

# 1            **Designing Experiments using Digital Fabrication in Structural Dynamics**

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## 8 9    **Abstract**

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11  
12    *In engineering, traditional approaches aimed at teaching concepts of dynamics to engineering*  
13    *students include the study of a dense yet sequential theoretical development of proofs and*  
14    *exercises. Seldom, structural dynamics are taught experimentally in laboratories since these*  
15    *facilities should be provided with expensive equipment such as wave generators, data-acquisition*  
16    *systems and heavily wired deployments with sensors. In this paper, the design of an experimental*  
17    *experience in the classroom based upon digital fabrication and modeling tools related to*  
18    *structural dynamics is presented. In particular, all experimental deployments are conceived with*  
19    *low-cost, open source equipment. Hardware includes Arduino-based open-source electronics*  
20    *whereas Software is based upon object-oriented open-source codes for the development of*  
21    *physical simulations. The set of experiments as well as the physical simulations are reproducible*  
22    *and scalable in classroom-based environments.*

## 23 24    **Introduction**

25  
26    For engineers of various areas, the study of vibrations and dynamics is an important cornerstone.  
27    In the particular case of civil and structural engineering, the vibration of beams and frames  
28    represent one of the first topics to be discussed in traditional courses of structural dynamics.  
29    Generally, these students have taken introductory and/or advanced courses of statics at this point

30 of their curricula. Both dynamics and statics erect the frame of the vast field labeled in civil  
31 engineering as structural analysis. In dynamics, basic concepts such as damping, frequency,  
32 resonance or isolation are of an utmost importance when understanding more complex  
33 phenomena related to single- or multi-degree of freedom systems. Classic textbooks such as  
34 (Chopra 2007; Clough and Penzien 2003; Paz and Leigh 2003) provide detailed information about  
35 the basics, the development of the formulae as well as the application of such concepts in seismic  
36 and structural engineering.

37

38 Moreover, open electronics have become considerably popular among entrepreneurs, designers,  
39 computer scientists, hobbyists and more recently, engineering educators. A vast array of low-cost,  
40 open source microcontroller platforms such as (Arduino 2016, Raspberry Pi 2016 and Adafruit  
41 2016) are nowadays commercially available and economically more affordable than professional  
42 equipment. These platforms, together with easy-to-use programming codes, allow bridging the  
43 existing physical-to-digital gap in civil engineering students. Simultaneously, it provides a low-  
44 cost source of creative technologies that may potentially be implemented in different educational  
45 ecosystems. Sensors and actuators of various sources can be coupled and controlled via i) open  
46 platforms ii) free and/or commercial Software iii) open platforms aimed at developing mobile  
47 applications. Active online communities are nowadays feeding the web with endless possibilities  
48 related to coding, electronics and physical applications of such technologies. Together with  
49 additive 3D printing and subtractive laser-cutting, digital fabrication and modeling (DFM) is  
50 continuously entering into schools and universities as an important part of the curricula.

51

52 The aim of this paper is to present the design of a hands-on set of experiments related to structural  
53 dynamics. Teaching includes an initial understanding of DFM tools and the reproduction of a set  
54 of experiments related to structural dynamics developed with open-source Hardware and  
55 Software. The aim of the experimental experience is to provide to students tools related not only  
56 to structural dynamics but also, to creative DFM technologies. Particular goals of the proposal  
57 include:

58

- 59 • Providing a theoretical framework related to structural dynamics, including concepts of  
60 frequency, period, damping, resonance and the equations of motion.
- 61 • Providing concepts of the open prototyping platform Arduino and its circuitry.
- 62 • Providing an introduction to object-oriented physical simulations of dynamic systems  
63 using Processing 2.0 (Processing 2016), an open-source language and development  
64 environment built on top of the Java programming language.
- 65 • Providing initial computational tools for using Arduino and Processing as an open-  
66 source, low-cost data acquisition system that may be used in the classroom with scale-  
67 reduced experiments. Beams, frames and other structures may be excited dynamically  
68 and studied experimentally and numerically within the classroom.

69

## 70 **Review of the earlier work.**

71

### 72 *Structural dynamics and education*

73

74 The importance of structural dynamics gives the topic a major position in civil,  
75 mechanical and geological engineering. Classic textbooks with a vast array of  
76 exercises are available (Chopra 2007; Clough and Penzien 2003; Paz and Leigh 2003).  
77 Experimental dynamics in the particular case of beams also play a continuous primary  
78 role in textbooks (Blanco et al. 2007) and state-of-the-art research (Chen et al. 2014;  
79 Ozelik et al. 2013; Adhikari et al. 2009). From an educational perspective, pedagogic  
80 platforms related to structural dynamics are not infrequent. Most of them are, however,  
81 based upon numerical simulations in desktop computers. Katsanos et al. (2014)  
82 developed educational computational tools for the seismic analysis of reinforced concrete.  
83 The platform was developed with Matlab (Matlab 2016) and accounts not only for the  
84 building structural dynamics but also, for the soil-structure interaction. With the aim of  
85 providing an educational learning environment for applications in dynamics, Elgamal et

86 al. (2005) built shake-table tests involving web-based educational platforms and a vast  
87 number of exercises. The platform has been used in several universities in California and  
88 includes Hardware developed by the authors as well as visual tools developed with  
89 commercial Software Labview (2016). Senatore and Pikers (2015) developed an  
90 intuitive game-like platform for the understanding of structural analysis via 3D, FE-  
91 based models.

92

### 93 *Use of open electronics and programming in engineering education*

94

95 Experimental experiences have always been a cornerstone in civil engineering education  
96 (Solís et al. 2012; Chanson 2004; Unterweger 2005; Nakazawa 2014). The vast majority  
97 of civil engineering schools include classic experimental-based courses related to  
98 structures, materials, hydraulics, soils, and pavement engineering, among other subjects.  
99 However, educational tests in classic laboratories involve either expensive data-  
100 acquisition equipment that is seldom used by students in a "hands-on" mode or, more  
101 often, involve no equipment at all. Classic laboratories are generally conceived for small  
102 audiences. For large courses, measurements and control are usually performed by  
103 laboratory staff that provides raw data to students for further analysis. This is particularly  
104 common in large universities with a considerable amount of students or in countries in  
105 which laboratories are not equipped with sufficient material for both research and  
106 education. In particular, in civil engineering, at the end of their degrees, even if students  
107 are satisfactorily acquainted with the physical phenomena, a basic understanding of the  
108 electronics involved in measurement and data-acquisition is less frequent among them.  
109 These facts do not contribute to bridging the existing physical-to-digital gap among  
110 engineering students that is absolutely necessary to overcome in the digital society. With  
111 the advent of open platforms, students of other branches of engineering such as robotics  
112 (Valera et al. 2014), control engineering (Ionescu et al. 2013), real-time systems (Cruz-  
113 Martín et al. 2012) or chemistry (Guo et al. 2007) are increasingly acquainted with data-

114 acquisition either with professional equipment or, via Do-it-Yourself (DIY) Hardware  
115 and Software. The convergence of 3D printing, open Hardware and open Software may  
116 revolutionize the educational experimental training nowadays provided in high schools  
117 as well as in technical universities (Pearce 2014). A deeper understanding of such  
118 possibilities may also help fostering entrepreneurial, innovative skills in civil engineering  
119 students in societies with no industrial manufacturing infrastructure (Fox 2014).

120

121 Examples of usage of open-source boards in engineering applications are not infrequent,  
122 particularly when coupled with wireless applications (Ferdoush and Li 2014). Control of  
123 experiments using Arduino boards and open source programming languages such  
124 as Python (2016) are available in platforms intended for physical and chemical  
125 experiments (Koenka et al. 2014) in a broader sense. In addition, open online  
126 communities and generators of content provide a vast array of blogs, web-based lectures  
127 and exercises to broader audiences (Shiffman 2016; MIT video website 2016; Coursera  
128 2016).

129

130 Nevertheless, academic examples of applications of digital fabrication and open  
131 platforms in the particular case of civil engineering education are less abundant. Kensek  
132 (2014) explored the integration of sensors (providing analogic signals) with the digital  
133 control of architectural Software (based upon Building Information Modeling BIM) and  
134 viceversa using Arduino boards. This represents an example of the potential manipulation  
135 of physical architectural features of buildings (facades, windows, or similar) via  
136 Software-controlled tools. All these examples were designed and implemented in  
137 laboratories with students. Kensek demonstrates the back-and-forth nature of bridging the  
138 physical-to-digital gap using Arduino open platforms and the endless possibilities with  
139 the integration of BIM.

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**Software and Hardware**

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144  
145 Processing and Arduino were chosen as the Software and Hardware combinations for the  
146 development of the educational experience due to availability at the school and the open-source  
147 nature of both. In addition, the Integrated Development Environment (IDE) of both platforms is  
148 very similar. Figure 1 shows both IDEs as well as a scheme of the coding syntaxes. Both cases  
149 include a *setup()* function (run once) and a *draw()* or *loop()* function, which runs repeatedly. For  
150 the case of Processing (Fig. 1(a)), the draw function allows developing computer simulations  
151 involving movement of objects. In the case of Arduino (Fig. 2(b)), the loop function defines all  
152 orders to be performed by the electrical flow designed with the corresponding circuitry.

153

#### 154 *Processing*

155

156 Processing is an open-source language and development environment built on top of the  
157 Java programming language. It allows generating computer simulations and visual  
158 graphics from scratch (Reas and Fry 2014). In this context, Processing is used for  
159 developing object-oriented physics simulations. For this purpose, it is vital to get an initial  
160 understanding of motion in simple computational visual graphics.

161

162 One of the most efficient ways of developing simulations of motion of bodies according  
163 to physical laws is the use of an object-oriented approach. Classes that depict the behavior  
164 of objects such as balls, springs or rigid bodies may be defined separately. In the main  
165 code, new objects can be called and used by applying methods defined in the classes.  
166 Processing includes widely depicted in-built classes defining the behavior of vectors or  
167 images (PVector, PImage). The result is a simpler *setup()*-*draw()* code.

#### 168 *The Arduino board*

169

170 Arduino is an open hardware-prototyping platform. Fig. 2 displays a sketch of the  
171 Arduino/Genuino UNO board, which may be deemed as the simplest kind of the Arduino

172 products. A set of up to 6 analog and 13 digital pins are available in this board. Connection  
173 to computers is performed via USB (for uploading programs or providing power) and an  
174 alternative power supply connection (batteries or similar) may also be used in boards in  
175 which programs are already uploaded. The board is open and any program following the  
176 Arduino syntax can be uploaded and erased as needed. The board can be programmed to  
177 sense the environment by receiving analog inputs from many sensors, and/or to affect its  
178 surroundings by controlling lights, motors, and other actuators or digital devices.

179

180 The typical structure of Arduino programs is fairly simple can be divided in three main  
181 parts: structure, values (variables and constants), and functions. These functions require  
182 at least two parts, or blocks of statements. The *setup()* function is called when a sketch  
183 starts. It is used to initialize variables, pin modes, start using libraries, etc. The setup  
184 function will only run once, after each power up or reset of the Arduino board. After  
185 creating a *setup()* function, the *loop()* function which is repeated consecutively.  
186 Programming with the Arduino environment provides capabilities related to the Serial  
187 Port Communication, which allows user acquiring analog signals from sensors and  
188 microcontrollers to be sent to the computer (to be used in any application able to open  
189 that port reciprocally)

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#### 194 **Class Methodology**

195

196 For educational purposes, experimental tests with enriched content related to digital fabrication  
197 are conceived. This experience represents a part of a vaster course on structural dynamics  
198 including theoretical background and exercises presented in a classic fashion. The entire course

199 consists of 15 sessions of 4 hours each (60 in total) and the experiments accounts for  
200 approximately a third (18 hours). The educational experience is conceived as hands-on with the  
201 use of computers, electronics and physical construction of 3D models. Lessons are separated in  
202 three main parts:

203

204 • Processing (6 hours). Introduction to OOVF with vectors and trigonometry and  
205 subsequently, simulation of two well-known dynamic systems, the pendulum and the  
206 spring.

207 • Arduino (6 hours). Introduction to Arduino circuitry by learning the basics, which include  
208 the control of a LED blink, introduction to sensing with Light Dependent Resistor LDR.  
209 Usage of the serial port to visualize analog magnitudes and the control of small motors  
210 and servos. Subsequently, design of two tests in simple cantilever beams.

211 • Scale reduced construction + Processing + Arduino (6 hours). Construction of a 3D frame  
212 in a hands-on experience. The frames are subsequently tested with a modal exciter and  
213 instrumented with Arduino. The obtained results are used and visualized. A comparison  
214 with theoretical analysis of n-degrees of freedom planar systems is performed for the sake  
215 of validation.

216

217 Table 1 displays the organization and schedule of the classroom as well as the educational  
218 activities that are suggested for the development of each part. From table 1 it is worth noticing:

219

220 • Master classes (Intro and Core) are given by the facilitator with a hands-on perspective  
221 for the first and second part. The students use desktop computers and electronic  
222 equipment in groups or individually. The third part is entirely driven by students as the  
223 constructors of 3D models.

224 • Homework (compulsory submission) are aimed at developing physical simulations or at  
225 analyzing physical results obtained in real models.



226 • Bonus (not compulsory) is a gamified feature of the experience, as an additional  
227 submission of creative projects. These creative projects may be also rewarded by  
228 featuring the results in social networks or in school days.

229

230 Finally, it is important to bear in mind that these 18 hours are part of a vaster course (60 hours in  
231 total) in which traditional lectures and evaluations are performed.

232

233 In the following, details concerning each part of the designed class classroom are provided.

234

235 *Physical simulations. Pendulum and Spring.*

236

237 First, a 2-hour long introduction related to motion, vectors, location, velocity and  
238 acceleration is presented. This part is needed for the sake of developing an  
239 interactive trial-and-error coding strategy with immediate feedback of results  
240 with the students. The mathematics related to all the depicted aspects are  
241 customized by students from scratch. The location of an object (rectangle, circle,  
242 pixel) is expressed in terms of its planar coordinates, time and its velocity. The  
243 velocity of such object is expressed in terms of the acceleration (two-dimensions).  
244 Similarly, the angular position, velocity and acceleration of a given object define  
245 the rotation in time.

246

247 After all initial information related to vectors and to trigonometry is depicted  
248 with the corresponding motion equations, the main core of this part is the  
249 development of two different dynamic systems: A pendulum and a spring.

250

251 For the former, the students need to use basic concepts related to vectors and  
252 trigonometry for the development of a simple yet realistic physical simulation of  
253 a moving object whose position is repeatedly updated. At each frame, forces are

254 applied to the object (self-weight, damping and anchor) and thus, acceleration,  
255 velocity and location of the object are updated. Figure 3 displays the result  
256 obtained by students in the Processing canvas as well as a scheme of the applied  
257 forces.

258

259 For the latter, the students need to use concepts related to Hooke's law for the  
260 development of a simple yet realistic physical simulation of a moving spring  
261 whose position is repeatedly updated. At each frame, the self-weight and the  
262 spring force are applied to the object and thus, acceleration, velocity and location  
263 of the object are updated. Figure 4 displays the result obtained by students in the  
264 Processing canvas as well as a scheme of the applied forces.

265

266

267 Mastering such simulations is cornerstone for the students from two perspectives:

268

269 • The students are required to submit a compulsory homework in which a more  
270 sophisticated simulation is assigned. Beams, Frames or multi-springs systems are  
271 visually simulated (all systems with a single degree of freedom).

272

273 • The students get acquainted with the object-oriented syntaxes of Processing, which  
274 is similar and subsequently, easier to follow in Arduino IDE.

275

276

277

278 *Physical experiments. Free vibrations and harmonic oscillations*

279

280 First, a 2-hour long introduction related to basic electronics is presented. The students are  
281 provided with kits containing the following equipment:

282

283 • Arduino UNO board with USB cable

284 • Light dependent resistors (LDR)

285 • A potentiometer

286 • Buttons

287 • A breadboard

288 • A 3-axis accelerometer

289 • A small 9V motor and a servomotor

290 • 330 $\Omega$ , 1k  $\Omega$  and 10k  $\Omega$  resistor, a Mosfet transistor and cables.

291

292 The intro is conceived as a trial-and-error hands-on experience of the students developing  
293 basic circuitries and codes. The main idea is to provide tools and exercises that allow  
294 students answering the following questions:

295

296 • How to obtain an analog magnitude from an accelerometer using an Arduino Board  
297 and plotting the results in a Desktop/Laptop computer?

298 • How to visualize acceleration values from an excited system in real time?

299 • How to control a 5V motor with an Arduino Board by using controllers such as  
300 buttons and potentiometers?

301

302 The core of this part is the design of two experiments: i) Free vibrations and ii) harmonic  
303 excitations in structural systems. Both experiments are performed in a cantilever steel  
304 beam of varying length and rectangular cross-section 20mmx4mm. The steel plate is  
305 connected to a rigid table with adjustable clamping devices. Thus, students can  
306 manipulate the steel plate and adjust its length. In both experiments, a three-axis  
307 accelerometer is connected to an Arduino board. In experiment 1 (free vibrations, Fig. 5),  
308 an initial displacement  $u_0$  is applied in the tip of the cantilever. The system vibrates freely

309 for several seconds. In experiment 2 (Fig. 6), an Arduino-controlled eccentric rotor  
310 excites the system in a harmonic way. The speed of the motor is controlled with buttons  
311 and a potentiometer. Finally, schemes of the circuitries that are used for acquiring values  
312 of acceleration (Fig. 7(a)) and for controlling an actuator (a small motor) are provided  
313 (Fig. 7(b))

### 314 *Hands-on construction and instrumentation of 3D frames.*

316  
317 The educational experience includes the construction of 3D frames using steel bars,  
318 plastic bars (polyamide), methacrylate plates for slabs, bolts and nuts and a rigid plate for  
319 the base. These elements offer versatility. Additional masses and varied geometry (height  
320 and number of stories) can be achieved by students. The students are given initial  
321 conditions to design their buildings: the structure should have a natural frequency ranging  
322 from 1Hz to 10Hz and a maximum of 5 kilograms. The lab facilities include a scale-  
323 reduced shaking table in which structures with such maximum characteristics may be  
324 tested. Consequently, the students use numerical concepts presented in the theoretical part  
325 of the course for designing the buildings. The students calculate the natural frequency of  
326 a 2-3 degrees of freedom system and play with the variables height, material, number of  
327 stories, and added mass. Fig. 8 shows the construction phases of such building in past  
328 editions of the educational experience.

329  
330 Subsequently, the models are tested with 2D axis accelerometers at each story. The base  
331 motion is generated with a scale reduced modal exciter available in the laboratory  
332 facilities. The exciter provides a 0-20Hz range available for frequency sweep. The base  
333 of each frame is clamped to the moving table. Harmonic amplified signals are provided  
334 to the actuator at varying values of frequency in order to analyze different vibration modes  
335 as well as in order to measure acceleration at each story. Resonance as well as different  
336 modes are activated for certain frequency values. Furthermore, the experience illustrates

337 to the students how unavoidable misalignments during the frame construction may lead  
338 to undesired torsional modes. Figure 9 shows a scheme as well as a lateral view of the  
339 test deployment.

340

341

#### 342 **Discussion of the educational experience**

343

344

345 The educational experience has been implemented in small groups ranging from 4 to 15 students  
346 from a Master Course of Construction Engineering. The methodology of some of these previous  
347 editions was not identical though. The results obtained so far when applying the depicted  
348 methodology prove satisfactory for small groups. Submissions of the compulsory homework are  
349 correct and their quality is remarkable. In small groups, however, the bonus submissions are not  
350 numerous so far. Figure 10 displays screenshots adapted from some examples of physical  
351 simulations. Moving frames, beams and pendulum are the main simulated systems. Concepts of  
352 damping, resonance, frequency and motion are inferred and studied from simulations. Figure 11  
353 displays images of the experiments (both cantilever and frame) and some of the results submitted  
354 by students in form of adapted plots. During these experiences, the students face typical situations  
355 related to experimental mechanics such as: validation of results and difference between theory  
356 and tests, which is very valuable as an educational experience for the particular case of structural  
357 dynamics. The students analyzed different alternatives to which these discrepancies may be  
358 attributed to. Imperfect clamping of the elements, imperfect horizontality of the sensors and/or  
359 frame elements or asymmetries are generally the main reasons of these differences.

360

361 One key aspect of the educational experience is the feedback from students. Since this course also  
362 includes hours of theory and exercises within a regular classroom, it is possible to check the  
363 experimentally obtained results with those derived theoretically. As a result, a validation process  
364 is performed by students. It is worth pointing out that this validation process is useful not only for  
365 its own sake, but also, for testing the educational capabilities of the experience as a whole. When  
366 results obtained match, the students gain self-confidence about the whole experience. If

367 conversely, these results do not match, students are entitled to enquire about potential mistakes  
368 (either theoretical or experimental). Concepts and methods are revisited and the educational  
369 experience is enriched.

370

371 Finally, it is worth pointing out that a more systematic assessment of the experience, including  
372 objective standard evaluation of the pedagogy is necessary if implemented in larger groups.  
373 Likewise, the extra activities suggested in table 1 as bonuses, are more likely to be performed by  
374 students in larger groups than in smaller ones.

375

### 376 **Reproduction of similar experience in classroom-based environments**

377

378

379 Similar educational experiences using DFM and physical simulations are feasible not only for  
380 structural dynamics but also for a broader scope of subjects. Processing and Arduino present a  
381 very similar programming environment and sending values from real sensors to Processing as  
382 input parameters is intuitive using OOV. In this particular case, the animations consist of bodies  
383 in which acceleration changes velocity and velocity changes their location with time. These values  
384 of acceleration may be collected in real time from external sources or alternatively, defined by  
385 the user internally in the code. In other simple systems in which any animation variable may be  
386 defined by external inputs, Processing and Arduino match satisfactorily.

387

388 Arduino-wise, the key aspect in the experience is to teach how to collect analog magnitudes from  
389 sensors. This process is relatively straightforward. Values obtained with potentiometers or light  
390 dependent resistors are useful for beginners since these magnitudes can be altered and understood  
391 easily by the users. Once the signal magnitudes are collected, the key issue is to send it via serial  
392 port to the computer to be collected by Software. In Processing, an Arduino object must be  
393 declared and thus, methods related to collecting analog values from sensors can be applied to  
394 these objects. In this particular set of experiments, the construction part involves “hands-on”  
395 experimental hours with previous design of a structure using theoretical and numerical tools. The

396 most important aspect in this part is to conceive a structure that may be excited appropriately by  
397 the laboratory facilities.

398

### 399 **Conclusions**

400

401 In this paper, a design of an experimental experience related to structural dynamics based upon  
402 DFM tools is presented. The classroom is designed in such a way that first, the students get  
403 acquainted with physics simulations using open-source codes. Second, a set of experiments with  
404 teaching purposes related to structural dynamics is reproduced using open-source low-cost  
405 electronics and third, a hands-on experience related to construction and instrumentation of scale-  
406 reduced 3D building is performed. Several conclusions can be drawn from this work:

407

408 • From the structural analysis perspective, the experiments are designed with open-  
409 electronics platforms and easy-to-follow Software. The experiments may be useful in  
410 basic courses of structural dynamics with a particular emphasis on the behavior of  
411 structural systems subjected to free vibrations and to harmonic oscillations. Concepts  
412 such as damping, sweep frequency response analysis and resonance can be analyzed  
413 experimentally. The experiments can be performed in a classroom-based environment  
414 and if needed, the entire preparation of the material can be performed by students from  
415 scratch.

416

417 • From the engineering education perspective, the design of such experiments may provide  
418 added value to students in a manifold fashion: i) Students may start bridging the existing  
419 physical-to-digital gap in civil engineering schools. ii) Students may start fostering the  
420 potential entrepreneurial attitude that digital fabrication and open-source labs are  
421 expected to generate. iii) Students may start getting acquainted with the development of  
422 object oriented physics simulations with open platforms. Such tools are not yet  
423 universally known and used in civil engineering schools.

424

425       • Education-wise, the experience includes a theory vs. experiments validation, which gives  
426 hints to the students and facilitators about the quality of the results but also, about the  
427 understanding of concepts. Indirectly, the educational experience is tested via this  
428 particular validation.

429

430       • As the main objective of the educational research, it is worth pointing out that the  
431 development of experiments using low-cost and easy-to-implement platforms may result  
432 in a profuse ecosystem of possibilities, in which students are focused in building their  
433 own theoretical framework via experimental design, rather than in classical lectures.  
434 Educators may divert the focus of such classical lectures to more “hands-on” experiences  
435 and to proper assistance of students during teaching hours. This is particularly interesting  
436 since increasingly, the design of experiments is in high demand by the societal changes  
437 in education.

438

439       • The educational experience provides insight of new technologies to civil engineering  
440 students. Electronics and object-oriented programming are seldom in classical curricula.  
441 An introduction to such topics, however, is necessary since increasingly, civil engineering  
442 professionals participate in construction and the internet of things using embedded  
443 technologies related to structural health monitoring as well as to automation.

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445

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#### 451 **References**

452

453

454 Adafruit platform for educators (2016), Adafruit. <<http://www.adafruit.com/educators>> (Jun. 6<sup>th</sup>, 2016)



455

456 Adhikari S., Friswell M.I., Lonkar K., Sarkar A. (2009). "Experimental case studies for uncertainty  
457 quantification in structural dynamics". *Probabilistic Engineering Mechanics*. Vol 24 (4). 473-492.

458 Arduino (2016) <<http://www.arduino.cc>> (Jun. 6<sup>th</sup>, 2016)

459

460 Blanco E., Oller S., Gil L. (2007). *Análisis Experimental de Estructuras*. Ediciones CIMNE. Barcelona.  
461 Spain. (In Spanish).

462

463 Chanson, H. (2004). "Enhancing Students' Motivation in the Undergraduate Teaching of Hydraulic  
464 Engineering: Role of Field Works." *J. Prof. Issues Eng. Educ. Pract.*, 10.1061/(ASCE)1052-  
465 3928(2004)130:4(259), 259-268.

466

467 Chen H., Kurt M., Lee Y., McFarland D.M., Bergman L.A., Vakakis A. (2014). "Experimental system  
468 identification of the dynamics of a vibro-impact beam with a view towards structural health monitoring and  
469 damage detection". *Mechanical Systems and Signal Processing*. Vol 46 (1). 91-113.

470

471 Chopra A. (2007). *Dynamics of Structures. Theory and Applications to Earthquake Engineering*. Third  
472 Edition. Pearson Prentice Hall. New Jersey. USA.

473

474 Clough R., Penzien J. (2003). *Dynamics of Structures*. Third Edition. McGraw Hill. Berkeley. USA.

475

476 Cruz-Martín A., Fernández-Madrigal J.A., Galindo C. , González-Jiménez J., Stockmans-Daou C., Blanco-  
477 Claraco J.L. (2012). "A LEGO Mindstorms NXT approach for teaching at Data Acquisition, Control  
478 Systems Engineering and Real-Time Systems undergraduate courses". *Computers and Education*. Vol 59  
479 (3). 974-988.

480

481 Elgamal A., Fraser M., Zonta D. (2005). "Webshaker: Live internet shake-table experiment for education  
482 and research". *Computer applications in engineering education*. Vol 13 (1). 99-110.

483

484 Ferdoush S., Li X. (2014). “Wireless Sensor Network System Design using Raspberry Pi and Arduino for  
485 Environmental Monitoring Applications”. *Procedia Computer Science*. Vol 34. 103-110.  
486

487 Fox S. (2014). “Third Wave Do-It-Yourself (DIY): Potential for prosumption, innovation, and  
488 entrepreneurship by local populations in regions without industrial manufacturing infrastructure”  
489 *Technology in Society*. Vol 39 (11). 11-30.

490 Guo J., Kettler D., Al-Dahhan M. (2007). “A chemical engineering laboratory over distributed control and  
491 measurement systems”. *Computer Applications in Engineering Education*, 15 (2). 174–184.  
492

493 Ionescu C.M., Fabregas E., Cristescu S.M., Dormido S., De Keyser R. (2013). “A remote laboratory as an  
494 innovative educational tool for practicing control engineering concepts” *Education, IEEE Transactions*.  
495 Vol 56 (4), 436–442.  
496

497 Katsanos E.I., Taskari O.N., Sextos O.A (2014). “A matlab-based educational tool for the seismic design  
498 of flexibly supported RC buildings”. *Computer applications in engineering education*. Vol 22 (3). 442-451.  
499

500 Kensek K.M. (2014). “Integration of environmental sensors with BIM: case studies using Arduino,  
501 Dynamo, and the REVIT API”. *Informes de la Construcción*. Vol 66 (536), e044.  
502

503 Koenka I., Sáiz J., Hauser P. (2014). “Instrumentino: An open-source modular Python framework for  
504 controlling Arduino based experimental instruments”. *Computer Physics Communications*. Vol 185(1).  
505 2724-2729.  
506

507 LabView (2016). <<http://www.ni.com/labview/>> (Jun. 6<sup>th</sup>, 2016)  
508

509 Matlab (2016). <<http://www.mathworks.com>> (Jun. 6<sup>th</sup>, 2016)  
510

511 MIT Video website (2016).< <http://video.mit.edu>> (Jun. 6<sup>th</sup>, 2016)  
512

513 “MOOC Coursera. Design, create, and deploy a fun IoT device using Arduino and Raspberry Pi platforms”,  
514 (2016). Coursera <<https://www.coursera.org/specializations/iot>> (Jun. 6<sup>th</sup>, 2016)  
515  
516 ] Nakazawa T., Matsubara M., Mita S., Saitou K. (2014). “Teaching Materials and Lessons Plans for Hands-  
517 On Mechanics Education”. *Experimental Techniques*. Vol 38 (6). 72-80.  
518  
519 Ozelik O., Attar P., Altan M.C., Johnston J.W. (2013). “Experimental and numerical characterization of  
520 the structural dynamics of flapping beams”. *Journal of Sound and Vibration*. Vol 332 (21). 5393-5416.  
521  
522 Paz M, Leigh W. (2003). *Structural Dynamics: Theory and Computation*. 5th Edition. Springer. New York  
523 USA.  
524  
525 Pearce J. (2014). *Open-Source Lab. How to Build Your Own Hardware and Reduce Research Costs*. 1st  
526 Edition. Elsevier. USA-UK-The Netherlands. 2014  
527  
528 Processing 2.0. (2016). < <http://processing.org> > (Jun. 6<sup>th</sup>, 2016)  
529  
530 Python 3.5 (2016). <<http://www.python.org>> (Jun. 6<sup>th</sup>, 2016)  
531  
532 Raspberry Pi (2016). < <http://www.raspberrypi.org> > (Jun. 6<sup>th</sup>, 2016)  
533 Reas C and Fry B. (2014). *A Programming Handbook for Visual Designers*, Second Edition. The MIT  
534 press. USA.  
535  
536 Senatore G., Piker D. (2015). “Interactive real-time physics: An intuitive approach to form-finding and  
537 structural analysis for design and education”. *Computer-Aided Design*. Vol 61 (4). 32-41.  
538  
539 Shiffman D. (2016). Online HTML and tutorial-based book, The nature of code.  
540 <<http://natureofcode.com/>> (Jun. 6<sup>th</sup>, 2016)  
541

542 Solís, M., Romero, A., and Galvín, P. (2012). "Teaching Structural Analysis through Design, Building, and  
543 Testing." *J. Prof. Issues Eng. Educ. Pract.*, 10.1061/(ASCE)EI.1943-5541.0000097, 246-253.

544 Unterweger, H. (2005). "Simple Structural Models for the Education of Structural Engineers at Graz  
545 University." *J. Prof. Issues Eng. Educ. Pract.*, 10.1061/(ASCE)1052-3928(2005)131:4(227), 227-230.

546

547 Valera A., Soriano A., Vallés M. (2014). "Plataformas de Bajo Coste para la Realización de Trabajos  
548 Prácticos de Mecatrónica y Robótica". *Revista Iberoamericana de Automática e Informática Industrial*.

549 Vol 11(4). 363-376.

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562 **List of tables and figures (Captions)**

```

Damping | Processing 2.2.1
File Edit Sketch Tools Help
Damping
void setup(){
  // put your setup code here, to run once:
  size(1200,1000);
  background(0,0,0);
}
void draw(){
  // put your main code here, to run repeatedly:
  fill(255);
  rect(500,500,100,100);
}

```

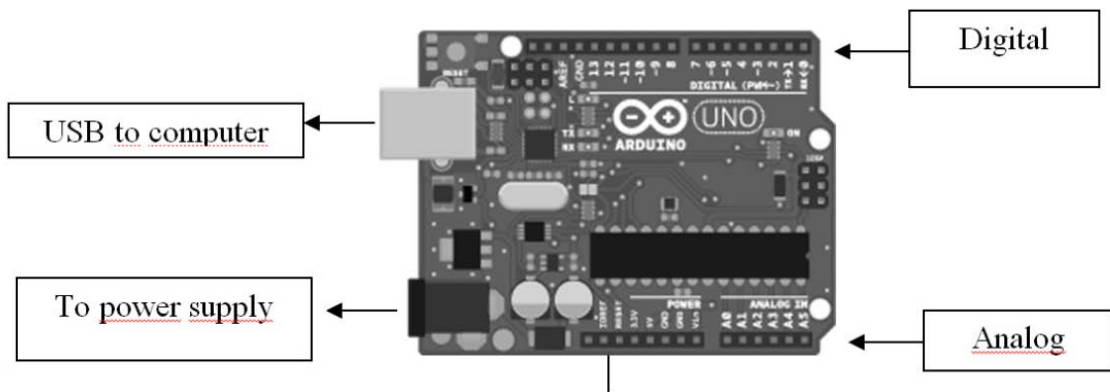
```

damping | Arduino 1.6.7
File Edit Sketch Tools Help
damping $
void setup() {
  // put your setup code here, to run once:
}
void loop() {
  // put your main code here, to run repeatedly:
}

```

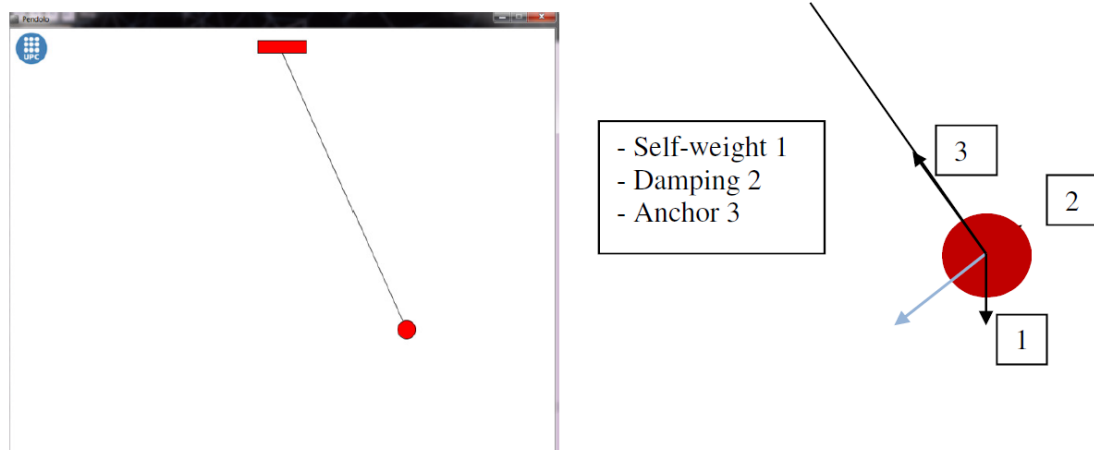
563

564 **Fig. 1.** Processing (a) and Arduino (b) Integrated Development Environment



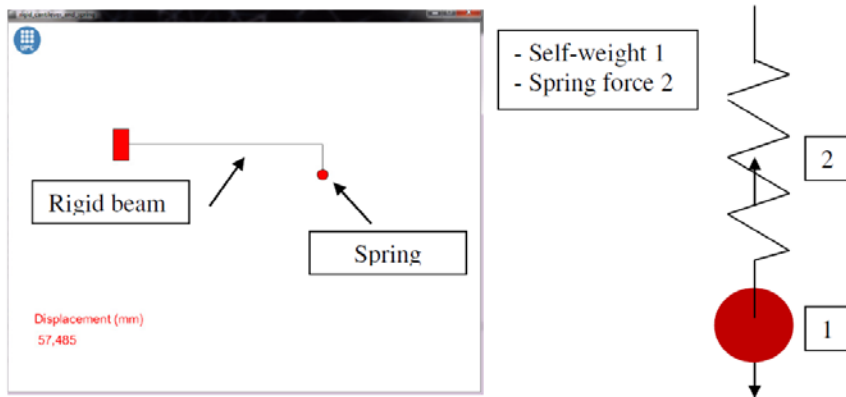
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566 **Fig. 2.** The Arduino/Genuino UNO board.



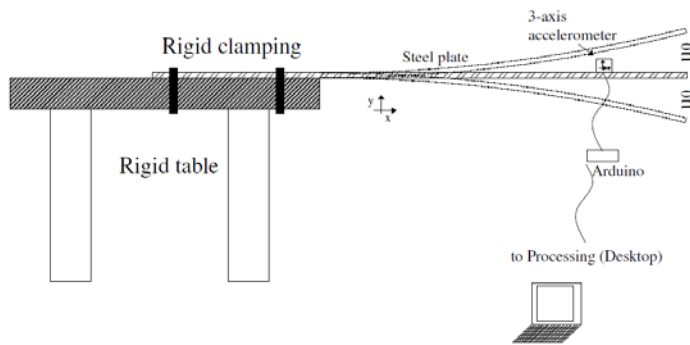
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568 **Fig. 3.** Pendulum in processing. Anchor, rod and mass.



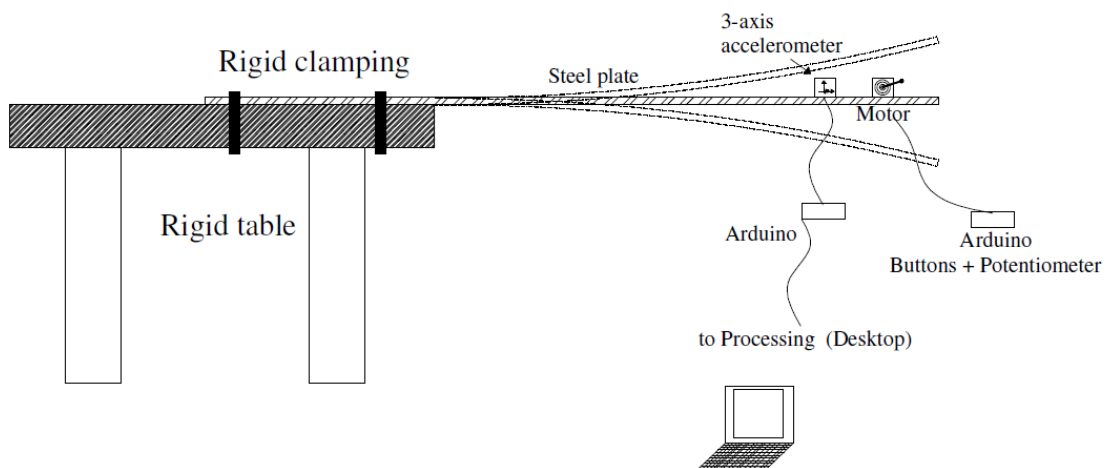
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570 **Fig. 4.** Spring in Processing. Rigid beam, spring and mass.



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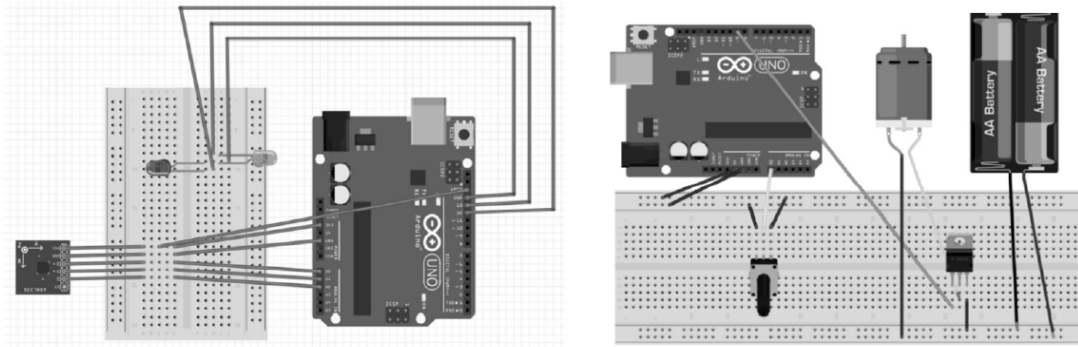
572 **Fig. 5.** Free vibrations. Connections and general view of the experimental setup



573

574 **Fig. 6.** Harmonic oscillations. Connections and general view of the experimental setup

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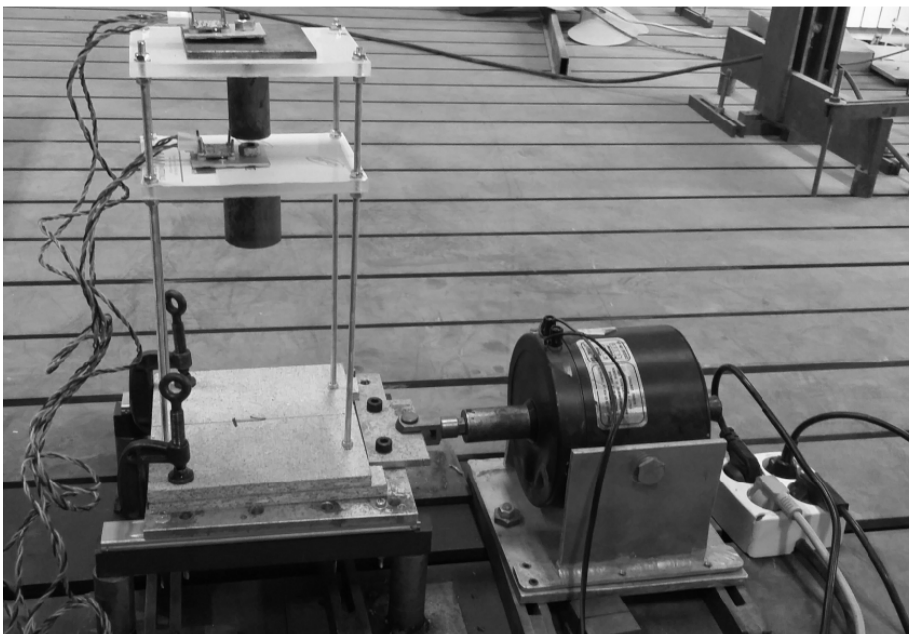
576

577 **Fig. 7.** Arduino circuitries (a) Acquiring acceleration analog magnitudes (b) Control of actuator



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579 **Fig. 8.** Construction of 3D frames with variable materials, masses and geometries

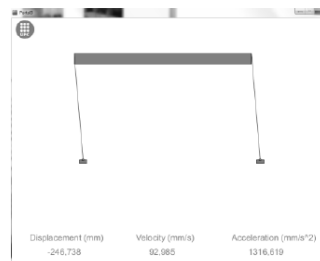
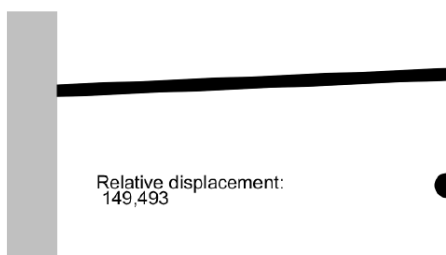
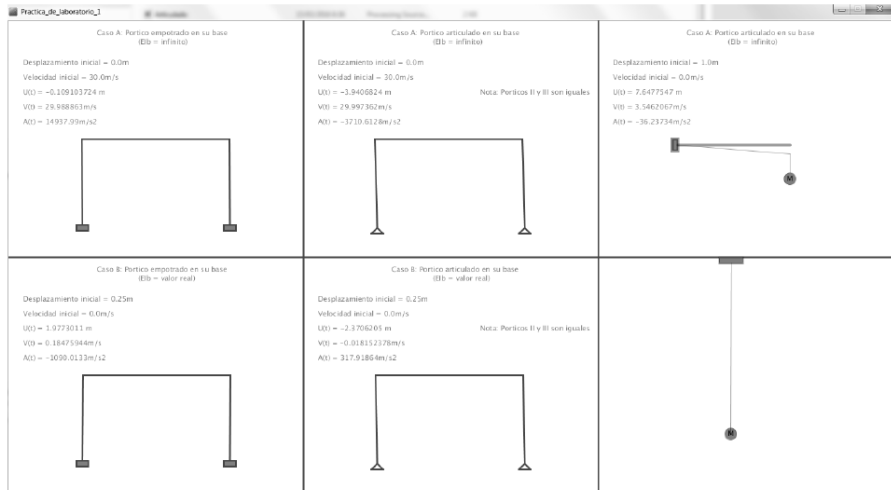


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581 **Fig. 9.** Scale-reduced test of 3D frames subjected to harmonic oscillations

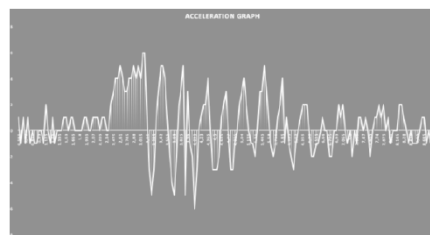
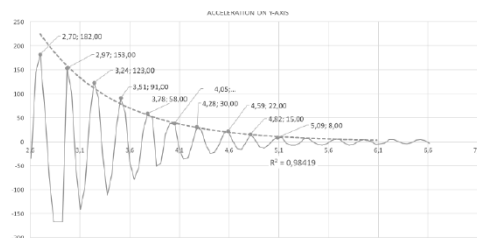
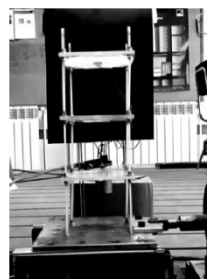
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585 **Fig. 10.** Drawings adapted from submitted codes including frames, beams and springs.



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587 **Fig. 11.** Illustrative results adapted from submitted data

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Intro 2 hours	Intro 2 hours	Intro 2 hours
Object-Oriented visual programming (OOVP) Vectors and Trigonometry in Processing	Basic circuitry. Blink a LED, Use a light sensor, Use a potentiometer, Activate a small motor or servo motor	Building 3D frames using basic tools and materials such as steel bars, plastic plates, screws, nuts. Hands-on experience
Core 4 Hours	Core 4 Hours	Core 4 Hours
OOVP. The pendulum OOVP. The spring	Test. Free vibrations of a cantilever Test. Harmonic excitations of a cantilever	Instrumentation and connection to a moving table coupled to a modal exciter. Test the system for various frequencies
Homework	Homework	Homework
Individual submission	1, 2, 3 up to 4 students	1, 2, 3 up to 4 students
Submission an animation of a more complex multi-pendula or multi-spring system concerning	Submission an in-depth analysis of the used equipment as well as the results obtained with particular focus on:	Submission an in-depth analysis of the dynamic behavior of their own structure with particular focus on:
Motion Force Acceleration	Frequency Damping Resonance	n-modes Acceleration Resonance
one degree of freedom	one degree of freedom	n-degrees of freedom
Bonus	Bonus	Bonus
Creative animation	Calibration of the accelerometers	Creative simulations
Submission an animation including images or other additional features to add realism	Additional features for the control of the motors. Use of mobile applications	Real-time use of the measured values for developing realistic animations

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593 **Table 1.** Organization of the educational experience

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