
AC 2011-254: FIVE FORCED-VIBRATION LABORATORY EXPERIMENTS USING TWO LUMPED MASS APPARATUSES WITH RESEARCH CALIBER ACCELEROMETERS AND ANALYZER

Richard J. Ruhala, Southern Polytechnic State University

Richard Ruhala earned his BSME from Michigan State in 1991 and his PhD in Acoustics from The Pennsylvania State University in 1999. He has 3 years industrial experience at General Motors and 3 years at Lucent Technologies. He was an Assistant Professor in the Engineering Department at the University of Southern Indiana before joining the faculty at Southern Polytechnic State University in 2010 as an Associate Professor, where he also serves as director for their new mechanical engineering program. He has taught a wide spectrum of engineering and mechanical engineering courses. He is a member of ASEE, the Acoustical Society of America, and the Institute for Noise Control Engineering, and conducts research in acoustics and vibrations.

Five Forced-Vibration Laboratory Experiments using two Lumped Mass Apparatuses with Research Caliber Accelerometers and Analyzer

Abstract

In 2004 a 3-credit engineering elective course in vibrations was created at the University of Southern Indiana. It consists of two hours of lecture and three hours of lab per week. One commercially available translational system and one rotational lumped mass system were purchased. Each turn-key system can be adjusted to study one, two, or three degrees of freedom systems in which the masses/inertial values can easily be changed. In addition, the translational system has three different types of springs and one variable air cylinder dashpot to choose from. Both systems come with an amplifier and motor which can optionally drive one of the masses in motion that is proportional to the signal on the input. However, instead of using the optical sensors to measure displacement, accelerometers were procured that are more representative of what engineers use in industry. Likewise, instead of purchasing the computer board and software that accompanies the lumped mass apparatuses (which in this case was primarily developed for controls laboratory experiments), a world-class analyzer (that also requires a PC and includes computer software for instrumentation) was purchased so that the sensors and analyzer can be used by students and faculty for research projects. This created hybrid vibration measurement apparatuses that combine the best combination of turnkey and custom systems. Another advantage with the hybrid approach is that the analyzer can also be used for acoustical measurements. A disadvantage is that the PC software that controls the analyzer is not user friendly, and requires substantial setup time by the instructor. The laboratory experiments that were developed include the study of free and forced vibration on various 1-DOF, 2-DOF, and 3-DOF vibration systems, with or without damping. Other experiments include designing a dynamic absorber visualizing modes of vibration, and determining the mechanical impedance.. In a 2010 ASEE Conference paper, four *free*-vibration experiments were described in detail.¹ In this paper five *forced*-vibration experiments are described in detail, as well as their impact on the student learning outcomes for the course. Other experiments may be developed without the turnkey apparatuses such as investigating vibrations of guitars or compressors. All experiments were developed and refined over several years. Student surveys have indicated that the laboratory experiments were effective in understanding the theory and provide an increased level of intellectual excitement for the course.

Introduction

There are two basic approaches to developing a vibrations laboratory for engineering students to study lumped parameter systems. One is to purchase a commercially available turnkey system complete with hardware and software. The other is to design and build a custom apparatuses to go with a research caliber accelerometers and analyzer, as well as potential software development. The laboratory experiments described in this paper use another approach which is a hybrid of the two.

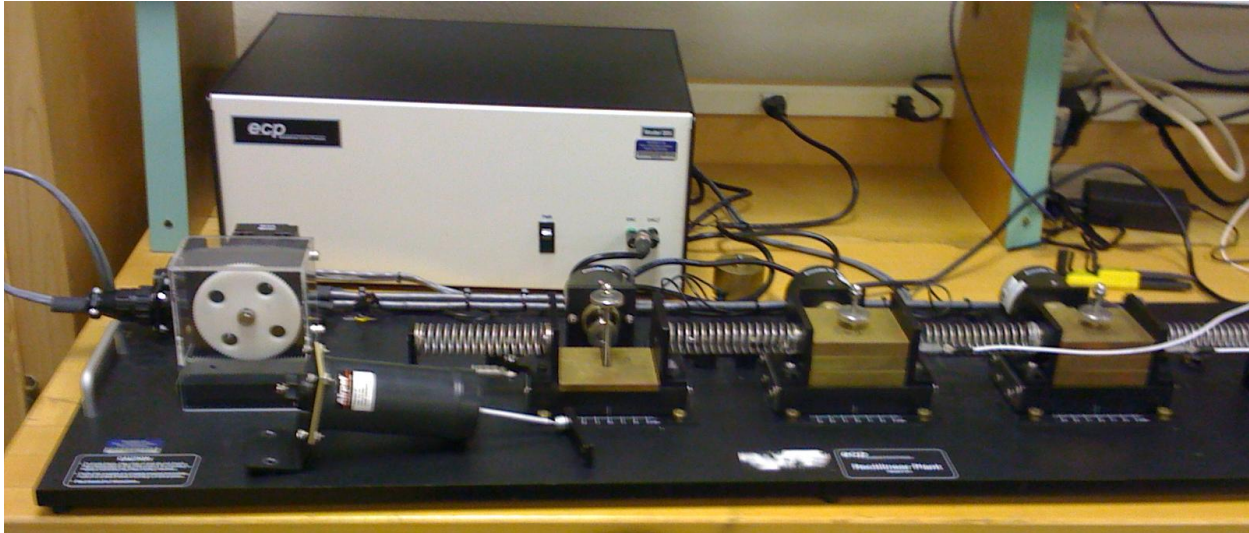


Figure 1: ecp Model 210 translational mass-spring-dashpot apparatus for evaluating one, two, or three DOF systems: forced or unforced.

Turn-key systems that are intended for engineering laboratory course in vibrations, controls, dynamics, and similar fields provide an effective way for the instructor to implement and conduct the course. One system for the study of vibrations is the Model 210 by Educational Control Products², as seen in Figure 1. This apparatus can have up to three degrees of freedom along a linear path in which the masses and stiffness, and damping properties can be varied. Each DOF is a carriage supported by linear ball bearings and has room for several plates that can be added to increase the mass. An air dashpot (seen unattached in foreground in Figure 1) with variable damping may be attached to any mass. The left mass can be forced into vibration via an electric motor connected to a rack and pinion link (as seen on left side of Figure 1). The manufacturer supplies transfer function data and the pinion radius so that one can determine the rms value of the sinusoidal force based on the rms value of the known electrical voltage signal. The translational position of each mass can be seen visually with a ruler, and more precisely, with an optical sensor, and each mass may be locked in place to reduce the DOF of the system to 2-DOF or 1-DOF. A computer board and software are used to control the frequency and amplitude of the force applied, and record the motion of each mass from the optical sensor. Force at another mass may be applied for the study of control theory. This system, as well as most systems by ecp, is designed primarily for the controls laboratory experiments, but are ideally suited for mechanical vibrations laboratory experiments.³

The Model 205 produced by Educational Control Products (ecp), as seen in Figure 2, is used to study the rotational vibration of up to three DOFs in a similar fashion. These systems are good at helping the students verify the theory of vibration with less time learning how to do the measurements. Up to four brass elements may be attached on each disk, and at varying radial positions, to change the polar moment of inertia for each disk. Like the Model 205, each disk may be locked to the frame to reduce the system to a 2-DOF system or a 1-DOF system. Unlike the Model 210, stiffness and damping cannot be varied without custom alterations.



Figure 2: ecp Model 205 rotational mass-spring-dashpot apparatus for evaluating one, two, or three DOF systems: forced or unforced.

One disadvantage of many turnkey systems is they do not use the type of instrumentation - accelerometers and FFT analyzers – that are most common for vibration analysis of vehicles and

machines in industry or research. However, much more time is required if one designs and builds custom apparatuses, such as a rig for 2 DOF torsional system developed by Souza et al.⁴ Also, with a custom apparatus, custom instrumentation and transducers are required – which may or may not be research caliber instruments. One unique apparatus that the author experienced as a graduate student at The Pennsylvania State University in the 1990’s used an air-hockey like track to connect mass elements with springs and measured using accelerometers and a 2-channel HP analyzer. It worked well, but a leaf-blower like device was required to produce enough air flow, which was noisy and sometimes would break down. When parts break down on custom apparatuses, repair or replacement is usually more difficult than a commercially available apparatus.

The hybrid approach developed by the author uses the “plant only” option of the ecp Model’s 205 and 210 (which omits the computer card and software). The optical sensors are disconnected and replaced with PCB uniaxial accelerometers as needed. The PC hardware and software for the turn-key systems are replaced with a Brüel and Kær Sound and Vibration Analyzer, Model 3560C and the accompanying PULSE software to design and use virtual instruments on a PC to control the analyzer and process the data. This particular analyzer module has two outputs and four inputs. This author has found that although the PULSE software is powerful and flexible, it is also not straight-forward to create custom experiment templates. (However, Brüel and Kær’s technical support has been very helpful.) However, once a PULSE template is developed for an experiment, it can be used in future semesters. Other high caliber transducers and analyzers should be suitable for the experiment described here, such as National Instruments with LabVIEW software, as described in Reference [4], or Agilent Technologies analyzers.

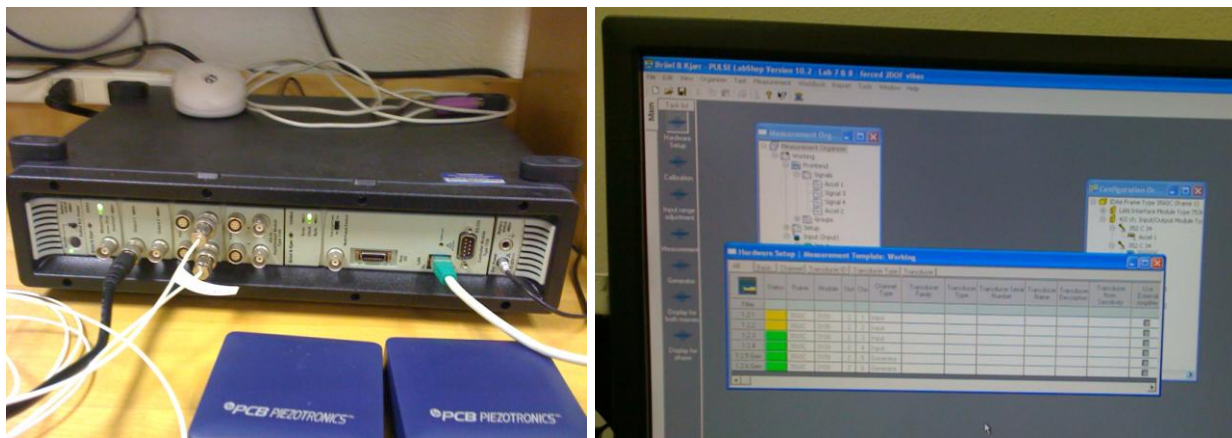


Figure 3: Brüel and Kær Sound and Vibration Analyzer, Model 3560C (left) and the accompanying PULSE software, Version 10.2, showing the hardware setup task (right).

Four different experiments for the study of free vibration have been presented in Reference [1]. In this paper five additional experiments are described that involving forced vibration. Each experiment correlates to material covered by the lecture to help reinforce the course learning outcomes. A semester laboratory course in vibrations would still have room in the schedule for additional experiments not describe here that can be done using the research caliber equipment to evaluate real world vibration of structures, machines, and/or consumer products, or used with student design projects involving vibration isolators. The combination of theory-reinforcing labs

and application-oriented labs are desirable to help student connect theory with to real-world engineering problems.

Course description and learning outcomes

ENGR 363 – Vibrations – at the University of Southern Indiana, is a three credit elective engineering course which has 2 hours lecture and 3 hours lab each week. (Most labs are broken into two 1.5 hour session to minimize the number of idle students. They should be preparing for lab or performing calculations during the other 1.5 hours they are away from the equipment, but close to the vibrations laboratory.)

The course is an introduction to vibration theory, including the modeling and analysis of oscillatory phenomena found in linear discrete and continuous mechanical systems. The two prerequisites courses are Dynamics and Differential Equations. This course will also introduce noise and vibration control as an application of vibrations theory. A hands-on laboratory should enhance the learning experience and bridge the gap between theory and practice.

Topics include undamped harmonic oscillator, natural frequency, mechanical resistance, damped natural frequency, torsional vibrations, forced vibrations, multiple degrees-of-freedom systems, control of vibrations, vibrations of strings, beams, membranes and plates, and a brief introduction to acoustics and noise control.

The student learning outcomes and performance criteria for this course as taught in 2009 are:

1. Students will have the ability to apply knowledge of mathematics, science, and engineering. (ABET Criterion a)
Performance Criteria
 - i Compute the natural frequency and predict the response for a one-degree-of-freedom system undergoing translational vibrations, with or without damping.
 - ii Compute the natural frequency and predict the response for a one-degree-of-freedom system undergoing torsion vibrations, with or without damping.
 - iii Compute the natural frequency and predict the response for a machine with a rotating unbalance.

2. Students will have the ability to design and conduct experiments, as well as to analyze and interpret data. (ABET Criterion b)
Performance Criteria
 - iv Practice vibration measurements on a structure using state-of-the-art equipment, rigor and documentation.
 - v Analyze the data from an experiment appropriately.
 - vi Assess the validity of the experimental results and compare with theoretical results when possible.

3. Students will have the ability to identify, formulate, and solve engineering problems. (ABET Criterion c)

Performance Criteria

- vii Compute the natural frequencies and illustrate the mode shapes of a two-degree-of-freedom system;
- viii Sketch the first several mode shapes for a string, bar, or membrane, and compute the natural frequency for each.

The laboratory component of this course directly supports ABET Criterion b, and indirectly supports ABET Criterion a and c.

Recall that the free vibration experiments were described in a separate paper.¹ The five experiments below describe the forced vibration experiments. A typical lab schedule would include a mix of the free and forced vibration experiments, as well as time left for a few applications-oriented experiments.

Experiment one – Transient response of a forced 1-DOF system

The two objectives are:

- To force a mass-spring-dashpot system into steady-state vibration (for a sinusoidal input force).
- To visualize the transient response and steady-state responses of a system undergoing forced vibration for under-damped, critically damped, and over-damped system.

The equipment consists of:

- The ecp Model 210, with force actuator connected to carriage 1 with one spring, one damper, and several plates.
- Brüel and Kær Sound and Vibration Analyzer (Model 3560C) using one input and 1 output,
- piezoelectric accelerometer (PCB model T352C34),

First, free vibration of the 1-DOF mass-spring-dashpot system is evaluated following procedures in Reference [1] to determine the natural frequency. Next, forced vibrations are created using the analyzer's signal generator connected to the ecp 210 amplifier/actuator (dc motor) to create the desired frequency and oscillating force on the carriage (mass 1). Frequencies are selected to be at, above, and below the natural frequency of the damped system. Time data are captured to show the transient and response of the 1-DOF system. The experiment is repeated for several damping conditions. The difference between natural and forced frequencies is identified.

The left carriage is the one to use for this experiment since this one has a link to the motor. The other carriages not in use are decoupled and locked to the frame. The graphical output along with the experience should help students identify and better understand the difference between the transient and steady-state regions in the time-domain.

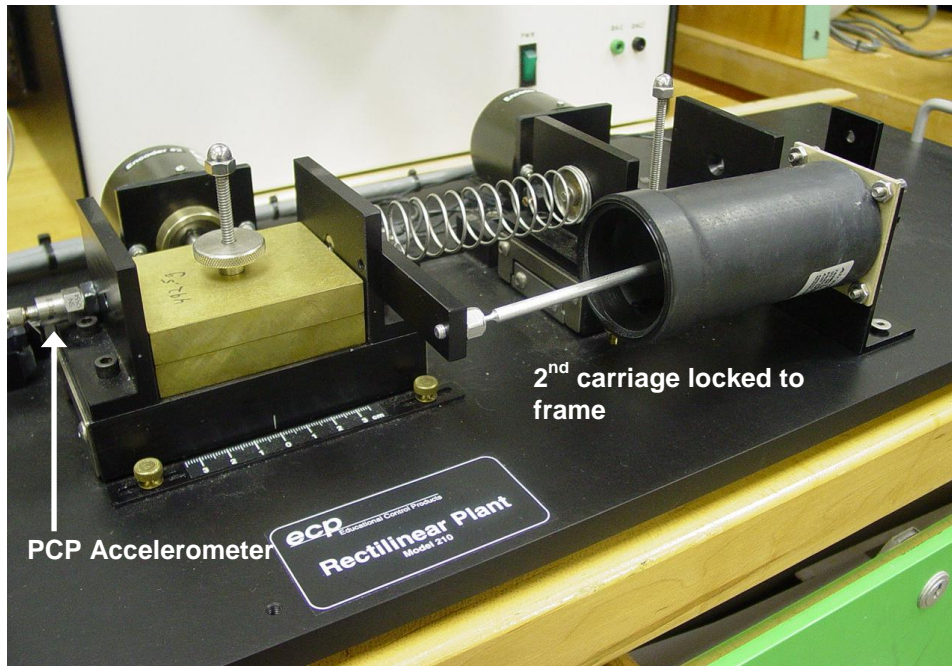


Figure 4: Setup for Experiments 1 and 2. In Experiment 2, the dashpot is disconnected.

In order to reinforce the instrumentation learning objectives and to reinforce best practices, calibration should continue in the forced experiments by first verifying the transducer's sensitivity using a hand held shaker that produces a known acceleration (1 g at 1000 rad/s) before each experiment. Then the accelerometer is then rigidly attached to one side of the carriage (via screw thread intended for the dashpot connection or the threaded plastic base bonded to the carriage– as shown in Figure 4). The natural frequency for each system is measured using the analyzer's Fast Fourier Transform (FFT, the most accurate and fastest method, but precision is limited due to the length of the FFT record and thus the time it takes for the system to return to static equilibrium).

As with other engineering laboratories, each student should be required to document all findings, calculations, observations, and answers to specific questions in their laboratory notebook, in order to stress professionalism.

Experiment two – Steady-state response and frequency response of a 1-DOF translational system

The three objectives are:

- To measure the steady-state response under a forcing function for a damped oscillator (a.k.a., a 1-DOF system or a mass-spring-dashpot system), and compare results with the appropriate figure (or equations) in the textbook, based on theory.
- To calculate the mechanical impedance from experiment and gain an understanding of what this value means.

- To understand the difference between resonant frequency and the damped natural frequency.

The equipment and setup are nearly identical to experiment one. Steady-state forced vibrations are measured for a lightly damped 1-DOF system using the FFT. The peak displacement from the analyzer (LabVIEW) FFT graph is compared to the peak visual displacement with a ruler. Thus, the student must wait until the system is running at steady-state before triggering the FFT. Data are collected at a number of frequencies above, at, and below the system's natural frequency, until a normalized displacement versus frequency graph is created, and compared to the theoretical curve found in every textbook on vibrations. This is repeated for increasing levels of damping.

The concept of frequency response is introduced by using the voltage signal from the signal generator (or force transducer on the mass) as the system input (channel 1) and the acceleration signal of the mass as the output (channel 2). Further, by dividing the force amplitude by the peak velocity, a mechanical impedance graph is created. If the experiment goes as planned, the dip of the mechanical impedance curves should always correspond to the natural frequency regardless of the level of damping, while the peak of the displacement curves correspond to the natural frequency only for cases of light damping (damping ratio below 0.1).

Experiment three – Forced Response of 2- & 3-DOF Translational Systems

The three objectives are:

- To visualize the response for a two-degree-of-freedom (2-DOF) translational system under a harmonic force input.
- To see how damping affects the free vibration and forced vibration for a 2-DOF system.
- To visualize the response of a 3-DOF translational system using a sweep-sine input.

The equipment consists of:

- the ecp Model 210 (translational system) set up with three masses (sliding carriage with optional extra plates) and three springs, and forced actuator, (no dashpot)
- Brüel and Kær Sound and Vibration Analyzer (Model 3560C) using three inputs and one output,
- three piezoelectric accelerometer (PCB model T352C34),

The ecp Model 210 Translational system is again used, but now three carriages connected together by springs and the carriage on the left is forced with by the actuator. First, a free-vibration experiment is conducted to determine the three natural frequencies of the system from an arbitrary initial condition. This can be accomplished by having one student hold two of the carriages (masses) in place while another student hold the third carriage so that one of the springs is compressed or extended. The students must work together to let all the carriages release at once while the FFT operation is triggered. This may need to be repeated with different initial conditions so that three distinct natural frequencies are measured, which should agree with the theoretical model.

Next, this signal generator is setup so that the oscillating force on the carriage one is slowly increased automatically over a set range of frequencies (i.e. sweep-sine) is applied to the carriage

mass at one end, while the acceleration of each mass, and the force input are measured. An order-tracking or waterfall like graph is created by the Pulse software to quickly create frequency response curves and identify the three resonant frequencies. The students should recall how long this took the previous week when data were gathered under steady-state conditions at many discrete frequencies to accomplish a similar task.

Experiment four – Forced Response of 2- & 3-DOF Rotational Systems

The two objectives are:

- To determine the natural frequencies for a 2-DOF and 3-DOF torsional system.
- To improve understanding of torsional vibration systems.

The equipment consists of the same as experiment three, but the ecp Model 210 is replaced with the ecp Model 205 (torsional system), set up with two and then three disks in motion, and various combinations of inertias evaluated. Recall that in the Model 205 the lowest disk is connected to the motor while the others are connected by thin steel rods that function as torsional springs.

Experiment five – Design of a Dynamic Vibration Absorber

The main object of this experiment is to design a dynamic absorber for a given mass-spring system using theory and then test it. The equipment and setup are nearly identical to experiment three.

First, large steady-state forced vibrations are measured with a lightly damped 1-DOF translational system excited at resonance. Next, a second set of mass-spring components are connected to the main mass, as determined by design, and within the design constraints of the project. These constraints are based on three type of springs that could be added, the number of springs added (one or two) and several thin and thick plates that can fit on the second carriage to adjust the mass of the dynamic absorber. Dashpot should not be used.

When properly designed, the dynamic absorber is a shock-and-awe type of learning experience. Under the same steady-state condition that resulted in large oscillations in the original system, that mass now is almost motionless. Yet the second mass-spring system oscillates significantly, balancing the applied force from the actuator (motor) – 180-degrees-out-of-phase. The design trade-off is that now there is a resonant frequency above and below the original system resonant frequency. A competition among lab teams should provide additional interest and incentive. There are many variations of this design-type experiment, such as allowing each team two or three trials by adding or removing lighter weight objects like washers to the secondary mass.

Student evaluations of learning objectives

At the end of fall semester 2009 a survey was conducted to evaluate how well each student agrees that they met each laboratory learning objective. Although most students did agree on each learning outcomes, the objective ratings associated with torsional vibration were slightly

lower. It is also important to note that the instructor of this laboratory left the course in the middle of the semester due to another faculty position opportunity. This may be a reason why these scores are lower than expected.

Prior to an ABET visit in 2006, direct and indirect assessment was performed for ENGR 363 Course Learning Objectives. One objective that year that related directly to the vibration lab was, to use teamwork and rigor in conducting engineering experiments. The result of the indirect survey was that five students *strongly agreed* and one *agreed* with achieving that learning outcome.

From an engineering education research standpoint, it would be very useful to compare the course learning outcomes with and without the laboratory component. Unfortunately there was no lecture-only vibrations course taught before the lab was developed at USI that could be used for comparison. Also, it would not be fair to current students to intentionally teach the vibrations course without a hands-on laboratory component.

Table 1: Assessment of some of the laboratory learning objectives as evaluated for the 2009 fall semester. Each student evaluated each objective as 1 for strongly disagree, 2 for disagree, 3 for neutral, 4 for agree, and 5 for strongly agree. The average score is based on 7 students who completed the anonymous survey at the end of the semester. [Needs to be updated with objectives associated with the forced vibration experiments.]

	Lab Learning Objective	Average Score
1	Measure the natural frequency of several one-degree-of-freedom (DOF) vibration systems using experiments and compare with theory.	3.9
2	Obtain the key properties of one-degree-of-freedom (DOF) freely vibrating system using experiments and theory.	3.9
3	Use an accelerometer (a type of transducer) and an analyzer to measure the vibration of a structure in both time and frequency domains.	3.9
4	Understand how varying amounts of damping affect the free vibration of a structure.	3.9
5	Work with one or two classmates to conduct an experiment and write a report together.	4.3
6	Obtain the key properties of one-degree-of-freedom (DOF) system undergoing Torsional vibrations using experiments and theory.	3.3
7	Understand the effect of inertia on a freely vibrating torsional system.	3.3
8	Understand the similarities and differences between torsional systems and translational systems undergoing vibrations.	3.3
13	Determine, experimentally, the natural frequencies for a two-degree-of-freedom (2-DOF) system.	3.7

Summary

Five forced-vibration experiments are described in this paper that, when sequenced with the four free-vibration experiments described in Reference [1] provide a base for an upper-level laboratory to study engineering vibrations. All of these experiments can easily be compared to theoretical equivalences that should create a higher level of understanding than one could achieve with lecture alone. The unique aspect of these experiments is that they are a hybrid of turn-key educational hardware apparatuses and precision measurement systems that are often used in research labs and industry. One apparatus is the ecp (Educational Control Products) model 210 and the other is the ecp model 205. The former provides translational vibration and the later provides rotational vibration. One, two, or three degrees of freedom can be easily setup with various changes in mass or inertia. The translational system (ecp model 210) has the ability to also change the stiffness and damping parameters. The optical sensors provided by ecp are disconnected and replaced with PCB uniaxial accelerometers. The PC hardware and software for the turn-key systems are not purchased and are replaced with a Brüel and Kær Sound and Vibration Analyzer, model 3560C, and the accompanying PULSE software to design and use virtual instruments on a PC to control the analyzer and process the data. PULSE templates were created by the author for each experiment to minimize the time students have to spend learning the software program. Yet the students do gain more experience with real word instrumentation and calibration than they would not if using the sensors and software provided in a complete turn-key system. The research caliber analyzer and transducers provide the flexibility to create custom laboratory experiments using more applied structures or machines; and can also be used for design projects, and research.

Bibliography

1. R. J. Ruhala, "Free Vibration Laboratory Experiments using two Lumped Mass Apparatuses with Research Caliber Accelerometers and Analyzer," Proceedings of the American Society for Engineering Education Annual Conference, June 2010.
2. Educational Controls Products website, <http://www.ecpsystems.com/>, accessed 18 Mar 2010.
3. P. J. Cornwell, "Vibrations Education –Striving for a Resonance in Learning," *Journal of Sound and Vibration*, November 2007.
4. N. Lin, E. Gildin, and R. Bishop, "Control Systems Lab Introduction, Hardware, Software, and Safety" published online at <http://cnx.org/content/m13025/1.3/>, accessed 18 Mar 2010.
5. S. D'Souza, N.W. Scott & B.J. Stone, "A Student Controlled Two-Degree of Freedom Vibration Laboratory," 1998 ASEE Annual Conference Proceedings.

APPENDIX – Example of a lab handout

Lab 5 (corresponds to forced experiment 2 in ASEE conference paper 2011)

ENGR 363, USI, Professor R. Ruhala

October 13, 2009

Team Lab Report due no later than October 27 (Tech memo format).

Objectives

1. To measure the steady-state response under a forcing function for a damped oscillator (a.k.a., a 1 DOF system or a mass-spring-dashpot system), and compare results with the appropriate figure (or equations) in the textbook based on theory.
2. To calculate the mechanical impedance from experiment and gain an understanding of what this value means.
3. To understand the difference between resonant frequency and the damped natural frequency.

Equipment

- Rectilinear apparatus arranged with one mass (a.k.a., the *carriage*) driven directly by the motor via a mechanical linkage. See attached sketch. The base motion is a sinusoidal motion whose force and frequency is controlled by the Generator in the PULSE analyzer and the power unit for the motor. The **carriage holds 1 small plate + 1 large plate, plus the effective mass of the motor/pinion/rack (0.34 kg)** which combine as the total mass (**M**) of this system. One stiff spring (**k₁**) connects the mass with the ground. Three different levels of viscous damping are applied by the damper create three different systems:
 1. Light damping with plastic damping plug removed
 2. Damping plug added, but still an underdamped system
 3. Damping valve adjusted to critical damping
- Piezoelectric accelerometer attached to the mass.
- Hand-Held Shaker (PCB model 394C06). Generates an acceleration of 1.0 g_{rms} (9.81 m/s²_{rms}) at 1000 rad/s.
- Brüel and Kær Sound and Vibration Analyzer, model 3560C, a.k.a., PULSE.
- Motor amplifier (for the Model 210 Rectilinear apparatus), with a gain of 1.5 amp/volt
- Motor (for the Model 210 Rectilinear apparatus), with a nominal torque constant of 0.086 N-m/amp, and a drive pinion radius of 3.81 cm.

Instrument Setup

- Record the model number and serial number of the accelerometer selected.
- Connect the accelerometer to the carriage that is to be measured.
- Connect the accelerometer cable to the PULSE vibration analyzer, Input 1 channel, using the white cable.
- Connect the Output 1 Channel of the PULSE vibration analyzer to the ecp motor amplifier input using the long, black BNC cable with the special adapter at one end.
- Start the PULSE icon for the current Lab project on from the desktop. **Save as a different file, using the last names or initials from you team.**
- *Detect Front End* command
- Select the “Hardware setup” task. **Press the F2 key to activate the system.** Make sure the correct transducers are selected. (You may need to add the calibration data manually.)
 - Check the **High-pass filter** setting and set to 0.7 Hz.
 - Set the **input gain to 1.0**
 - Set the **Max Peak Input** to 0.707 V for now. Only adjust if you get an overload signal during a test.
- ***Skip the accelerometer calibration procedure*** using the hand-held shaker for this test (due to time constraints), unless early results are questionable.

Experiment 1 – Free Vibration to find f_n

1. Set the system with Lightest damping, with plastic damping plug removed.
2. Go to the Input Range task in the PULSE project. Given an initial displacement of 3 cm, make sure that the system is not overloaded. Adjust only if necessary.
3. Go to the Measurement task in the PULSE project. Set the FFT analyzer #2 settings to:

200	lines
20 Hz	span
NO	overlap
1	averages
Uniform	Window (right click vibration group inside + of FFT analyzer to change)

4. Write down any additional settings of the FFT (you may want to also do a print screen and save to a Word doc.)
5. Go to the Display task. Start the measurement, wait about 2 seconds, and then give the mass a max initial displacement (approx 3 cm).
6. Repeat 3 if necessary. Write down the frequency that is associated to the maximum velocity amplitude (above 1 Hz). Assume that this is the undamped natural frequency of the system.

Experiment 2 – Forced Vibration with light damping

1. Set the system to Light damping (plastic plug of dashpot removed), with plastic damping plug removed.
2. Set the signal generator to a sine wave of 200 mV_{rms} at f_n determined from experiment 1. **(NOTE: 3000 mV_{rms} is the MAX voltage to use!)** (Right click generator 1, then select properties) Adjust voltage down if mass carriage is sliding too much. Likewise, adjust voltage up if the displacement is less than 1.5 cm peak on the ruler.
7. Go to the Measurement task in the PULSE project. Set the FFT analyzer #2 settings to:

200	lines
20 Hz	span
66.67%	overlap
3	averages
Hanning	Window (right click vibration group inside + of FFT analyzer to change)

3. Go to the Display task. Start the generator by activating the appropriate icon.
4. Go to the Input Range task in the PULSE project and make sure that the system is not overloaded. Adjust if necessary.
5. Set the signal generator to 2.0 Hz.
6. Go to the Display task. Wait until motion appears steady-state, then start the FFT measurement (by pressing the F5 key or the finger-button icon).
7. Estimate the peak displacement based on the ruler next to the mass.
8. Measure x_{peak} (in units of m or mm) and \dot{x}_{peak} (in units of m/s or mm/s) at the drive frequency using the analyzer’s FFT plot.
9. Increase the frequency of the motor generator by approximately 0.5 Hz, or as fine as 0.1 Hz when close to f_n , or as coarse as 1 Hz when farther away from f_n .
10. Repeat steps 5-10 Increase the frequency and repeat process up to 8 Hz. See table below for example.

Frequency (Hz) output of generator	Voltage output of generator	Visual peak Displacement (mm) from ruler	Measured peak displacement (mm) from FFT	Measured peak velocity (mm) from FFT
2				
3				
...				
...				
...				
8				

Experiment 3 – Forced Vibration with medium damping (but still underdamped)

1. Add the damping plug added, but still make it an underdamped system.
2. Set the signal generator to a sine wave of $800 \text{ mV}_{\text{rms}}$ at f_n determined from experiment 1. (**NOTE: 3000 mVrms is the MAX voltage to use!**) Adjust voltage down if mass carriage is sliding too much. Likewise, adjust voltage up if the displacement is less than 1.5 cm peak on the ruler.
3. Repeat steps in experiment 2.

Experiment 4 – Free Vibration to find f_d for case with medium damping same system as experiment 3.

1. Repeat steps in experiment 1.

Experiment 5 – Forced Vibration with critical damping

2. Increase the damping until it is at a critical damping level (based on free vibration visual response).
3. Go to the Measurement task in the PULSE project. Set the FFT analyzer #2 settings to same as experiment #2.
4. Set the signal generator to a sine wave of $1.0 \text{ V}_{\text{rms}}$ at f_n determined from experiment 1. (**NOTE: 3000 mVrms is the MAX voltage to use!**) Adjust voltage down if mass carriage is sliding too much. Likewise, adjust voltage up if the displacement is less than 1.5 cm peak on the ruler.
5. Repeat steps in experiment 2.
6. **Save your PULSE file. Leave your files on the computer's desktop and your instructor will save a backup copy, and then delete the files from the PC.**

Calculations, etc.

1. Present your **raw data in table form**. The easiest way would probably be entering the data into Excel and then copying it as a table into your Word document.
2. Calculate the force amplitude (F_o) of the motor for each frequency for both experiments. Again, using Excel would be the most efficient way to do this.
3. Calculate the amplitude ratio and the frequency ratio and create a graph similar to Figure 3.11a on page 230 in your textbook. Use the peak amplitude data from your accelerometer and PULSE analyzer instead of the ruler. You should have three different curves on one graph. Determine the **damping ratio** based on the above data and theory.
4. Determine the **Q factor** for the system with the lightest damping.
5. Divide the force amplitude by the velocity amplitude (\dot{x}_{peak}) for each frequency for both experiments. This is the **magnitude of the mechanical impedance** of the system at a given frequency. Create a graph of this. Show three curves on one chart – one curve for each type of damping (with the dashpot).
6. Take the inverse of the above. These graphs now show the magnitude part of the frequency response (system output / system input) of each system. The force amplitude is the input and the velocity amplitude is the system output.

7. Determine the **power absorbed** by the dashpot at each frequency for each system (again using Excel) and make a graph of this.

Questions: (to be indirectly addressed in your discussion section)

- Did you have good correlation between your visual amplitude data and your amplitude data from the accelerometer & PULSE analyzer?
- What is the frequency for the maximum amplitude ratio? Is it the same for both systems?
- Did you get a peak displacement and peak velocity at the same frequency for all systems? Is this result what you expect from theory?
- What is the frequency for minimum mechanical impedance? Is it the same for all systems?
- Does each system have the same natural frequency?
- Does each system have the same resonant frequency?

Technical Memo:

Follow the same format as in Lab 2.

What to hand in for credit?

- Technical memo (lab report).
 - Schematic sketch of the basic setup as a figure within the report. May also include a photograph.
 - Measured data in a table in the report.
 - Graphs from the calculations section.
- Calculations on engineering paper in an appendix. Email me your Excel file used to create your graphs.

Only one lab report per team of two students.