



Implementation and Assessment of a Remotely Accessible Laboratory in an Engineering Dynamic Systems Course

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Abstract

ME340 is a junior level, 4-unit required core course for all mechanical engineering students at Cal Poly Pomona in southern California. It is considered to be a bottleneck course because it is a prerequisite for several senior level courses, yet the DFW (non-passing grade) rate is historically high. The average DFW rate across all sections of this course over the past 7 years is 20%. Part of this course requires students to employ abstract mathematics to characterize the behavior of real dynamic systems. One potential cause of the high DFW rate is that students have difficulty reconciling the abstract mathematics to the real systems they represent. At many universities with similar engineering programs, the equivalent course contains a laboratory element designed specifically to bridge the gap between theory and practical application. Cal Poly Pomona does not contain such a laboratory element, which may be part of the culprit. To study the effects of whether or not a laboratory component would help students taking ME340 a mobile laboratory experiment developed at San Francisco State University was implemented in ME340 at Cal Poly Pomona.

This paper presents the results of implementing a remote laboratory assignment ME340 over two quarters. Student survey data was collected before and after the completion of the mobile laboratory assignment. In these experiments, the authors intended to assess the effectiveness of the San Francisco State University mobile lab using several questions designed to address students' self-efficacy as well as core knowledge competence. The data from all surveys are analyzed and conclusions are drawn regarding the effectiveness of the remote laboratory implementation.

1 Introduction

Incorporating active learning in STEM based disciplines has been shown to improve student engagement and overall classroom performance [1], [2]. In particular, improvements in student performance in engineering courses has been linked to the integration of an active learning environment into the classroom [3], [4], [5]. This is well documented and it should not be surprising that an active learning approach is especially beneficial for engineering students. One of the primary means of incorporating an active learning environment in engineering is through the engineering laboratory, where students can reinforce their knowledge by validating classroom theory with real life experimentation. The engineering laboratory is a long-standing staple of any engineering curriculum and, while its benefits are clear, it comes with particular challenges such as initial costs, maintenance, staffing, and eventual obsolescence.

Recent alternatives which attempt to combat the abovementioned include virtual laboratories and remote laboratories, in which physical presence is not required in order to run experiments [6], [7], [8], [9], [10]. While the effectiveness of these types of laboratory environments is still largely being investigated, it is irrefutable that virtual or remote laboratories can make a laboratory experience feasible in cases where it otherwise would be impossible.

This paper presents the results of a recent implementation of a remote laboratory developed at San Francisco State University [11], [12], [13] into a junior level engineering course at Cal Poly Pomona. A description of the remote laboratory is included as well as a discussion of how the remote lab was systematically incorporated into the classroom at Cal Poly Pomona. Then the data is analyzed, and conclusions are drawn.

2 San Francisco State University Remote Shake Table Experiment

A brief summary of the mobile remote shake table laboratory (mRSTLab) is included here, since a full description of the experimental platform is available [11]. Figure 1 below depicts the system architecture of the mRSTLab.

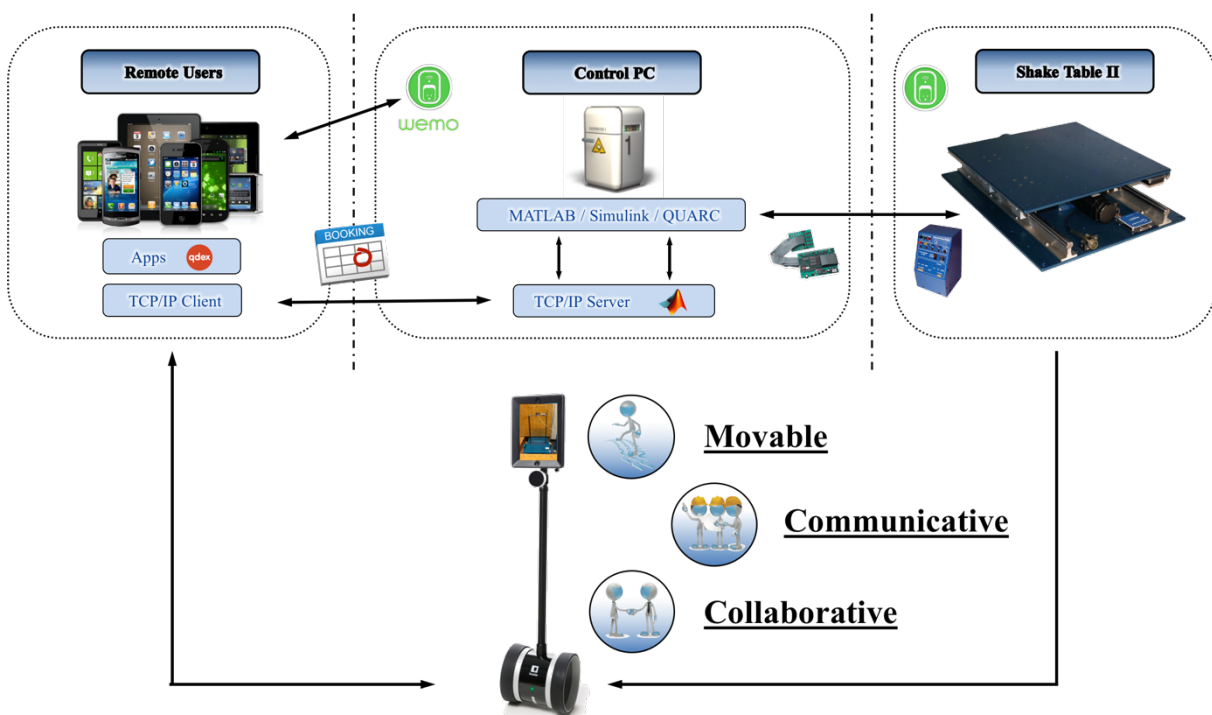


Figure 1. Schematic diagram of the Remote Shake Table (RST) Laboratory

The physical plant is a structure consisting of a rigid bar mounted horizontally atop two parallel vertical flexible members. The overall rectangular structure is a lightly damped second-order dynamical system designed to represent a structure like a building. The base of the structure is mounted to the surface of the shake table, which can be remotely actuated. Accelerometers at the base and at the top of the structure record acceleration data at a sample rate of 100 Hz.

Each student is able to reserve a 30-minute window using an online booking system. During their 30-minute window, they interact with the system in a one-on-one environment; no one else can drive the system or collect data during that time. If necessary, students can book multiple time slots if they do not complete all of the required data collection in the first 30 minutes.

The mRSTLab is developed through a mobile development platform called qdex™. The qdex platform is provided by a world-leading educational equipment provider, Quanser Inc. It offers a fast and easy way to transform conventional static training materials into highly interactive, concept-rich knowledge applications that fully exploit the convenience and power of mobile devices. The apps developed via this platform are directly usable in both Android and iOS devices without modifications. From the mRSTLab app, the user can connect to the shake table and specify input command parameters such as: input type, frequency of oscillation, amplitude, and duration.

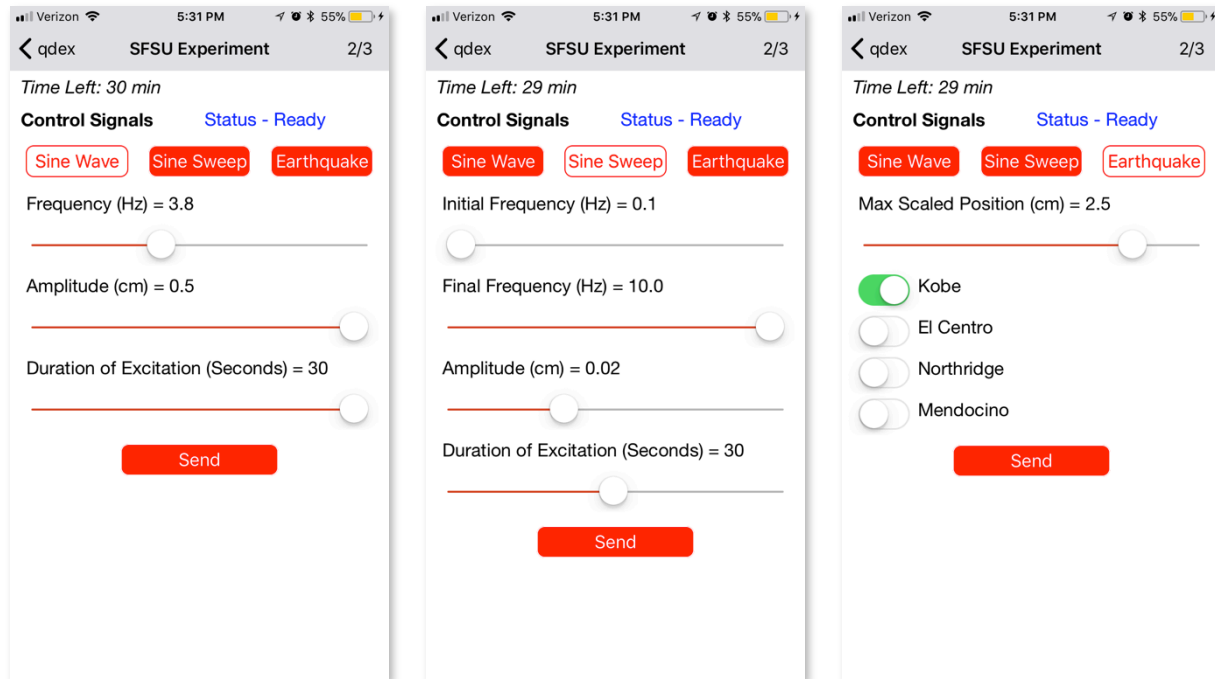


Figure 2. qdex user interface showing various input parameters

A telepresence robot is adopted as part of the mRSTLab to offer live audio/visual feedback on the experiment in the physical laboratory. The telepresence robot, Double, is built by a technology startup company, Double Robotics. It is a remote-controlled robot stand that works together with an Apple iPad to provide low-cost real-time control and communication. The user can run the Double app in parallel with the mRSTLab, as shown in Fig. 3, which offers a nearly true-to-life laboratory experience.

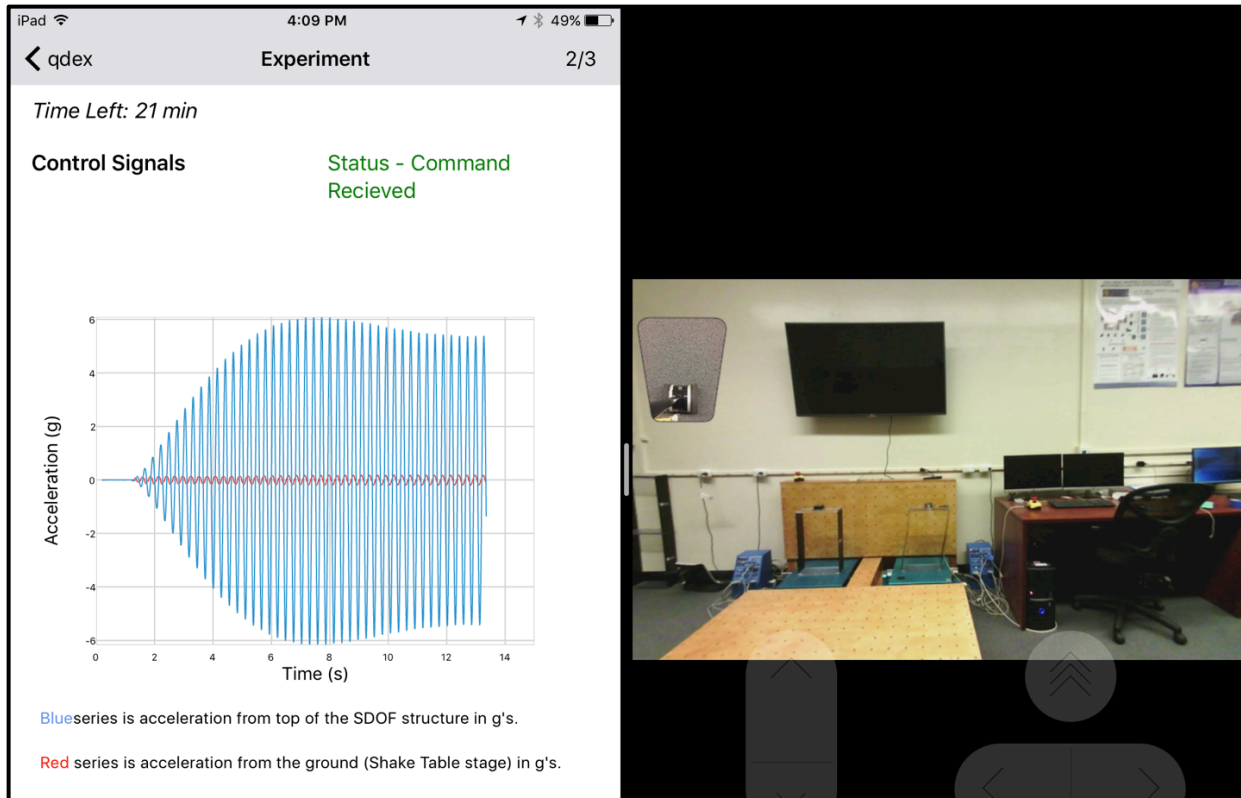


Figure 3. mRSTLab and Double running side by side on an iPad

After each experimental run, the raw data is automatically emailed to the student in a convenient form for further analysis in a numerical computation package like MATLAB.

3 Implementation at Cal Poly Pomona

Part of the original goal of the development of the mRSTLab was to offer a high quality experimental experience to students who otherwise do not have access. The concepts that can be taught using the mRSTLab are common across all reputable engineering universities making it a desirable system to implement.

At Cal Poly Pomona (CPP) ME340 is a 3-unit, junior level, required mechanical engineering course in modeling and simulation of dynamic systems. While many universities have a laboratory component for their equivalent course, it is a lecture only course at CPP. ME340 at CPP is considered a bottleneck course because it is a prerequisite for several senior level courses, yet the DFW (non-passing grade) rate is historically high. The average DFW rate across all sections of this course over the past 7 years is 20%. This course is particularly well suited for a laboratory component because, while the mathematical concepts are abstract, there is a direct application to physical systems. The hypothesis is that students have difficulty in reconciling the theoretical concepts to real physical systems primarily due to the abstract nature of the mathematics. In order to offer students a first-hand demonstration of the theory applied in practice, the mRSTLab was incorporated into the ME340 curriculum.

During the Summer and Fall 2017 quarters, the mRSTLab was incorporated into one section of ME340 and pre- and post-survey data was collected to gauge students' impressions of the system. In this implementation, the outcome of the surveys yielded overall student feedback on the effectiveness of the mRSTLab and the perceived benefits by the students. Part of this implementation also served to gauge the degree of difficulty from a faculty standpoint pertaining to incorporating the mRSTLab into a pre-existing curriculum.

4 Assessment of the Implementation

To assess the effectiveness of the mRSTLab regarding student learning, three surveys were developed. Specific survey questions are available in Appendix (6.a-6.c). Two portions of the survey asked questions probing students' sense of self-efficacy in both frequency response and damping / resonance concepts. The third portion of the survey was developed to address specific knowledge competence on particular concepts. All questions were combined and administered before the mRSTLab assignment and then again after the mRSTLab assignment was completed. Data obtained from both pre- and post-survey were analyzed using the Statistical Package for the Social Sciences (SPSS) [14]. A diagnostic analysis was conducted to determine data distribution and to appropriately normalize the data. A paired sample two-tailed Student's T-test was calculated for each measure between the pre- and post-surveys to find statistical differences. Figures 4 and 5 show the participant characteristics for the two terms.

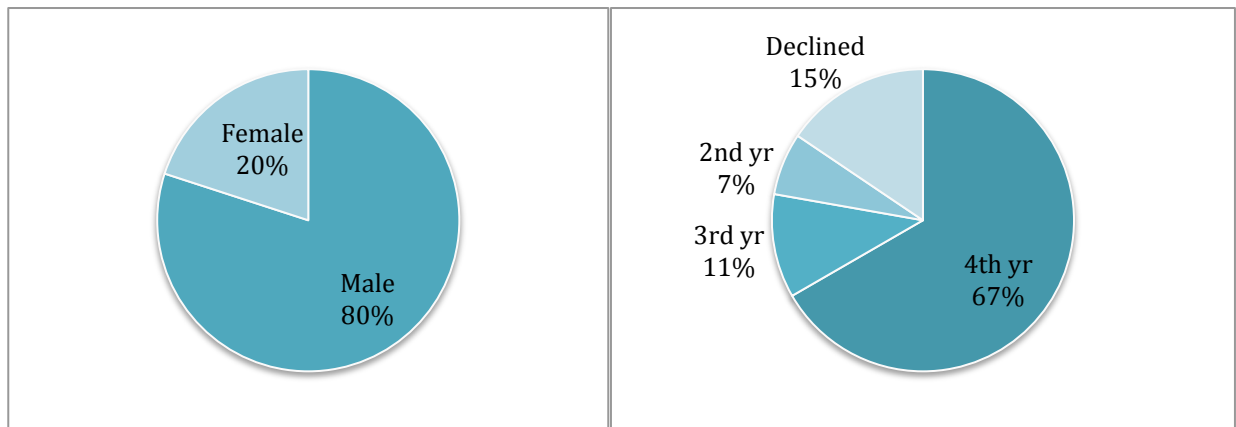


Figure 4. Summer 2017 participant characteristics

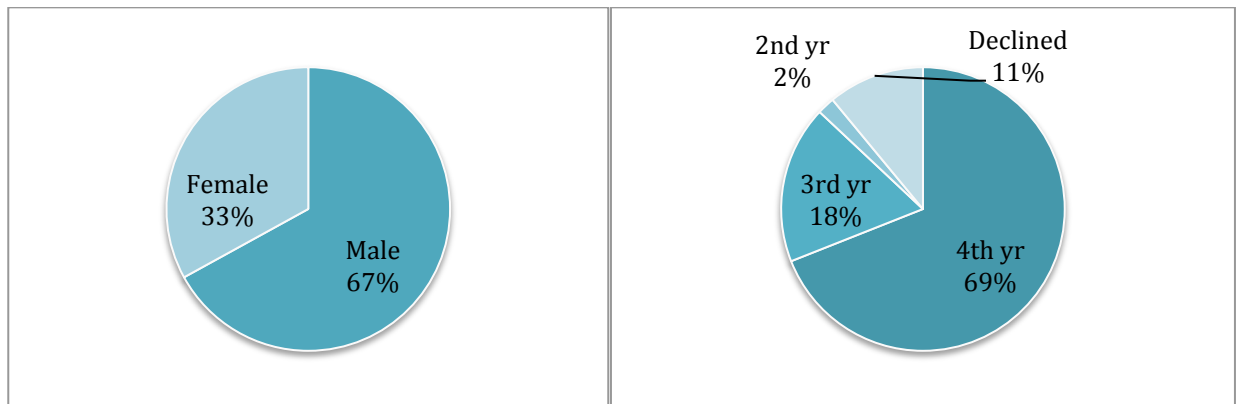


Figure 5. Fall 2017 participant characteristics

4.1 Self-efficacy

The self-efficacy portion of the survey consists of questions adopted from a pre-validated instrument, which assesses students' self-efficacy on critical engineering concepts using a five-point Likert-type scale from strongly agree to strongly disagree [15]. In this context, self-efficacy is defined as the ability of students to learn concepts and perform tasks efficiently [16].

Summer 2017 Results: Self-efficacy, Frequency Response

Measures	Mean Pre/Post	T-test	<i>p</i> value
Q1	1.94/1.50	3.259	0.03
Q2	2.19/1.75	3.458	0.02
Q3	2.47/1.81	4.116	0.000
Q4	2.13/1.66	3.695	0.001
Q5	2.44/1.66	5.079	0.000
Q6	3.13/3.44	-1.408	0.169
Q7	3.53/3.59	-0.304	0.763

Summer 2017 Results: Self-efficacy, Damping and Resonance

Measures	Mean Pre/Post	T-test	<i>p</i> value
Q1	2.00/1.53	4.267	0.000
Q2	2.38/1.88	3.215	0.003
Q3	2.63/1.88	3.832	0.001
Q4	2.03/1.66	3.832	0.001
Q5	2.34/1.84	3.521	0.001
Q6	3.19/3.38	-0.882	0.385
Q7	3.53/3.56	-0.154	0.879

Fall 2017 Results: Self-efficacy, Frequency Response

Measures	Mean Pre/Post	T-test	<i>p</i> value
Q1	1.48/1.45	0.255	0.800
Q2	1.81/1.67	1.523	0.135
Q3	2.07/1.62	3.522	0.001
Q4	1.74/1.62	1.220	0.230
Q5	1.86/1.55	3.117	0.003
Q6	3.69/3.64	0.280	0.781
Q7	3.86/3.79	0.318	0.752

Fall 2017 Results: Self-efficacy, Damping and Resonance

Measures	Mean Pre/Post	T-test	<i>p</i> value
Q1	1.50/1.48	0.227	0.822
Q2	1.88/1.71	1.361	0.181
Q3	2.07/1.67	2.876	0.006
Q4	1.90/1.64	2.311	0.026

Q5	1.90/1.64	2.127	0.040
Q6	3.74/3.67	0.464	0.645
Q7	3.93/3.86	0.518	0.607

Table 1: Results from Self-efficacy Questions

Due to the nature of the questions (Appendix 6.a-6.b), for each of the charts in Table 1, it is desired to see a decrease in the mean value (2nd column) from pre- to post-survey on questions Q1-Q5, and an increase on questions Q6-Q7. All of the bold rows show instances where a statistically significant outcome was observed, indicating that for many of the questions their level of confidence was greater once they completed the mRSTLab assignment. Non-bolded rows show no statistical difference before and after the assignment.

4.2 Knowledge Competency

The knowledge competency portion of the survey consists of questions on a four-point scale (I don't understand the statement, I understand the statement but don't know the answer, the statement is true, and the statement is false). The test was designed to directly assess student learning of engineering concepts.

Summer 2017 Results: Knowledge Competency			
Measures	Mean Pre/Post	T-test	p value
Q1	0.38/0.53	-1.539	0.134
Q2	0.34/0.53	-1.531	0.136
Q3	0.41/0.69	-2.738	0.010
Q4	0.81/0.66	1.717	0.096
Q5	0.59/0.53	0.701	0.488
Q6	0.19/0.28	-1.139	0.263
Q7	0.44/0.50	-0.701	0.488

Fall 2017 Results: Knowledge Competency			
Measures	Mean Pre/Post	T-test	p value
Q1	0.57/0.67	-1.071	0.290
Q2	0.40/0.64	-2.677	0.011
Q3	0.5/0.64	-1.432	0.160
Q4	0.93/0.81	1.952	0.058
Q5	0.64/0.74	-1.432	0.160
Q6	0.26/0.31	-0.628	0.534
Q7	0.45/0.60	-1.635	0.110

Table 2.8 Results from Knowledge Competency Questions

Due to the nature of the questions (Appendix 6.c), for each of the charts in Table 2, it is desired to see an increase in the mean value (2nd column) for all questions. Most of the rows indicated at least some increase in knowledge after completing the mRSTLab assignment, but the bold rows show instances where a statistically significant outcome was observed.

In both Summer and Fall terms, question Q4 (Table 2, red rows) indicated a *decrease* in knowledge competency after the mRSTLab assignment. The authors hypothesize that this question was flawed in that it fundamentally addresses the concept of System Identification, which was not explicitly covered on the mRSTLab assignment. Modification will be made in the future implementations.

5 Concluding Remarks

Overall, the implementation of the mobile laboratory assignment shows a positive impact on the learning outcomes for the students taking ME340 at CPP. The results from the assessment indicate that students generally gained a deeper understanding of specific concepts within frequency response and damping / resonance, which are key concepts throughout the course. It is likely that the underlying reason for the improvement in student understanding is through the visual feedback offered by the Double robot system as well as the data analysis that they performed on their real, collected data.

The amount of work required for an instructor to implement the mRSTLab into an established lecture-only classroom is minimal, as the students only needed a mobile device and to download two free apps. The assignments can be developed with the same concepts in mind, but the instructor has the flexibility to ask students to collect data from an actual system, which has shown to produce positive results. In this implementation, no administrative changes were necessary, as dedicated laboratory sections were not required. The enrollment process for students is the same as adding any lecture-only class.

6 Appendix

- a. List of **self-efficacy** survey questions pertaining to **frequency response** concepts

Q1: I am confident that I have the ability to learn the materials about frequency response.
Q2: I am confident that I can do well on exam questions about frequency response.
Q3: I am confident that I can explain concepts on frequency response learned in this class to another person.
Q4: I am confident that I can understand topics that build on the knowledge of frequency response.
Q5: I am confident that I can do well on the lab experiment related to frequency response
Q6: I feel like I don't know a lot about frequency response compared to other students.
Q7: I don't think I will be successful on exam questions about frequency response.

- b. List of **self-efficacy** survey questions pertaining to **damping and resonance** concepts

Q1: I am confident that I have the ability to learn the materials about damping and resonance within a system.
Q2: I am confident that I can do well on exam questions about damping and resonance within a system.
Q3: I am confident that I can explain concepts on damping and resonance within a system learned in this class to another person.

- Q4: I am confident that I can understand topics that build on the knowledge of damping and resonance within a system.
- Q5: I am confident that I can do well on the lab experiment related to damping and resonance within a system.
- Q6: I feel like I don't know a lot about damping and resonance within a system compared to other students.
- Q7: I don't think I will be successful on exam questions about damping and resonance within a system.

c. List of **knowledge competence** survey questions

- Q1: A flexible beam or structure, such as a building or bridge, exhibits 2nd-order dynamics if the system has only one resonant peak.
- Q2: If a system has a resonant peak in its frequency response, it is impossible to excite the system in a way that results in amplification (>1) of the output.
- Q3: Regardless of the excitation frequency, the magnitude of the output of a system with 2nd-order dynamics is always less than that of the input.
- Q4: It is possible to experimentally construct the Bode plots of a system if you can accurately measure the input and output signals.
- Q5: If the system is subject to an impulsive input, the damping ratio can be determined by the free response.
- Q6: If the excitation frequency is much larger than the resonant frequency, the magnitude of the output of a 2nd-order system approaches infinity as well.
- Q7: If the excitation frequency is much larger than the resonant frequency, the phase of the output of a 2nd-order system approaches -180 degree.

d. Sample Assignment using mRSTLab

REMOTE SHAKE TABLE LABORATORY

Due: Monday, 3/12/2018, at beginning of final exam

Before you do anything: you must complete a short pre-survey using the link provided by Prof. [REDACTED]. All members in your group need to take a screenshot of the final page at the end of the survey to receive credit for this assignment. You will do another survey after you are finished with this assignment as well. Pre-survey link:

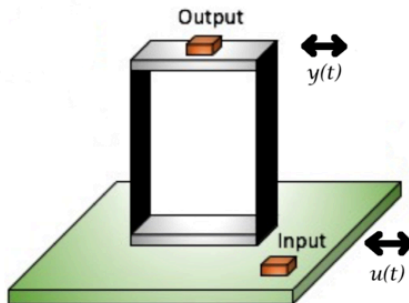
[https:// \[REDACTED\]](https://[REDACTED])

For this assignment you will remotely interact with a real dynamic experimental system that is set up in [REDACTED]. The apparatus is meant to resemble a building or structure with flexibility. You will book a 30-minute time slot during which you will collect actual measured data from the system. You will then apply frequency response concepts to perform analysis on your data and answer the questions below. Furthermore, you will access a telepresence robot so you can stream live video of the experiment in real time.

Copy and paste the following link into a web browser to watch a video that illustrates this process:

[https:// \[REDACTED\]](https://[REDACTED])

Carefully read the supplemental document on Blackboard (mRSTlab_Instructions.pdf) which explains how to remotely interact with the lab.



The experimental platform is a flexible structure mounted atop a shake table. You can apply an input to the base and that acceleration is measured by an accelerometer. The motion at the base causes an acceleration at the top of the flexible structure, which is measured by a second accelerometer. This is the output of the system. The damped flexible structure has 2nd-order dynamics, described by the following transfer function:

$$P(s) = \frac{Y(s)}{U(s)} = \frac{535.5}{s^2 + 0.0324s + 535.5}$$

where $U(s)$ is the Laplace transform of the input and $Y(s)$ is the Laplace transform of the output.

The Assignment

IMPORTANT: Before you begin work on this assignment, each student must complete the short pre-survey using the link provided by XXXXXXXXXX

Once you have completed the pre-survey, review the questions below before your time slot, so that you know exactly what data you need to collect during your 30-minute window.

- From the analytical model given above, state the natural frequency ω_n in $\frac{rad}{s}$ and in Hz , as well as the damping ratio ζ .
- Explain whether or not you will see any amplification in the output. In other words, can you excite the system with a sinusoidal input such that the resulting output has *larger* amplitude than the input? If so, at what frequency will this output amplification be the maximum?
- Validate your response in (b) by sketching the Bode plot for the system.
- State the complex-valued frequency response *function* $P(j\omega)$ and write it as the sum of a real portion and an imaginary portion. Then derive the magnitude and phase functions.
- Recall that for an LTI system, a sinusoidal input results in a sinusoidal output of the same frequency, but that is scaled by the magnitude and shifted by the phase angle. Use your result from (e) to compute the analytical Bode magnitude $|P(j\omega)|$ for the specified frequencies in the *Analytical* rows of Table 1 below: (ω_{max} is the frequency at which the maximum output amplitude is achieved)

	Input frequency ω (Hz)					
	0.5	1.0	1.5	2.0	2.5	3.0
$ P(j\omega) $ (Analytical)						
$ P(j\omega) $ (Empirical)						

	Input frequency ω (Hz)					
	3.5	4.0	4.5	5.0	5.5	ω_{max}
$ P(j\omega) $ (Analytical)						
$ P(j\omega) $ (Empirical)						

Table 1: Analytical and empirical Bode magnitude for selected frequencies

- Data collection:** Fill in the *Empirical* rows of Table 1 above by applying sinusoidal inputs of varying frequency to the actual shake table laboratory using the provided instructions. Keep

in mind that the amplitude of the *input* sinusoid is not always equal to 1; if the amplitude of the input is a , then the output is scaled by the same amount. In other words:

$$u(t) = a \cdot \sin(\omega t) \longrightarrow \boxed{P(s)} \longrightarrow y(t) = |P(j\omega)| \cdot a \cdot \sin(\omega t + \angle P(j\omega))$$

- (g) When you are finished with the assignment, be sure each group member completes the short post-survey and take a screenshot of the final page as proof of completion.

https://

Hints for running experiments:

- Running the qDex app in along with the Double app (for telepresence) will give you the fullest experience, as you will be able to watch the system move in real time as you apply various inputs.
- For each run, take a long enough data set so that the transient response decays to zero.
- For each run, use a large enough input amplitude to avoid seeing noise in the output.
- After each successful run, be sure to email the data to yourself (button in app).
- Determine the magnitude for each frequency by plotting both the input and output in MATLAB on the same axes. Divide the amplitude of a steady-state output peak by that of a steady-state input peak to obtain the magnitude for that frequency.

What to submit:

Submit a short report (1 per team) summarizing your responses to all of the questions above. Being as concise as possible, include:

- Screenshots of the final page of the pre-survey and post-survey (everyone in the group needs to provide these documents).
- All hand calculations and justify any conclusions you draw
- A hand sketch of the Bode plot of the system
- A MATLAB Bode plot of the system to verify your hand sketch (maintain consistent axes)
- MATLAB plots of the input / output data for each frequency (zoomed to show enough detail to determine magnitude)
- A completed Table 1 (above)
- Plot the analytical and empirical magnitude data points on the MATLAB Bode plot to validate your data.
- Discuss any discrepancies between your analytical and empirical data in a paragraph or two.

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