 8 conditions of a structure considered, including one healthy condition and 7 damaged conditions with severity ranging from 8% to 25% stiffness reduction. For determining the frequency response of each condition, a Gaussian white noise random signal was driven for 100 seconds using the PASCO mechanical driver. This process was done 60 times for each condition. Each experiment produced 4 sets of 4 natural frequencies (from 4 floors). As a result, after 60 experiments, 240 values of each natural frequency of each case were collected. The result then was recorded for observing the shifting in natural frequencies of each case:
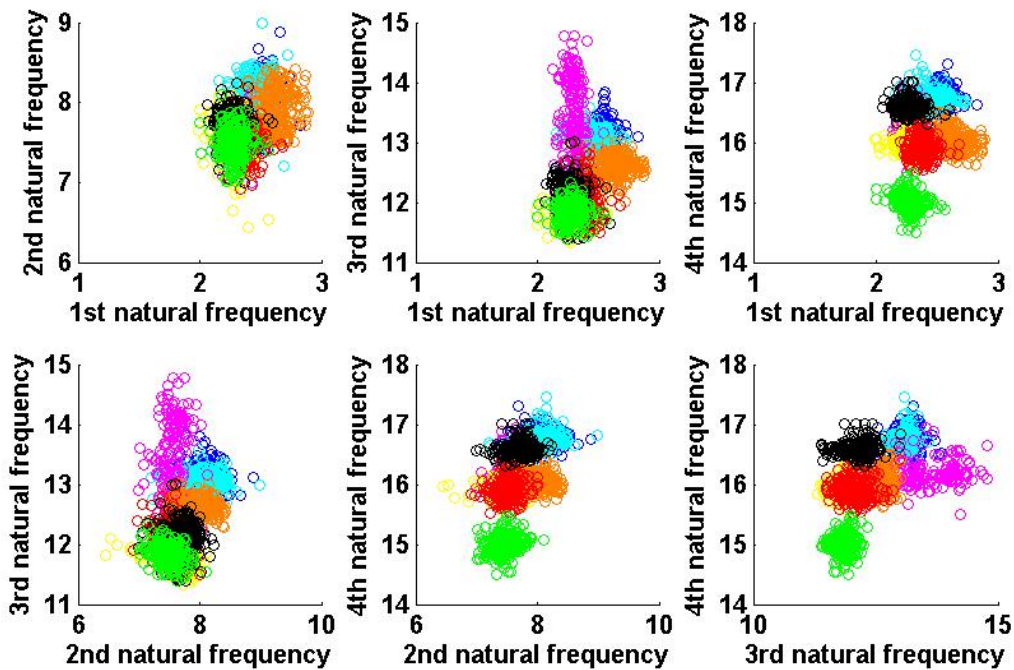

Figure 15: Natural frequencies of different structure conditions

For better visualization, collected acceleration data were assumed to be normally distributed:
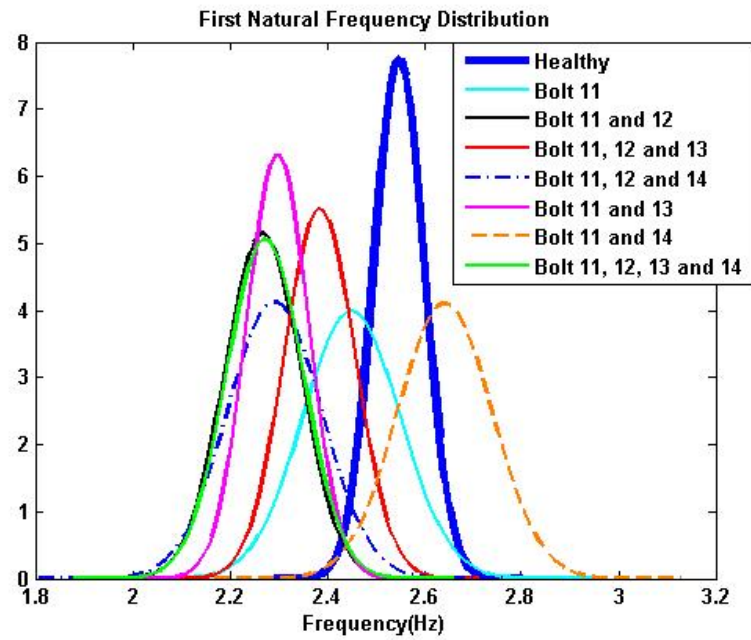

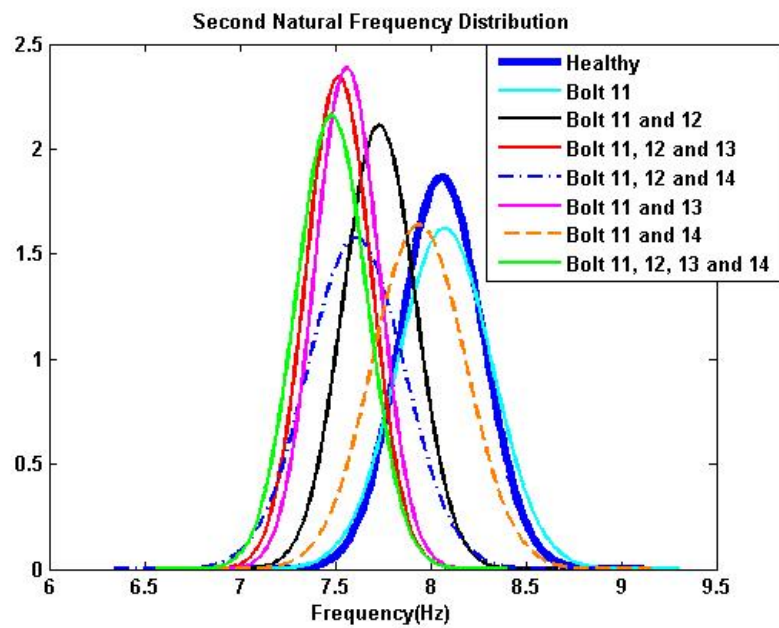Figure 16: First natural frequency distribution

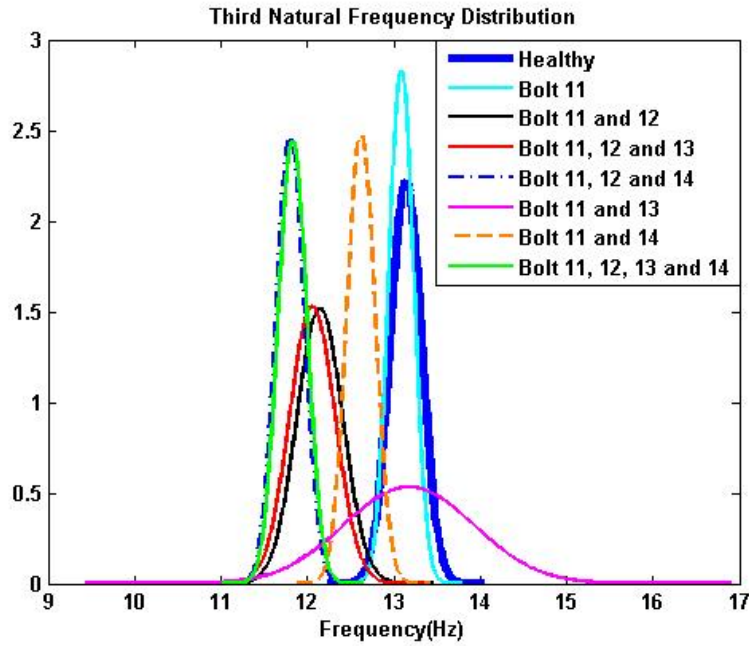Figure 17: Second natural frequency distribution

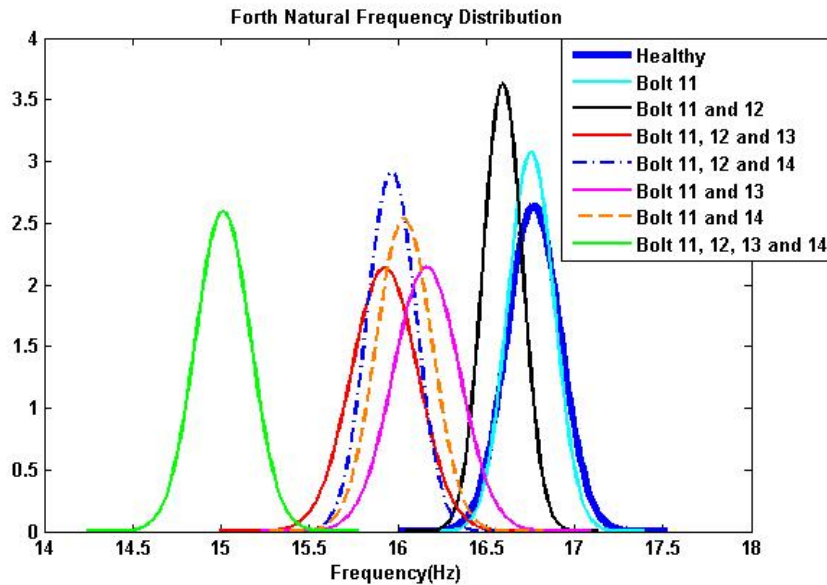Figure 18: Third natural frequency distribution

Figure 19: Forth natural frequency distribution

Although the difference between each condition could easily been recognized, it could not guarantee that one data point only belonged to one set because of the overlapping areas. To make the data boundary more defined, the mean values of randomly picked 80 data in the same condition were used. This provided a much better result with highly recognizable boundary of each data condition. This is method is not only applicable but also very important

in real life. Data size and standard deviation are so large due to various conditions of operations and environment that normalization is essential to reduce the spread-out of data but still convey the general characteristics of the structure (Farrar and Worden, 2007). This could be observed in figure 20 and figure 20, which show highly separated sets. Using this result as a reference, decision could be made to determine structure condition.
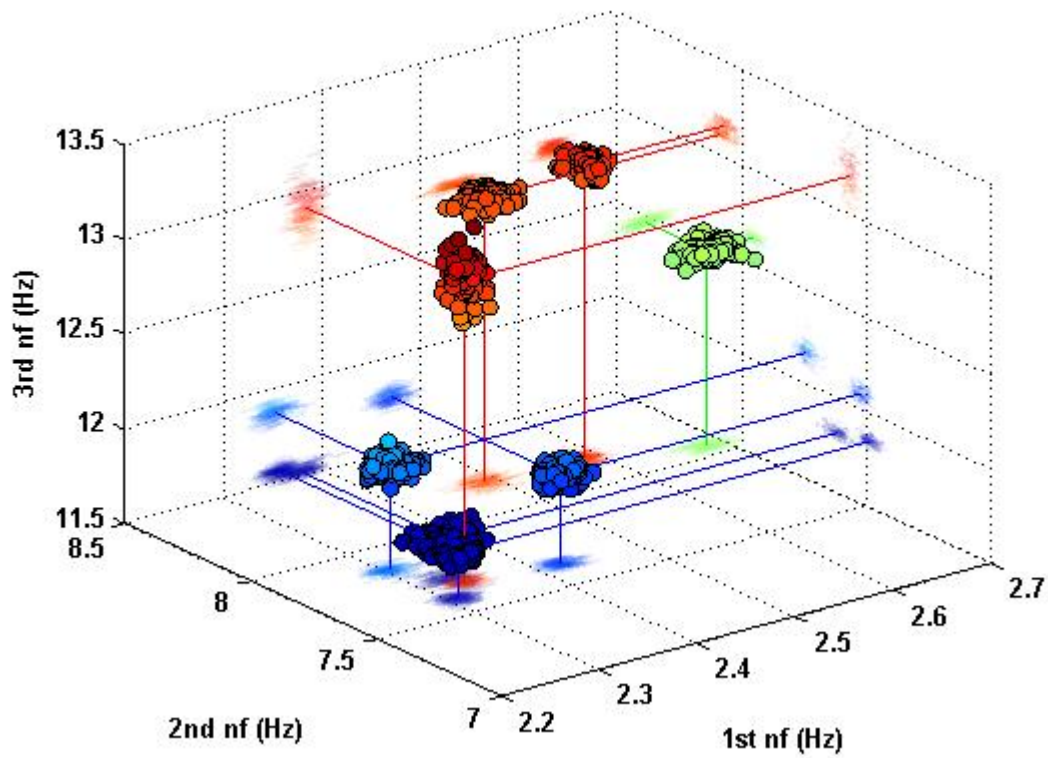

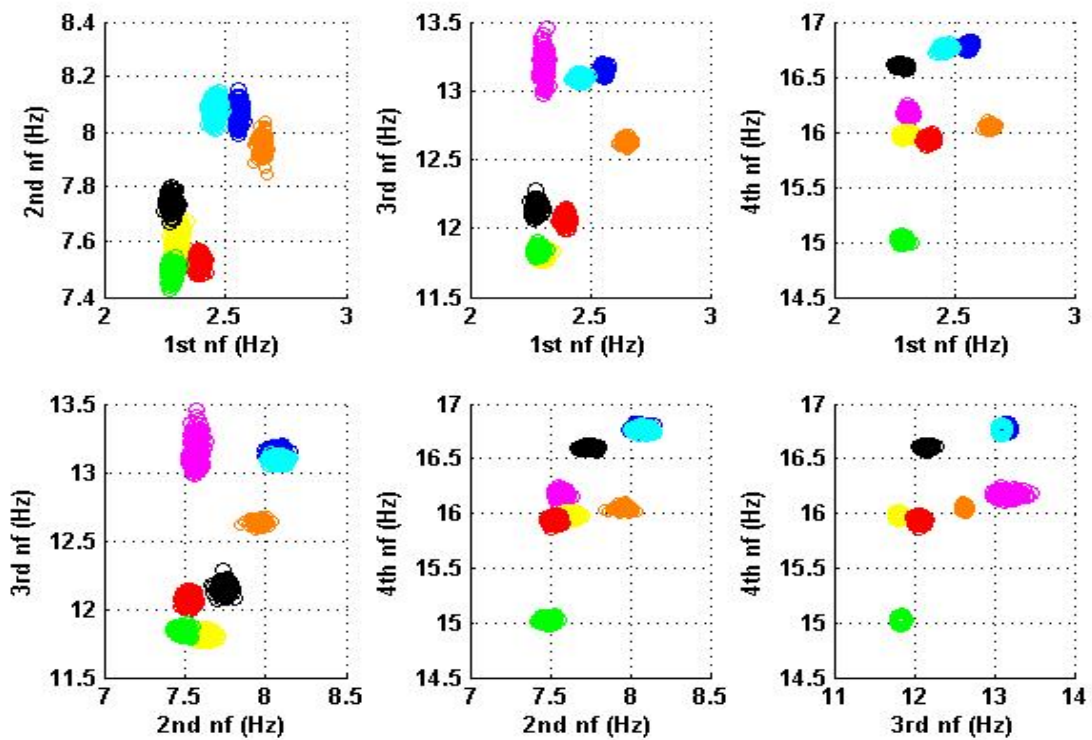Figure 20: Normalized data of natural frequencies

Figure 21: Normalized data of natural frequencies

6. Limitations

As a matter of fact that our approach was the first design and it emphasized on both functionality and cost-effectiveness, there were still some limitations that, in our opinion, did not affect the output but should be eliminated in the next studies. First, due to the fact that the PASCO structure set was not optimized for modeling the soil model, our structure connection to the soil model was not perfect. This resulted in a connection to the ground that did not carry all of the moment. Although this was negligible when the input vibration frequency was high, it caused a small torsion in the top of structure under low input vibration frequency (less than 2Hz). The solution to this could be to use a bigger rod that fits perfectly inside the truss hole to make the soil model. Second, as the price of sensors was high and the goal of this project was to produce a cost-effective package, it was compromised by minimizing the number of sensors. For example, the shake table project of Colorado University, the authors used Analog Device Accelerometers (Wallen and Larson, 2007) instead of the PZT ones. This could increase our number of accelerometers by 3-4 times while still maintaining the cost-effective factor.

7. Conclusions

A hands-on activity-based educational module is developed in this paper. It is developed through the integration of PASCO models, LabView, NI hardware, sensors, and MATLAB software. Despite some existing limitations, the results successfully showed that this structure worked precisely and stably, producing good output data. It was proved as a potential tool for Structural Dynamics as well as SHM education and study in which, each case of damaged structure had a distinctive property (in this paper, the property was demonstrated in term of natural frequencies) and could be separated using classifying algorithms. In conclusion, this project successfully proposed the development of a novel hands-on toolbox for advanced educations. This toolbox is expected to serve as a link between theory and practice in Structural Dynamics education. Moreover, the tool would enhance student motivation by providing them valuable experience working with physical model and collecting real data. The toolbox was developed through the extensive integration of PASCO models, LabVIEW computational program, sensors, and actuators. Although there still exist some limitations, it plays an important role in proposing the potentials of this toolbox with its cost-effective, user friendly and stable factors. Further studies should concentrate on optimizing, making the system more reliable and stable to increase the potential. Also, this tool would be used as an additional laboratory activity for students in Structure Dynamics related courses. The results and feedbacks will be monitored and analyzed for future improvement.

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