ONLINE LABORATORIES IN PANDEMIC TIMES: CASE OF STRUCTURES/STATICS USING THE ZEEMAN'S MACHINE

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DOI: 10.37702/REE2236-0158.v41p297-311.2022

ABSTRACT

The Engineering Education is a strategic branch of the educational system of any organized State that aims to maintain an adequate interaction between the development and application of new technologies, and the transmission of concepts used to build the physical environments of their societies. These educational activities involve the controlled observation of facts and their correct interpretation, usually conducted during in-person experimental classroom lectures. The blooming of viruses in the highly concentrated modern societies, which the recent experience showed that may conduce to pandemics, exposes the need of experimental lectures or activities in the context of online, or hybrid online/in-person Engineering classes. This study presents a successful application of an experimental learning activity, which required students to launch a theoretical investigation, collect experimental data, compare theoretical and experimental results, interacting effectively to present a report with their understanding of the experiment. The study was conducted joining two hybrid Statics classes (with online and in-person students), a fundamental discipline of Civil Engineering, using as challenging motivator an adaptation of the Zeeman's machine. A competition was organized for the students to present solutions of questions related to the machine. The equations and data obtained by the students are described in this study for further applications. Aspects of didactics, students' reception, feasibility of the activity are discussed, showing the adequacy of this initiative in experimental learning for remote and hybrid teaching models.

Keywords: Remote learning, online laboratory, online Engineering education, Zeeman's machine, didactic catastrophe machine.

INTRODUCTION

Virus blooming reality

Despite the blooming of viruses and microorganisms already playing a part in the history of the humankind (HUREMOVIĆ, 2019 a, b), the COVID 19 Pandemic exposed some unexpected fragile aspects of the organization of the modern societies.

The proper transfer of knowledge in educational institutions, that guaranties the evolution (non-stagnation) of the societies is one of the activities profoundly affected by pandemic conditions. The education activity is heavily based on the confidence deposited in the direct contact between institutions composed by academicians, and the continuous flow of the young masses of the ever-renewing population. Focus, generation and spreading of knowledge, science honesty (search of rational explanations of facts) are positive aspects linked to our educational institutions (Universities, Research Institutes) making them be valued as sound environments to form the new generations of thinkers and scientists. However, pandemic periods impede the immersion of young minds in these environments. Further, despite the large use of the internet as a host for consulting, virtual meetings, and already adapted online course programs, a some-what rough transition was felt for the traditional in-person Engineering courses to adapt to the distance learning modes during the COVID 19 pandemic.

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Blackmon and Major (2012) mention that, in the time of their study a rise of 21% was observed in online courses, against only 2% of overall growth in the whole higher education. The authors opined that it showed the willingness of universities and students to use the online option, and the adequacy of such courses. But COVID 19 showed that it did not measure the emergency reality of a pandemic.

The growth of online education was also stressed by Paul and Jefferson (2019), who statistically analyzed the performance of students in the period of 2009 to 2016 for in-person and online education No statistically significant difference was found between the scores of the two student populations, considering both men and women students, and the different class ranks. Similar result was presented. formerly by Nguyen (2015), mentioning strong evidence that online learning is at least as effective as the in-person format. But no study considered emergency impositions like those demanded by COVID-19, when no margin exist for voluntary decisions between the two modes of classes.

More recent studies must be considered for emergency conditions. Burns and MacCormack (2020) mentioned procedures of three universities to adjust courses to online needs, and commented case studies in three branches of the human knowledge. Auburn University, where the current study was conducted, was also considered by the cited authors, who commented: "Auburn staff and faculty realized that some classes were struggling mightily with the move to on-line delivery, especially labs, studios, and other experiential courses". Burns and MacCormack (2020) showed the solution adopted for laboratory classes of Chemistry by placing a 360º camera in the lab to introduce "students to the lab, the safety procedures, the equipment, and the lab processes in a virtual environment".

Already adapted online courses may not need interactive laboratories for complex phenomena. But Engineering laboratory classes may involve several complex phenomena, for which adequate material must be available for the online students.

We describe a laboratory experiment proposed to students of Statics classes, a fundamental discipline of Civil Engineering in the main area of structures, during the COVID-19 pandemic. The method and the experiment, however, are suited for any course that uses concepts of forces, moments, stability of systems, as well as regression analyses, in areas of Engineering and Physics, for example.

The theme was presented to the students as a set of questions, and organized as a competition. The students were organized into groups of 4 to 5 members optimizing the homogeneity of the already obtained scores in the Statics course, and involving in-person and online members. This combination tried to induced classmate interaction, since online students are literally isolated from the colleagues. Interactions are coined Social Presence in studies of online courses, being discussed, for example, by van Wart et al. (2020), who mentioned studies with opposite conclusions: some point the social presence as relevant, and other consider it insignificant. Hermann (2020) is much more acute in his opinion about the students' point of view, citing a survey made with his students, which led to the "clear" result that the students "hated" online learning during the COVID-19 conditions.

In the present study, interaction was a basic need for the students to answer the proposed questions of the online experiment, and was incentivized.

Context of this study

As mentioned, the Statics classes (USA jargon) contextualize this study. Moments and equilibrium of forces, the stability of structures in their static condition are some of the concepts evoked in the initial stages of the calculation of structures, and which are linked to practical situations in the discipline of Statics. Practical observations occur in laboratory classes. For example, stability in laboratory may be demonstrated loading thin gesso or plaster bars that imitate beams leading to sudden collapses. The Hooke's Law may be demonstrated using rubber bars or springs, by loading and unloading them. These "structures" deform and return to the initial position. In-person labs allow the experiments to be controlled by the students, capturing their attention while new loading situations are applied.

Despite the well-thought-out and used laboratory practices, online laboratories do not accommodate this direct interaction, so that alternative techniques must be explored. In this sense, the experiment of this study slowly evolves to a sudden change, an aspect meant to tingle the curiosity of the students. It was designed to engage students by providing access to an online platform, which contains the needed observation data for analysis (Schulz and Simões, 2021a, b). Because of the competition format, the rules and the template of the report were also provided in the platform. The didactic goals were: 1) to direct the student efforts to understand the operation and behavior of the used device (named the Zeeman's Catastrophe Machine); 2) to work with concepts of the theoretical lectures in a laboratory application, and 3) to engage in team work during the COVID-19 pandemic using an online class platform. The activity was itself a test for such proposals, and its reception by the students was observed and analyzed. It was conducted along the spring term of 2021 at the Auburn University, Alabama, USA, with the analyses made together with the Federal University of Bahia, Brazil.

Zeeman's machine for Statics classes

The search of an experiment that evolves in such a way that arouses curiosity (the mentioned sudden change) also allowing applying concepts of forces, moments, geometrical and trigonometric properties used in Static classes, led to adopt the mentioned Zeeman's Catastrophe Machine. This device was presented by Zeeman (1972) for the Catastrophe Theory of Thom (1972), which experienced a time of more general discussion in the seventies of the twentieth century. The machine is a simple device composed by a free rotating circle fixed to a plane, and which static equilibrium angle in relation to a convenient reference (horizontal line, for example) is controlled by two elastics. The curious aspect of the machine is that it allows adopting a sequence of positions for stable geometrical measurements before suddenly snapping or jumping while setting a further position, inducing interesting questions for analysis. This "snap" was linked by Zeeman (1972) to one of the basic "catastrophes" proposed by Thom (1972) in the Catastrophe Theory.

THE ACTIVITY

Sudden behaviors, or instabilities in structures, may be studied with varying levels of complexity. For sophomore-level Statics classes, quantifying moments and forces using the Hooke's Law for elastic materials is a relevant part of the discipline, while stability is assumed to exist. This experiment was thus directed to evidence the quantifications of moments and forces, being the instability explored as an empirical fact to be approximated through a regression equation. Its discussion was induced to be more qualitative than quantitative. For more advanced classes the emphases of the activity may evidently be modified.

Theoretical based experiment

The Zeeman's machine used here is presented in figures 1a and 1b. Details of the device are given in the item "The Experimental Device". The online course platform allowed the students to access an explanation video and a complete set of photos showing the machine in 272 sequential positions of loading cases (SCHULZ; SIMÕES, 2021a, b). In-person students were also able to tangibly interact with the device, and to exchange information with the online colleagues. Using the photographs or own measured data, the students were tasked to:

i- Calculate the value of the spring stiffness coefficients K_F and K_B of the free and the fixed springs, respectively, used in the device (see figures 1a, b). A minimum set of 30 measured values was to be used for analysis.

ii- Calculate the initial length of the fixed spring (see figures 1a, b). Again, 30 measured values were to be used for analysis.

iii- Present the experimental evolution of the ordered pairs (x, y) of the free end of the free spring for a fixed condition of the machine, and compare it with the theoretical prediction.

Full empirical based experiment

Using the 272 photographs or own data obtained by in-person members of the groups, the students were asked to:

i - Present the evolution of the ordered pairs (x, y) of the free end of the free spring for the limiting position of the changing events. In this case, an empirical best-fit equation (regression analysis) was requested to be presented with the data (qualitative approach).

Need of the activity and motivation of students

The proposal of the online laboratory experiment and competition derived from the pandemic reality. In this sense, it filled a need of the Statics lectures, independently of any propensity of the students to such activities. But the competition was set as a voluntary activity to also generate information of its acceptance. Although the groups were formed following the criteria of homogeneity and online/in -person interaction, their joining in the competition was a free decision of each group.

To help to motivate the participation, a list of awards was prepared, conferring extra points in the grade composition of the students, which effect on the final grade was:

- Group classified in the first place: The members would have an increment in the grade of about 22% of the maximum grade.
- Group classified in the second place: The members would have an increment in the grade of about 20% of the maximum grade.
- Group classified in the third place: The members would have an increment in the grade of about 15% of the maximum grade.
- Groups that participated and did not attain the first places: a possible increment of 10% of the grade would be possible, depending on the quality of the answers.
- Groups that decided not to participate would have no penalty. Joining the contest was a free decision.

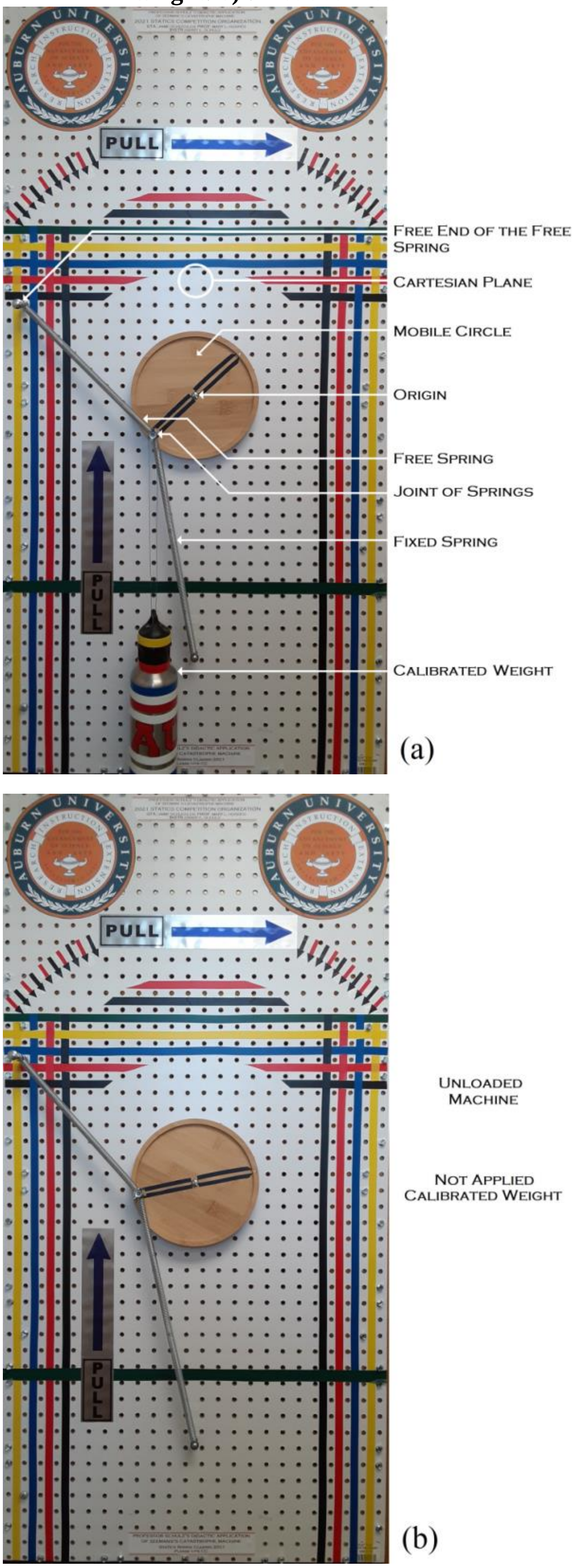
THE EXPERIMENTAL DEVICE

The constructive aspects (geometry and moving elements) of the Zeeman's machine directly affect the relevant variables. The two springs impose the static equilibrium and generate the underlying geometrical characteristics of the lines of action of the forces.

The mentioned sudden change adds the stability aspect, resembling a structural "collapse", but still in the elastic limit of the springs. No "collapses" are thus expected by sophomore students, used to the elastic proportionality range of the stress-strain diagram of the Hooke's Law for a single spring or elastic material The "snap" due to the composition of forces of two elastic elements (springs in this case) is a new experience for the students.

The Zeeman's device was adapted here to allow the easy registering of ordered pairs (x, y) using a Cartesian plane as background, as shown in figures 1 a and b. A perforated plate of wooden fiber 2.0 ft (60.96 cm) width, and 4.0 ft (121.92 cm) height formed the plane. The holes formed the cartesian points, having a distance of 1.0" (2.54 cm) between each other (vertical and horizontal directions). The center point of the plate was adopted as origin of the coordinate system. A mobile wooden circle with diameter of 20 cm was fixed at the origin. One end of each of the two springs was fixed at the radius position of 3.43" (8.7 cm) maintaining a rotating free movement about the fixture point. The so called "fixed spring" had its other end fixed on the Cartesian plane 16" (40.64 cm) vertically below the origin, also with a rotating free movement about the fixture point. An adequate set of screw and nuts was adapted to the free end of the second spring (so called free spring), allowing fixing it in any of the perforated holes of the Cartesian plane).

Figure 1 – Adapted Zeeman's machine, Auburn University (Schulz and Simões 2021 a). a) The components of the machine with the calibrated weight. b) unloaded machine

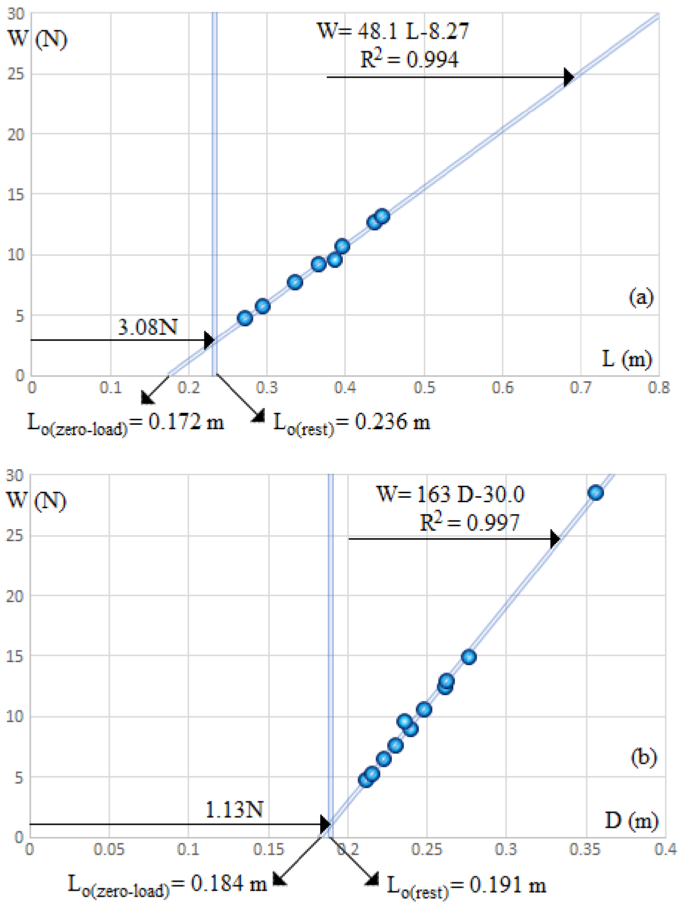


Source: Authors

A thermos with water served as a calibrated mass fixed to the junction of the two springs (Figure 1a) when needed. The calibrated mass added a constant vertical force to the problem for any position of the machine. The mass value was 0.9788 kg (weight = 9.60 N). Figures 1 a, b show the device with and without the calibrated mass, respectively, for different positions of the free end of the free spring.

Zeeman's machines are usually described using rubber elastics instead of springs (LITHERLAND; SIAHMAKOUN, 1995; JIA et al., 2015; CAZZOLLI et al., 2020). But our tests with elastics showed improper nonlinear evolutions of the stiffness coefficients. Instead, the use of springs guaranteed the didactic adequacy of the device. It was informed that generally compression commercial springs (used here) are produced having a prestress, so that the observed "length at rest" is always greater than the "zero-load position". It does not affect the stiffness coefficient (k), but implies care in the analyses.

Figure 2 – Load vs. displacement; a) Free spring. Pre-stress = 3.08 N. Stiffness coeff. k_B = 48.1 N/m; b) Fixed spring. Pre-stress = 1.13 N. Stiffness coeff. k_F = 163 N/m



Source: Authors.

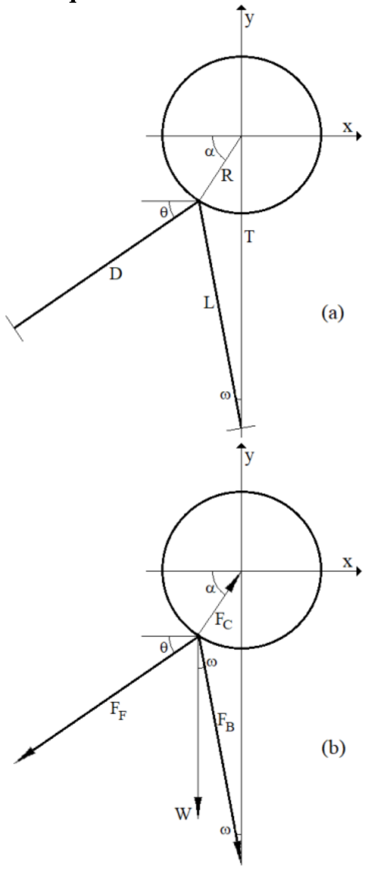
The tests made with the free (index *F*) and fixed (index *B*) springs yielded the stiffness coefficients k_F = 163 N/m, and k_B = 48.1 N/m. Figures 2a and b show the graphs of applied loads (*W*) and measured lengths (*L* and *D*) for the fixed and free springs, respectively. The prestresses are evident, and the "rest length" and "zero-load length" are indicated. The small difference between the two lengths of the free spring helped the calculations of the students.

The main aspects of the experimental device were described to allow its reproduction in future similar experiments in different sites.

THE BASIC FORMULATION

Formulation is a natural step of the laboratorial activities. Measurements aim to check predictions, or to quantify physical constants contained in the equations. Figures 3 a and b illustrate the variable lengths, angles, and forces used to obtain the governing equations for the loaded machine (with calibrated weight).

Figure 3 – a) Geometrical variables; b) Forces. Third Cartesian quadrant chosen for the example



Source: Authors.

The third quadrant of the Cartesian plane was chosen for the experimental data used here. Angles and distances are thus defined for this quadrant. Taking the location of joint of the two springs, the equilibrium condition in the *x* and *y* directions lead, respectively, to:

$$-F_F\cos\theta + F_C\cos\alpha + F_B\sin\omega = 0 \quad (1)$$
$$-F_F\sin\theta + F_C\sin\alpha - F_B\cos\omega - W = 0 \quad (2)$$

The equilibrium of moments around the origin leads to:

$$F_F\sin(\alpha-\theta) - F_B\cos(\alpha-\omega) = W\cos\alpha \quad (3)$$

An identity is obtained by applying (3) to (1) and (2), so that no variable is left to be calculated. This shows that the force and moment equations equally express the condition of equilibrium of the device.

Stiffness coefficients and initial length of the fixed spring

This derivation was asked as part of the analyses. To avoid the mentioned identity, only equations (1) and (2), <u>or</u> only equation (3) were to be used. The Hooke's law forces of the springs, result in:

$$F_F = k_F(D - D_o) \quad (4)$$
$$F_B = k_B(L - L_o) \quad (5)$$

When (4) and (5) are plugged into (3) and rearranged, the resulting equation is:

$$(D-D_o)\sin(\alpha-\theta) - \frac{k_B L}{k_F}\cos(\alpha-\omega) + \\ + \frac{k_B L_o}{k_F}\cos(\alpha-\omega) = \frac{W\cos\alpha}{k_F} \quad (6)$$

By defining the auxiliary variables

$$f = (D-D_o)\sin(\alpha-\theta) \quad (7a)$$
$$g = L\cos(\alpha-\omega) \quad (7b)$$
$$h = \cos(\alpha-\omega) \quad (7c)$$
$$m = W\cos\alpha \quad (7d)$$

it is obtained that:

$$f - g\,k_B/k_F + h\,k_B L_o/k_F - m/k_F = 0 \quad (8)$$

Equation (8) is linear for the variables *f, g, h*, and *m*. The constant coefficients $1/k_F$, $k_B L_o/k_F$, and k_B/k_F can be adjusted with at least three sets of measured *f, g, h,* and *m* (set of photographs available in the students' online database, and Schulz and Simões (2021a, b). To obtain more precise values of the constants, the use of at least 30 experimental points was asked. Multiple linear regression analysis was indicated to calculate $1/k_F$, $k_B L_o/k_F$, and k_B/k_F (Zar, 1984, chapter 20, for example), allowing obtaining immediately the values of k_B, k_F, and L_o.

During the activity the students observed that the unloaded machine [without W, or imposing m=0 in (8)] used together with the loaded machine implied that W is a controllable variable. The use of more weights was then requested, but this possibility was denied for consistency with the original proposed problem. Future studies may of course involve several ranges of weights.

Evolution of free end ordered pairs (x,y)

The "theory-focused" study was the formulation of the position of the free end of the free spring (x, y) under the conditions α=0, and W=0. Applying these conditions in equation (6) leads to:

$$(D - D_o)\sin\theta = \frac{k_B}{k_F}\left(1 - \frac{L_o}{L}\right) L\cos\,\omega \qquad (9)$$

The right member is a constant [$\Lambda=(k_B/k_F)(1\text{-}L_o/L)L\cos(\omega)$], producing, thus:

$$(D - D_o)\sin\theta = \Lambda \qquad (10)$$

The equations for sin (θ) and D are obtained from figure 2a leading, respectively, to:

$$\sin(\theta) = -\frac{y}{D} \qquad (11a)$$

$$D = \sqrt{y^2 + (x - R)^2} \qquad (11b)$$

From (10), (11a), and (11b) we obtain

$$x = -R \pm y\sqrt{\left(\frac{D_o}{y - \Lambda}\right)^2 - 1} \qquad (12a)$$

Equation (12a) shows that $-D_o+\Lambda \leq y < D_o+\Lambda$ guarantees real results of x for $-R \leq x < \infty$. Outside of this range of y there is no real solution for x to maintain α=0. Equation (12a) thus establishes regions of validity of the restriction α=0 on the cartesian plane. It is a gain of knowledge for the students, who observe that restrictive conditions may exist even in the range of validity of the elastic behavior of the materials (the Hooke's law).

Although not asked to the students, the equation that relates x and y for any α and W is given by

$$\begin{aligned} D_o^2[y\cos\alpha - x\sin\alpha]^2 &= \\ = [y\cos\alpha - x\sin\alpha - \Xi]^2 &* \\ *\{[(y - R\sin\alpha]^2 & \\ + [(x - R\cos\alpha]^2\} & \end{aligned} \qquad (12b)$$

$$\Xi = \pm\left[W + \frac{k_B T}{k_F}\left(1 - \frac{L_o}{L}\right)\right]\cos\alpha \qquad (12c)$$

Equation (12b) is a 4th order polynomial for both x, and y, thus allowing studying its four theoretical solutions in activities for more advanced classes. It is a result of this study in laboratory measurements, reason to present it here. For sophomore students, however, (12a) is the best choice.

Unrestricted catastrophe ordered pairs (x, y)

Equation (12a) shows that simple analyses help to understand the behavior of the machine without excessive theoretical work. In the sense of using simplified equations, it was asked to the students to present a regression equation (best fit equation) for the ordered pairs (x, y) of the instability positions of the free string (as mentioned, this machine may reach unstable or catastrophic conditions). Because of the absence of a model, the expected best fit equation was a polynomial, that is:

$$y = \sum_{i=1}^{N} C_i x^i \tag{13}$$

The order *n* of the polynomial would be a choice of each group. No "correct" order was specified. For discussions on the solution see Zeeman (1972).

THE LABORATORY RESULTS

Stiffness coefficients and length of fixed spring

The angles α, θ, and ω and the experimental variables *f*, *g*, *h* and *m* of (7 a, b, c, d) were obtained from the online photographs (Schulz and Simões, 2021b). They allowed computing α, θ, ω, *f*, *g*, *h* and *m* of Table 1. Measurement errors on the images certainly induced errors in the further calculation of k_B, k_F, and L_o., but the results were very adequate. A multilinear regression using a digital spreadsheet and (8) was then made with *f*, *g*, *h*, *m* and taking *f* as dependent variable. The values of k_B, k_F, and L_o may also vary if taking *g*, *h*, or *m* as the dependent variable in the regression analysis rather *f*, although the results usually remain similar. Figure 4 shows the graph of *f*. The vertical axis is the measured *f* (Table 1) and the horizontal axis is *f* obtained with (8) and the adjusted coefficients. A determination coefficient R^2= 0.990 was obtained. Table 2 shows the calculated values of $L_{o\ (zero\text{-}load)}$ of the fixed spring and of the stiffness coefficients k_F, and k_B, together with those presented in figures 2a, b (measured values). It shows that the physical parameters of the springs were closely quantified.

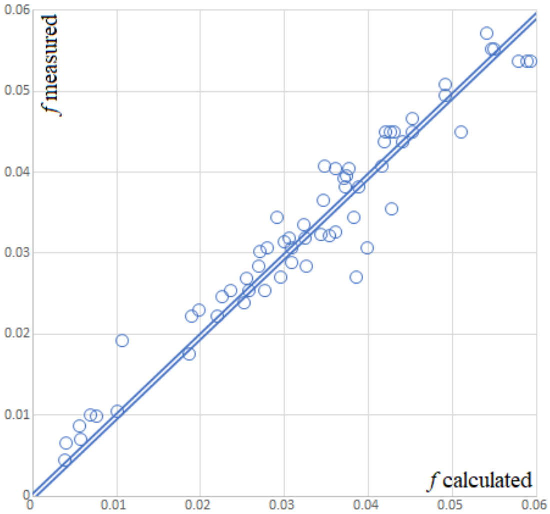
TABLE 1
ANGLES AND FUNCTIONS OF (7 a, b, c, d) AND (8)

N	α	θ	ω	f	g	h	m
1	64.8	35.6	7.24	0.0592	0.1730	0.5364	4.089
2	66.8	37.9	6.84	0.0492	0.1601	0.5006	3.782
3	69.6	40.5	5.94	0.0418	0.1415	0.4433	3.343
4	73.0	43.0	5.07	0.0345	0.1188	0.3756	2.806
5	77.5	45.8	3.69	0.0295	0.0882	0.2793	2.083
6	85.4	58.3	1.40	0.0068	0.0328	0.1051	0.776
7	79.0	40.9	3.23	0.0251	0.0776	0.2459	1.833
8	74.5	38.2	4.61	0.0322	0.1088	0.3442	2.570
9	71.1	35.9	5.48	0.0416	0.1318	0.4132	3.114
10	64.8	31.6	7.24	0.0587	0.1730	0.5364	4.089
11	64.8	27.3	7.24	0.0578	0.1730	0.5364	4.089
12	69.1	29.0	5.89	0.0510	0.1451	0.4511	3.429
13	71.6	30.6	5.53	0.0373	0.1285	0.4061	3.036
14	76.8	31.8	3.35	0.0308	0.0927	0.2848	2.191
15	74.1	25.2	4.57	0.0381	0.1116	0.3505	2.638
16	68.2	23.7	6.39	0.0452	0.1509	0.4724	3.566
17	69.1	18.6	5.89	0.0452	0.1451	0.4511	3.429
18	77.5	18.4	3.69	0.0386	0.0882	0.2793	2.083
19	64.1	12.5	7.18	0.0546	0.1773	0.5453	4.189
20	69.1	12.9	5.89	0.0430	0.1451	0.4511	3.429
21	64.1	6.9	7.18	0.0549	0.1773	0.5453	4.189
22	69.1	6.8	5.89	0.0419	0.1451	0.4511	3.429
23	63.1	0.9	7.65	0.0540	0.1839	0.5673	4.345
24	69.1	0.6	5.89	0.0425	0.1451	0.4511	3.429
25	86.9	73.5	0.94	0.0040	0.0216	0.0696	0.511
26	85.4	67.6	1.40	0.0077	0.0324	0.1041	0.766
27	81.3	62.7	2.25	0.0107	0.0618	0.1907	1.460
28	74.1	50.9	4.57	0.0290	0.1116	0.3505	2.638
29	71.1	47.6	5.48	0.0347	0.1318	0.4132	3.114
30	69.6	44.3	5.94	0.0441	0.1415	0.4433	3.343
31	66.2	42.0	6.79	0.0490	0.1640	0.5090	3.876
32	58.5	37.6	8.38	0.0427	0.2124	0.6412	0.000
33	61.0	39.8	8.04	0.0361	0.1969	0.6020	0.000
34	62.7	42.7	7.62	0.0280	0.1861	0.5719	0.000
35	67.6	45.0	6.34	0.0258	0.1547	0.4805	0.000
36	70.3	48.2	5.71	0.0190	0.1367	0.4284	0.000
37	83.8	58.9	1.86	0.0058	0.0437	0.1397	0.000
38	74.5	42.2	4.61	0.0187	0.1088	0.3442	0.000
39	68.2	40.2	6.39	0.0226	0.1509	0.4724	0.000
40	63.1	38.3	7.65	0.0270	0.1839	0.5673	0.000
41	55.9	34.2	9.25	0.0372	0.2279	0.6866	0.000
42	55.0	30.3	9.18	0.0370	0.2331	0.6968	0.000
43	61.4	30.9	8.07	0.0353	0.1946	0.5973	0.000
44	64.8	32.8	7.24	0.0269	0.1730	0.5364	0.000
45	69.6	34.8	5.94	0.0198	0.1415	0.4433	0.000
46	66.2	27.1	6.79	0.0254	0.1640	0.5090	0.000
47	61.3	26.2	7.79	0.0344	0.1950	0.5942	0.000
48	61.7	20.4	7.82	0.0324	0.1927	0.5894	0.000
49	67.6	20.9	6.34	0.0235	0.1547	0.4805	0.000
50	55.9	14.3	9.25	0.0388	0.2279	0.6866	0.000
51	61.7	14.4	7.82	0.0305	0.1927	0.5894	0.000
52	53.7	9.2	9.61	0.0360	0.2403	0.7176	0.000
53	62.7	7.8	7.62	0.0308	0.1861	0.5719	0.000
54	53.7	3.1	9.61	0.0376	0.2403	0.7176	0.000
55	62.1	1.3	7.85	0.0300	0.1904	0.5847	0.000
56	86.1	73.9	1.16	0.0039	0.0274	0.0877	0.000
57	82.3	69.0	2.33	0.0056	0.0544	0.1741	0.000
58	80.8	63.4	2.79	0.0100	0.0651	0.2080	0.000
59	70.3	52.0	5.71	0.0220	0.1367	0.4284	0.000
60	67.6	48.8	6.34	0.0277	0.1547	0.4805	0.000
61	64.8	45.7	7.24	0.0325	0.1730	0.5364	0.000
62	62.7	43.0	7.62	0.0398	0.1861	0.5719	0.000

Source: Authors.

The theoretical and experimental exercises gave the online students a means to collect data without being physically present, and to use regression analysis to obtain the coefficients of *f*, *g*, *h*, and *m*, while in-person students were able to make direct measurements, to observe the instabilities of the device, and also to use regression analysis to obtain the coefficients of *f*, *g*, *h*, and *m*. The aimed link between online/in-person students was attained.

Figure 4 – Measured vs. calculated values of *f* (see 7, 8a, b, c, d), generating a determination coefficient of R^2=0.990



Source: Authors.

TABLE 2
RESULTS OF THE PHYSICAL VARIABLES

Known			*Obtained*		
k_B *N/m*	k_F *N/m*	$L_{o(\text{zero-load})}$ *m*	k_B *N/m*	k_F *N/m*	$L_{o(\text{zero-load})}$ *m*
48.1	163	0.172	46.8	161.4	0.140

Source: Authors.

Experimental evolution of free end pairs (*x*, *y*)

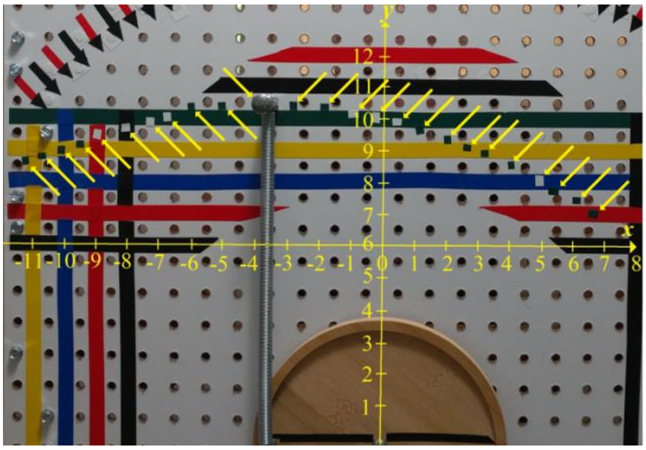
In this second part of the activity, equation (12a) should be checked. Already having, k_B, k_F, and L_o, they could be used in $\Lambda=(k_B/k_F)(1-L_o/L)L\cos(\omega)$ so that Λ=0.0781 m. Pairs (*x*, *y*) were collected for the unloaded machine (*W*=0) and α =~0. Five of the 272 furnished photographs satisfied α =~0. To obtain the needed 30 points, the in-person students should collect the extra 25 pairs (*x*, *y*) and share them with the online colleagues for analysis. One example is shown in figure 5. The pairs (*x*, *y*) for unstable events were marked with light and dark adhesive tapes and photographed. The *x*, *y* values could be measured from the image using a ruler or a digital plotting code (a decision of each group).

Table 3 shows the (*x*, *y*) pairs from Figure 5, and pairs marked with light brown taken from the set of 272 photographs. Figure 6 shows the measured (*x*, *y*) pairs and calculated with (12) and the obtained values of Table 2. It can be seen that the theoretical prediction follows the measured data, validating the measurements and calculations of the students.

This part thus also involved a short theoretical work to obtain (12), and an experimental work to measure the pairs (*x*, *y*) for comparison. This procedure gave once more the in-person and online students a way to interact through the generation of a solution and its corresponding analysis.

Instability or catastrophe free end pairs (*x*, *y*)

Figure 5 – Arrows show the adhesive tapes of the (*x*, *y*) points selected to test the theoretical solution for α=0



Source: Authors.

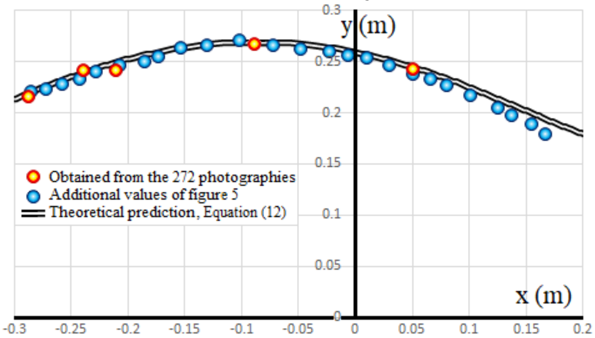
TABLE 3

ORDERED PAIRS (*x*, *y*) FOR α =0

N	*x* (*m*)	*y*(*m*)
1	-0.28702	0.21590
2	-0.23876	0.24130
3	-0.21082	0.24130
4	-0.08890	0.26670
5	0.050800	0.24257
6	-0.28489	0.220313
7	-0.27219	0.223602
8	-0.25790	0.228512
9	-0.24203	0.233430
10	-0.22857	0.240754
11	-0.20712	0.246506
12	-0.18567	0.250646
13	-0.17297	0.255547
14	-0.15395	0.263706
15	-0.13007	0.265439
16	-0.10225	0.270416
17	-0.07274	0.265726
18	-0.04802	0.262625
19	-0.02330	0.259523
20	-0.00654	0.256382
21	0.010215	0.253240
22	0.029402	0.246079
23	0.050988	0.238124
24	0.066177	0.232556
25	0.080570	0.226983

Source: Authors.

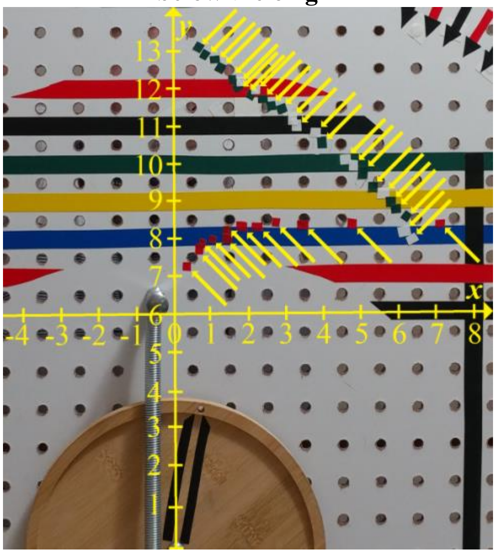
Figure 6 – Theoretical and experimental points for the condition α=0 in the Zeeman's machine. The observed data follow the theoretical trend developed in this activity



Source: Authors.

The instabilities of the device implied in sudden jumps of the angle of the wheel, to be expressed through best fit equations. Qualitative answers were based primarily on the localization of the ordered pairs of the jumps conducted in-person or through the explanation video provided in the online database (see Schulz and Simões, 2021a). The in-person students visited the laboratory also to generate the needed supplementary data. An example is presented in Figure 7. The positions of the free spring corresponding to the jump of the wheel were again marked with adhesive tape. The jump occurred for the joint of the springs passing "above the origin" or "below the origin", so that two sets of pairs (*x*, *y*) were marked, indicated by the two sets of arrows. After having obtained the photograph, the values of *x* and *y* could also be measured using a ruler or a digital plotting code.

Figure 7 – Upper set of arrows shows adhesive tapes locating pairs (*x*, *y*) for jumps of the junction point "above the origin". Lower set of arrows shows tapes locating pairs (*x*, *y*) for jumps of of the junction point "below the origin"



Source: Authors.

Table 4 shows 30 pairs for the "above the origin" jump, and 14 pairs for the "below the origin" jump. Again, the light brown pairs were taken from the 272 photographs. Regression analyses led to a linear equation for the jump above the origin, and a 4th order polynomial for the jump below the origin, shown respectively as (14) and (15). As mentioned, no correct order was asked to the students, as long as this question had a qualitative nature. The intent here was to draw attention to the instability. The graphs and comments of the students provided proof of mastery of this particular question.

$$y = 0.347 - 0.817x \qquad R^2 = 0.98 \quad (14)$$

$$y = 0.186 + 0.951x - 11.4x^2 + +54.8x^3 - 90.2x^4 \qquad R^2=0.75 \quad (15)$$

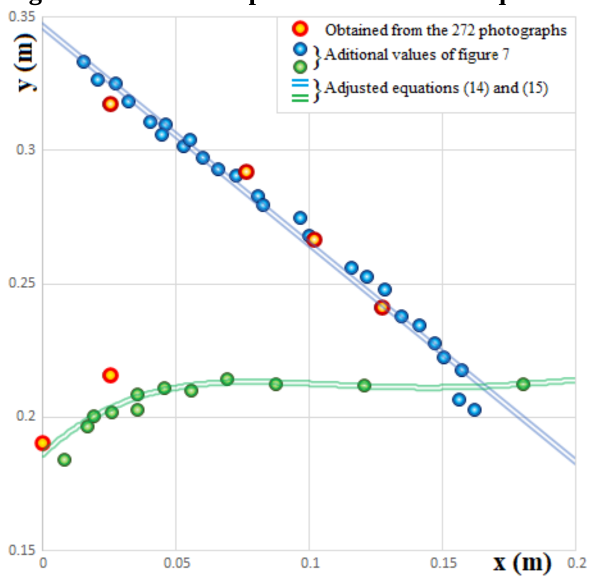
Figure 8 presents (14) and (15) and the measured data, showing effects of friction and of the length of rest D_o of the free spring for $0.125 \leq x \leq 0.180$

TABLE 4

	Jump above origin		Jump below origin	
N	*x* (*m*)	*y* (*m*)	*x* (*m*)	*y* (*m*)
1	0.0254	0.3175	0.0254	0.2159
2	0.0762	0.2921	0.0000	0.1905
3	0.1016	0.2667	0.0084	0.1839
4	0.1270	0.2413	0.0168	0.1963
5	0.0158	0.3334	0.0193	0.2004
6	0.0207	0.3267	0.0259	0.2020
7	0.0273	0.3250	0.0359	0.2028
8	0.0323	0.3183	0.0359	0.2086
9	0.0405	0.3108	0.0459	0.2110
10	0.0464	0.3099	0.0558	0.2101
11	0.0447	0.3057	0.0691	0.2141
12	0.0529	0.3015	0.0874	0.2123
13	0.0554	0.3040	0.1205	0.2121
14	0.0604	0.2973	0.1803	0.2124
15	0.0662	0.2931		
16	0.0728	0.2906		
17	0.0811	0.2830		
18	0.0827	0.2797		
19	0.0968	0.2746		
20	0.1001	0.2679		
21	0.1158	0.2561		
22	0.1216	0.2528		
23	0.1282	0.2477		
24	0.1348	0.2377		
25	0.1414	0.2343		
26	0.1472	0.2276		
27	0.1504	0.2226		
28	0.1571	0.2176		
29	0.1562	0.2068		
30	0.1620	0.2026		

Source: Authors.

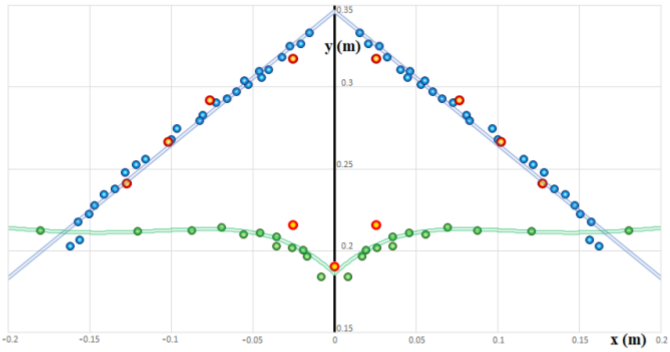
Figure 8 – Measured points and obtained equations



Source: Authors.

Figure 9 shows the symmetrical reflection of the results about the *y* axis, creating cusp-like forms for the two sets of points, which however are asymmetrical about the *x* axis. This part of the activity focused on the behavior of the machine. Online and in-person students had a means to discuss their observations and to propose a practical equation to model the phenomenon for the range of observed variations.

Figure 9 – Forming cusp-like forms by reflecting data and equations about the y axis. Same notation of Figure 8



Source: Authors.

APPLICATION DETAILS - DIDACTIC ASPECTS OF THE ACTIVITY

The activity filled the experimental learning gap during the transition involving online and in-person education due the COVID-19 pandemic. It may guide similar actions during exceptional conditions in which the usual mass-gathering of people in educational institutions must be avoided. The authors conducted the online activity to supplement students learning, intending to maintain the quality of the laboratory classes. The authors were inclined to also show its feasibility to educators engaged in fulfilling laboratory needs during online education.

Application strategy of the activity in the course

The competition form was decided on the start of the term. The University required to offer in-person and online classes, allowing the students to choose their format. The preferred classroom format was thus initially unknown, which naturally prevented the groups from being assigned for the competition, postponing its application. Independently of the competition activity, the performance evaluations of the classes were composed of 3 quizzes, 3 tests, 1 final exam, and also including grades of notes of each lecture and of weekly homeworks.

This condition induced to form the groups based on intermediary performance evaluations. Useful profiles of the classes were at hand after the first quiz and test (also with the notes and homeworks of the period), so that the groups were formed, and the competition was defined to begin between the first and the second test, in the midterm of the semester. The machine was of course already built.

Explaining video, set of 272 photographs, rules, and template for the Report were uploaded to the online database (also at Schulz and Simões, 2021a, b). The rules informed that the reports could be delivered any time to the instructor, being the final date the last class before the final exam. This time interval should allow the adequate understanding of the activity, data collection, and analyses.

Involvement of the students

7 groups with 4 to 5 participants were formed from the class rosters, and 6 groups decided to take part in the competition. It implied that, of a set of 30 students, 86.7% assumed a proactive posture and followed their groups in the participation. The highest performing students at the time of group formation were chosen as group leaders, although this was not announced. Note that having a high performance does not imply in being a leader, or to be able to induce a proactive posture to colleagues, but it was intended to guarantee the reading and the understanding of the problem within an adequate time. After understanding the activity, other group members may have been more proactive competing for the extra credit, inducing more efficiently the collaborative work of the group.

Despite the described intention, one group leader requested he separate from his group and take part in the competition individually. The instructor denied the request and stressed that collaboration was one of the primary goals of the activity.

The voluntary joining of 86.7% of the students showed that the activity was viewed positively among them. Some students were motivated by the possibility of increasing their final grades, showing that awards related to the grades of each student are a good strategy to induce participation.

Project reports

The template of the report contained the needed information on how to organize data and results, providing all groups with the same starting point.

Firstly, the reports were blindly evaluated by the instructor and the graduate teaching assistant. In this first phase the reports were analyzed for correct results and proper quality of explanation.

Secondly, a comparative analysis between the reports was made. It was observed that the students were not used to describe step-by-step procedures of experiments. Although focused on the problem, the answers did not detail duly the methodology. This aspect induces to suggest, for future online experiments, to furnish guides informing the level of details that will be valued. Examples of step-by-step derivation of equations, of reading variables from photographs, a review of simple and multiple linear regressions, would have guided the students in the problem, inducing more similar procedures.

The absence of homogeneity was not a difficulty for the evaluation of the activity, but showed the different background of the different groups. This aspect alone shows that online experiments with common databases can also be used to better equalize the background knowledge of the classes.

Group cooperation

Some groups naturally performed better as a team than others, with the reports showing two different focuses and styles in the writing of the groups: (1) the general introduction, and (2) the problem taken as the object of the activity.

Considering the introductions, in higher or lower degree each group valued its merit in conducting efforts to attain the presented results. This part allowed to recognize more personal or more group writings. Individualist postures were detected, like for example one report in which a decision was presented as "…our group and myself think that…". But the name of the leader-writer was not furnished. It seems that (this is not a conclusion, but a digression) the social evolution of sophomore students (the age as a possible parameter) endued them interaction tools that enable them to exercise self-promotion (in group or alone).

Considering the problem taken as the object of study, the texts were directed to the discussion of measurements and results, being focused on the theme of the competition. In this part of the reports the arguments were presented impersonally, like in usual academic descriptive texts, although, without detailing adequately the methodology.

The general impression was that the groups identified themselves as collaborative units worthy of attention (introductions) in the environment of the activity (solutions of the problem). This is a positive posture as group cooperation.

General observations of the activity

The described online laboratory experiment was an imposition of the COVID-19 pandemic. It induced a "quick-thinking/quick-solving" posture that led to positive results, and to suggestions for future applications of online experimental learning.

Positive results:

i) Engagement of the students.
ii) Evidence of coincidence between theory and practical results (increasing of confidence of the students).
iii) Interaction through online contacts.
iv) High level questions from online and in-person students.

Suggestions:

i) To furnish guides with procedures for the presentation of results.
ii) The guide should contain the basics of the tools (conceptual, mathematical) to be used.

CONCLUSIONS

The procedures of this study were built while setting up a strategy to conduct complex laboratory experiments in online Engineering classes. The need of these procedures was observed in the context of the COVID-19 pandemic, and may also help already structured online courses.

The online laboratory used a Zeeman's Machine for early Engineering students in the discipline of Statics. The machine showed to be well suited for experiments involving forces, moments of forces, and statistical tools of regression analyses. The explanation of the device through video, and the collecting of data from photographs showed to be adequate for online laboratory projects.

The activity demonstrated that it can be well used for online/in-person classes of Statics, being also suggested for online/in-person classes of Statistics (regression analyses) and Physics (forces and moments of forces).

The proposed theoretical derivations were obtained and further validated with experimental data, both activities conducted adequately by the students. Considering existing formulations for the Zeeman's machine, this study involves original equations, but which derivation is a basic exercise of equilibrium of forces and moments, adequate for sophomore Engineering students.

The students adhered well to the idea of having an online laboratory activity, and online students could interact well with in-person students. The interest on the activity increased with time, which is considered to be linked to the awards given in the form of points in the final grade of the discipline. In this sense, running the activity in the form of a competition (the best ranked groups would receive more points) induced more focused works. This is inferred from the increase of the quality of the questions to the instructor during the activity.

The material furnished to the students was composed by an explanation video, a set of 272 photographs for collecting data, the rules of the activity, and the template of the final report. It is suggested that future similar activities also furnish a manual informing basic aspects of the tools to be used (basic review of regression analyses, review of simple concepts of calculus, for example).

The present study furnishes procedures, results and theoretical derivations that are useful for similar applications of the Zeeman's machine. Different physical variables and questions may of course be proposed, which will certainly enrich the didactic deployment of online laboratory activities that will use this device. The authors understand this first application as a motivational study for new online laboratory classes, which are specially needed for exceptional times like the COVID-19 pandemic.

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