Hardware Article

Response spectrum devices for active learning in earthquake engineering education

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ABSTRACT

Structural and geotechnical engineers regularly use response spectra to assess the response of civil infrastructure to earthquakes; however, the underlying concepts of response spectra are often difficult for civil engineering students to grasp. Hardware specifications for two low cost response spectrum devices (RSDs) facilitate an inductive approach for teaching response spectrum concepts to students. The RSDs, which consist of wooden masses, compression springs, and accelerometers, can be excited manually or on a portable shake table to show the effects of mass and stiffness on the dynamic response of structures subjected to earthquake ground motion. Auxiliary Python scripts record real time accelerometer data, enabling students to compare the observed RSD response to numerical computations.

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1. Hardware in context

Earthquakes produce horizontal motion in buildings whose mass, although initially resistant to motion, generates lateral forces that the building must resist. Vertically oriented structural members (moment frames, shear walls, or braces) provide stiffness to restrain the building mass from lateral motion during an earthquake. For simplified analysis and design to mitigate seismic effects, structural systems can be idealized as single degree-of-freedom (SDF) oscillators with mass, m, stiffness, k, and natural period of vibration, $T_n = 2\pi\sqrt{m/k}$.

An earthquake response spectrum describes the response of a structural system to an earthquake ground motion. The response spectrum is a fundamental tool in earthquake engineering research and practice [1], because it shows the maximum dynamic response (i.e., displacement, velocity, or acceleration) of an SDF oscillator relative to the earthquake ground motion as a function of the oscillator's natural period, T_n, and damping ratio, ζ. Prior to digital computing, engineers developed response spectra using mechanical pendulums. Response spectra are now developed quickly by repeated numerical solution to the SDF equation of motion for a wide range of natural periods and damping ratios [2]. The construction of an acceleration response spectrum for oscillators with natural period up to 3 s and 2% damping is summarized in Fig. 1 using an earthquake motion recorded during the April 2015 Ghorka, Nepal M7.8 earthquake [3].

Table 1
Specifications table.

| Hardware name	Response Spectrum Desktop Learning Modules
Subject area	Earthquake engineering, Structural engineering, Geotechnical engineering, Mechanical engineering, Physics, Mathematics
Hardware type	Accelerometers, Mechanical oscillators, Structural dynamics, Measuring physical properties
Open source license	GNU General Public License v3.0 (GNU GPLv3)
Cost of hardware	$264.67 (1 x Variable Mass DLM and 1 x Variable Stiffness DLM)
Source file repository	github.com/OSU-Geomatics/OregonState_DLM
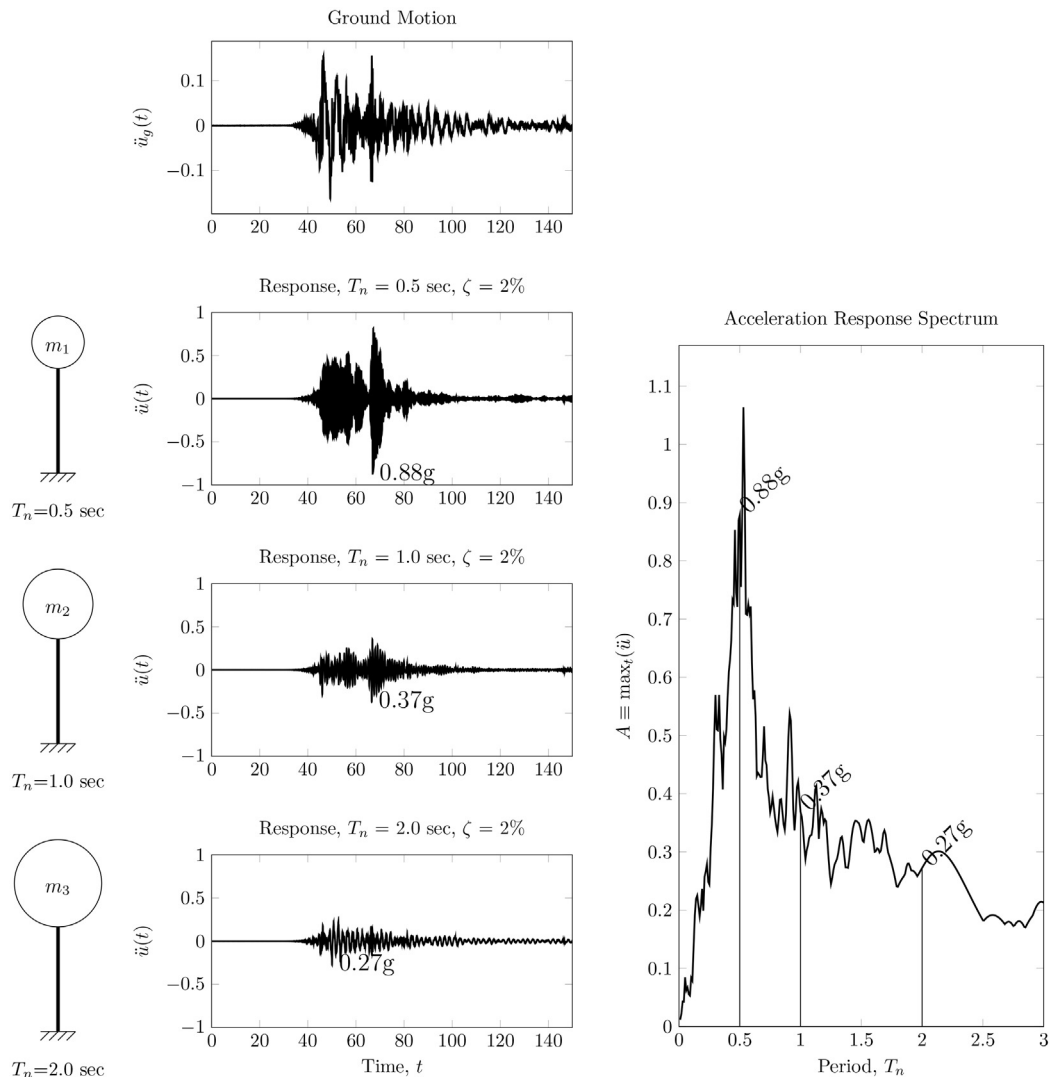
Fig. 1. Construction of acceleration response spectrum for an earthquake ground motion recorded during the April 2015 Gorkha, Nepal M7.8 earthquake. (Figure adapted from Chopra [1].)

Although response spectra are widespread in earthquake engineering, teaching the underlying concepts can be difficult when using a deductive approach. The first step in a deductive approach is to derive the governing equation of motion for an SDF oscillator using Newton's second law of motion or by alternative approaches. Then, students learn how to solve the equation of motion, parametrized by mass, stiffness, and damping, using a numerical methods technique, such as the central difference method or Newmark's method [4]. Finally, students plot numerically-obtained maximum response values against natural period to generate the spectrum. Although students are able to produce response spectra, they often lose perspective on the effects of mass and stiffness on dynamic structural response. The inductive approach, in contrast, allows the students to observe physical behavior first, and then develop theory from the observations.

To facilitate classroom demonstrations of dynamic structural response, proprietary teaching equipment is available from companies such as Pasco and Armfield; however, the availability of reliable, open source, and inexpensive electronic components has put the design and fabrication of structural dynamics modules within reach of the academic community. For example, a set of experimental modules were developed using Arduino-based electronics and deployed as laboratory activities in structural dynamics courses [5]. In addition to exposing civil engineering students to new technologies, the modules help bridge the physical-to-digital gap in civil engineering education.

Adding to the ecosystem of low-cost structural dynamics teaching equipment, Desktop Learning Module Response Spectrum Devices (DLM RSDs, or RSDs), are detailed herein. The RSDs are built from inexpensive mechanical and electronic components and utilize open source software to measure and visualize structural response to various excitations. The RSDs offer an affordable return to inductive approaches for teaching response spectrum concepts in undergraduate and graduate courses in civil engineering, as well as in mechanical engineering, physics, and geology.

2. Hardware description

The RSD shown in Fig. 2 promotes the teaching of response spectra via an inductive learning approach, which has been shown to be effective in engineering education [6]. The schematic in this figure shows four single degree-of-freedom spring-mass systems with varying spring stiffness. Acceleration data is logged to a computer, as described in subsequent sections of this paper. The use of variable spring stiffnesses, as well as a second RSD with variable masses, provides students with perspectives on structural behavior, e.g., how the seismic response of a building changes with respect to changes in mass or stiffness.

Using an inductive approach, students first load the mass-spring systems, then plot acceleration measurements from the RSD, and discuss trends and observations on the effects of mass and stiffness on dynamic structural response. From the measurements and guidance from the faculty member, students develop underlying theory without relying on equations, i.e., the guided inquiry approach. After taking measurements from the RSDs, students then learn the underlying theory and computations for generating response spectra. In the final step, the measurements taken during the RSD demonstration can be plotted directly against the numerically-obtained response spectrum as shown in Fig. 3. The preceding process allows students to further discuss which modeling assumptions contribute to differences between theory and measurements.

The RSDs could be broadly useful to educators and researchers in other disciplines, for instance:

- Physicists and mechanical engineers can explain spring energy;
- Mathematicians can demonstrate applied ordinary differential equations;
- In addition to shake table excitation, civil engineers can apply other excitations; for example, wind loads via a small, portable fan to examine structural response to wind loads; and
- Civil engineers can explain more complicated phenomena, such as base isolation and soil-structure interaction by placing the RSDs on flexible bases.

Additional design and construction details for the RSDs are provided in the following sections.
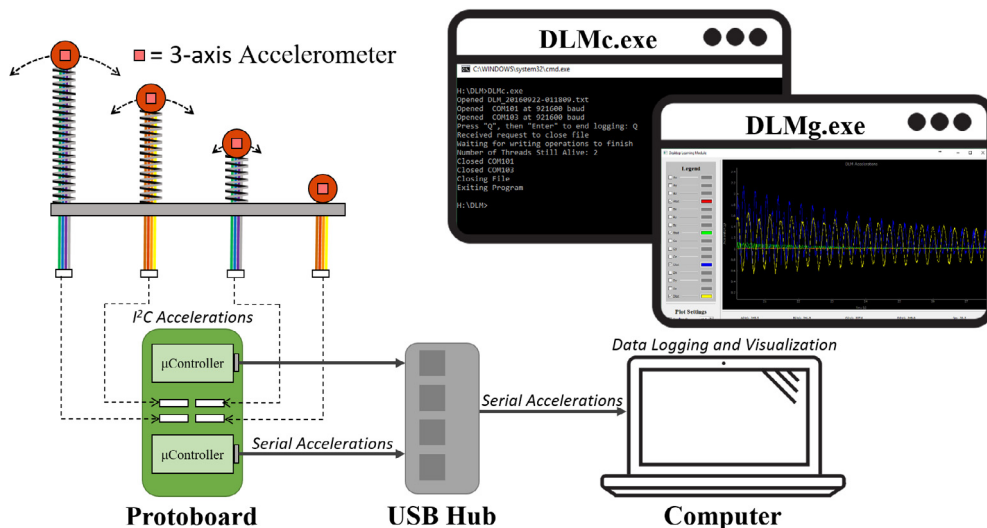

Fig. 2. Data flow for the RSD modules. See Figs. 10 and 11 for larger screenshots of `DLMc.exe` and `DLMg.exe`, respectively.
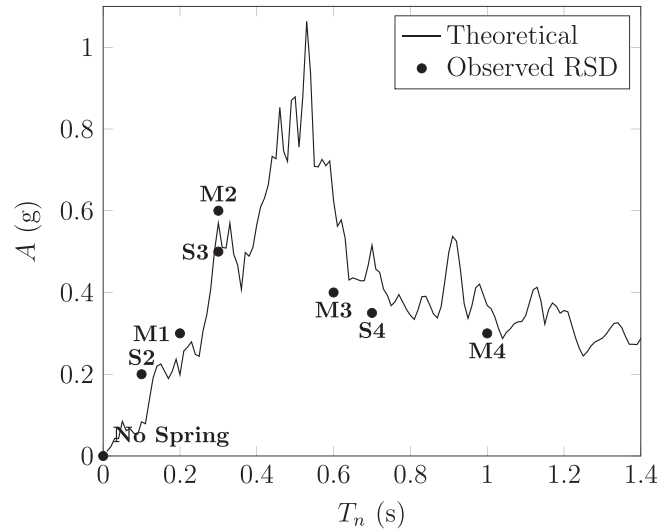
Fig. 3. Comparison of theoretical acceleration response spectrum (2% damping) with observations made from the variable mass (M1–M4) and variable stiffness (S2–S4) RSDs for ground motion recorded during the April 2015 Gorkha, Nepal M7.8 earthquake.

3. Design files

As indicated in Fig. 2, the processing and visualization of the RSD data relies on the communication of serial data to a computer and design files for this communication are listed in Table 2. The protoboard layout and electrical schematic for the RSD electronic hardware components are shown in Figs. 4 and 5, respectively, with parts described in the bill of materials (Table 3). Micro USB cables connect the protoboard to a computer, on which two Python files reside for processing and visualizing the acceleration data. The first Python file, `DLMc.py`, logs RSD data to a text file and the second Python file, `DLMg.py`, provides a GUI for real-time visualization of the RSD data.

4. Bill of materials

The bill of materials for the physical and electronic components of both the variable mass and the variable stiffness RSD is shown in Table 3. All materials are readily available online. A portable shake table is not listed in the bill of materials because it is not necessary for operation and data collection with the RSDs, though suitable table top sized shake tables are available from various companies.

5. Build instructions

This section describes the build instructions for the physical (mass-spring) and electronic systems of the RSDs using the components listed in the Bill of Materials (Table 3).

5.1. Physical components

Several iterations of RSD DLM prototypes were developed with varying masses and spring lengths and coil diameters. The springs were required to be stiff enough to support the weight of each wooden sphere, but slender enough so that their weight is small compared to the weight of each sphere. Fig. 6 shows a sample of the arrangements investigated including various masses and springs of different lengths, coil diameters, pitches, base connection details, and spring spacings. The

Table 2
Design files summary.

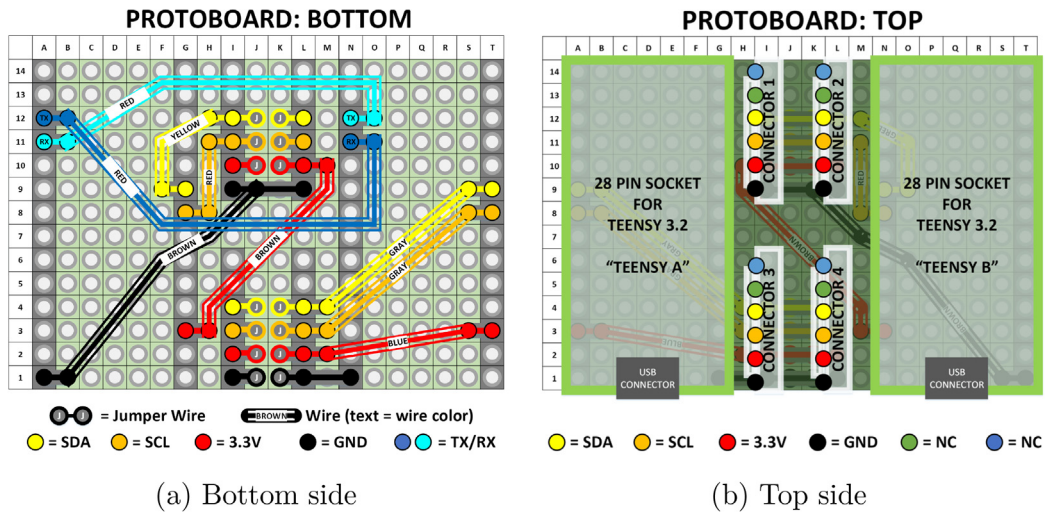| Design file name	File type	Open source license	Location of the file
Protoboard Layout	Figure	GNU GPLv3	Fig. 4 of this article
Electrical Schematic	KiCAD schematic	GNU GPLv3	Fig. 5 of this article
Controller (`DLMc.py`)	Python	GNU GPLv3	github (see Table 1)
GUI (`DLMg.py`)	Python	GNU GPLv3	github (see Table 1)

Fig. 4. Protoboard layout and design for RSD electronics hardware.

samples include undesirable cases of springs that were not able to support their attached spheres in at-rest conditions, either due to the weight of the sphere or the slenderness of the spring.

After the trial iterations, two sets of optimal spring and mass combinations shown in Fig. 7 were determined: one that demonstrates the effect of varying mass (with constant stiffness) and the other that demonstrates the effect of varying stiffness (with constant mass). The variable mass RSD uses four varying masses (M1, M2, M3, and M4) and four 10 cm springs (S1) listed in the Bill of Materials (Table 3); the variable stiffness RSD uses four small masses (M1) and three springs (S2, S3, and S4). Note that one mass on the variable stiffness RSD does not use a spring because its intent is to record the base, or ground, acceleration and also represent the response of very stiff, or rigid, structures.

A design alternative considered for the variable mass RSD was to use spheres of constant diameter but with materials of increasing density, e.g., styrofoam, wood, and metal. This approach, however, was found to make fabrication more difficult compared to the chosen design based on wooden spheres of increasing diameters.

For the variable stiffness RSD, an alternative was to use springs of the same length but with variable coil diameters. Although the variable diameter approach can increase student understanding of the effect of using stiffer members in seismic structural design [7], controlling the stiffness by spring length led to a better separation of natural frequencies among the masses and also demonstrated the response of taller, more flexible buildings during an earthquake.

With spring lengths and wooden masses selected, each mass was glued to one end of its accompanying spring. Then, the other end of each spring was attached to a base. Details of the base construction are omitted; however, the RSDs shown in the images of this paper are welded to a 30 inch by 2.5 inch, 1/16 inch thick metal plate that is mechanically fastened (at its ends and center) to a 3/4 inch thick piece of wood of slightly larger plan. The 30 inch length of the base plate gives sufficient space for the mass-spring systems to oscillate without colliding. Alternative base designs are possible, but do not affect the design of physical or electronic components of the RSDs. Prior to assembly, the physical components of the RSDs were finished with black and orange spray paint.

For simplicity and to reduce expense, we used epoxy to connect the springs to the base in initial iterations. However, after we observed the fracture shown in Fig. 8, we welded the springs to the aluminum plate in subsequent designs, which led to a stronger connection between the springs and the base. After switching to welds, no fractures have been observed.

5.2. Electronic components

The following steps apply to both the variable mass and the variable stiffness RSD.

1. Cut two 24 inch segments of ribbon cable (RC), then split each segment into two four wire segments, e.g., a brown-red-orange-yellow segment and a green-blue-purple-grey segment. This gives four 24 inch lengths of four wire cables.
2. Solder one end of each four wire cable to an accelerometer (AC).
3. Glue one accelerometer to the side of each mass. Make sure the accelerometers are oriented within a vertical plane.
4. To keep the wires tidy and to reduce the possibility that the wires would induce a pulling force on the masses, run the free end of each wire through the spring coil to the spring base, then pull the wire out from the base (n.b., this step is optional).
5. For each cable, connect the four wires to a jumper wire assembly (JW).
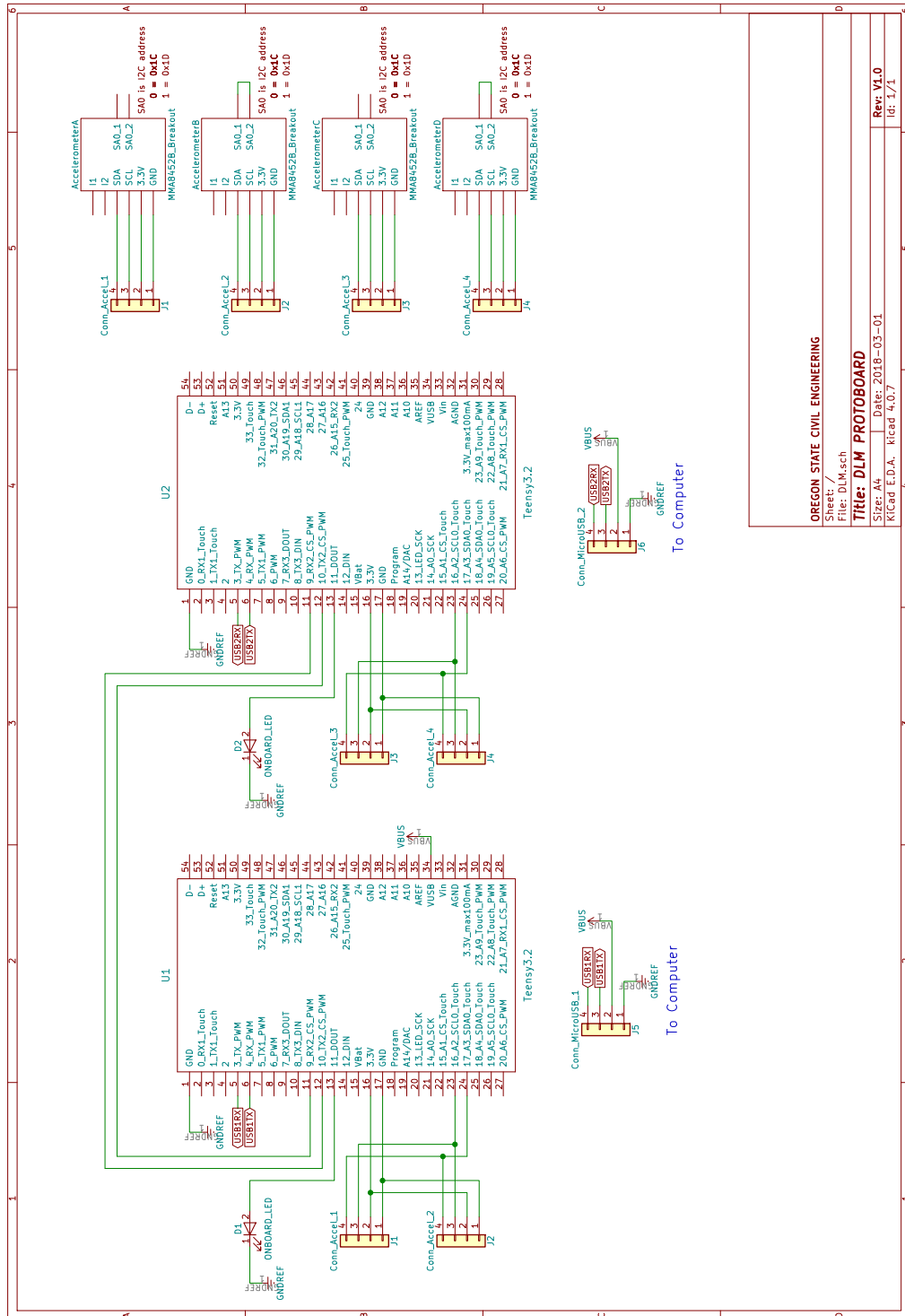
Fig. 5. KiCAD electrical schematic for the RSD electronics. This schematic is available as a higher resolution PDF on github (see Table 1).

The foregoing steps are one-time build instructions. For day-to-day use, the jumper wires (JW) connect to a protoboard built according to the design shown in Fig. 4. Two micro USB cables (MU) connect the protoboard to a 4 port USB hub (UH), which is in turn connected to a computer to record and visualize RSD data using the software described in the following section. A fully instrumented variable stiffness RSD is shown in Fig. 9.

Table 3

Bill of Materials for variable mass and variable stiffness RSDs. Prices are current as of February 1, 2018 and no commercial endorsement is implied by the authors.

| Designator	Component	Number	Unit cost ($)	Total cost ($)	Source of materials	Material type
M1	Small mass (3.1 cm diam.)	5	0.52	2.60	McMaster-Carr #9941K21	Birch Wood
M2	Medium mass (5.08 cm diam.)	1	3.50	3.50	McMaster-Carr #9941K27	Birch Wood
M3	Large mass (6.35 cm diam.)	1	5.30	5.30	McMaster-Carr #9941K31	Birch Wood
M4	XLarge mass (7.62 cm diam.)	1	7.85	7.85	McMaster-Carr #9941K33	Birch Wood
S1	Spring (2.22 cm o.d., 10 cm length)	4	0.51	2.04	McMaster-Carr #9662K31	Metal
S2	Spring (2.22 cm o.d., 7 cm length)	1	0.36	0.36	McMaster-Carr #9662K31	Metal
S3	Spring (2.22 cm o.d., 15 cm length)	1	0.77	0.77	McMaster-Carr #9662K31	Metal
S4	Spring (2.22 cm o.d., 23 cm length)	1	1.18	1.18	McMaster-Carr #9662K31	Metal
AC	Triple axis accelerometer MMA8452Q	8	9.95	79.60	Sparkfun #12756	Electronic
MC	Teensy 3.2 Microcontroller	4	19.95	79.80	Sparkfun #13736	Electronic
MU	Micro USB cable (6 ft)	4	4.95	19.80	Sparkfun #10215	Electronic
RC	Ribbon cable (10 wire, 15 ft)	1	4.95	4.95	Sparkfun #10647	Electronic
UH	USB hub (4 port)	2	6.99	13.98	Amazon, Sabrent HB-UMLS	Electronic
PB	Protoboard (4x6 cm, 10 pack)	1	3.95	3.95	Amazon, Vktech #53568	Electronic
IC	IC socket (28 pin, 3 pack)	2	1.25	2.50	Adafruit #2206	Electronic
JW	Jumper 6 wire assembly	8	1.95	15.60	Sparkfun #09922	Electronic
HS	1/16" heat shrink 3:1 (10 ft)	1	6.99	6.99	Amazon, Electriduct	Electronic
JK	Jumper wire kit	2	6.95	13.90	Sparkfun #00124	Electronic
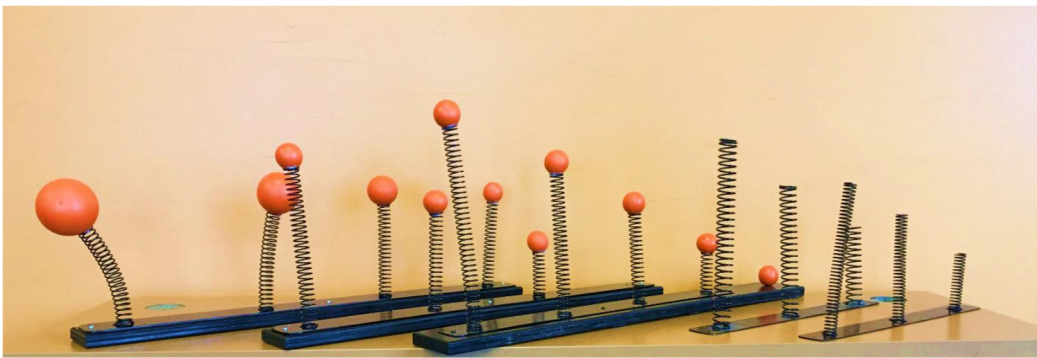
Fig. 6. Various spring and mass trial combinations investigated to determine the finalized RSD configurations.
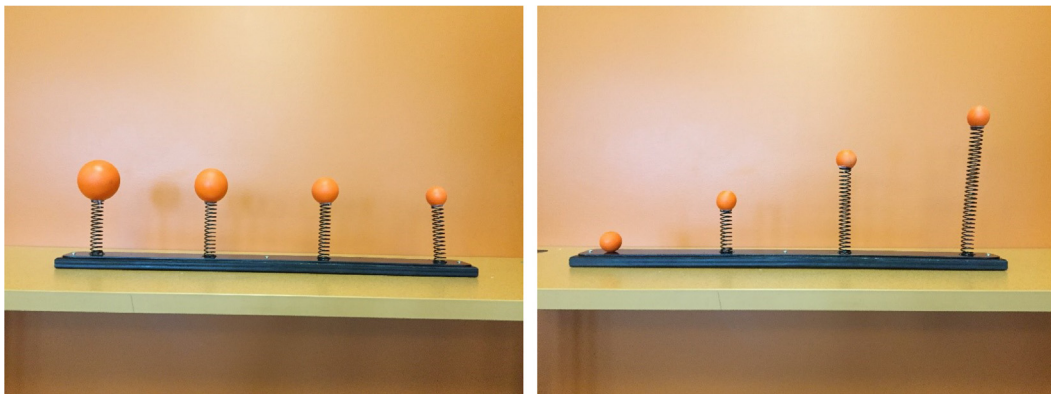
(a) Variable mass RSD

(b) Variable stiffness RSD

Fig. 7. Finalized spring and mass combinations for RSDs (without instrumentation). The model on the left demonstrates the effect of varying structural mass and on the right the effect of varying structural stiffness.

6. Operation instructions

The following steps describe how to use the DLMs with a Windows computer and how to install the supporting software.
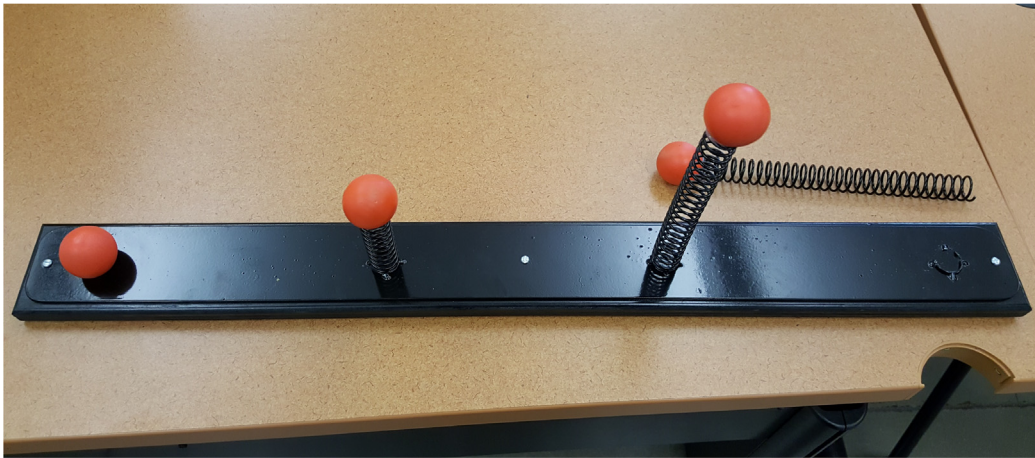
Fig. 8. Fracture of one spring-mass oscillator from the RSD base.
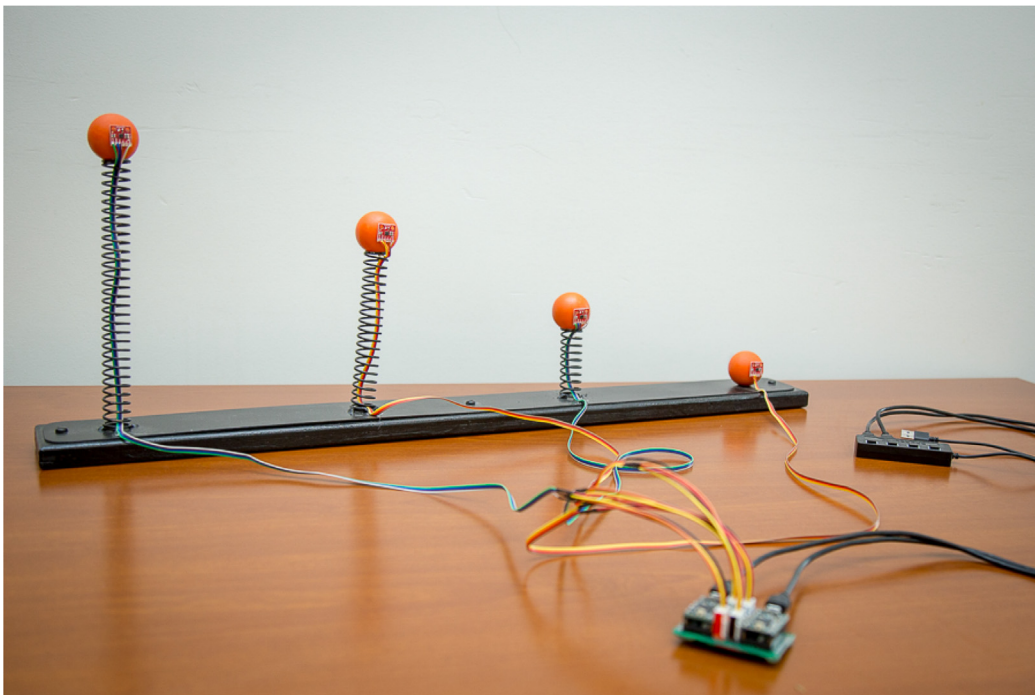

Fig. 9. Instrumented variable stiffness RSD.

1. *Tell Windows how to detect the RSD*
   For Windows to detect the microcontrollers as COM ports, `serial_install.exe` must be run with system administrative privileges. The executable can be downloaded from `https://www.pjrc.com/teensy/td_download.html`.
   Note that this step only needs to be done once on a computer, and does not need to be run with new releases of the RSD software.
2. *Download the latest software release*
   The latest version of the software is available here.
   `https://github.com/OSU-Geomatics/OregonState_DLM/releases`
   Two software executables are available:
   - `DLMc.exe` – a command line tool to log data to a text file
   - `DLMg.exe` – a GUI to visualize and log data to a text file

Download the desired executable to your local machine. The executables do not rely on each other and they can be run independently. The executables are compiled on a Windows machine using `pyinstaller`, which is compatible with Linux and Mac OS for generating hardware specific versions.

3. *Plug in all DLM connections except for those to the computer*
   - Plug the USB cables into the Microcontroller Micro-USB ports
   - Plug the USB cable into the USB hub
   - Plug the accelerometer connectors into the protoboard by matching the connector colors
4. *Plug the USB hub into the computer*
   The USB hub has "power" buttons for each available USB switch. Ensure that the corresponding two power switches are powered on as shown by the LEDs. The computer will display pop-ups on the taskbar saying that Windows is installing drivers. Continue after the installation is complete.
5. *Cycle power to both the USB ports*
   To cycle power to the USB ports, press the two power buttons that correspond to the USB ports connected to the protoboard on and off. Importantly, both microcontrollers must receive power at the same time to perform an initial "time synchronization".
6. *Wait 5 s*
   Wait until one microcontroller has a solid orange light, and the other has no orange light, which indicates that the microcontrollers are completing their time synchronization and are not detectable via the COM ports.
7. *Run DLMg or DLMc executables*
   Each executable is programmed to automatically detect the stream of data from the COM ports and will print a message showing the status of the detection.

After following these steps, the RSD masses can be excited manually into free vibration either by pulling a mass to an initial displacement then releasing it or by tapping a mass with a hammer to impose an initial velocity. In addition, the masses can be excited by attaching the RSD to a portable shake table and entering a pre-programmed time series of ground motion.

6.1. Important points

- A "reset" button is located on top of each microcontroller. Avoid pressing the reset button, because it will nullify the microcontroller synchronization.
- Each microcontroller must be powered on at the same time. A power reset, via the buttons on the USB hub, may be necessary if the microcontrollers are unable to synchronize. Disconnecting the USB from the computer will also force a power reset.
- If `serial_installer.exe` has not been run, the COM ports will not be detected and you cannot acquire data from the sensors.
- The accelerometers are programmed to a sampling frequency of 400 Hz with range ± 8 g; however, they can be programmed in the Arduino code to sample between 1.56 and 800 Hz with range ± 2 g, ± 4 g, or ± 8 g.

6.2. How to run DLMc

The `DLMc.exe` executable is a command line tool that logs RSD data to a text file whose name is based on the current computer time as shown in Fig. 10. The `DLMc.exe` executable can be started by double-clicking its Windows icon or from the command line.

Fig. 10. Operation of the DLMc executable from the command line.

An optional command line argument can be specified for the name of the file to which RSD data will be logged, e.g.,

>DLMc.exe myData.txt

Logging can be stopped by pressing Q, then <Enter> at the command line.

6.3. How to run DLMg

The DLMg.exe executable is a Python-based GUI for visualizing RSD data in real time. It can be started by double-clicking its Windows icon or from the command line, and it will launch the GUI shown in Fig. 11. The GUI shows the current RSD status, plot settings, and data display legend. Three orthogonal acceleration components, e.g., A_x, A_y, and A_z for mass A, as well as their vector magnitude, can be reported for each of the four RSD masses.

To start and stop data collection, use the Restart and Stop buttons, respectively. To save RSD data, check the File Name box and navigate to a valid text file, or leave the box unchecked to not save data. Note that all data, including that not selected for plotting, will be saved to the specified text file.

7. Validation and characterization

The RSDs were used in four classroom settings in the School of Civil and Construction Engineering at Oregon State University during the 2016–17 academic year. Two of the demonstrations are shown in Fig. 12. Additional details on the classroom activities along with instructor and student feedback can be found in [8,9,7]. The following key points arise from the preceding studies:

- Qualitative data produced and analyzed from four in-person interviews with instructors who used the RSDs indicated that all the instructors enjoyed using the RSDs and intend to use them in the future.
- Classroom observations revealed that the instructors prepared unique inductive learning activities around the RSDs, indicating that the devices can be utilized in a wide variety of civil engineering courses on structural and geotechnical engineering.
- Survey results of 100 students who observed lectures with the RSDs either agreed or strongly agreed that the RSD activities were beneficial to their learning of dynamic structural response.

Under normal operation, the RSDs can enter the resonance condition over a harmonic excitation frequency range of up to 10 Hz, which is easily attainable on a portable, instructional shake table. Based on free vibration tests, the natural frequencies for the variable stiffness RSD are approximately 1.4, 3.3, and 10 Hz for springs S4, S3, and S2, respectively; and 1.0, 1.8, 3.3,
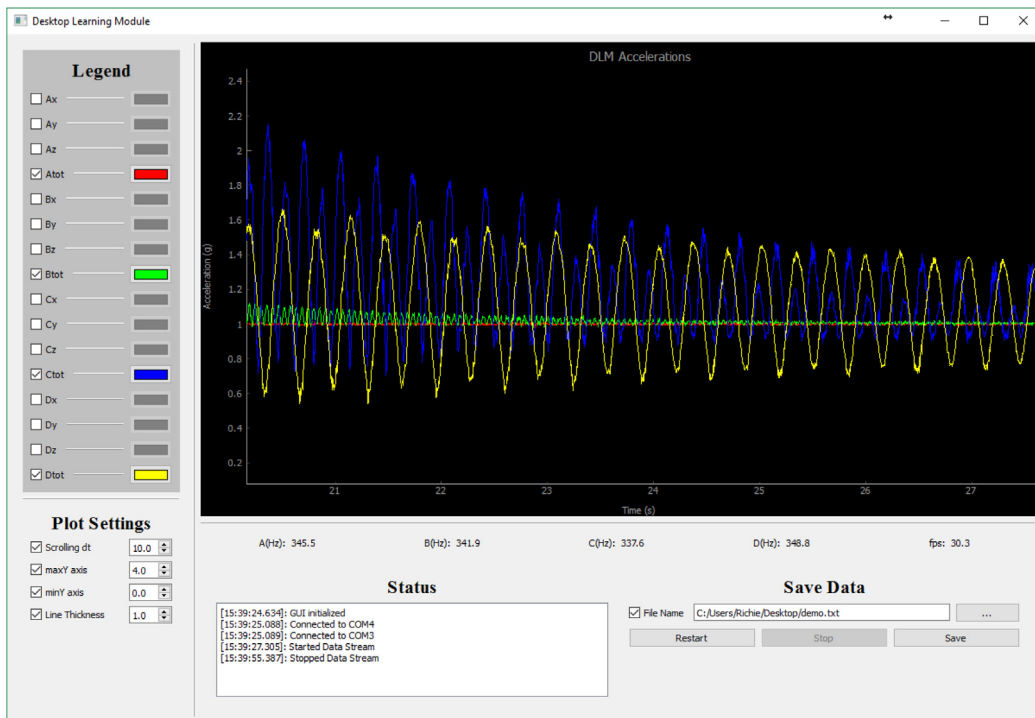

Fig. 11. Graphical user interface available using the DLMg executable.

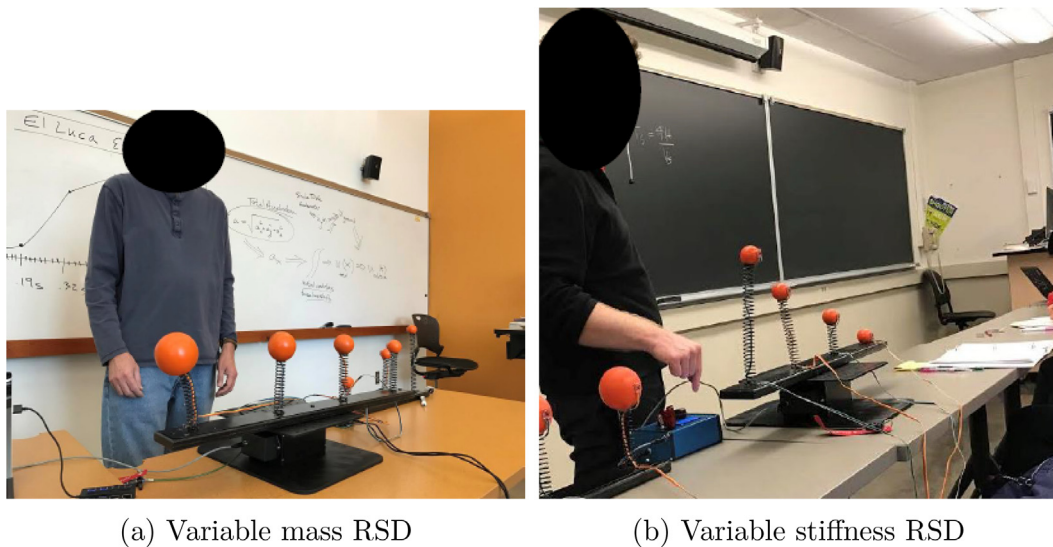(a) Variable mass RSD   (b) Variable stiffness RSD

Fig. 12. In-class demonstrations of dynamic structural response using RSDs on a portable shake table.

and 5.0 Hz for masses M4, M3, M2, and M1, respectively, of the variable mass RSD. Using logarithmic decay measurements [10,1], damping for each spring-mass system was found to lie in the range of 0.5–1.5% of critical damping. Due to inherent variability, particularly for the connection details of the springs to the base, the natural frequency and damping ratio for newly constructed RSDs, even those with the same specifications listed in Table 3, should be determined using similar procedures.

In addition to the foregoing natural frequency and damping characteristics, the capabilities and limitations of the RSD hardware and accompanying software are as follows:

- The wooden masses are unconstrained, which can lead to multi-directional motion of the mass-spring systems under uni-directional excitation.
- The DLMc and DLMg executables record only time series of acceleration. Velocity and displacement-time series can be computed from the time series of acceleration using numerical integration, and baseline correction and bandpass filtering can be used to mitigate the numerical propagation of accelerometer bias and noise. The manufacturer's specification for the accelerometer noise is 99 μg/$\sqrt{\text{Hz}}$.
- Simple trial and error may be required to determine which RSD mass is displayed as A, B, C, and D in the DLMg GUI and also to determine which physical direction corresponds to the x, y, and z display components (Fig. 11).
- The use of Python to record RSD response opens up linkages with structural dynamics finite element software such as OpenSees [11] for direct, real-time comparisons of the dynamic response of experimental and analytical models of structural systems.

Further details on the design and operation of the RSDs are found at the project's github page (github.com/OSU-Geomat ics/OregonState_DLM).

Conflict of interest

No conflict of interest.

Acknowledgments

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ohx.2018.e00032.

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