OPINION PAPER

Increasing Student Understanding of Response Spectra: An Argument for the Inductive Learning Approach

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Creating and interpreting earthquake response spectra are important fundamentals in earthquake engineering education. We argue that an effective approach for teaching the fundamentals of earthquake response spectra is to use an inductive learning approach in an interactive classroom, which is well supported by engineering education literature. To demonstrate this approach we use desktop learning modules that exhibit response spectra concepts. Preliminary data based on post-class interviews with instructors support our opinion. Notably, all interviewed instructors have chosen to adopt the inductive learning approach when teaching response spectra concepts in future iterations of their classes. [DOI: 10.1193/040417EQS060O]

INTRODUCTION

"It would be impossible to teach this concept to undergraduate students; it is too difficult." We have heard colleagues (and ourselves) use this general phrase when discussing how to teach students to understand and develop earthquake response spectra (hereafter shortened to "response spectrum/spectra"). Our opinion is that teaching undergraduate students the fundamentals of response spectra is difficult using the deductive learning approach (i.e., theory first, applications second), which is the most common learning approach in engineering classrooms (Prince and Felder 2006). However, we firmly believe that undergraduate students can learn the fundamentals of response spectra when instructors employ an inductive learning approach (i.e., applications first, theory second). Furthermore, we believe that graduate students and practicing earthquake engineers could benefit from reexamining the fundamentals of response spectra using the inductive approach.

Before the advent of modern computing, earthquake engineers developed response spectra concepts using an inductive approach. The original "seismic vibration analyser" developed by Suyehiro in the 1920s measured the movement of pendulums during strong shaking (Suyehiro 1926), which allowed for the creation of response spectra (Chopra 2007). Later, Housner (1941), Biot (1941), and Newmark (1959) developed the mathematics and computational techniques for understanding the response of undamped and damped single degree of freedom mass-spring oscillators to earthquake motion. The switch from mechanical

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pendulums to computational methods for creating response spectra was transformative for the field of earthquake engineering, and led to its proliferation in the 1960s and beyond (Chopra 2007, Riddell 2008). Increased computational power also made the deductive learning approach much easier when teaching response spectra concepts.

For educational purposes, we believe that earthquake engineering educators should reincorporate devices similar to Suyehiro's mechanical pendulum, which will allow instructors to teach the concepts of earthquake response spectra with a more intuitive and powerful inductive approach. Previous research (e.g., Paul et al. 2009, Peterson et al. 2012, Burgher et al. 2013, Brown et al. 2014) has shown that desktop learning modules (DLMs), which are portable physical models designed to display important learning outcomes, help instructors use inductive, interactive teaching methods. In addition, Arasteh et al. (2013) note that instructors who properly implement DLMs in engineering classrooms create an educational experience that develops robust problem-solving skills. With the foregoing engineering education research as motivation, herein we outline an inductive and interactive approach for teaching response spectra concepts to students using DLMs. In addition to design details, we provide preliminary evidence about the effectiveness of the DLMs based on post-class interview data from three instructors at Oregon State University, and post-class Likert assessments from students in a large, upper-level undergraduate civil engineering course.

INDUCTIVE LEARNING AND INTERACTIVE CLASSROOMS

Two fundamental engineering education concepts are important for understanding the work presented herein: (1) the inductive learning approach (Felder and Silverman 1988), and (2) interactive classrooms (Chi 2009). The engineering education literature on the preceding two topics is extensive, and our aim is not to present an exhaustive literature survey. Instead, we give a cursory background to inform the reader before discussing the design and construction of our DLMs.

Inductive learning engages students with specific examples or activities that provide the students with opportunities to observe and interpret resulting patterns. The students construct generalizable understanding with the observations and interpretations (e.g., Felder and Silverman 1988). In contrast, deductive learning requires students to learn general theory first, then apply the theory to engineering design scenarios. Figure 1 shows a schematic

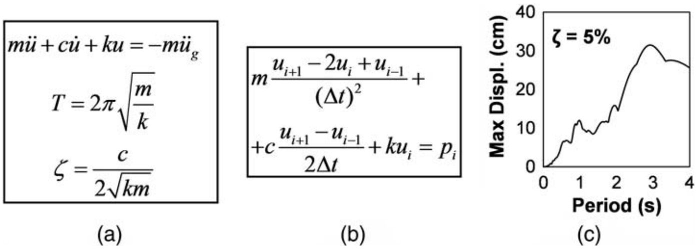


Figure 1. The deductive learning approach: (a) the equation of motion and dynamic properties of a single-degree-of-freedom oscillator, (b) the numerical solution to the equation of motion, and (c) the displacement response spectrum.

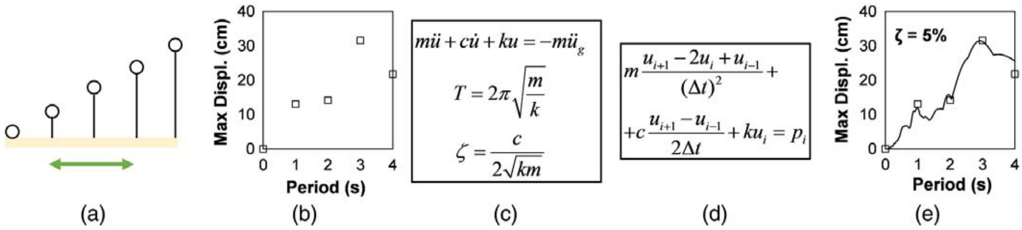


Figure 2. The inductive learning approach: (a) a DLM for simulating response spectra, (b) physical measurements from the DLM, (c) the theory behind the DLM and measurements (i.e., equation of motion and vibrational properties of the single-degree-of-freedom oscillator), (d) the numerical method used to solve the equation of motion, and (e) the theoretical and experimentally determined displacement response spectrum.

of the deductive learning approach applied to response spectra concepts. Figure 2 shows our recommended inductive learning approach for teaching response spectra concepts. We note that the inductive learning approach usually requires more effort and preparation from the instructors for successful deployment in the classroom.

A literature synthesis on the effectiveness of inductive learning by Prince and Felder (2006) has shown that inductive learning approaches are at least as effective as deductive learning approaches for improving student-learning outcomes. Instructors can incorporate the inductive learning approach into engineering classrooms using a variety of techniques. One commonly used technique that we recommend when using the DLMs is guided inquiry, which starts when the instructor poses questions and problems or provides observations. The guided inquiry process finishes when the instructor guides the students to the answers or explanations by encouraging group work (e.g., think/pair/share) or by classroom discussions (Lee 2012).

The inductive learning approach goes hand-in-hand with interactive classrooms. Evidence suggests that engaging students in the learning process during a presentation—that is, motivating students to be interactive learners—is an effective method for changing their conceptual understanding (e.g., Prince 2004, Chi 2009). Instructors who use interactive learning techniques motivate students to listen actively by requiring subsequent activities such as writing, discussion, and tactile problem solving. The preceding activities engage students in higher-order thinking tasks such as analysis, synthesis, and evaluation.

DLM DESCRIPTION AND SPECIFICATIONS

Developing effective DLMs is an iterative process, as detailed by Buker (2017). Through iteration, we minimized the cost and leveraged open-source software so that future users can adopt the DLMs without a large financial investment. We designed the DLMs to be mobile, robust, and have natural periods that can easily be excited with a shake table or by hand. We prioritized developing DLMs with a reasonable natural period range. Figure 3 shows two non-instrumented DLMs, which are masses-on-springs (i.e., wooden balls on springs) attached to a baseboard. The constant stiffness DLM has springs with the same stiffness, but each mass is different (see Figure 3a). Conversely, the constant mass DLM has springs

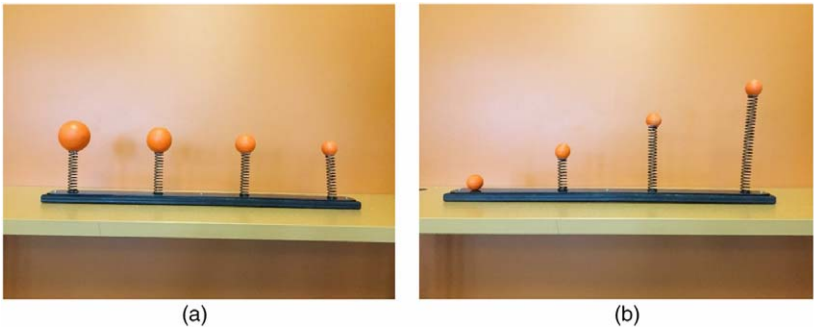

(a) (b)

Figure 3. Finalized DLMs without instrumentation. The model on the left demonstrates the effect of varying structure weights and on the right the effect of varying stiffness of the structure.

with different stiffnesses, but each mass is the same (see Figure 3b). The wooden balls have approximate diameters of 76, 64, 51, and 31 mm (see Figure 3a from left to right) and respective masses of approximately 142, 84, 48, and 21 grams. The constant mass DLM utilizes the 31 mm diameter, 21 grams mass, and the baseboard of the constant mass DLM contains one rigidly attached mass (i.e., mass without a spring). The rigidly attached mass represents the infinite stiffness case (i.e., period, T, equals zero), which corresponds to the peak ground acceleration (PGA) on the response spectrum.

The tempered-steel compression springs have an outside diameter of 22 mm, wire diameter of 2 mm, and mass per length of approximately 0.22 grams/mm. The constant stiffness DLM springs are all approximately 100 mm in length, and the constant mass DLM springs are zero and approximately 70, 150, and 230 mm in length (see Figure 3b left to right). Accordingly, the mass of each spring in the constant stiffness DLM is approximately 22 grams, while those for the constant mass DLM springs are zero and approximately 15, 33, and 51 grams, respectively. Each spring has finished ends, which contribute an additional mass of approximately 3 grams per spring. The preceding specifications of the spring masses are important for assessing the validity of the single degree-of-freedom assumption when generating response spectra.

We use the EE2-3 shake table from Engineering Education (2017) to provide input motions (n.b., instructors can also excite the DLMs by shaking the base or initiating free vibration with initial displacement). The payload area of the shake table is 250 by 250 mm, and the maximum payload is 9 kg. The table has a frequency range from 0.1 to 10 Hz and a maximum stroke of +/−20 mm, which is capable of exciting the natural periods of our DLMs. Although the shake table is not strictly necessary for successful operation of the DLMs, we firmly believe that it helps promote the inductive learning approach and creates an interactive classroom environment because the students can see how the DLM response changes with respect to changes in the amplitude and frequency of excitation.

We attached accelerometers to the wooden masses on each DLM to track the real-time response during excitation. The accelerometers track the total acceleration of the masses, $\ddot{u}_t$, which includes the acceleration of the mass, $\ddot{u}$, relative to the base and the acceleration of the base (or the "ground" acceleration), $\ddot{u}_g$; i.e., $\ddot{u}_t = \ddot{u} + \ddot{u}_g$. If $\ddot{u}_t$ is double integrated, then we calculate the total displacement, u_t; though we need the relative displacement of the mass, u, to plot response spectra. Accordingly, we track the acceleration (and displacement) of the shake table with an additional accelerometer. For the constant mass DLM (Figure 3b), the accelerometer on the rigidly attached mass also tracks the ground acceleration.

The accelerometers require an electronics package as shown in Figure 4. The electronics package logs data from the accelerometers directly to a computer via a serial port. We used Sparkfun Triple Axis Accelerometers (model MMA8452Q) to measure acceleration of the DLM masses. We used the open-source Arduino software (i.e., Arduino IDE) with an I^2C protocol (Sparkfun 2017) to initialize the accelerometers, and we used two Teensy 3.2 microcontrollers to log the accelerometer data.

Figure 5 shows the proto-board diagram. Sockets and connectors attach the microcontrollers and accelerometers to the proto-board. Using sockets and connectors allows for easier transport of the DLMs, reduces the risk of damage to the electronics package, and improves the ease of debugging. The complete electronics package also contained two micro-USB cables, a ribbon cable, a USB hub, jumper wires, and heat shrink, and the total cost of the electronics package for one DLM was approximately \$130 in 2016.

We developed two Python scripts that enable users to record and visualize the acceleration data. The first Python script logs the acceleration data to a single text file, and the second Python script generates a graphical user interface (GUI) that allows users to visualize the acceleration data in real time. We built the GUI using the cross-platform modules PyQt and PyQtGraph so that users can easily customize the display for their particular applications. The GUI contains an "interactive legend" that enables users to select response variables for plotting, and users can vary the colors and line widths to optimize visualization. The GUI also allows users to define the window of data acquisition and save the data. We packaged both Python scripts to binary executables so users can run the scripts with no required external dependencies or installations. Figure 6 shows the fully instrumented constant mass DLM as well as the GUI. We provide detailed documentation of the development and instrumentation of the DLMs on the research team's GitHub page, which serves as a central repository for

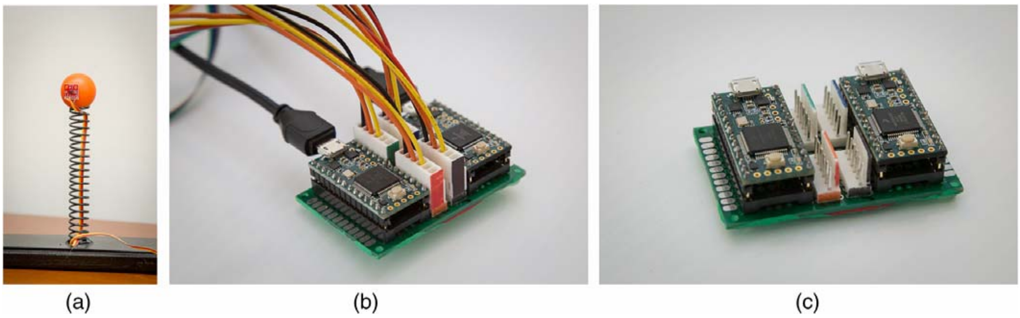

(a) (b) (c)

Figure 4. (a) Mass and spring with a single triple axis accelerometer attached near the center of mass, (b) proto-board connected to 4 triple axis accelerometers, and (c) close-up on the 2 microcontrollers.

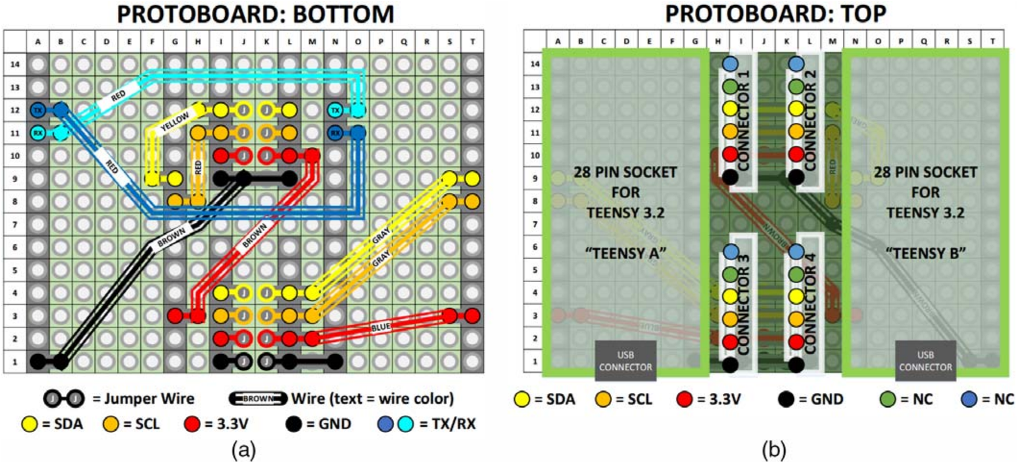


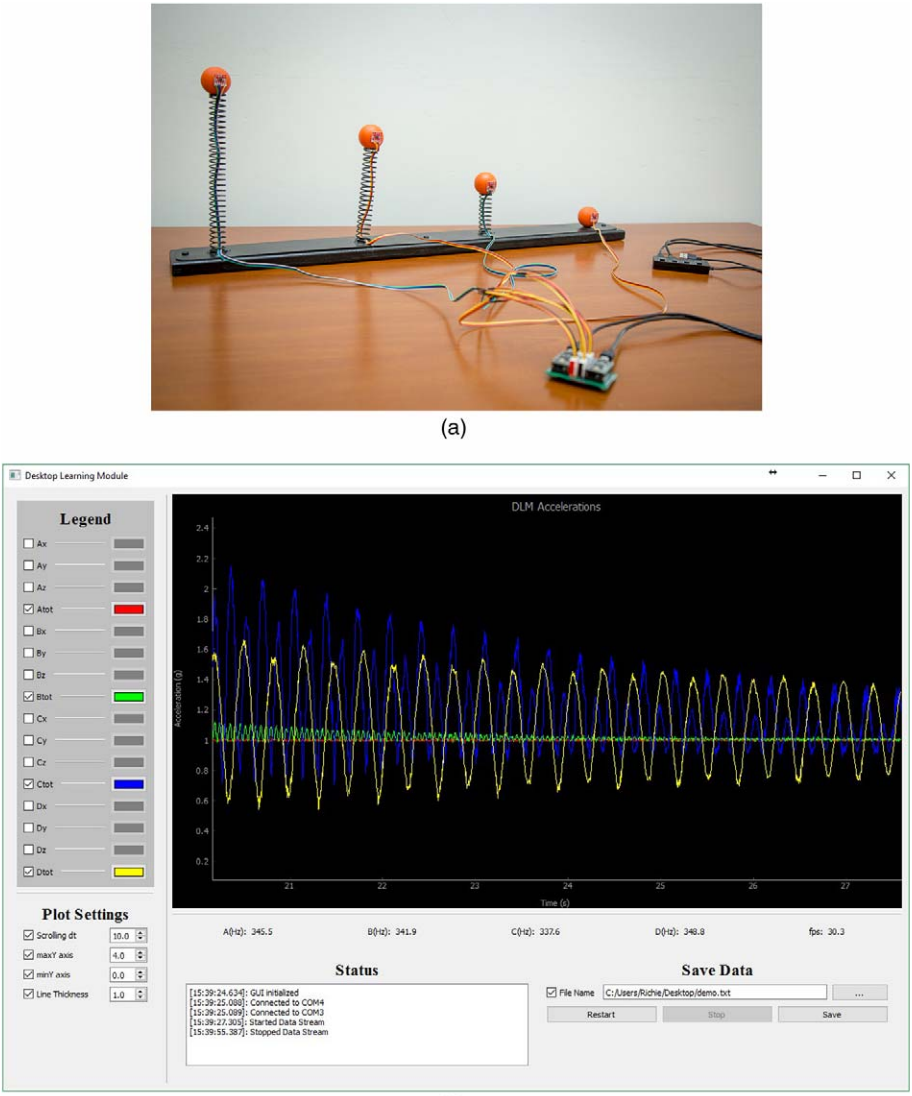
Figure 5. The proto-board design for each electronics package: (a) wiring diagram, and (b) interface between the microcontrollers and the accelerometer connectors. SDA = serial data access; SCL = serial clock; 3.3 V = Voltage for universal serial bus (USB); GND = ground for USB; TX/RX = transaction/receiver pins for USB; NC = no connection.

access to and continued development of the DLMs: https://github.com/OSU-Geomatics/OregonState_DLM (last accessed: 20 September 2017).

We examined the dynamic properties (natural frequency and damping ratio) of the constant stiffness and constant mass DLMs by inducing free vibration and using the logarithmic decay procedure (Clough and Penzien 1975). For the constant stiffness DLM, the natural frequencies of the oscillators, f_n, from the heaviest mass to the lightest mass are approximately 1.0, 1.8, 3.3, and 5.0 Hz, respectively, and the corresponding damping ratios, ζ, are approximately 1.6%, 1.4%, 0.5%, and 0.8%, respectively. Similarly, for the constant mass DLM, the natural frequencies of the oscillators from the tallest spring to the shortest spring are approximately 1.4, 3.3, and 10 Hz, respectively, and the corresponding damping ratios are approximately 1.4%, 1.0%, and 0.4%, respectively.

CLASSROOM TRIALS

To test the efficacy of the DLMs, we collaborated with three instructors (A, B, and C) at Oregon State University, who agreed to use the DLMs during the 2016–17 academic year. The instructors used the DLMs in three courses, herein labeled I, II, and III. Courses I and III are required courses, and Course II is an elective course. Course I is an upper-level undergraduate course that had an enrollment of 50 students, and Courses II and III are graduate courses that had enrollments of 15 graduate students and 9 students (7 graduate students, 2 undergraduate students), respectively. The three instructors developed lesson plans to use the DLMs independently and without our input. A graduate student researcher trained the instructors to use the DLMs, observed the in-class use of the DLMs, and then conducted post-class interviews with the three instructors (Buker 2017).


(a)

Desktop Learning Module

Legend

☐ Ax
☐ Ay
☐ Az
☑ Atot 🟥
☐ Bx
☐ By
☐ Bz
☑ Btot 🟩
☐ Cx
☐ Cy
☐ Cz
☑ Ctot 🟦
☐ Dx
☐ Dy
☐ Dz
☑ Dtot 🟨

Plot Settings

☑ Scrolling dt 10.0
☑ maxY axis 4.0
☑ minY axis 0.0
☑ Line Thickness 1.0

A(Hz): 345.5 B(Hz): 341.9 C(Hz): 337.6 D(Hz): 348.8 fps: 30.3

Status

```
[15:39:24.634]: GUI initialized
[15:39:25.088]: Connected to COM4
[15:39:25.089]: Connected to COM3
[15:39:27.305]: Started Data Stream
[15:39:55.387]: Stopped Data Stream
```

Save Data

☑ File Name C:/Users/Richie/Desktop/demo.txt

(b)

Figure 6. (a) Finalized DLMs with instrumentation, and (b) the Python GUI for data acquisition visualizes the accelerometer data in real time.

Through classroom observation, we found that the three instructors implemented different in-class learning activities to promote inductive learning approaches with the DLMs. In particular, all three instructors used the DLMs to create response patterns that the students could observe, and the observations helped the students develop formal theory with guided inquiry from the instructors. Moreover, instructors A and B allowed students to operate the DLM and had the students hypothesize the response of the DLMs to different input motions before using the DLMs. Finally, instructors B and C utilized the Python scripts to further the students' understanding of the underlying theory by showing how response trends change with respect to excitation frequency and amplitude in real time. Notably, instructors B and C also used a deductive learning approach by providing the students with background information on response spectra before using the DLMs. All three instructors required the students to participate in a think/pair/share activity before using the DLMs to predict the response patterns, and all three instructors asked students questions before using the DLMs and encouraged the students to ask questions before, during, and after each DLM demonstration.

We conducted post-implementation interviews with all three instructors to gather more information. All three instructors found that students were more actively engaged in the classroom when they used the DLMs (as compared to previous lessons when the instructors covered similar content using a deductive learning approach). In addition, all three instructors agreed that they would use the DLMs again in the future. Finally, using the DLMs sparked the instructors' imaginations for creating other DLMs for use in future course offerings.

After the initial collaboration with instructors A, B, and C, a fourth instructor, Instructor D, used the DLMs in a required upper-level undergraduate course with an enrollment of 110 students. Students rated the effectiveness of the DLMs for understanding the influence of mass and stiffness on structural vibration using a five-anchor Likert scale. The Likert-based assessment garnered 99 student responses (summarized in Figure 7). We note that the student responses demonstrated a slight preference for the effectiveness of the DLMs with respect to changes in mass as compared to stiffness. Although stiffness is a more difficult concept to grasp, it is also possible that using spring length instead of coil diameter to vary stiffness can be confusing, because the tallest spring has the lowest stiffness.

In addition to the Likert assessment, 97 of 99 students responded "Yes" when asked if the DLM demonstration should be adopted in future offerings of Instructor D's course. The two

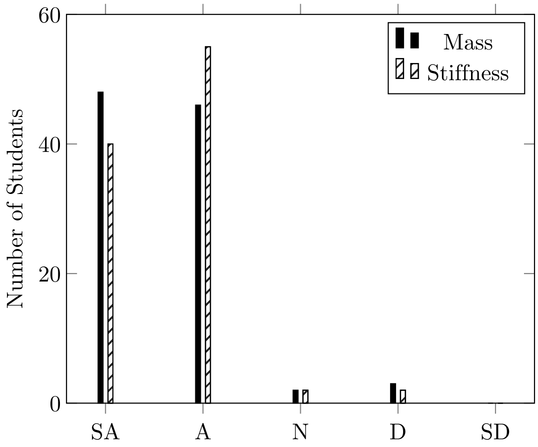


Figure 7. Student Likert assessment responses regarding the DLMs' effectiveness in conveying the influence of mass and stiffness on the vibration of structures. SA = strongly agree, A = agree, N = neutral, D = disagree, SD = strongly disagree.

students who responded “No” did not give written reasons for the DLMs not being used in future course offerings. A vast majority of the students commented that the DLM demonstration was an excellent, hands-on, visual approach for teaching an abstract concept.

CONCLUSIONS

In summary, our opinion is that the inductive learning approach should be the preferred approach for teaching response spectra concepts. In addition to allowing students to observe physical behavior, we believe that the inductive approach helps further students’ understanding of the computational techniques used to develop response spectra. Notably, the inductive learning approach usually requires more preparation for instructors than the deductive learning approach. However, given the importance of response spectra for earthquake engineers, it is our opinion that taking the time to use the inductive learning approach is appropriate. By engaging students with interactive and experiential learning of such a fundamental earthquake engineering concept, we firmly believe that we can motivate talented students to pursue careers in earthquake engineering. Our opinions are well-supported by the engineering education literature; by our informal conversation with earthquake engineering educators across the country; and through our preliminary observations, interviews, and Likert-assessments with four instructors and 99 students at Oregon State University.

We note that many challenges arise with the current DLMs from the realities of physical modeling. As an example, most earthquake engineers construct response spectra by assuming massless springs, which is an experimental impossibility. As another example, most response spectra are developed using horizontal earthquake motions recordings, and the motion of the DLM masses should also be horizontal (i.e., rotation of the masses is not considered). Structural dynamics textbooks (e.g., Clough and Penzien 1975, Humar 2010, Chopra 2011) provide methods to consider the preceding complications, so students can be encouraged to describe the differences between theory and experimental measurements. The challenges allow instructors to discuss differences between theoretically predicted and experimentally measured response spectra as well as to provide context for more complex structural dynamics concepts. Based on the foregoing results and observations, we will proceed with additional DLM design and construction iterations, and we will continue to update the Python scripts and other related materials on our GitHub page.

Finally, following the discussions in the previous paragraph, informal talks with earthquake engineering educators about the topics discussed in this opinion paper were instrumental in formulating our ideas and opinions. We would be grateful to hear from other earthquake engineering educators about teaching response spectra concepts or about using the inductive learning approach. In addition, we fully encourage earthquake engineering educators to use our DLMs (we have purposely chosen low-cost materials and instrumentation to promote adoption by other educators) and to use our GitHub page to contribute and suggest improvements.

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