

Achieving Student Outcomes through Hands-on Design of Experiments

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Abstract

Hands-on learning in engineering is one of the most effective ways to understand basic theory and its application to practice. Several first and second-year lab courses utilize standardized lab in which students are introduced to a step-by-step procedure to complete the exercises. A different approach was used in two upper-level courses in Mechanical Engineering, wherein students are required to design an experiment in order to demonstrate some of the basic concepts and principles learned in their earlier semesters. Students were given a broad definition of the problem and divided into groups to design an experimental set-up which included sensors, instrumentation, and procedure to carry out the experiment. Through these experiments, students are expected to collect and analyze data using LabVIEW; subsequently interpreting the results and relate them to the theory. In addition, they were required to simulate the system response using SolidWorks, compare theoretical responses to experimental data and generate a report. The objective of having hands-on design experience is for students to apply theory to practice and appreciate the possibilities when it comes to experimental design. The courses also consider the impact of the students' work in the context of ABET Outcomes 1, 5, and 6, relating to working in teams to design experiments, analyzing and interpreting data and drawing appropriate conclusions. This paper presents sample experiments that were designed by the students involving the use of basic concepts in vibrations, mechanics of material, and heat transfer.

Introduction

For engineering students, laboratory experiments constitute an essential part of their curriculum. The engineering theories become observable and a few times palpable during these experiments. In general laboratory experiments are designed to have a single path to reach the desired results. Although this approach is effective in connecting the theories and the results, it does not offer the option for the student to research, explore the theories extensively and find other ways to reach the desired answer.

This paper describes a hands-on approach where students are asked to design experiments for an upper-level mechanical engineering course, ME 4504 Process Monitoring and Control; the students are provided with appropriate guidelines. Students in this course may be upper-level Juniors or Seniors and would have completed Mechanical Vibrations and Heat Transfer courses. The ME 4504 course is similar to Experimental Methods or Design of Experiments course in other engineering programs. The experiments are based on first and second-order systems that make use of basic concepts dynamics and thermal-related systems. The aim of this approach is to allow students to understand the theoretical models pertaining to the experiments and

appreciate how theory and practice come together, and which further validates results from software models. For each design experiment, the guidelines are formulated with the ABET Outcomes in mind. This course focuses on three outcomes as defined by ABET Criterion 3 for the BSME programs; they are as follows:

Outcome 1: An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.

Outcome 5: An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.

Outcome 6: An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.

Design of Experiments: Guidelines and Instructions

An average of three to four different experiments are performed by the students in this course during the semester, where they get to apply principles learned in earlier courses. The students are introduced to the underlying theory in class which relate to the experiments they will be carrying out (for example, 1st and 2nd order systems models which can be related to the thermal and vibration experiments respectively). In addition to the theory, students have guidance from the graduate assistant for the lab and undergo training exercises with LabVIEW (they are also encouraged to develop a couple of sample demo exercises which include signals and processing, display, and saving data as an Excel file and so on). Moreover, they are introduced to the hardware and how it is used for data acquisition and analysis. A sample system set-up is discussed and demonstrated to the class. Signal processing fundamentals are discussed in the lectures as well. Additional research may be required in some cases when it comes to furthering their understanding of the problem, fabricating a set-up, writing the required software code, and so on.

Between 25 and 30 students are divided into groups of 3 or 4 members each to work on various aspects of the experiments. It starts with the design, fabrication and set-up, conducting the experiment and acquiring the data, data analysis and conclusions. The student groups also work on developing the underlying theory for each experiment, and run a software model for comparison with the experimental and theoretical results. Following are the major steps that they are required to follow (there is some amount of flexibility depending on the experiment).

Problem definition: Here students are provided with a problem statement and are asked to provide a summary of the underlying theory and experimentation, and how they plan to obtain results. The definition also includes the experimental set-up, aim of the experiment, data to be gathered, plots, etc., to be obtained, calculations to be made, comparison to theoretical and modeled results, conclusions, etc. The results may include, in addition to the numerical

data/plots, validating the underlying theory, computation of specific parameters or properties depending on the type of experiment, drawing conclusions and commenting on errors and so on.

Equipment and data acquisition software: For each experiment, students are given a list of equipment and software that are available in the lab, and which must be utilized by the groups. Some of the standard required pieces of equipment include data acquisition modules, accelerometers, thermocouples, strain gauges, etc., and associated instrumentation. As far as software is concerned, data collection, processing and analysis with real-time plots, etc., is standardized around LabVIEW software. Data is normally in the form of a digitized signal which is saved in an Excel format for further analysis, plotting, curve-fitting and so on. Further simulation and analysis of the system is done using SolidWorks. Students are free to use additional material, equipment and/or software that they believe will help improve their experimental design/analysis, including any fabrication (if required) in the workshop.

Experimental design and procedure: Prior to starting the experiments, each student works through a set of pre-set LabVIEW exercises to become familiar with the software, especially with regard to acquiring and saving data and analysis. The student group then come up with an appropriate set-up for the experiment, and put together a step-by-step methodology/procedure to carry out the experiment. There are two parts to this – one is the hardware set-up, connections and wiring diagram, etc., and the other pertains to the data/software. Details include the type of data they will gather, including any physical measurements and preliminary calculations. Hardware details about the equipment used, data analysis tools and processing techniques employed, are also included.

Data Analysis, Interpretation and Conclusions: Following the completion of each experiment, the groups are required to validate their findings by comparing the experimental results with theoretical and simulated results. SolidWorks is the main software used for the simulation and comes equipped with finite element analysis modules which allow simulation of 1st and 2nd Order systems. It is important to note that at this point in their engineering studies, students are all familiar with SolidWorks which is the package used for system modeling and obtaining results for both the thermal and vibrations experiments.

The final step is report writing which will include all the details of the experiment, including the theory, experimental set-up details, procedure, results, analysis, interpretation and conclusions. Comparison of the results with theory and software simulation helps students understand and appreciate the limitations of some of what they are doing in the lab, as well as assumptions and approximations used in theoretical derivations. Students are already familiar with report writing and are expected to follow engineering standards for this. Report writing skills developed in this course will also be critical when they get into the Capstone/Senior Design I course, which they should be taking at this point. Furthermore, students are encouraged to identify sources of errors

and try to explain and suggest ways to correct them or improve on their current experimental set-up and/or analysis.

Examples of experiments

Two experiments are presented here as examples – a Thermal-based experiment involving study of heat transfer from a single fin and a Vibrations-based experiment involving study of vibrations of a cantilever beam. These were selected as they represent two basic types of systems that are discussed in the course - the thermal experiment as an example of a 1st Order system design and the vibrations experiment approximated as a 2nd Order system design [1][2]. The students in this course are familiar with the underlying theory related to these two experiments which helps them understand the experiments and the data that they will be analyzing. Thermal and vibration-based experiments have the advantage of having more variations and configurations. For instance, students could design an experiment based on the vibration of a string or a building model and change the complexity by adding a combination of spring and damper.

The list of experiments that can be carried out using this approach is not exhaustive. As long as a 1st or 2nd order system generates data that can be collected (with a sensor and data acquisition unit) and analyzed, students can design experiments around it. A good example would be a design of an acoustic experiment where students could collect data with a microphone and relate the soundwave with the vibration generated by the system, captured with an accelerometer.

Thermal experiment – Heat transfer using a single fin

The objective of this experiment is for the students to observe heat transfer through a fin and acquire the temperature data (temperature vs. time signal) for a duration of time [3]. Both heating and cooling curves are obtained, but the focus is mainly on the cooling curve as it takes longer and is better defined. From the cooling curve, they are to compute the time constant for the 1st Order system, rate of heat transfer, heat transfer coefficient and fin efficiency. The experiment is conducted for free cooling, forced cooling (using a table-top fan), and free cooling with the base fully insulated. Results are compared for these cases with theoretical results as well as those obtained from software simulation using SolidWorks.

Experiment set-up and procedure: A standard experimental set-up for this thermal experiment is shown in Figure 1.

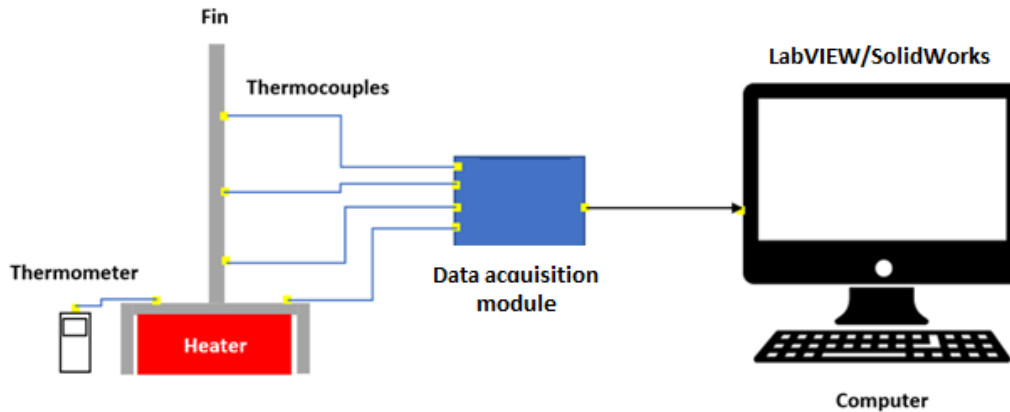


Figure 1. Thermal Experiment set-up – Heat transfer through a single fin

The main components of this experimental set-up are as follows:

- Mild Carbon steel single fin welded on to a mild Carbon steel base (box like) with a coil-type heating element inside (designed and fabricated by the student group).
- Fin dimensions: 400mm Long x 50mm Wide x 2.5mm thick
- Omega K-type thermocouple with a self-adhesive backing mounted on the fin
- Omegaette Thermometer Model HH308 for K-type thermocouple
- National Instruments Data Acquisition Module NI 9211 for Thermocouple connected via NI 9162 USB Carrier [4]
- Digital Thermometer for K-type thermocouple input
- Table-top cooling fan and Insulation material
- PC with LabVIEW and SolidWorks installed

With this kind of a standardized set-up, students were also given the option of fabricating heat sinks with various combinations of fins and sizes and types (such as tubes). Figure 2 shows an example of the single fin heat sink designed and fabricated by a student group; the setup shows free cooling as well as cooling with an insulated base. An additional case of forced cooling was also studied by some groups.

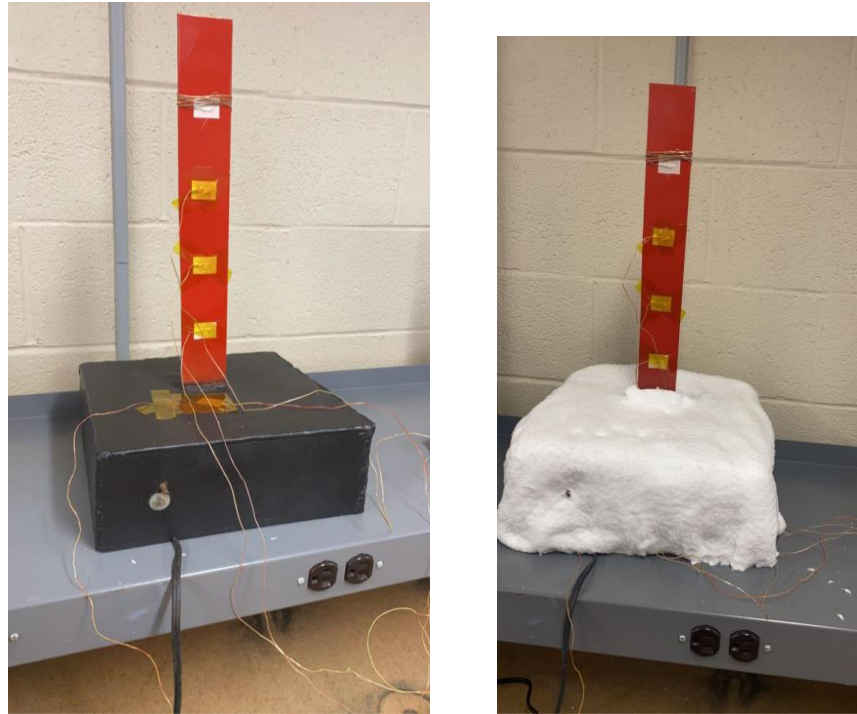


Figure 2. A Single fin designed and fabricated by a student group
Set-up for Free Cooling (Left) and Insulated base (Right)

Procedure: A step-by-step procedure was written by the group with details on how the experiment is to be carried out. After the fin was fabricated and readied, the thermocouples were mounted at different locations along the fin: two at the top, one each in the middle and bottom of the fin, and one on the base (close to the center of the base). The thermocouples were then connected to the data acquisition module. The base thermocouple was connected to the thermometer and served as a reference to indicate how much the system was to be heated. The base was initially heated to a temperature of about 90 deg. C and then allowed to cool to room temperature. Temperature data was collected and saved as an Excel file. Data for both the heating and cooling were collected.

- A simple LabVIEW .vi (virtual instrument) routine was written to capture the temperature data and write it to an Excel file (was configured accordingly). Figure 3 shows the block diagram of this routine.
- The dimensions of the fin were taken as well as its material properties (density, thermal conductivity, specific heat capacity). Then the ambient temperature was recorded.
- The thermocouples were connected to the corresponding devices. The data acquisition module was connected to the computer via a USB port and was configured for acquiring data. Figure 4 shows the NI 9211 Thermocouple module used.
- The LabVIEW .vi was then run to start data collection. The heater (under the base) was turned on and the base was heated up to a temperature of between 80-90 deg. C.

- After the heater was turned off, the fin was left to cool until its temperature was approximately equal to the ambient temperature.
- During both heating and cooling, the LabVIEW .vi is continuously collecting data and writing it to an Excel file.
- The steps were repeated for the cases of forced cooling and cooling with an insulated base.

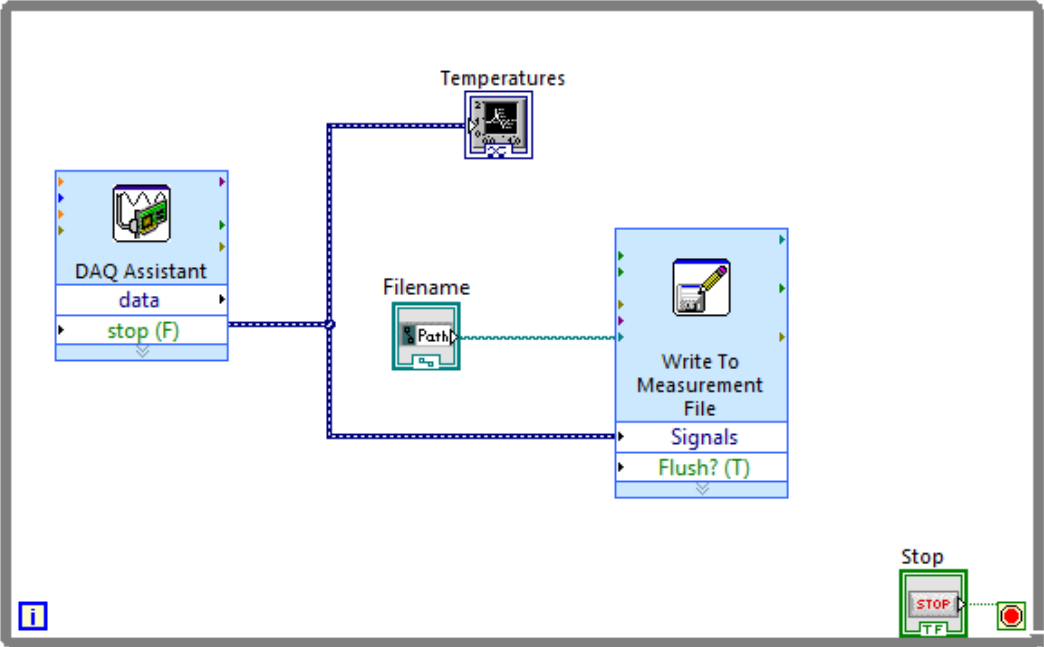


Figure 3. Thermal experiment LabVIEW .vi – Block Diagram



Figure 4. NI 9211 Thermocouple module used for data acquisition

Experimental Data: After the data was collected, the heating/cooling curves for each thermocouple were constructed for each thermocouple [5]. One test output is shown in Figure 5; a very fast rising portion on the left during heating, and the slow decaying following the peak temperature, till the temperatures reached the ambient (room temperature).

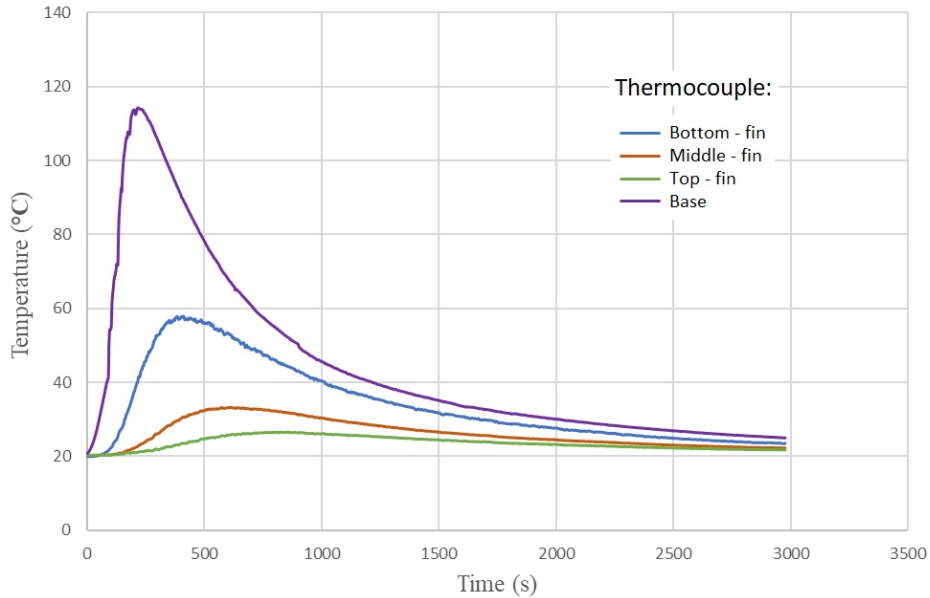


Figure 5. Temperature vs Time plots for Free cooling (Heating and Cooling)

SolidWorks Simulation: The 3D model of the single fin set-up was built in SolidWorks. Thermal conduction is analyzed using Thermal Study in SolidWorks’ simulation [6]. The resulting model is shown in Figure 6. The rectangles on the base and the fin represent the thermocouple in its exact location as was in the experimental set-up.

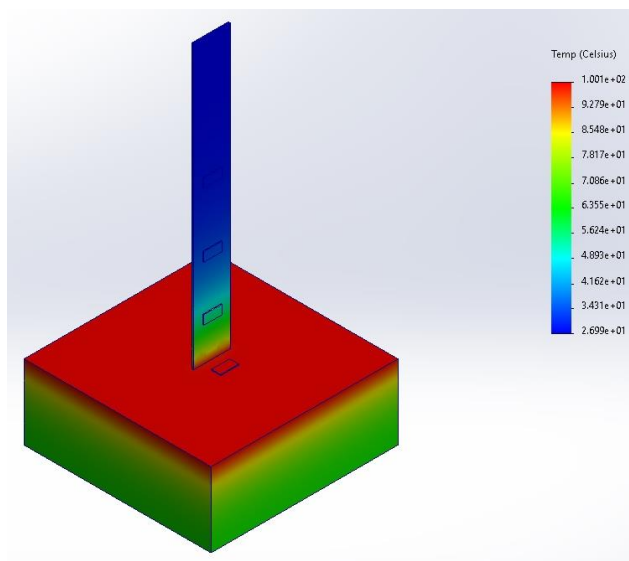


Figure 6. SolidWorks simulation for Free Cooling of the Single fin

Analysis, Interpretation and Discussion: After the heating and cooling curves were obtained, several of the parameters pertaining to the fin and the system were computed [7]. The time constant was obtained through curve-fitting from experimental data and utilizing the fact that this process could be modeled theoretically as a 1st Order system. Several equations from the underlying theory were used to compute other parameters such as the Heat transfer coefficient, Rate of Heat transfer and Fin efficiency based on measurements and observations. Conclusions can be made and correlated with physical observations, starting with the temperature differences at each thermocouple location, time constants for the different curves, comparisons with results from theory, experiment and model for some of the parameters and so on [8].

An example would be the rise in temperature - the base was the fastest one to heat up while the fin locations slowly picked up the heat; temperatures rise was slower as they got further away from the heat source[9]. This is consistent with the governing equation for conduction where the larger the distance, the smaller the heat transfer rate. It can also be seen that only the base temperature went past 100°C while other locations did not. Next, the value of the time constant ' τ ' computed from the cooling curve (for the base) showed that the process was approximately 66.3% complete, as against the theoretical completion of 63.2%. A similar result was found for the fin - 58.7% approximately vs. 63.2%. The difference could be attributed to the accuracy of curve fitting and assumptions of the initial and final temperatures from the curves [10].

The SolidWorks simulation showed a good agreement with the experimental observations on the temperatures at the different thermocouple locations. This also suggests that the assumptions and heat transfer calculations were fairly accurate, the errors notwithstanding. Also, as can be seen from the simulation, approximately the top third of the fin was at ambient temperature which implies that the fin need not be this long for the given heat source. This of course has practical implications when it comes to large scale fabrication and material consumption.

The data also points to the fact that the rate of heat transfer of a fin system is greatly affected by the relative motion and presence of a convective fluid along its surface. Adding a fan that can move air around the fins increased the convective fluid velocity thus increasing the heat transfer rate. Conversely, it can be seen that adding insulation to the base decreases the rate of heat transfer and heat transfer coefficient because of the limited presence of air. Thus, insulating the base increased the time it took for the system to return to the steady state ambient temperature. These observed properties can be used to thermally isolate or increase the cooling rate of any system. Overall, the experiment provides a very good insight into the practical aspects of heat transfer, conducting such experiments under the given constraints, the assumptions and approximations made in the calculations. Mathematical modeling and computer simulations can be used to generate reliable information which can be used in design. The hands-on experience

of designing a set-up and obtaining data in real-time is extremely valuable and helps the students understand what they learn in the classroom and how to relate theory to practice.

Vibrations-based experiment - Beam vibration

The beam vibration experiment is a three-part experiment in which students are asked to determine the properties of a cantilever beam through vibration. Firstly, students perform a static test on the beam to find its stiffness k by adding weights at the tip of the beam and measuring its displacement and strain with a strain gauge [12]. Secondly, students have to perform a free vibration test where the response of the beam is collected with a data acquisition unit and an accelerometer. Finally, students are asked to have the beam go through forced vibration to find its natural frequencies and modes. At this point, only the latter portion of the experiment will be discussed.

For the forced vibration part, students were provided with a data acquisition unit (Figure 4), a frequency generator and a shaker [13]. Other requirements for this experiment were a simulation to support their findings and to use of LabVIEW to collect the data. The design of the setup and the selection of the metal to be used was left to the students.

Experiment set-up and procedure: A standard experimental set-up for this vibration experiment is shown in Figure 7.

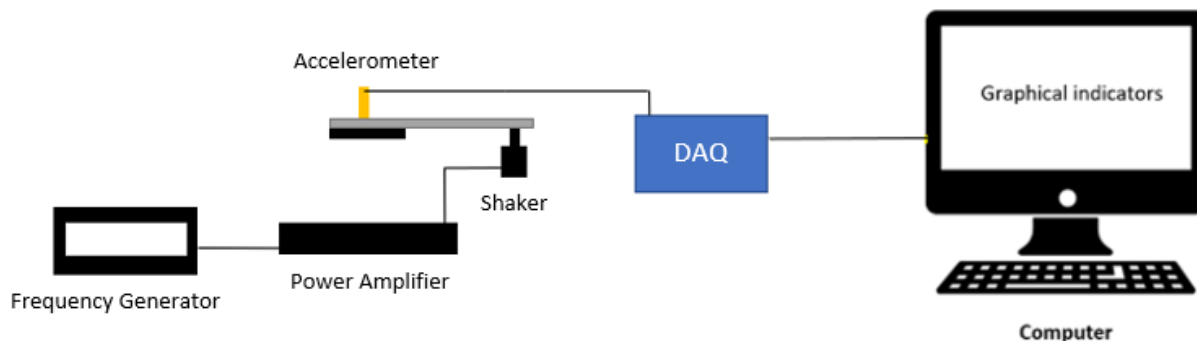


Figure 7. Forced Vibrations Experimental Setup block diagram

The data was to be collected with LabVIEW, processed with MS Excel, and simulated with Solidworks. The required equipment was as follows:

- Thin rectangular metal piece cantilever on a base (student design)
- Mechanical shaker connected to the non-fixed end of the beam
- Power Amplifier (pa-119) connected to mechanical shaker
- Frequency Generator (Model 4011A) connected to a power amplifier

- National Instrument Data Acquisition Module (NIcDAQ-9174)
- Accelerometer (Model 603C01)
- Computer

Students were able to design a metal beam that would be used during the experiment. The rectangular pieces of metal that modeled the beam could be of varying thicknesses for each group of students. When given the proper equipment, the students designed the set-up for the experiment. The reoccurring set-up that the students created is modeled in Figure 6.

The students' designed a piece of rectangular metal with a varying thickness that modeled the beam. By using the frequency generator, power amplifier, and shaker, the students were able to select certain frequencies to excite the beam to find the five different modes. Figure 8 shows the students' experimental setup for the forced vibrations experiment.



Figure 8. Forced vibration experimental setup by students

Procedure: For a successful experiment, the students were tasked to create a procedure for forced vibrations. Prior to Conducting the experiment, students utilized LabVIEW .vi to build block diagrams that were capable of collecting data from the data acquisition unit and transforming the collected data into graphical outputs. Since the procedures were very consistent throughout each group, a sample procedure for this experiment can be seen below.

- The first step was to supply a power and frequency generator to the shaker.
- Next, attach an accelerometer to the beam to read the vibrations.
- Connect a data acquisition (DAQ) unit to the accelerometer to send signals to LabVIEW.
- Utilize a block diagram in LabVIEW to display the frequency response of the beams on graphs.

- Induce a vibration in the beam by controlling the frequency generator while simultaneously recording the outputs on LabVIEW.
- An amplitude peak in LabVIEW would indicate a natural frequency.
- Repeat the process through varying frequency ranges to find the five natural frequencies.

Experimental Data: The data collected was also transferred to MS Excel for further data processing and analysis. Figure 9 shows a created block diagram for forced vibrations and Figure 10 shows an amplitude peak at a found natural frequency.

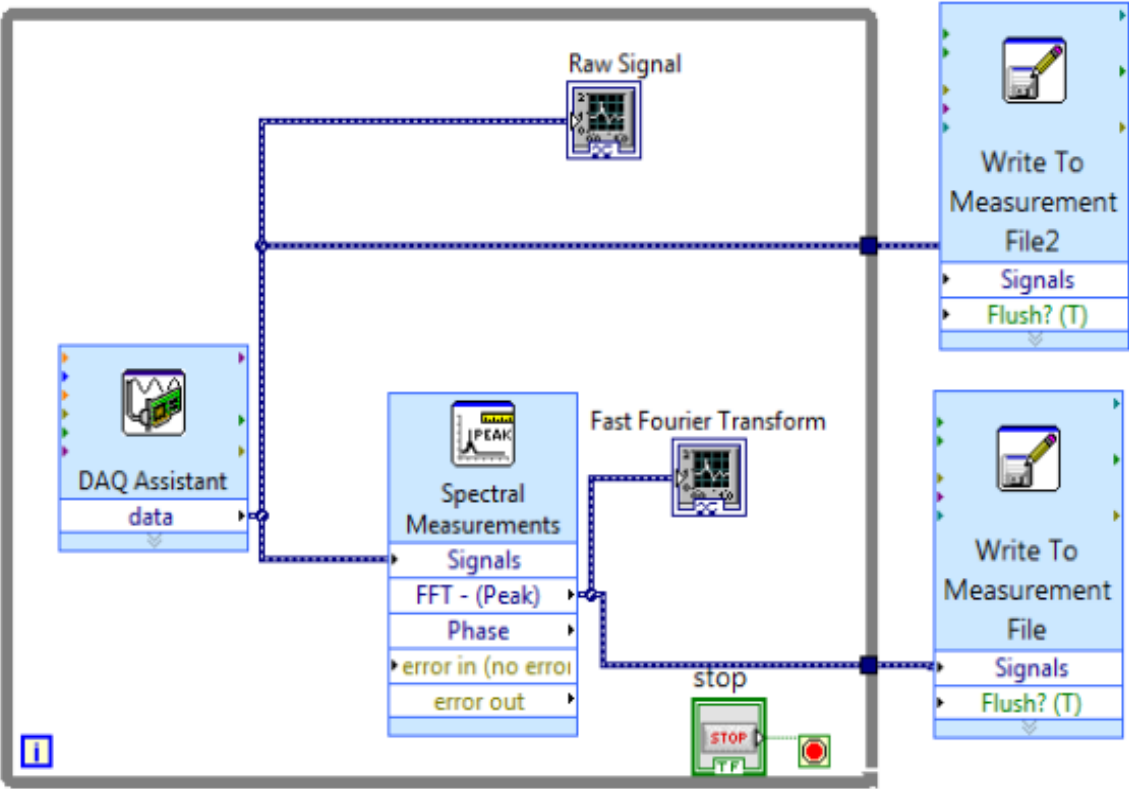


Figure 9. Forced Vibrations LabVIEW .vi – Block Diagram

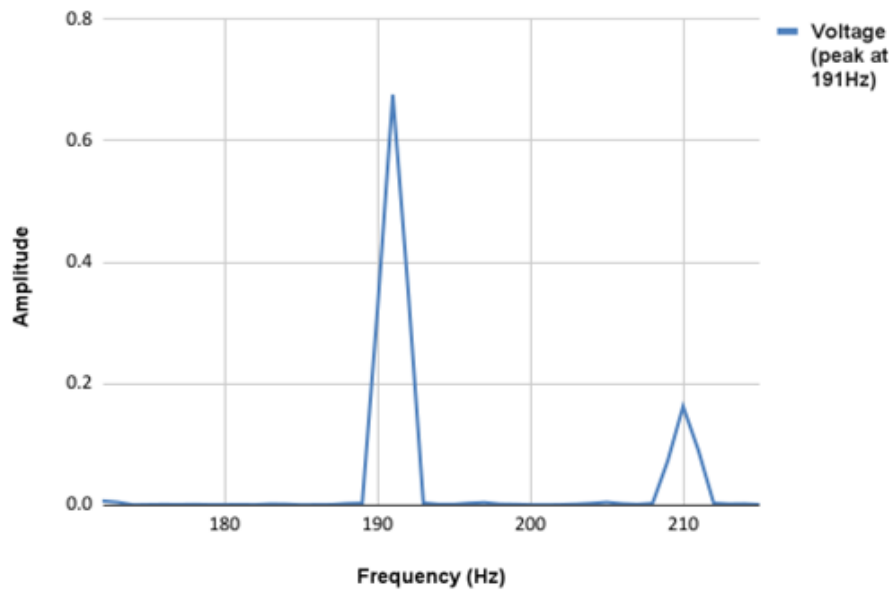


Figure 10. Amplitude Peaks vs vibration frequency

SolidWorks Simulation: After the five different natural frequencies were found, students validated the results of the experiment through 3D simulation. SolidWorks was the program that the students used when performing the simulations. An example of a students' simulation can be seen in Figure 11.

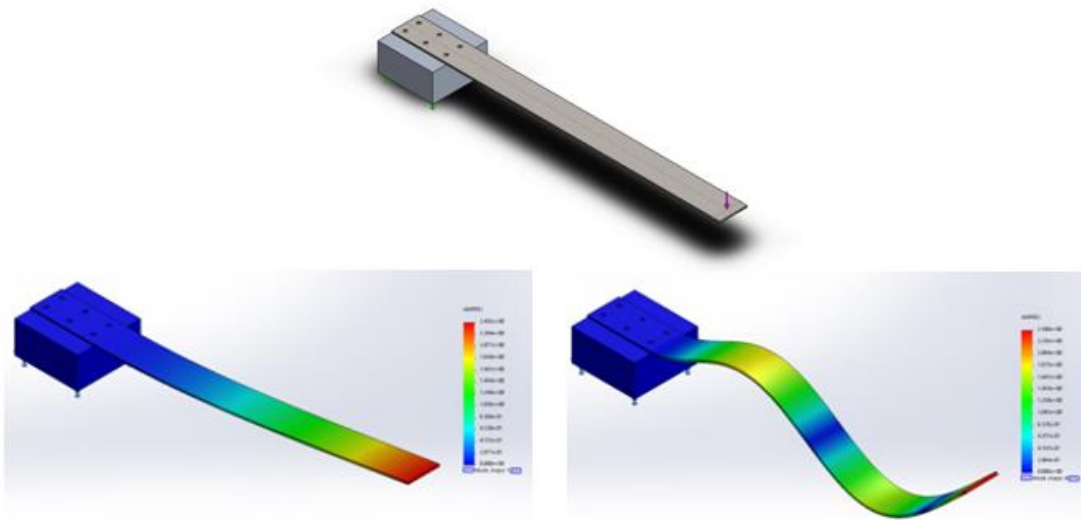


Figure 11. Simulation Results of Forced Frequencies

Analysis, Interpretation and Discussion: The natural frequency was found by tuning the frequency generator until the highest peak or amplitude was shown; an example of this is in Figure 11. An illustration of the second mode the beam, what the student could physically observe when vibrating at its second natural frequency is shown in Figure 12 below. The first natural frequency was found to be 22 Hz. The second natural frequency was found to be 39 Hz. The third natural frequency was found to be 98 Hz. The fourth natural frequency was found to be 191 Hz. The fifth natural frequency was found to be 318 Hz.

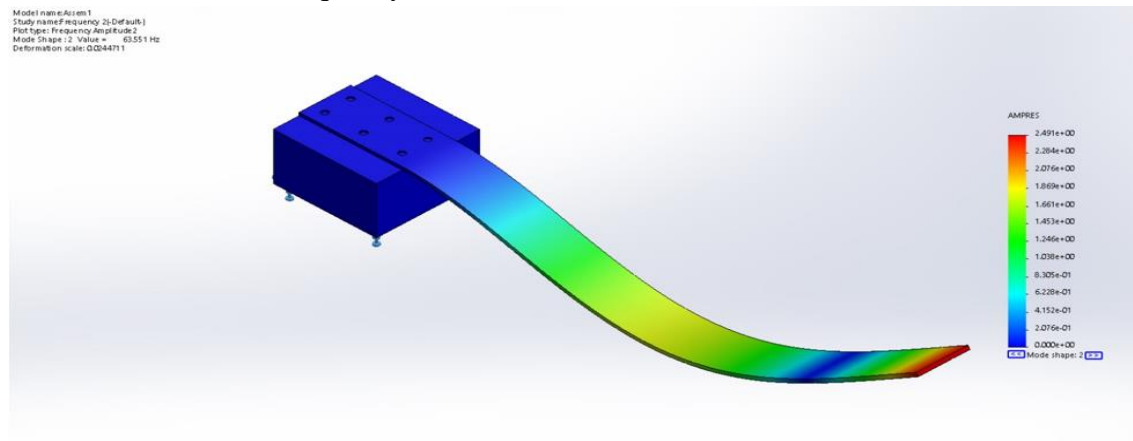


Figure 12. Beam second mode

Conclusion

For engineering students, laboratory experiments constitute an essential part of their curriculum. The engineering theories become observable and a few times palpable during these experiments. In general, laboratory experiments are designed to have a single path to reach the desired results. The results path highly takes into consideration the ABET outcomes for the engineering course pertaining to the experiments. For the labs that were conducted in the Process Monitoring and Control course, the students were able to design and achieve the desired results that modeled the first and second-order systems through heat transfer and beam vibration problems. Overall, the experiments conducted were a success in allowing the students to achieve the ABET outcomes during the process of the experiments. The students were able to research the engineering theories, and applied the theories through multiple variations of the experiment to find the desired answers for the course.

Assessment and Impact: Several aspects of what they have done in this course are reflected in their Capstone Sr. design projects as well as projects in other courses that involve experimental set-ups and using LabVIEW code, modeling and so on. Numerous groups use data acquisition set-ups to capture signals to analyze their data. This course also helps them envision test set-ups required for their design projects wherein they can gather data to validate their theoretical or model findings. One such course which follows this is Control Systems for the ME students which contains hands-on projects including working with PLCs. Rather than carrying out a set of procedures given to them, going through the process of the setting up, instrumentation,

coding, data acquisition and so on, students discover and learn a lot more through this hands-on method. It also gives them the opportunity to research further and look at and collect additional data and perform additional analysis as they see fit.

Students who work on research projects with faculty members, are better prepared when it comes to testing and designing experimental set-ups. Some of the companies who have been involved with us on projects are very interested in using LabVIEW as they have standardized on this package wherein work with sensors (such as strain gauges and accelerometers) instrumentation and data acquisition are critical. Former students have regularly reported using design of experiments in a professional setting for testing – developing test set-ups, and acquiring and analyzing data for their applications. This course has definitely had an impact on student learning with specific focus on hands-on experimentation and testing.

At this point, an average class size varies between about 25-30 and this is comfortably handled as the lab is open for the students to come in and do their work. Scaling it up or down will not be a problem as increase in class size will be handled through an additional section. Logistics for this will of course will need to be worked out. This course requires student groups to write reports for each experiment that they have carried out, and includes all pertinent details including the set-up, data acquisition, analysis and conclusions. These reports are used in the assessment of ABET outcomes. There are no formal surveys conducted in this course, but this is something that is being considered for the long term. Student feedback, however, has been very positive as they find that they are able to think through a given problem and obtain results through

Challenges and limitations: This course addresses many of the lab components in the lecture portion wherein the students are provided with the background material and explanations where required. Learning LabVIEW for the first time and implementing it for a practical experiment is a challenge for some students. The students go through a steep learning curve through training exercises and simulated data. Using data acquisition hardware for the first time, the students go through the process of trial and error to get the right set of data. Most students are doing such hands-on experiments for the first time; nevertheless, they quickly adapt to becoming familiar with LabVIEW, setting up the experiment and thinking through the entire process of conducting, data acquisition, processing, analysis, etc. Finally, as the number of experimental set-ups is limited, accommodating larger classes gives rise to some logistical problems; sometimes a group has to wait its turn to complete their work. Currently, the experiments are limited to dynamics and thermal areas as the labs are equipped to handle this. Down the road, this may be expanded to include fluids as well.

Dan Kilula

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Logan Neal

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Dr. Shivan Haran

Dr. Shivan Haran is the Director and Associate Professor of Mechanical Engineering at Arkansas State University. His areas of interest include application-oriented projects relating to sensors and sensing systems, signal processing algorithms, controls and robotics, structural health, and vibration monitoring. As a professor, he is responsible for teaching upper-level mechanical engineering classes such as mechanical vibrations, robotics, controls, and experimental methods, including various hands-on labs. He is involved in outreach and extra-curricular activities, including engineering summer camps for high schoolers and elementary robotics competitions.

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