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ISSN 1645-4774 | e-ISSN 2183-038X
https://www.eduser.ipb.pt

INSTITUTO POLITÉCNICO DE BRAGANÇA

Submetido: 2024-08-31 | Aceite: 2024-12-14 | Publicado: 2024-12-18

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ABSTRACT: This study investigates the applicability of descriptive statistics in teaching oscillatory motions through experiments. Using test bench, it was evaluated the effectiveness of a passive damper in mitigating vibrations in a single-degree-of-freedom system. The educational approach incorporated practical experimentation to reinforce the theoretical understanding of oscillatory systems and damping, aligning with active learning methodologies and critical thinking. The results demonstrate that using water as the operating fluid in the damper not only provides a practical and accessible solution for vibration attenuation but also promotes a teaching methodology that develops students' critical thinking and practical skill. This methodology, by integrating the philosophy and teaching methodologies in engineering education, proves to be replicable in other areas, promoting a more practical and interactive education.

KEYWORDS: Descriptive statistics; Engineering education; Teaching by experimentation.

RESUMO: Este estudo investiga a aplicabilidade da estatística descritiva no ensino de movimentos oscilatórios por meio de experimentos. Utilizando uma bancada de ensaio, avaliou-se a eficácia de um amortecedor passivo na mitigação de vibrações em um sistema com um grau de liberdade. A abordagem educacional incorporou experimentação prática para reforçar a compreensão teórica sobre sistemas oscilatórios e amortecimento, alinhando-se às metodologias ativas de aprendizagem e pensamento crítico. Os resultados demonstram que a utilização de água como fluido operante no amortecedor não só oferece uma solução prática e acessível para atenuar as vibrações, mas também promove uma metodologia de ensino que desenvolve o pensamento crítico e a habilidade prática dos estudantes. Esta metodologia, ao integrar a filosofia e metodologias de ensino em engenharia, mostra-se replicável em outras áreas, promovendo uma educação mais prática e interativa.

PALAVRAS-CHAVE: Estatística descritiva; Educação em engenharia; Ensino por experimentação.

RESUMEN: Este estudio investiga la aplicabilidad de la estadística descriptiva en la enseñanza de movimientos oscilatorios a través de experimentos. Utilizando un banco de pruebas, evaluado la eficacia de un amortiguador pasivo en la mitigación de vibraciones en un sistema de un solo grado de libertad. El enfoque educativo incorporó la experimentación práctica para reforzar la comprensión teórica de los sistemas oscilatorios y el amortiguamiento, alineándose con las metodologías de aprendizaje activo y pensamiento crítico. Los resultados demuestran que el uso de agua como fluido operante en el amortiguador no solo ofrece una solución práctica y accesible para atenuar las vibraciones, sino que también promueve una metodología de enseñanza que desarrolla el pensamiento crítico y la capacidad práctica de los estudiantes. Esta

e202417 | Doi: https://doi.org/10.34620/eduser.v16i2.323

metodología, al integrar la filosofía y las metodologías de enseñanza en ingeniería, demuestra ser replicable en otras áreas, promoviendo una educación más práctica e interactiva.

PALABRAS CLAVE: Estadística descriptiva; Educación en ingeniería; Enseñanza por experimentación.

1. Introduction

The importance of education, particularly in engineering, extends beyond mere transmission knowledge. It is a complex process of pedagogical communication that prepares students for social and professional challenges (Brophy et al., 2008; Gillespie Rouse & Rouse, 2019). In engineering education, practical application and experimentation are teaching activities that can provide a deeper understanding of theoretical concepts (Magin & Kanapathipillai, 2000). Implementing experiments, such as systems with passive dampers that control oscillatory motions, not only facilitates a more practical and engaging approach but also promotes a broader understanding of oscillatory motions and their applications in vibration analysis. This creates a bridge for students to integrate theoretical knowledge with real-life practice (Pan et al., 2010).

The Tuned Liquid Column Damper (TLCD), a passive device, has been studied and applied to control vibrations in different types of systems effectively (Gao et al., 1997). However, the existing literature does not readily present the use of TLCD for educational experiments. Most studies focus on the development, modeling, and practical application of these devices for vibration control in structures without a direct connection to didactic or pedagogical experiments within the context of science or engineering education (Altunişik et al., 2018; Cao et al., 2020; Chakraborty et al., 2012; Di Matteo et al., 2015).

The operating principle of a TLCD is based on the movement of liquid within a column, with its natural frequency tuned to match the frequency of the structure which is intended to control. Figure 1 illustrates some variables involved in its motion phenomenon. The fundamentals of physics and the applications of TLCD technology, as discussed by Chakraborty, Debbarma, and Marano (2012) regarding its effectiveness in structural vibration control, provide a starting point for developing educational experiments. To this end, the present study uses a test bench to learn about oscillatory motions. Although initially designed for non-parametric statistical models, it also facilitates engineering students' demonstration of how TLCDs function and how descriptive statistics can be applied to demonstrate their effectiveness in mitigating mechanical vibrations.

This study recognizes both the importance of integrating experimental practices into engineering education and the gap that exists in the didactic application of devices like the TLCD. Based on this, it aims to investigate the feasibility of descriptive statistics in assessing the effectiveness of a passive damping device—specifically a TLCD coupled to a single-degree-of-freedom system. The effectiveness of such a device refers to its ability to mitigate the system vibrations mentioned above. To fulfill this purpose, the research has the following primary objectives: (i) to identify suitable methodologies for integrating descriptive statistics into vibration analysis; (ii) to understand the principles involved in vibration analysis and its conventional treatment; and (iii) to explore the role of descriptive statistics both as an analytical tool and as a pedagogical resource in engineering education. This approach aims not only to deepen students' technical understanding of damping systems but also to highlight the applicability of descriptive statistics in interpreting experimental data, fostering an integrated and applied learning experience.

2. Background

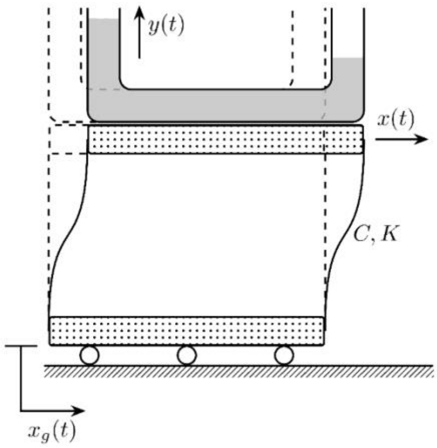
2.1 Philosophy and teaching methodologies used in engineering education

In engineering education, various theoretical proposals have been highlighted in the academic literature focused on teaching and learning. In recent years, there has been a prevalence of methodologies that emphasize critical thinking skills (Ahern et al., 2019), the formulation and application of the STEM approach (Science, Technology, Engineering, Mathematics), and active learning methodologies (Reis et al., 2023). However, when considering the application of these methodologies in engineering education, it is necessary to reflect on the training of the instructors who will implement them and to recognize that engineers with a bachelor's degree can also assume roles as educators in higher education or vocational courses. In this context, Souza (2019) notes that there is a tendency for engineering educators to reproduce conservative methodologies. However, as they gain teaching experience, they move away from a hegemonic educational model, rooted in technical rationalism and traditional academic formation, towards an emerging educational model founded on reflection, research, and critique (Souza, 2019).

It is not difficult to recognize that the practice of engineering requires critical thinking, in addition to practical and inventive intelligence. This need reflects the complexity and dynamics of the contemporary challenges faced by professionals in the field, which go beyond the application of technical knowledge and encompass the ability to analyze, question, and innovate in the face of complex and multifaceted problems. For example, Ahern et al. (2019) emphasize that critical thinking skills enable engineers to more effectively assess the implications of their decisions, considering both technical aspects and interpersonal, social, economic, and environmental impacts. According to the researchers, there is a gap between what newly graduated engineers can demonstrate and what employers expect from them regarding critical thinking. However, the implementation and evaluation of methodologies that promote this competence remain a challenge in engineering education, as "there is little clarity on the relationship between how critical thinking is taught and how it is assessed" (Ahern et al., 2019, p.3).

Figure 1

Illustration of a single-degree-of-freedom system with an attached TLCD, where $\boldsymbol{x(t)}$ *is the system displacement,* $\boldsymbol{y(t)}$ *is the fluid displacement within the TLCD,* $\boldsymbol{C}$ *and* $\boldsymbol{K}$ *are the damping coefficient and stiffness constant, respectively, and* $\boldsymbol{x_g(t)}$ *is the excitation force acting on the system.*



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The reintegration of the concepts of *techné* (art, technique), *lógos* (reason, word), and *métis* (cunning, inventiveness) in engineering education, as discussed by Aravena-Reyes (2016), proposes an educational model that values cunning and innovation, which are essential skills for developing innovative technical solutions and promoting critical thinking. Aravena-Reyes suggests that the lack of training in inventiveness may contribute to misunderstandings and criticisms regarding the role of engineers in contemporary technical production, arguing that engineering should extend beyond problem-solving to include the invention of solutions in response to a dynamic and variable reality.

Among the teaching techniques available are Problem-Generating Discussions, the STEM approach, and Active Methodologies, which have been discussed, respectively, by Machado and Pinheiro (2010), Oschepkov et al. (2022), and Reis, Alves, and Wendland (2023). However, implementing such methodologies may face obstacles for various reasons, including the lack of academic training for instructors in any of these teaching models and the absence of clear definitions of the methodologies or how to assess learning effectively. Pugliese (2020) specifically addresses the challenges related to the STEM technique, indicating that "the term today carries a much more complex and entangled connotation of meanings... it is still a confusing and ambiguous term" (Ibid, authors' translation).

To overcome the challenges discussed and seek an effective integration of descriptive statistics in teaching oscillatory motions through experiments, one can consider the work of Hassan (2011), who critically reviews learning theories from the engineering education perspective. Hassan proposes aligning relevant assessment methods with each learning theory: Behaviorism, the historical-cultural learning school (Vygotsky), and the cognitive/constructivist learning school (Piaget). Thus, following the findings and adapting the author's suggestions as mentioned earlier, integrated learning methods can be combined, considering cognitive levels, social factors, teamwork, and behavioral elements, to optimize the educational process for engineering students.

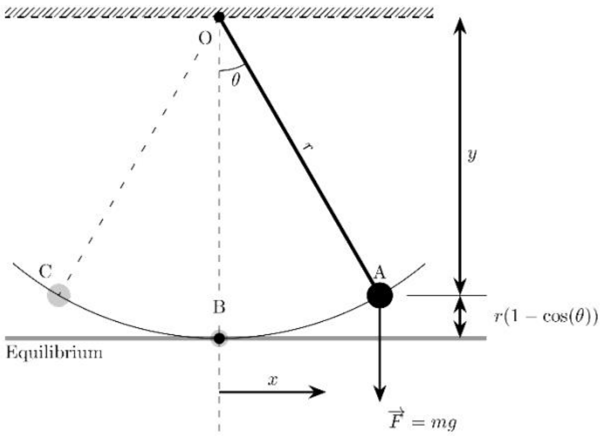
2.2 Vibrations and classical approach to their analysis

In mechanical systems, oscillatory motion, known as vibration, is the repetitive movement of a body or system around an equilibrium position, typically in response to an external force (Dimarogonas, 1990; Meirovitch & Parker, 2001). Understanding how different systems respond to stimuli—such as periodic forces or time-varying loads—is key. A vibratory system comprises elements that store potential energy (spring), kinetic energy (mass), and dissipate energy (damper) (Rao & Griffin, 2017). In conservative systems, energy alternates between potential and kinetic forms during oscillation, as illustrated by a simple pendulum experiment (Erol & Oğur, 2023).

Consider a pendulum, as shown in Figure 2, displaced to position A, where its velocity and kinetic energy are zero, but it has maximum potential energy. When released, the pendulum swings, converting potential energy into kinetic energy until it reaches position B, then continues to swing to position C due to momentum. This oscillatory process repeats until damping forces, such as air resistance and friction at the pivot, gradually reduce the amplitude, bringing the pendulum to rest at equilibrium (Rao & Griffin, 2017; Rossini et al., 2024).

Figure 2

Illustration of a simple pendulum vibration.



Source: Produced by the authors

In summary, vibration analysis can be described as shown in Equation (1) (Paez, 2006), which can be scalar or vectorial, where X represents the response of the system, for example, displacement; if there is a dot above it, it denotes differentiation concerning time t. Additionally, Q represents the excitation, a represents the system parameters, and $g(.)$ is the deterministic function that relates the previous quantities to the derivative of the response. Figure 3 provides a generic illustration for Equation (1).

$$\dot{X} = g(X, Q, a), \qquad X(0) = X_0, \qquad -\infty < t < \infty. \tag{1}$$

Figure 3

Basic scheme of excitation, system, and response in vibration analysis.

Source: Adapted from Paez (2006)

In terms of difficulty, the complexity of the analysis increases when dealing with systems with multiple degrees of freedom. The degrees of freedom of a system are defined by the number of independent variables required to describe its state fully. Basically, as explained by Rao and Griffin (2017), the analysis of a vibratory system often involves mathematical modeling, derivation of the governing equations, solution of the equations, and interpretation of the results.

For example, consider the classic case of a simple pendulum, illustrated in Figure 2, using a conventional approach to vibration analysis. Its motion can be described using the angle θ or the Cartesian coordinates x and y. If we use the Cartesian coordinates, x and y are not independent. In fact, by the Pythagorean Theorem, they are related to each other as follows: $x^2 + y^2 = r^2$, where r is a positive constant. Therefore, only one of the coordinates describes the pendulum's motion. Thus, we have a system with one degree of freedom. However, for practical purposes, it is more convenient to choose θ as the independent coordinate for the equation of motion of the simple pendulum.

In a conventional perspective, the next step in vibration analysis would be to obtain the governing equations for the simple pendulum, i.e., its equation of motion. When the pendulum of mass m is displaced from its equilibrium position to point A (see Figure 2), it experiences a restoring force due to gravity g. The component of this force that acts in the tangential direction of the pendulum's motion is given by Equation (2). The resulting torque on the suspension point is the product of the restoring force and the length of the rod, which can be expressed by $-r \cdot \overrightarrow{\mathrm{F_t}}$. The negative sign indicates that the torque is restoring, bringing the pendulum to equilibrium (Nussenzveig, 2014). On the other hand, Newton's second law for rotation ensures that the torque is also equal to the moment of inertia of the pendulum, which is obtained by $m \cdot r^2$ multiplied by the angular acceleration, which is $\mathrm{d}^2\theta/\mathrm{dt}^2$ or simply $\ddot{\theta}$. Combining the expressions for torque, substituting $\overrightarrow{\mathrm{F_t}}$, and simplifying, we arrive at Equation (3), which describes the motion of the simple pendulum.

For angles in radians, we can use the approximation $\theta \ll 1 \Rightarrow \sin(\theta) \approx \theta$ for small θ. The notation $a \ll b$ indicates that a is much smaller than b, making a insignificant or negligible in comparison. With this, the governing equation for the motion of the simple pendulum reduces to Equation (4).

$$\overrightarrow{\mathrm{F_t}} = m \cdot g \cdot \sin(\theta). \tag{2}$$

$$\ddot{\theta} + \frac{g}{r} \cdot \sin(\theta) = 0. \tag{3}$$

$$\ddot{\theta} + \frac{g}{r}\theta = 0. \tag{4}$$

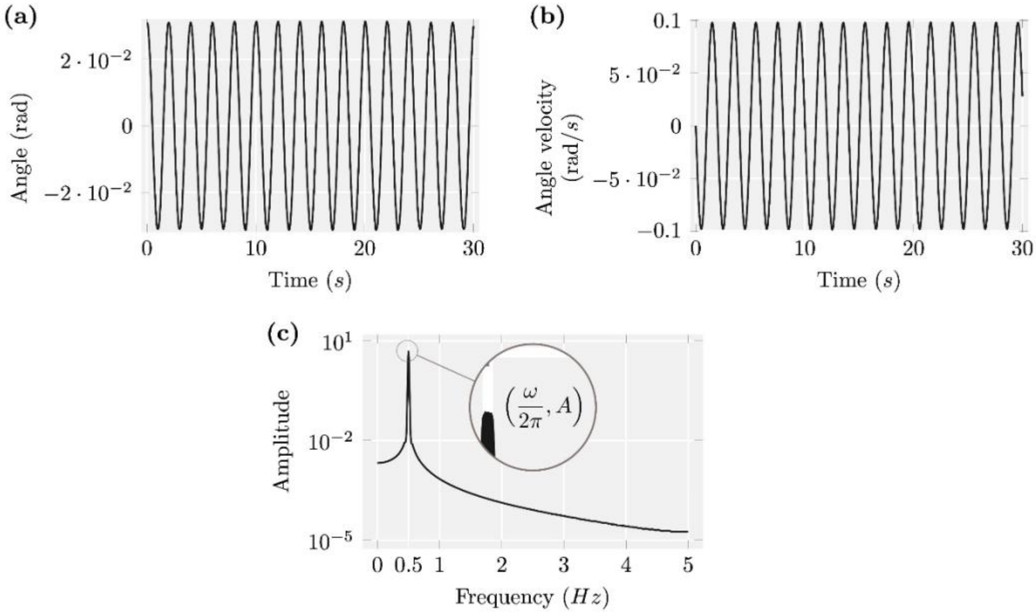
From Equation (4), it is possible to analyze the vibrational dynamics of the pendulum. By defining $g = 9{,}81\, m/s^2$, $r = 1$, and using a numerical simulation with initial conditions of a displacement angle of $\pi/100$ rad and an initial angular velocity of zero, and considering a time interval of 30 seconds, we generated the graphs presented in Figure 4a and Figure 4b. These illustrate, respectively, the variations in displacement amplitude θ and angular velocity $\dot{\theta}$ of the pendulum over time without the influence of dissipative forces.

Following the analysis, by applying the Fast Fourier Transform (FFT) (Rao & Griffin, 2017, chap. 10) to the amplitude data, we obtain the frequency spectrum of the pendulum shown in Figure 4c. This transformation allows us to visualize the main vibration frequencies of the pendulum, meaning that the analysis shifts from the time domain to the frequency domain. The data were simulated using the R programming language (R Core Team, 2023) with the deSolve package (Soetaert et al., 2010). Theoretically, the dominant frequency should be $f = \omega/2\pi$, where $\omega = \sqrt{g/r}$ is the natural frequency of the simple pendulum and is associated with the maximum spectral amplitude A. Indeed, substituting the assumed values, we have $f \approx 0{,}5\, Hz$, which is consistent with the simulated data.

As noted, introducing students to oscillatory motion and vibration analysis through a classical approach requires at least prior knowledge in multivariable calculus, differential equations, and numerical analysis. However, to understand the functioning of vibrational systems and the effectiveness of dampers in mitigating oscillatory motions, an alternative approach can be adopted. Revisiting the discussion from the previous subsection, integrating descriptive statistics into vibration analysis offers a less arduous path. Moreover, this approach may align with the expected capabilities of students in the early years of an engineering degree, enhancing the understanding of complex concepts in an intuitive and applied manner.

Figure 4

Classical vibration analysis for a simple pendulum simulation: (a) amplitude variation, (b) frequency variation, and (c) frequency spectrum with amplitude in $\boldsymbol{log}$.



Source: Produced by the authors

2.3 The use of descriptive statistics in engineering education

The descriptive statistics, grounded in elementary mathematics, allows for the development of a comprehensible framework through techniques that encompass measures of central tendency, dispersion, and frequency distribution, transforming raw data into accessible and interpretable information (Dong, 2023; Saleem et al., 2013). Given the volatility or even variability of real data sets, the descriptive statistics establishes itself as an almost indispensable tool in the synthesis and organization of these data (Larson, 2006; Turner & Houle, 2019). This branch of statistics extends across many areas of science, finding its place from analysis in fields such as family medicine or emergency medicine to the interpretation of stock market dynamics, demonstrating its essentiality in conducting meaningful analyses in various areas (Reed III et al., 2003).

Within the educational context, the descriptive statistics serves as a foundation for introducing students to different research fields. Before delving into more in-depth approaches, it is often necessary to apply elementary statistical treatment to identify the main study variables (Alabi & Bukola, 2023). In this direction, Saleem, Aslam, and Azam (2013) investigated the frequency of statistical methods in papers published in mechanical engineering journals. For each of the five journals analyzed, they created tables that recorded the number of times different analysis methodologies were employed, also presenting the corresponding percentages. Among the methodologies, the absence or presence of statistical methods, including descriptive statistics, was highlighted. The latter was employed 150 times out of 359 studies, representing 41.7% of the total, highlighting its prevalence in mechanical engineering research. Such results regarding the use of statistical methods may have implications for engineering education, suggesting the need to integrate into the curriculum the skills to effectively summarize, describe, and analyze data, as well as to make inferences from data sets.

Engineering education, full of complexities and nuances in the phenomena studied, such as oscillatory motions and vibrations, requires a pedagogical approach that goes beyond the transmission of theoretical knowledge, equally emphasizing the ability to interpret and analyze data. In this regard, the study conducted by Limanto, Kartikasari, and Oeitheurisa (2020) highlights the improvement in students' learning outcomes through the application of mobile learning models, based on descriptive statistics. This research underscores the value of this approach in enriching the educational experience and broadening students understanding, demonstrating the significant potential of integrating such pedagogical methods into engineering education.

The inclusion of descriptive statistics in engineering education through experimentation can facilitate the understanding of fundamental concepts in various sciences or different types of scientific investigation. It can also prepare students to face professional and social challenges, making decisions based on evidence (Dimic et al., 2019). Therefore, it is important to familiarize engineering students with these techniques from the beginning of their academic training. In this way, the integration of descriptive statistics into engineering curriculum courses, especially those that favor experimental activities, aligns with the National Curriculum Guidelines for engineering courses in Brazil (BRASIL, 2019, see Chapter II Art. 4° II a; Chapter III Art. 6° VIII paragraphs 1° 2° 4°; Chapter III Art. 9° paragraph 1°), ensuring that future engineers are qualified to analyze and interpret the large amounts of data that define the modern industrial professional environment (Raptis et al., 2019).

Therefore, the descriptive statistics goes beyond its practical applicability, becoming an interdisciplinary tool in the educational process of engineering. By equipping students with the ability to organize, summarize, and interpret data, the descriptive statistics enriches both theoretical and experimental learning. Furthermore, it underpins the development of analytical skills for the professional and academic performance of future engineers. This approach reflects the intersection of theory and practice and highlights the value of descriptive statistics as fundamental in the training of competent and versatile engineers.

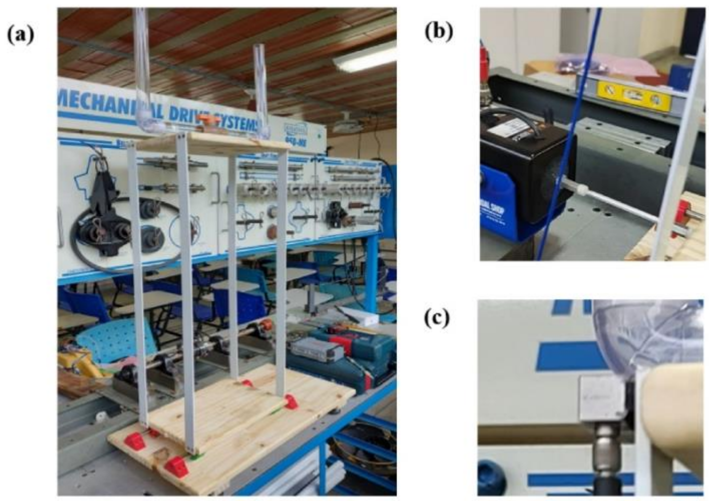
3. Materials and methods

To investigate the feasibility of descriptive statistics in evaluating the effectiveness of passive damping devices, tests were conducted with a vertical structure to which a TLCD was attached, as illustrated in Figure 5a. This structure was originally designed for research on non-parametric statistical models in collaboration with researchers from the Structural Analysis, Vibrations, and Acoustics Laboratory (LAEV) of the institution, but for this study, the test bench was adapted to the research objectives. The technical specifications required to tune the natural frequency of the TLCD to the system had already been determined, allowing us to use existing calculations. Thus, previously available material at the educational institution was used to conduct the tests and collect data for descriptive analysis, aiming to verify its effectiveness in vibration analysis for educational purposes.

The excitation at the base of the test bench was performed using a mini shaker equipped with an integrated amplifier (Figure 5b). A PCB Piezotronics accelerometer was used to capture the data (Figure 5c). Data acquisition was carried out using the SPIDER-80X equipment, and the signals were stored using the Engineering Data Management System software, both provided by Crystal Instruments.

Figure 5

Devices used in the test: (a) vertical structure with attached TLCD; (b) shaker with integrated amplifier; and (c) accelerometer.



Source: Produced by the authors

The disturbance force in the experiment consisted of pink noise combined with a 1.0 Hz sinusoidal wave. This signal was generated by the Function Generator 4 mobile app and transmitted to the amplifier integrated with the shaker. The preference for pink noise is due to its power spectrum, which decreases with frequency, resulting in higher energy at lower frequencies (Stoyanov et al., 2011). As a result, we observed an almost harmonic motion in the system response with the attached TLCD.

The data processing and storage procedures were carried out using an acquisition system, which converted the signals received from the accelerometer from millivolts (mV) to acceleration (g). Three signals were measured: initially, the excitation acceleration; subsequently, the signals with and without the active TLCD. These measurements were facilitated by a control mechanism (valve) in the TLCD (see Figure 5a), allowing tests with the fluid moving through the TLCD columns (valve open) and without movement (valve closed), corresponding to the active and inactive state of the TLCD, respectively. Each test lasted 25.6 seconds, and each sample contained 1024 observations.

The water was chosen as the operating fluid in the TLCD. This choice, by demonstrating effectiveness in mitigating oscillatory motions of a system, has significant potential to engage students' interest. The descriptive analysis of the data can show students how effective and accessible solutions, such as the use of water, can be experimentally employed to control oscillations. This emphasizes the application of critical thinking and inventiveness (Ahern et al., 2019; Aravena-Reyes, 2016). Additionally, it should be noted that the only manipulation during the tests was the position of the valve (open or closed).

The statistical analyses were developed using the R programming language (R Core Team, 2023). Within this programming environment, we processed three distinct time series: one representing the disturbance force (excitation) and the other two corresponding to the system responses, one with the TLCD deactivated (valve closed) and the other with the TLCD activated (valve open).

At the end of the analysis of the collected data, a theoretical consideration will be conducted on the practical application of the proposed approach in engineering education or related technical fields. Although no research involving a group of students was conducted, by Resolution CNS No. 466/12, which regulates research involving human subjects in Brazil, this analysis aims to propose how the described experience can be implemented in an educational context, highlighting the specific roles of students and teachers in the process (Magin & Kanapathipillai, 2000; Machado & Pinheiro, 2010; Hassan, 2011). The intention is for students to take on an active role, applying theoretical concepts to practical experimentation. At the same time, teachers act as facilitators and mediators, promoting discussions and guiding the construction of a testing bench, data acquisition, and critical analysis of results. This approach aims to align the methodology with the perspective of active learning methodologies, reinforcing student engagement and the development of competencies in their professional education.

4. Presentation and discussion of results

The first steps in a univariate descriptive statistics analysis include data visualization, for example, using line graphs (Fávero & Belfiore, 2024b). The study variables are related to time, in seconds, and acceleration, in g. Thus, the analysis will be primarily conducted and compared using the acceleration variable.

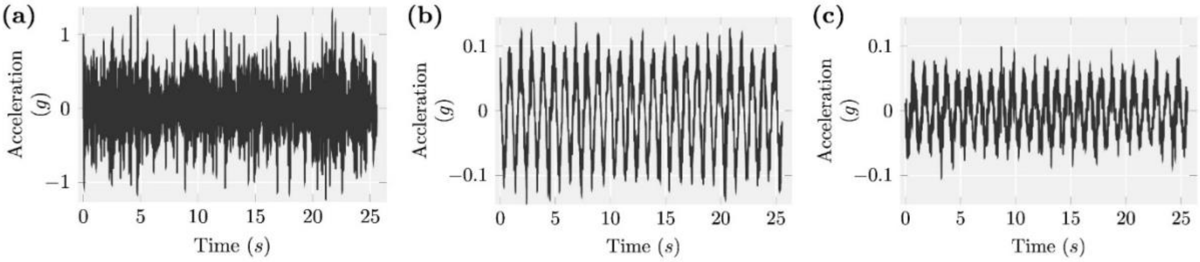
In Figure 6a, it can be observed that the system excitation follows a stationary distribution around zero. In contrast, the system responses, both with the TLCD active and inactive, exhibit an almost harmonic pattern. This validates the choice of pink noise. Additionally, comparing the response amplitudes, illustrated in Figures 6b and 6c it indicates a reasonable reduction in system oscillations. Although this difference could be verified through appropriate hypothesis testing, that would mark a transition to inferential analyses. This study focuses on the exploration of descriptive analysis.

To better understand the amplitude of oscillatory motions, we plotted histograms for the acceleration variable under the three conditions investigated: excitation, system response with TLCD active, and system response with TLCD inactive, as shown in Figure 7. As expected, the amplitude of the system response with the TLCD active is considerably lower, which can be visualized by the higher concentration of values around the mean in the histogram. This characteristic reaffirms the TLCD's ability to reduce system oscillations.

Table 1 presents the statistical measures of the collected data. The statistical analyses of the system responses, with and without the action of TLCD on the system, reveal the device effectiveness in reducing vibrations. From the analysis of the 'excitation' column in Table 1, it is observed that the mean acceleration of

Figure 6

Line graphs of the (a) excitation and the vibrational responses (b) without TLCD activation and (c) with TLCD activation.



Source: Produced by the authors

the applied signal is close to zero, as anticipated due to the nature of pink noise and its sinusoidal component. The significant variation in this signal is evidenced by the minimum and maximum values and confirmed by the standard deviation of $4.356418 \cdot 10^{-1}$. Observing Figure 7a, the stochastic nature of the excitation process is highlighted.

The analysis of the system response, in the absence of the TLCD, observed in the 'without TLCD' column of Table 1, reveals that both the mean and median accelerations are close to zero. This indicates that, despite a slight potential negative mean displacement, most observations are concentrated around zero. On the other hand, with the TLCD active, as shown in the 'with TLCD' column of Table 1, an improvement in the structure response is observed, evidenced by a change in data dispersion, as demonstrated by the comparison between the boxplots in Figures 7b and 7c. In this scenario, the mean and median are even closer to zero, with a smaller standard deviation, suggesting a reduction in response variability. Furthermore, the minimum and maximum values which is an indicative of the response amplitude, are reduced in magnitude compared to the test without TLCD activation. These results corroborate the effectiveness of the TLCD in attenuating the structure vibrations.

Table 1

Summary measures of the signals obtained in the experiment, expressed in $\boldsymbol{g}$. Comparison between the system without and with the attached TLCD during the test.

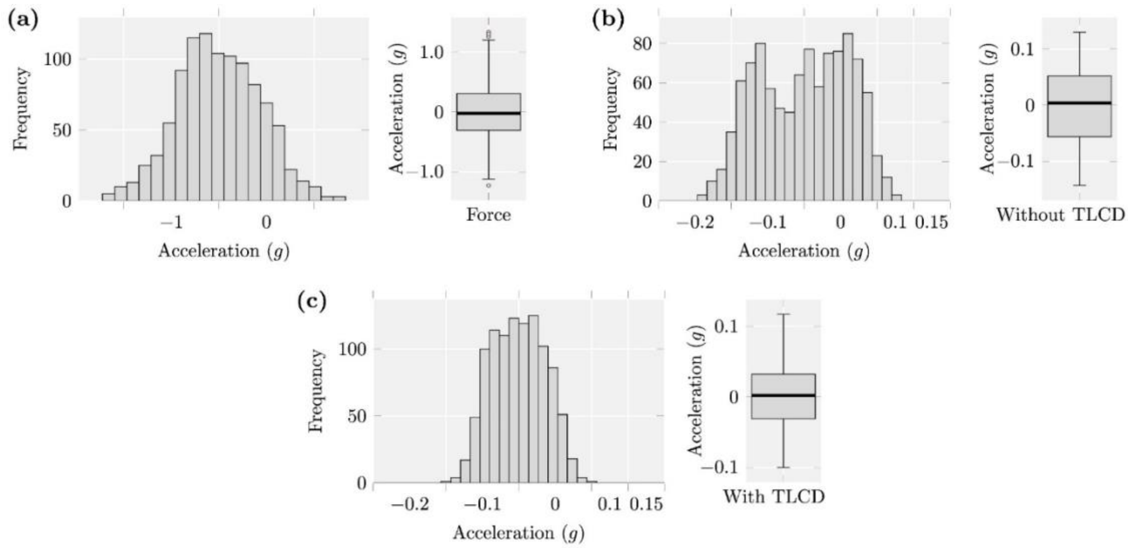
Summary measures	Excitation	Without TLCD	With TLCD
Mean	$7.492926 \cdot 10^{-5}$	-0.0008170216	-0.0005044255
Median	$-2.130326 \cdot 10^{-2}$	0.0038458213	0.0004402464
Standard deviation	$4.356418 \cdot 10^{-1}$	0.0616803689	0.0363516139
Minimum	-1.222281	-0.1428739789	-0.1024098069
Maximum	1.329333	0.1300124583	0.0961613325

Source: Produced by the authors

The results obtained from analyzing the system responses, with and without the TLCD, relate to the discussions presented in subsections 2.1, 2.2, and 2.3. The notable decrease in system oscillations, indicated by the reduction in standard deviation and vibrational response amplitude when the TLCD is activated, aligns with the principles of vibration analysis discussed in subsection 2.2. Additionally, the results illustrate the practical applicability of descriptive statistics, as described in subsection 2.3, by offering a clear and accessible understanding of the variables of interest. This understanding is expected in engineering education for the training of future engineers capable of critically and effectively interpreting data. Finally, the connection between theory and practice, as suggested in subsection 2.1, is reinforced by the experimental results, which highlight how innovative pedagogical methodologies, such as the use of educational experiments, can enhance the learning experience by allowing students to directly observe and analyze complex phenomena in an applied manner.

Figure 7

Histogram on the left and boxplot on the right for each of the signals captured in the experiment: (a) disturbance force (excitation), (b) system response without TLCD, and (c) response with TLCD.



Source: Produced by the authors

4.1 Bivariate descriptive analysis

The purpose of bivariate descriptive analysis is to explore the relationship between two variables (Fávero & Belfiore, 2024a). In this study, the focus is on analyzing the relationships between the quantitative variables of the system responses, both in the inactive condition and with the TLCD active. For this analysis, scatter plots are used, complemented by correlation measures, including covariance and Pearson's correlation coefficient. These techniques allow for the evaluation of the interdependence between the variables under study.

In Figure 8, one may see a scatter plot of the responses with and without the TLCD active, with the color bar providing a visual aid to emphasize the magnitude of the responses with the damper in action. The color distributions indicate:

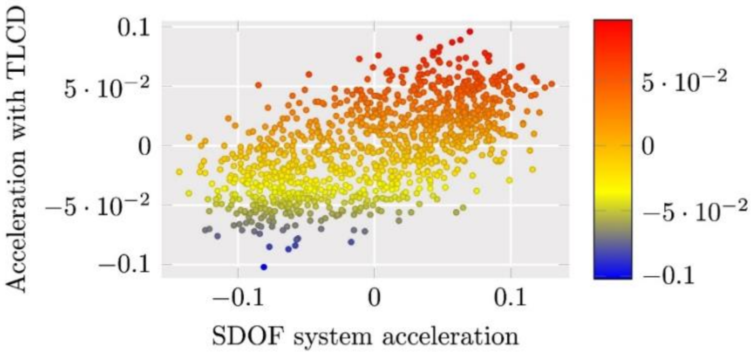
(a) **Concentration around zero:** most points are concentrated around the center, implying that, for many data points, both the system acceleration and the acceleration with the TLCD are small, indicating that the damper is functioning as expected in reducing the acceleration response of the system.

(b) **Variation in response with TLCD:** the variation in colors from blue to red and the dispersion of points away from the center suggest that there are moments in time or specific conditions where the TLCD exhibits a greater acceleration response. This may occur during more significant excitation events or at times when the TLCD is being challenged by larger vibrations.

Table 2 shows that the relationship between excitation and the system responses, both with the TLCD inactive and active, is very weak, as demonstrated by the Pearson correlation coefficients close to zero. The covariance, which measures the direction of the linear relationship between variables, also shows values very close to zero. This reinforces the interpretation that there is no strong linear relationship between excitation and the system responses, regardless of the state of the TLCD. However, when examining the system responses, the values indicate a moderate to strong negative correlation. This means that, generally, when the system response without damping increases, the system response with the TLCD active tends to decrease, and vice versa. Therefore, the TLCD is effectively altering the system response.

Figure 8

Dispersion of the acceleration of the single-degree-of-freedom (SDOF) system with TLCD. Each point represents the relationship between the measured acceleration in the system and the observed acceleration when the TLCD is active.



Source: Produced by the authors

Table 2

Pearson Correlation (ρ) and Covariance (Cov) comparing acceleration during excitation with the system's response without the TLCD, excitation with the system's response with the TLCD, and the system's response without the TLCD versus with the TLCD.

Statistics	Excitation vs. without TLCD	Excitation vs. with TLCD	Without and with TLCD
ρ	-0.0088	-0.0189	-0.7833
Cov	-0.00024	-0.00032	-0.00187

Source: Produced by the authors

Thus, the use of descriptive statistics guided our analysis and facilitated the interpretation of the results presented above. From such an analysis, we can further infer that the TLCD effectively reduces the variability of the system responses to excitation.

The results obtained in this bivariate analysis, particularly the moderate to strong negative correlation between the system responses with the TLCD active and inactive, highlight the effectiveness of the TLCD as a vibration mitigation device, providing additional statistical evidence that can be presented to students. This observation aligns with theoretical discussions on engineering education, where the importance of critical thinking and practical application should be emphasized. Implementing experiments that allow students to observe the influence of devices like the TLCD in vibratory systems facilitates the understanding of complex concepts and promotes a practical approach to teaching (Ahern et al., 2019).

Moreover, the results also reinforce the importance of descriptive statistics in interpreting experimental data, as discussed in subsection 2.3. The use of statistical measures such as covariance and Pearson's correlation coefficient not only simplifies the interpretation of results but also provides a solid foundation for the critical analysis of the collected data. The descriptive analysis plays a key role in identifying patterns of interdependence between variables, showing how simple statistical tools can be extremely valuable for students and professionals in the engineering field (Dimic et al., 2019).

In summary, the results presented in the univariate and bivariate analyses demonstrate the successful application of theoretical principles discussed earlier, illustrating how an educational approach that integrates practical experimentation and statistical analysis can enrich students' learning experiences, preparing them to face professional and academic challenges with a solid foundation of knowledge and analytical skills.

4.2 Educational approach with experimentation

Based on the results of descriptive statistics, the proposed educational approach can be implemented for a group of students through active learning methodologies to explore oscillatory movements (Estévez-Ayres et al., 2014). As discussed by Reis et al. (2023), active learning methodologies involve the direct and continuous engagement of students in the learning process. In the present educational approach with experimentation, the active role of engineering students or those from related technical fields can be developed through collaborative activities, including research and the construction of an experimental test bench equipped with the TLCD. As described in section '3. Materials and methods,' this study utilized test bench adapted to the research objectives. However, based on prior experience, allowing students to actively participate in the construction of the testing bench, as well as in subsequent univariate and bivariate descriptive analyses, can enhance learning in the analysis of oscillatory movements, promoting advancements at the following levels:

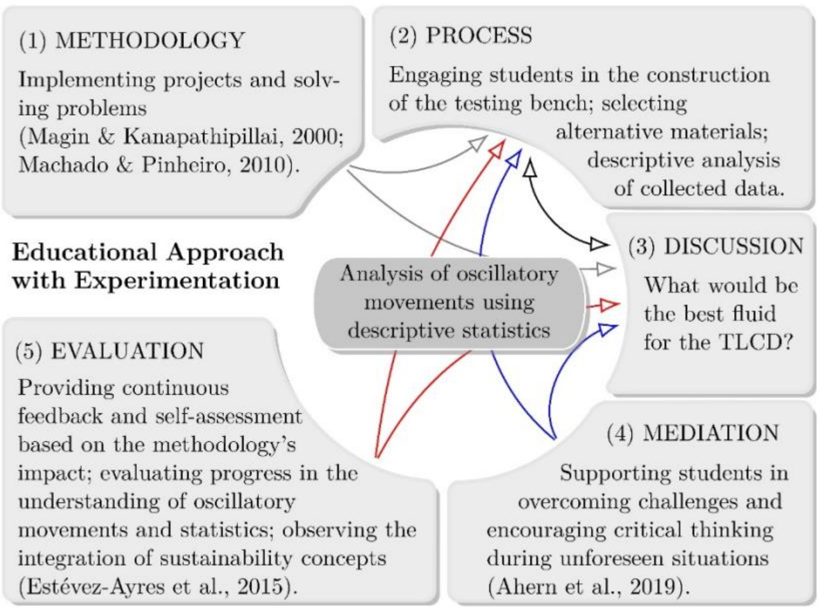
(1) understanding the elements involved in oscillatory movements and the application of passive vibration dampers;
(2) advancing the understanding of descriptive statistics for inference on the effects of the TLCD in mitigating vibrations;
(3) using water as a resource in the fabrication of a damper, integrating sustainability concepts into the process.

Challenges may arise in the proposed approach. The main anticipated difficulties include those already discussed in the literature, such as students' resistance to participating in active tasks and taking responsibility for their own learning, as well as reluctance to engage in group activities (Reis et al., 2023). Other challenges may be related to the need to adapt data collection due to the absence of a data acquisition system with connected accelerometers. As an alternative, it is possible to propose the use of mobile applications with data collection functions, such as the Phyphox mobile app. Additionally, another expected difficulty relates to statistical processing using programming languages, such as R (R Core Team, 2023). In this regard, teacher mediation can address this challenge by providing ready-made analysis scripts or recommending appropriate packages for the required statistical processing.

Further details of this application can be found in Figure 9. It illustrates the cycle of basic steps involving the application of active learning methodologies. Indeed, step (1), methodology, can be based on the proposal by Magin and Kanapathipillai (2000), who highlight the importance of integrating theory and practice through experiments that confront discrepancies between simulated theoretical results and real data. This can be more effectively applied in step (2), process. By involving students in collaborative and practical activities, such as the construction of the experimental bench and the analysis of the collected data, autonomy, and

Figure 9

Cycle of basic steps for exploring oscillatory movements using active methodologies.



Source: Produced by the authors

contextualization of learning are encouraged. These activities may also raise questions, leading to discussions. In this sense, the approach described by Machado and Pinheiro (2010), emphasizing the methodology of problem-generating discussions, can be linked to step (3), discussion. By fostering reflections on issues such as the choice of the best fluid for the TLCD, and integrating theory, practice, and result analysis, there can be greater integration of scientific, technological, and sustainability knowledge.

In Figure 9, steps (4) and (5), mediation and evaluation, are interdependent, as indicated by the arrows. Teacher mediation, following the intervention strategies highlighted by Ahern et al. (2019), serves as initial support, providing tools and guidance for students to overcome challenges during the process and discussion. Meanwhile, evaluation, reinforced by the principles of Estévez-Ayres et al. (2015), employs continuous feedback and self-assessment to adjust the methodology, fostering the evolution of learning and the development of skills in descriptive statistics and the analysis of oscillatory movements.

5. Final considerations

In this work, an experiment was developed to evaluate the effectiveness of the TLCD via descriptive statistical analysis. This study aims to contribute to the teaching and learning of oscillatory motions in engineering. Regarding the effectiveness of the TLCD, the descriptive analysis of the data was sufficient to demonstrate its impact in mitigating vibrations in the system. The statistical measures, histograms, and time-domain analysis revealed that the TLCD can be a solution to vibration problems. The description of the experimental results through descriptive statistics confirms previous work done with TLCDs (Gao et al., 1997).

Although there is extensive literature on TLCDs, with various suggestions for designs of this type of passive device, a gap was observed in these studies, given the limited interest in its application in science and engineering education. Thus, this research presents a satisfactory approach, contributing both to the existing literature and to the development of new studies. This novel perspective not only enriches the field of study but also reinforces the relevance and importance of the work presented, as it integrates descriptive statistics with vibration analysis from an engineering education perspective.

Regarding engineering teaching methodologies, the challenge, as observed, is not limited to training professionals who master scientific and technical fundamentals, but also to preparing them to think critically and inventively. This challenge extends to educators, who are at the forefront of this academic training. The choice and application of appropriate teaching methodologies are not trivial tasks.

Additionally, knowing that the signals analyzed in this research are time series, other characteristics can be studied. This may include stationarity tests and the analysis of autocorrelation functions. The results related to these characteristics could provide theoretical details for a future interest in obtaining a parametric model for the system responses. These topics can be discussed within the fundamentals of engineering education.

Finally, to overcome any limitations in the educational approach presented in this study, a more comprehensive investigation could be conducted with engineering students or those from related technical fields. This research would require the involvement of several students, allowing for randomization and the formation of an experimental group, which would be subjected to the proposed educational approach, and a control group to be used as a reference. Thus, the study would be conducted with a representative sample, ensuring greater internal and external validity. Consequently, this would result in a work distinct from an experience report or a theoretical essay, characterizing it as an empirical study grounded in an experimental design, with statistical analysis evaluating the effectiveness of the educational approach presented in the context of oscillatory motion analysis.

Contribution

M. O. SILVA: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Validation; Visualization; Writing – original draft, review and editing. B.C. CAYRES: Conceptualization; Data curation; Investigation; Methodology; Validation; Writing – original draft, review and editing. T.C. FARIA: Conceptualization; Methodology; Validation; Writing – original draft. D. C. GUERRIERI: Conceptualization; Methodology; Validation; Writing – original draft, review and editing. F. L. C. SILVA: Conceptualization; Formal analysis; Methodology; Validation; Writing – original draft, review and editing.

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