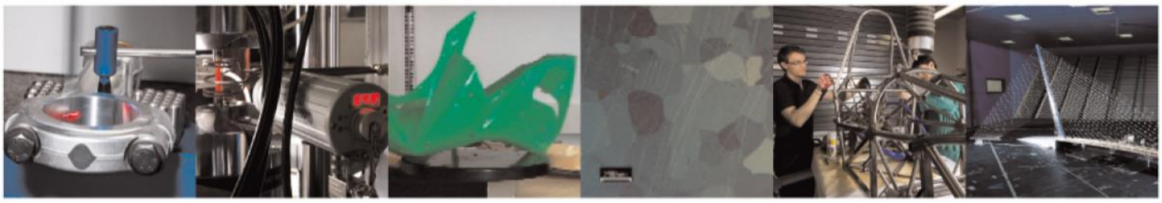

Active learning approach to enhance rotor dynamics understanding: A classroom demonstration

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This is a post-peer-review, pre-copyedit version of an article published in Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit. The final authenticated version is available online at: http://dx.doi.org/10.1177/09544097231163487

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Active learning approach to enhance rotor dynamics understanding: a classroom demonstration

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Abstract

In the last decades, novel teaching strategies have been increasingly adopted to improve and enhance students learning process by promoting their involvement and engagement during classes. In this context, this work presents a laboratory experience proposed to the third-year bachelor students of the course of "Mechanics of Vibrations", held at the faculty of mechanical engineering of Politecnico di Milano. The experience consisted in the presentation of a rotor test bench specifically designed for educational purposes. Main concepts of rotor dynamics were analysed and showed, together with a critical discussion on the discrepancies between Jeffcott-Laval model and experimental results. This project, that is one of the outcomes of an educational project for post-covid teaching promoted by Politecnico di Milano, involved almost two hundred students in total. An anonymous evaluation survey proposed to students revealed a general appreciation of the experience, especially for the possibility to visualize important theoretical concepts. Given the positive feedback, the demonstration will be repeated in the next academic year, with some changes according to students' suggestions.

Keywords: *Active learning-teaching, Jeffcott rotor, bending critical speeds, mechanical engineering, vibrations, rotor dynamics*

Introduction

A great portion of undergraduates engineering students are reported to find difficulties with topics featured by complex and highly abstract mathematical formulations[1,2]. Achieving teaching and learning objectives have become an even more demanding task for faculties during COVID-19 pandemic[3], both for students and lecturers. At its beginning, in 2020, this dramatic crisis forced universities to a sudden move from face-to-face lectures to online ones. That was certainly a moment for faculties to rethink and redesign some of their teaching activities[4,5], with the aim of making them more effective. According to the existing literature, novel active learning approaches[6,7], that may consist of assigned projects based on numerical simulations[8], laboratory experiences[9,10,11] or of experimental demonstrations[12], may ease and improve students' learning process. In this context, the present paper aims at investigating and demonstrating the positive contribution provided to students by an experimental demonstration held on rotor dynamics.

Rotor dynamics[13] is a key-topic when dealing with mechanics of vibration and it is the subject of this experience proposed to students. It consists of a topic not always easy to be handled and tackled by bachelor students of mechanical engineering. Therefore, to enhance students' deep understanding of the mathematical equations governing this physical phenomenon, an active learning activity was given during the course of "Mechanics of Vibration", taught in the second semester of the last year of the bachelor's degree in mechanical engineering at Politecnico di Milano. The starting model adopted in this work is the so-called Jeffcott rotor[14], which is a system commonly used to represent the physics of rotor dynamics. Starting from model equations, an experimental laboratory bench was designed and realized, with the aim of showing main theoretical concepts to students. In particular, for the present academic year, the focus of the demonstration was put on bending critical speeds, showing resonance phenomena occurring to rotating elements. Due to some construction constraints and design choices, a remarkable discrepancy between experimental and numerical results was found. This outcome represented an opportunity for discussing about the reasons of such difference directly with the students, during the demonstration, promoting critical thinking and analysis.

After the practical demonstration, given in front of almost two hundred students, an online anonymous questionnaire was administered to them: the same survey was proposed to students that attended the experience both in presence and online. Therefore, in this way, it was possible to quantitatively evaluate the effectiveness of this activity perceived by students participating in presence and in remote mode. The questionnaire showed promising results, pointing out a general good opinion of the students towards the proposed experience.

The paper is organized as follows: the first section is dedicated to the presentation of the main equations regarding Jeffcott-Laval model. The second section describes the test bench together with the proposed experience. The third section illustrates and describes the questionnaire provided to students after the demonstration. Results of the survey are presented and discussed in the fourth section. Finally, conclusions are drawn.

Jeffcott rotor model

Jeffcott rotor, even called Laval rotor, is a two-degrees of freedom system commonly adopted to introduce students to significant concepts regarding rotor dynamics, such as bending critical speeds. This model foresees a homogenous, simply supported, weight-free shaft, which rotates at a constant angular speed Ω. A thin disk of mass M is mounted on the rotor centre line and it is perfectly perpendicular to the rotor axis[14]. A schematic representation of the presented model is shown in Figure 1. From this scheme, it is clear that the disk centre of mass (COM) G is not coincident with the axis of rotation (in S): this aims to represent the fact that, due to small manufacturing imperfections, the rotor is generally unbalanced. In other words, an eccentricity is present along rotor axis, with a certain distribution. This eccentricity gives birth to inertial forces that excites harmonically the rotor. This excitation is detrimental since it leads to possible fatigue damages (and abrupt failures) and significant noise during operations. Referring to Figure 1b vector (S-O) represents the absolute position of disk centre, while (G-S) is the position of the COM of the disk relative to its rotation centre. Therefore, (G-O) which represents the absolute position of disk COM is the vectorial sum of (S-O) and (G-S) vectors.

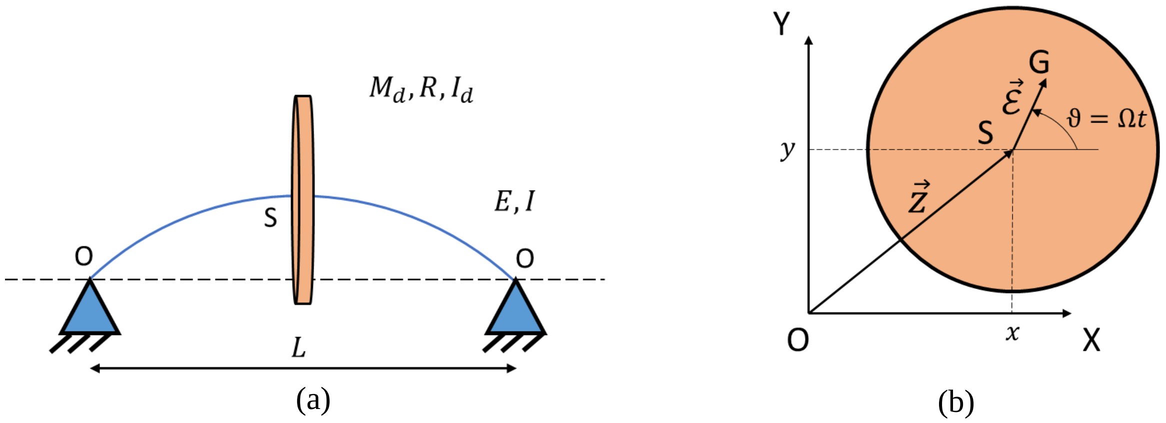


Figure 1. Jeffcott rotor scheme. (a): side view. (b): cross-sectional view.

The equations that are presented in this section holds in case the following assumptions are valid:

- Negligible damping.
- Negligible gyroscopic effect.
- Shaft with symmetric cross-section.
- Constant rotating speed Ω.

As mentioned before, Jeffcott rotor is a two-degrees of freedom system. The free coordinates describing system motion are gathered in the column vector $\boldsymbol{z} = (x, y)^T$. According to D'Alembert's dynamic equilibrium principle, it is possible to write the following equation:

$$\sum \boldsymbol{F_{ext}} + \sum \boldsymbol{F_{in}} = 0 \tag{1}$$

Which means that the external forces acting on the system and the inertial forces must be in dynamic equilibrium. In this regard, Figure 2 schematically represents the system of forces acting on the rotor's disk.

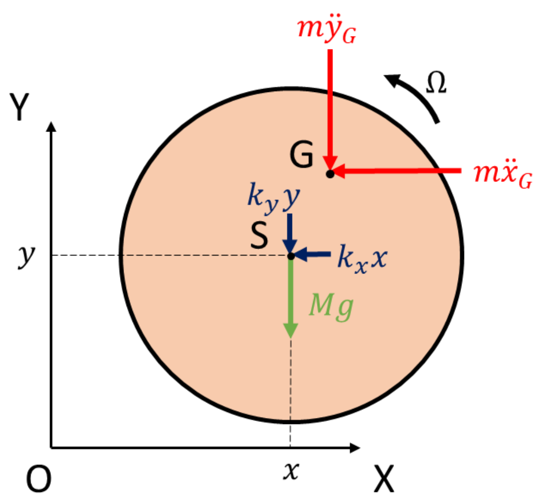


Figure 2. System of forces acting on the disk rotating at constant speed Ω.

Referring to Figure 1, Equation (1), since vectorial, can be de-composed by means of projecting it on x and y axes respectively, obtaining the following system of equations:

$$\begin{cases} -m\ddot{x}_G - k_x x = 0 \\ -m\ddot{y}_G - k_y y - Mg = 0 \end{cases} \tag{2}$$

Where x_G and y_G define the coordinates of the disk centre of mass (point G in Figure 1) according to the reference system X, Y. From the two equations of the system (2), it is possible to obtain the static deflection of the rotor due to its own weight:

$$\begin{cases} x_0 = 0 \\ y_0 = -\dfrac{Mg}{k_y} \end{cases} \tag{3}$$

Where the rotor stiffness k_y, given the symmetry of the shaft cross section (circular cross-section), is equal to k_x and defined according to the following equation, assuming that the shaft is simply supported:

$$k_x = k_y = k = \frac{48\,EI}{L^3} \tag{4}$$

Where *E* is the material modulus of elasticity (i.e., Young modulus), while *L* is the distance between shaft supports (see Figure 1a). Since the shaft is assumed to have a circular cross-section, whose diameter is *D*, *I* is therefore equal to:

$$I = \frac{\pi D^4}{64} \tag{5}$$

Given equation (2), it is possible to define a new vector of free coordinates $\tilde{\boldsymbol{z}} = (x - x_0, y - y_0)^{\,T}$ which now refers to the motion of the system about its static equilibrium position. In other words, we are interested in system's dynamic motion around its static deflection.

The next step is represented by the expression of disk COM absolute position. As mentioned before, there exists an eccentricity between the centre of mass of the disk and the axis of rotation. Therefore, referring to Figure 1b, it is possible to write:

$$\begin{cases} x_G = x + \mathcal{E}cos\ \Omega t \\ y_G = y + \mathcal{E}sin\ \Omega t \end{cases} \tag{6}$$

According to the new free coordinate vector $\tilde{\boldsymbol{z}}$, it is possible to write:

$$\begin{cases} x = \tilde{x} + x_0 \\ y = \tilde{y} + y_0 \end{cases} \tag{7}$$

Therefore, once expressed x and y as functions of $\tilde{x}$ and $\tilde{y}$ (refer to (7)), (6) becomes:

$$\begin{cases} x_G = \tilde{x} + x_0 + \mathcal{E}cos\ \Omega t \\ y_G = (\tilde{y} + y_0) + \mathcal{E}sin\ \Omega t \end{cases} \tag{8}$$

By a double time-derivation of (8), it is possible to attain the expression of disk centre of mass acceleration both in x and y directions:

$$\begin{cases} \ddot{x}_G = \ddot{\tilde{x}} - \Omega^2 \mathcal{E} cos\ \Omega t \\ \ddot{y}_G = \ddot{\tilde{y}} - \Omega^2 \mathcal{E} sin\ \Omega t \end{cases} \tag{9}$$

The expressions of $\ddot{x}_G$ and $\ddot{y}_G$can be finally substituted in (2), obtaining the following system of second order dynamic equations:

$$\begin{cases} m\ddot{\tilde{x}} + k\tilde{x} = m\Omega^2 \mathcal{E} cos\ \Omega t \\ m\ddot{\tilde{y}} + k\tilde{y} = m\Omega^2 \mathcal{E} sin\ \Omega t \end{cases} \tag{10}$$

On the right side of the equation, it is possible to observe the inertial forces that act as exciting terms on the rotor. From their analytical expression it can be noticed that when the rotor is rotating at high speed, even small eccentricities can head to high excitation forces. Considering the free motion, which means no inertial forcing terms on the right, and given the symmetry of the shaft cross-section, the system eigenfrequencies:

$$\omega_x = \omega_y = \sqrt{\frac{k}{m}} \tag{11}$$

Finally, the Frequency Response Function[14] can be expressed according to:

$$\frac{X_0}{\mathcal{E}} = \frac{Y_0}{\mathcal{E}} = \frac{m\Omega^2}{k - m\Omega^2} = \frac{(\Omega/\omega)^2}{1 - (\Omega/\omega)^2} \tag{12}$$

The expression obtained in (12) is a real quantity, since the damping is assumed to be negligible, and it can be represented by two diagrams: the first one regards the magnitude while the second refers to its phase. As shown in Figure 3, the former tends to infinity when the excitation frequency is equal to the system's eigenfrequency, while the latter reaches the value of -π/2. The system is said to be in resonance: the dynamic amplification of the motion is infinite, and the output Z (which stands for X_0 and Y_0) is in quadrature with the input. By introducing damping in the Jeffcott model (see orange curve in Figure 3), the FRF becomes a complex function: its module in resonance is now limited, since, differently from before, there is not a cancellation of the denominator, because the imaginary term remains. Moreover, the phase goes through a smoother change, moving from 0 to -π, reaching at resonance the value of -π/2.

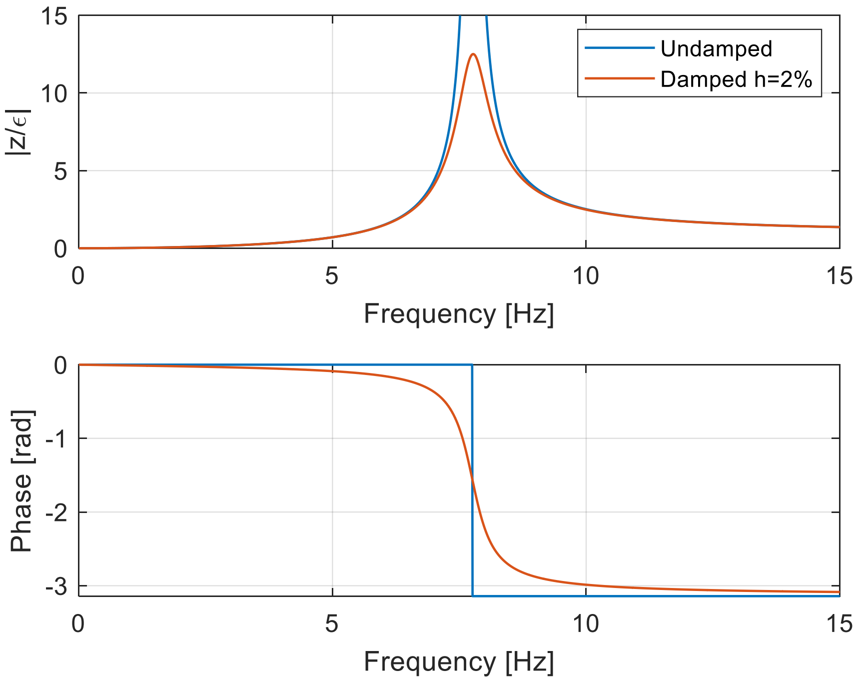


Figure 3. FRF in case of undamped (blue line) and damped (orange line) system.

The equations written so far were firstly faced by the students during lecture and briefly recalled again during the first part of the proposed activity, just before the experimental demonstration. Details are given in the relative section of the paper.

Classroom demonstration

Given the large number of students attending this course, it is difficult to propose hands-on experiences (e.g., PBL activities[9]), which would certainly be more engaging for the student and, consequently, more effective from an educational point of view. For this reason, instead of hands-on activities, a classroom experimental demonstration was organized, divided into two main parts: during the first one, the equations behind Jeffcott rotor formulation were briefly described and explained to students, by means of a group of slides. After that, the experimental test bench, physically present in the classroom was described in its main components.

Experimental test bench

As mentioned in the previous section, the subject of the proposed experience consisted of a visual demonstration of the concept of vertical bending frequencies, which is critical when dealing with rotor dynamics. The test bench used during the demonstration, shown in Figure 4, was firstly designed according to the following specifications:

- Shaft: cross-section with a diameter of 10 mm (*D* in Eq.5);
- Disk: diameter of 150 mm, width of 15 mm;
- Bearings distance of 1000 mm (*L* in Eq.4);

Both shaft and central disk were realized in steel, while bearing supports were made with aluminium and allow for the insertion in the system of an encoder to measure shaft rotation. The shaft can be manually put in motion by means of a pulley system, specifically designed to have a gear ratio equal to 8. This was done to ease the achievement of higher angular speeds for the user and therefore easily excite the rotor also in its seismic region.

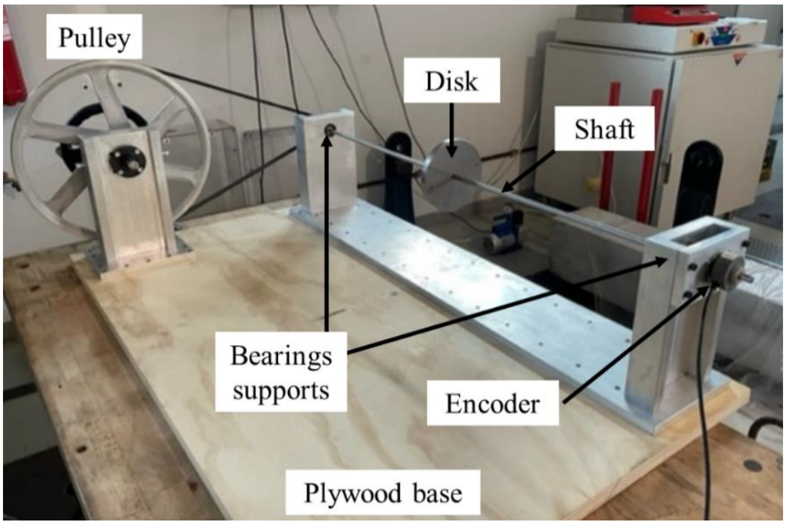


Figure 4. Experimental test bench. The main components of the system are highlighted.

Nominally, given the design specifications presented before, according to Jeffcott rotor assumptions and (11), the first bending frequency should result equal to 7.8 Hz.

Discussion about the differences between experimental and numerical results

To verify the correspondence of model and experimental results, in terms of dynamic behaviour, a first test was performed in front of the students to establish the experimental first bending frequency. The test consisted of hammering the central disk horizontally and measure its vibrations by means of a laser transducer: for the system, this impulsive excitation is equivalent to a situation of free motion with an imposed initial velocity. The time history of the disk displacement due to the hammering is shown in Figure 5a, while Figure 5b shows its resulting PSD function. A peak at 13.4 Hz was obtained, meaning that the first bending frequency of the experimental system (13.4 Hz) is much higher than the numerical one (7.8 Hz). This large discrepancy was critically discussed with students during the demonstration. Some of the students present in classroom, once asked about the possible reasons for this significant difference between numerical and experimental outcomes, tried to give a possible explanation. This interaction resulted in good feedbacks, in the sense that some of the students guessed the reason for this discrepancy: the first problem indeed, relies in the wrong estimation of the stiffness of the system.

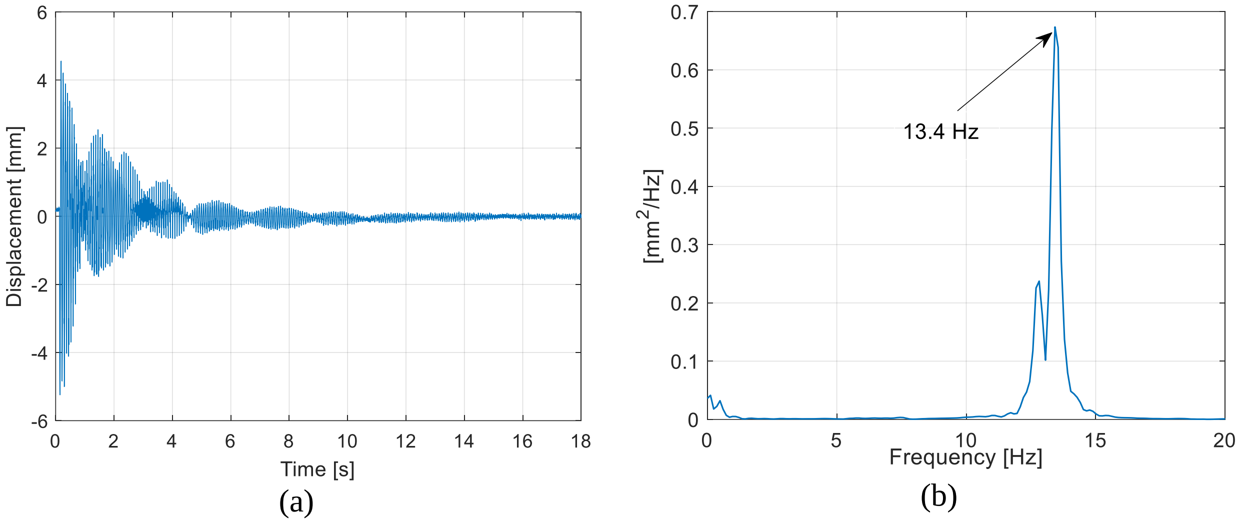


Figure 5. (a): Disk displacement due to the hammering action on the central disk. (b): PSD function of the time history in (a). A peak is highlighted corresponding to the first bending frequency of the system.

In fact, Eq. (4) refers to a case of simply supported beam, which means that at both ends shaft rotation are not constrained at all. This is not valid for the experimental bench: in fact, to avoid big motion of the shaft close to bearings support and allow for the insertion in the system of an encoder, the supports, consisting of double bearings, are more likely to be represented by fixed than hinge supports. In other words, a first difference between numerical and experimental results relies in that the test bench is much stiffer than the numerical model: the actual stiffness of the shaft must be indeed computed according to the following expression.

$$k_x = k_y = \frac{192\ EI}{L^3} \tag{13}$$

Substituting the stiffness expression in (13) inside equation (11), a new eigenfrequency is obtained, equal to 15.5 Hz. This value is closer to the experimental outcome (refer to Figure 5b) than the numerical one obtained considering a simply-supported beam, but still a difference of the 13.5 % is observed.

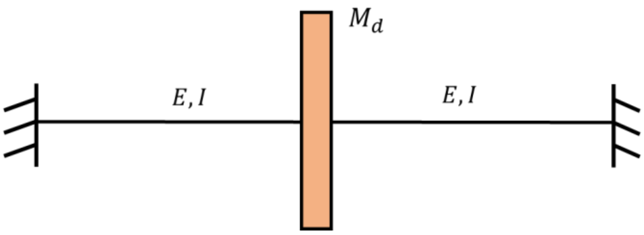


Figure 6. System scheme with fixed ends instead of hinged supports.

At this point, the students were again asked about this residual discrepancy between the experimental evidence and the numerical results. Also in this case, a student guessed the reason for the observed difference, which simply relies in that the model, even if updated in terms of stiffness, is still not able to properly represent the system. In fact, a basic assumption of the Jeffcott rotor is that the shaft is weight-free, or at least that its mass is negligible if compared to the disk one. This assumption is not valid for the presented test bench, since the mass of the shaft is about the 30% of the disk one, which is not a negligible percentage indeed.

A more sophisticated model, that is more representative of the actual behaviour of the system, is represented by a beam, fixed at both ends, with distributed mass, plus a central concentrated mass, representing the disk (see Figure 7). In this way, the rigidity of the constraints (double bearings) is taken into account, as well as the inertia of the rotor shaft. Studying this new system, modelled as a continuous deformable body, the obtained bending frequency is 13.5 Hz, that is very close to the numerical one (i.e., difference of 0.7%). The students were directly given this result, but not the analytical calculations to get to it, since this procedure is out of the scope of this course and it will be part of the subjects treated in future courses of the master degree in mechanical engineering.

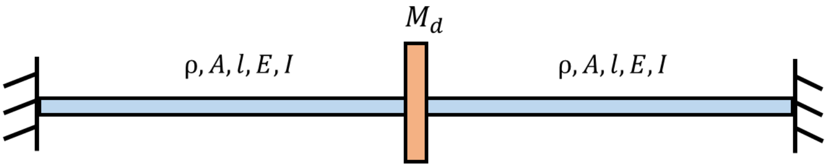


Figure 7. Improved model: shaft (light blue) with distributed mass, and a central concentrated mass (light orange) modelling the disk.

Critical bending speed

The second part of the experience consisted instead of a visual demonstration of the three different phases of the rotor dynamic motion, namely quasi-static, resonance, and seismic regions (shown in Figure 3). In particular, the focus was put on resonance, to help the students visualizing the concept of critical bending frequencies. In fact, when the rotor rotates at a speed Ω that is equal to the circular frequency of the system (refer to expression (11)), the system is excited at resonance: that angular speed is referred to as critical bending speed. This condition leads to high dynamic amplification of the rotor motion around its static deflection. Therefore, it represents a critical scenario for the integrity of the rotor, since featured by high oscillation, which result also in significant dynamic loads on the bearings. It is then clear that resonance condition represents an operating scenario that is particularly detrimental in presence of high intrinsic unbalance of the system (high eccentricity), which means higher inertial forces acting on the rotating shaft.

Thanks to the pulley system, shown in Figure 4, the rotor was put in motion manually by one of the lecturers present in classroom during the demonstration. The system motion, plotted in Figure 8, was recorded in real time: the disk displacement was acquired by means of a laser transducer (see Figure 8a), while the shaft angular velocity was computed starting from the measurement of a digital encoder (see Figure 8b). It is clear that Figure 8 represents disk lateral displacement when the rotor is around its resonance condition: high oscillations are then reached, with peak amplitude of 10 mm. As expected, this scenario takes place when the shaft angular velocity is close (or equal to) the rotor critical bending speed, namely 13.4 Hz. This frequency means a critical angular speed of 84.4 rad/s, as shown by the dashed red line in Figure 8b.

Therefore, after a theoretical and critical discussion about the rotor dynamics modelling, the students had the possibility to observe and visualize rotor motion under different operating conditions. After the demonstration, thanks to the time acquisition of disk displacement and shaft rotation, the curves in Figure 8 were shown and analytically described.

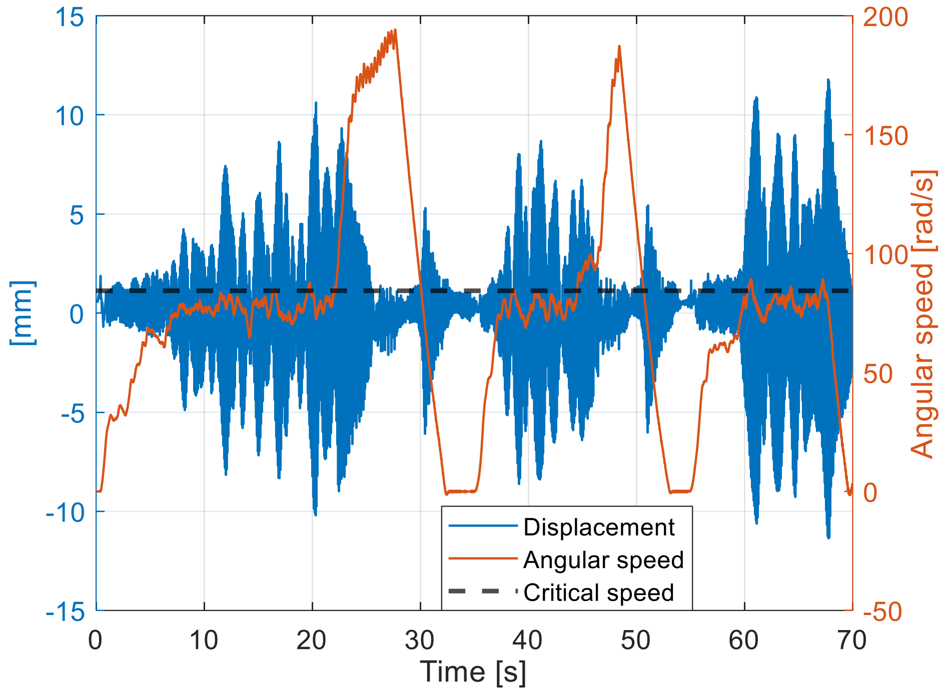


Figure 8. Disk displacement measured by the laser transducer (blue) and shaft angular speed computed from encoder measurements (orange).

Questionnaire formulation

The described experience on Jeffcott rotor was proposed for the first time during the present academic year. To get a quantitative evaluation of the activity, a questionnaire was administered to students. The online survey, completely anonymous, was divided into two sections. The first one asks the students to provide a rate on a five-point Likert scale[15] to five sentences regarding the experience. Namely, the students were asked to express their agreement (1 total disagreement, 5 total agreement) with the following sentences:

1. The experience was clearly proposed and described.
2. The experience improved your comprehension and understanding of the problems related to rotor dynamics.
3. The experience improved your approach to technical problems.
4. The theoretical explanation was sufficient for the comprehension of the shown phenomenon.
5. I would repeat the experience.

It is then clear that the purpose of the first section of the survey is to globally evaluate the perception by the students of the effectiveness of the activity in enhancing their understanding of the phenomenon, by means of a practical perspective.

Instead, in the second part of the questionnaire, the students were asked to answer two open questions, that are the following:

1. What did you appreciate the most?
2. Do you have any suggestions for improving the experience?

Therefore, the second part of the survey aims to get a deeper understanding about what worked and did not, according to students (both in presence and connected from remote) perception, collecting suggestions for future repetitions of the activity. In this way, it will be possible to fix possible issues and apply changes to further improve the experience before it will be repeated during next academic year.

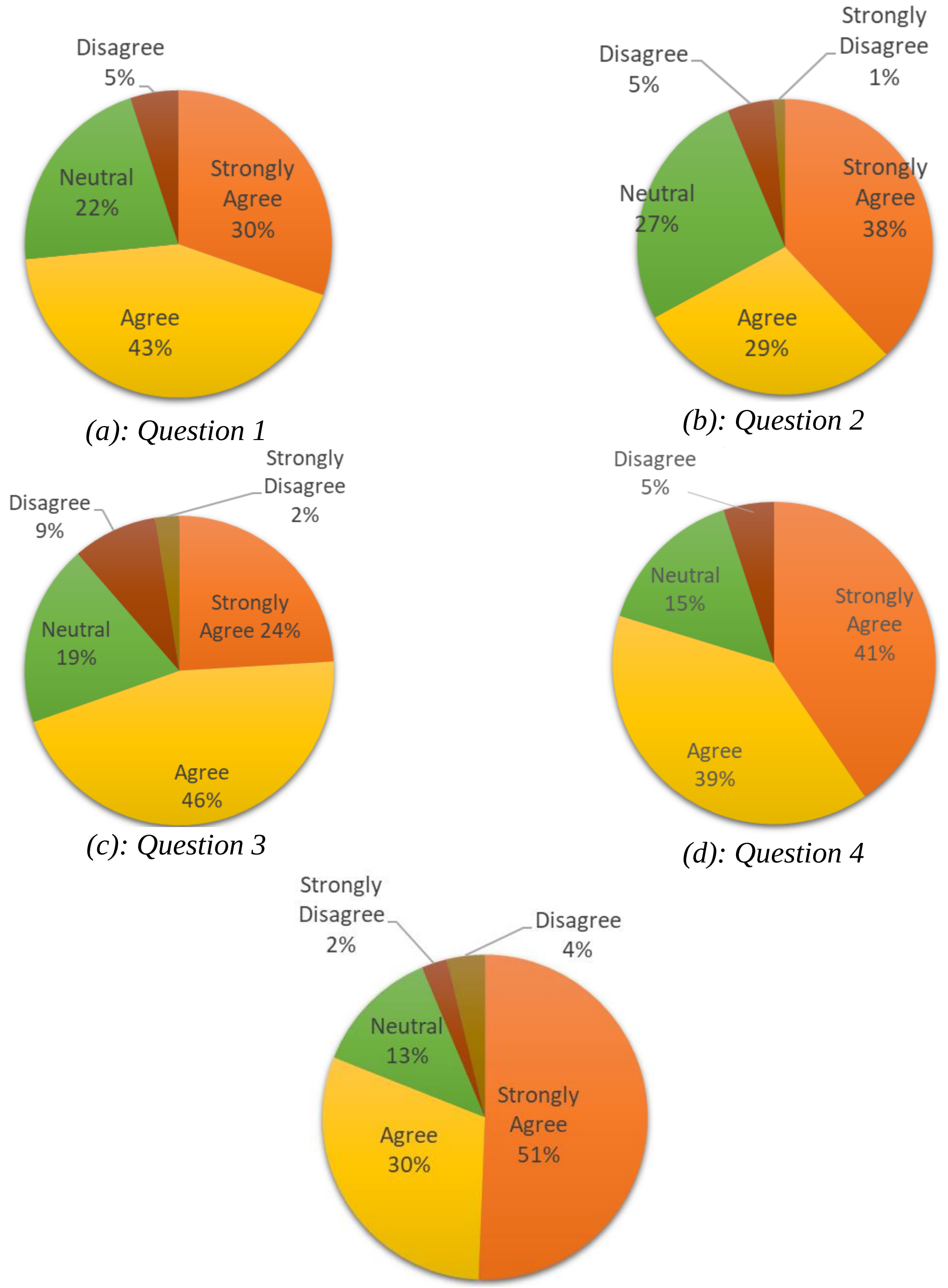
Results

The questions presented in the previous section were administered to students through a voluntary online survey. As mentioned previously, the number of students participating to the experimental demonstration in presence and in remote were about two hundreds. Instead, the total amount of feedbacks received by means of the proposed online survey are 79: 62 of them by students participating in presence, 17 from remote.

Table 1 gathers the results regarding the first part of the questionnaire: a general appreciation of the experience by students of the experimental demonstration can be observed. In particular, as witnessed by Figure 9, the 67% of the students participating to the survey declare that the experimental demonstration improved their understanding of the problems related to rotor dynamics. Moreover, the 80% of the students, which means their great majority, state that they would repeat the experience. The lowest score resulted from the third question, where, anyway, the 68% of the students declare to agree or strongly agree on the idea that the experimental demonstration improved their approach to technical problems. According to authors, this outcome comes from the fact that students attend few experimental activities during their bachelor, and they would like to perform the proposed experience first-hand, according to a learning by doing approach[15], but, in this case, the number of students in the classroom make it unfeasible.

Table 1. Outcomes collected from the first part of the questionnaire.

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly disagree	Mean score
1	22	34	17	4	0	**4.00**
2	29	22	21	4	1	**3.97**
3	18	35	15	7	2	**3.80**
4	31	30	12	4	0	**4.15**
5	38	24	10	2	3	**4.22**



(a): Question 1
(b): Question 2
(c): Question 3
(d): Question 4
(e): Question 5

Figure 9. Statistical analysis of the answers (from 1 to 5) provided by students to the first part of the questionnaire.

A further analysis on collected data from students' questionnaire was made up, dividing the total number of feedbacks in two categories: namely, feedbacks by students that participated from remote and in presence. Table 2 highlights some differences in terms of medium score for the five administered questions, but, in general, the results are similar. The difference between medium scores regarding the two categories (i.e., remote and in presence) does not always point towards one side, meaning that, from this sample of data, it is not possible to clearly outline that one of the two modalities was perceived by students as more effective than the other. Given that the authors strongly believe that the most effective teaching modality is the one held in presence, the obtained outcomes point out that satisfying results, in terms of teaching goals, were achieved also for students from remote. Since the proposed demonstration is an experimental activity, this outcome was not expected.

Table 2. Comparison between medium scores given by students in remote and in presence.

Question	Presence	Remote	Global
1	4.02	3.88	4.00
2	3.94	4.12	3.97
3	3.82	3.71	3.80
4	4.18	4.06	4.15
5	4.20	4.29	4.22

For what concerns the second part of the questionnaire, most of the students participating to the survey point out as a very positive aspect the fact that, thanks to the experimental demonstration, they had the possibility to visualize a phenomenon studied in theory. Some students proposed to repeat this kind of activity also for other topics, meaning that they found it useful. Moreover, some suggestions came out from the second question of this part of the survey: a number of students suggested to propose the experience in a larger classroom with step benches, in order to ease the sight of the bench, or to divide the class in smaller groups. For the next year, the demonstration will be given in a classroom that may better allow students to follow it. Moreover, the presentation slides will be given in advance, in order to ease their comprehension and make the experience more effective, from a didactical point of view.

Conclusions

This paper presents an experimental demonstration proposed to the students of the course of "Mechanics of Vibrations", held during the second semester of the third year of the BSc in Mechanical Engineering. The demonstration consisted in the presentation and discussion over a test bench specifically built up to help students visualize the main concepts related to rotor dynamics. The purpose of the work was to improve and promote students' engagement during the course, by enhancing their deep understanding of the governing mathematical equations behind the theory of rotor dynamics. Another important aspect of the demonstration consisted in a critical discussion over the difference between numerical model and experimental results. The students were asked to bring their thoughts and opinions on the possible causes of such a difference: according to authors belief, this kind of discussion represents an important tool for the improvement of student's engagement and critical understanding of the topic. Moreover, the students had the possibility to quantitatively experience the effect and influence of modelling choices over the capability of a model to properly represent experimental phenomena.

At the end of the demonstration a questionnaire was proposed to students: the survey was made up of two parts, one based on a five points Linkert scale, while the second consisted of two open questions. According to survey feedbacks, the work led to the following outcomes:

- Overall, students appreciated the proposed experimental demonstration, which allows them to visually experience what they learnt during lecture.
- The proposed experience was beneficial for improving students' comprehension and understanding of the problems related to rotor dynamics.
- The difference observed between state-of-the-art Jeffcott rotor model and the outcomes from experiments resulted into an occasion to discuss on the fact that models with increasing complexity may be capable to give a more accurate quantitative description of a physical phenomenon, while simpler ones can be sufficient to provide a qualitative description able to capture its nature.
- No significant differences were observed in terms of perceived effectiveness of the demonstration for students following from home or in presence.
- The 80% of the students would repeat the experience. Given this result, the experience will be proposed next year, with some adjustments according to students' suggestions. In particular, it will be held in a bigger classroom, with step benches, and the related handouts (i.e., introduction slides) will be made available in advance.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship and/or publication of this article.

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