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DEVELOPMENT OF A TEACHING BENCH TO SIMULATE THE VIBRATORY EFFECTS IN A FLAT BEAM

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ABSTRACT

This study aimed to develop a didactic bench for simulating the vibration effects in a flat beam. The methodology consisted of four steps: first, a bench was made to represent the system of 1 degree of freedom, followed by obtaining a mathematical model to represent the physical phenomena of the real system, followed by the study of dynamic behavior, in which it was verified the temporal response and the frequency domain of the output variables in relation to the input and ended with the validation and application of the mathematical model found. All system parameters were obtained experimentally, except for the damping rate value, which was estimated using the half power bandwidth method. From the measured and estimated parameters, a model was obtained and tuned, which resulted in the mathematical model that represents the system of an embedded flat beam. The conclusion shows that the methodology was efficient in determining a mathematical model that represents the system of a 2 ”x 3/16” x 1m flat bar with a 675g mass installed at the end and instrumented by a PCB model 352C65 piezoelectric accelerometer, which can be used on simulation benches in the Mechanical Vibration classes.

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INTRODUCTION

The creation of didactic resources for professional education has been a challenge for several institutions worldwide (Halqi, Willian & Muntari, 2020; Yang & Bai, 2020; Manganello, Persico & Passarelli, 2020; Camilleri Grima, 2020; Segui, 2020). As new skills are required by society and the job market, new challenges are posed for educational institutions to train professionals with that desired profile. As changes in skills have changed with increasing speed, the teaching resources needed to generate the desired training must also be created. And this is often done by the institutions themselves, especially those that are essentially technological, as is the case with the Brazilian federal education, science and technology institutes. In this sense, this study aimed to develop a didactic bench for simulating the vibration effects in a flat beam, which should be used in the practical classes of the subject of Mechanical Vibrations, offered by the Control and Automation Engineering Course (ECAT) of the Campus Manaus Industrial District (CMDI) of the Federal Institute of Education, Science and Technology of Amazonas (IFAM). The purpose of creating this didactic resource was to make it possible to simulate the vibratory effects and to train students in obtaining models through the development and implantation of equations or set of equations that approach the real system.

The methods for obtaining the equations of a model for a system can be developed analytically, using the principles of Physics and Chemistry; by the empirical method, with the observation and correlation of the input and output data of the system; or by analogy, using equations that describe an analogous system and with the variables identified by analogy (Garcia, 1997). To be able to use an analytical model, it is necessary to know certain parameters of the system, which usually must be evaluated from physical experiments or else obtained from operational data of the system (Garcia, 1997). Due to the knowledge and time required to model a system based on the equation of the phenomena involved, it is not always feasible to use the analytical model. On the other hand, empirical modeling has been shown to be easier to generate, because it has the characteristic of requiring little or no prior knowledge of the system. Empirical modeling, also known as black box identification (Rimorov *et al*, 2020; Cooper *et al*, 2020; Simorgh, Razminia & Shiryaev, 2020), is an area of knowledge that studies alternative mathematical modeling techniques (Aguirre, 2000). For this study, we opted to use the analogous method. For the embedded flat beam system, the equations that describe a linear oscillating system with 1 degree of freedom were used, as shown in figure 1.

According to Garcia (1997), there are three basic steps for obtaining a dynamic model of a system: 1) obtaining a mathematical model to represent physical phenomena, whose behavior fits well enough with the behavior of the real system; 2) study of the dynamic behavior of the mathematical model, in which the temporal response of the output variables in relation to changes in the input variables is verified; and 3) application of the mathematical model found. In figure 2, the steps for obtaining a dynamic model for a system can be seen. The feedback characteristic of the system is perceived, which allows errors in the original mathematical model to be detected and corrected by comparing the simulated and real values. This process of comparison and correction is called Model Validation.

For the vibration analysis technique to be used properly, it is important that the people responsible for processing the data have adequate training. For this, the techniques of using practical classes to simulate real environments in technical and technological education allow an approach with a greater understanding of the phenomena in a shorter period of time, which provides immediate learning to the students being trained. On the other hand, currently the Federal Institutes are facing some difficulties to make new investments in vibration laboratories, hindering the teaching of practical classes due to the lack of essential equipment for their realization.

The hypothesis that guided this investigation was that it is possible to create a didactic bench for simulating the vibratory effects with existing resources at the Campus Manaus Distrito Industrial of IFAM. In this sense, the general objective was to create a didactic bench to represent the under-damped linear system, with 1 degree of freedom, that can be used in the practical classes of the subject of Mechanical Vibrations. Specifically, the design of the investigation sought to obtain a mathematical model to represent the physical phenomena of the vibratory behavior of an embedded flat beam; use the half power bandwidth method to estimate the damping rate value; to study the dynamic behavior of the mathematical model obtained for embedded flat beam; validate the mathematical model found; and apply the mathematical model found and make the methodology available for use in the Mechanical Vibration classes.

Theoretical Reference

Dynamic modeling by the analogous method for an embedded flat beam: When it is proposed to obtain a dynamic model for any system, it is not sought that it has a complete and detailed description of the plant, but rather a simple and adequate model (Nascimento, 2004). In the case of an embedded flat beam, the model must contain all forces that significantly affect the movement of the beam, including forces due to the rigidity, inertia and damping of the system. Figure 3 presents a model of a mass, spring and damper system designed by Correia (2017) and Cossolino and Pereira (2010).

Where Fd is the bonding force exerted by the shock absorber, proportional to the velocity u 'of the mass M, and Fs is the bonding force exerted by the spring, proportional to the displacement u of the mass M. Whereas the resultant of the sum of all forces is null, we have:

$$F_i + F_d + F_s = P(t) \tag{1}$$

Figure 4. Equation 1.

For a linear viscoelastic system, the previous equation becomes in:

$$Mu''(t) + Cu'(t) + Ku(t) = P(t) \tag{2}$$

Figure 5. Equation 2.

Considering free oscillation, where P (t) = 0, we have:

$$Mu''(t) + Cu'(t) + Ku(t) = 0 \tag{3}$$

Figure 6. Equation 3.

Rewriting this equation, we have:

$$u''(t) + \frac{C}{M}u'(t) + \frac{K}{M}u(t) = 0 \tag{4}$$

Figure 7. Equation 4.

Defining it:

$$W_0 = \sqrt{\frac{K}{M}} \quad \text{e} \quad psi = \frac{C}{2\sqrt{KM}} \tag{5}$$

Figure 8. Equation 5.

where, *Wo* is the natural frequency of vibration and *psi* represents the rate of damping or just damping. In this way, rewriting the equation, and using the new parameters, we have that:

$$u''(t) + 2psiW_0u' + W_0^2u = 0 \tag{6}$$

Figure 9. Equation 6.

Considering a solution like:

$$u = e^{gama.t} \tag{7}$$

Figure 10. Equation 7.

We get to:

$$gama = W_0\left(-psi \pm \sqrt{(psi^2 - 1)}\right) \tag{8}$$

Figure 11. Equation 8.

The behavior described by equation 11 depends on the gamma solution: for *psi* greater than 1, there are two real solutions and it will be called the super-cushioned system; for *psi* equal to 1, there is a real solution and it will be called a critically damped system; and for *psi* greater than 0 and less than 1, there are two complex solutions and it will be called an under-damped system. The over-damped and critically damped systems are non-oscillatory, while the under-damped system has an oscillatory response. Considering that the embedded flat beam system is an under-damped linear system with 1 degree of freedom, it is expected that the answer to equation 6 is as follows:

$$u(t) = A_0 e^{-psiW_0 t} cos(W_d t + fi) \qquad (9)$$

Figure 12. Equation 9.

where, A_0 is the initial amplitude of vibration, *fi* is the initial phase of the vibration and *Wd* is called the damped natural frequency, and is described by:

$$W_d = W_0 \sqrt{1 - psi^2} \qquad (10)$$

Figure 13. Equation 10.

Half power bandwidth method: The methods for determining damping are diverse, as shown by the studies by Sun and Dias (2018) and Foong *et al* (2018), and the choice depends mainly on the damping range and the frequency of vibration. The most used are the logarithmic decrement method, as used in the studies by Little and Mann (2019; 2020) and Joo (2016), and the half-power bandwidth method, as used by Treszkai, Sipos and Feszty (2020), Yu *et al* (2020) and Zhu *et al* (2020), and for this work it was decided to use the second method. In the half power bandwidth method, the damping measure is based on the frequency response. The bandwidth (half power) is defined as the width of the frequency response curve when the magnitude (Q) is equal to 0.7071 times the peak value of the amplitude, as can be seen in figure 14.

The bandwidth value can be related to the damping as follows:

$$\Delta\omega = 2.psi.\omega_r = 2.psi.\omega_0 \qquad (11)$$

Figure 15. Equation 11.

Therefore, the damping can be estimated through the bandwidth, using the relation:

$$psi = \frac{1}{2}\frac{\Delta\omega}{\omega_0} \qquad (12)$$

Figure 16. Equation 12.

MATERIALS AND METHODS

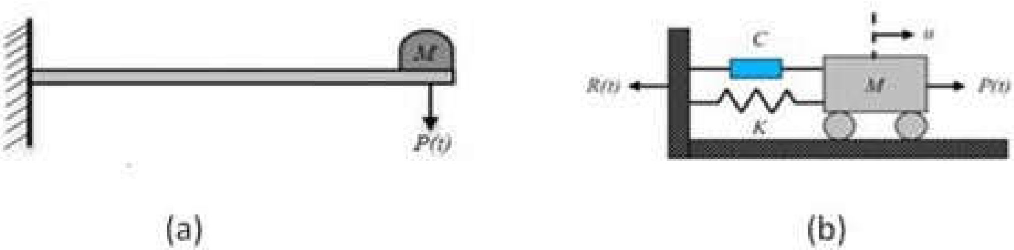
Damping rate estimation for embedded flat beam: In mechanical systems, even with prior knowledge of a mathematical model that roughly portrays its dynamic behavior, under given circumstances it is practically impossible to obtain parameters directly.

In such cases, one can resort to the parameter estimation technique, which aims to determine the unknown values of the system parameters from the plant's input and output signals (Mariano *et al*, 2003; Silva *et al*, 2003). This research used the half power bandwidth method to estimate the damping rate of the embedded flat beam. For that, it was necessary to make a workbench to represent the under-dampened linear system, with 1 degree of freedom, formed by a flat bar set in 2”x3 / 16” x1m, with a mass of 675g, installed in the cantilevered end and instrumented by a PCB model 352C65 piezoelectric accelerometer, as shown in figure 17. To measure the acceleration response, an HBM data acquisition module, model MX 1601B, was used with 16 channels for piezoelectric sensors (ICP / IEPE), with individual 24-bit A / D converter per channel, sampling rate up to 19,2 kS / s and dynamic band up to 3 kHz, and a HBM data recording and processing module, model CX22B-W, with Catman-Easy software, Ethernet interface and wi-fi.

During the test, the embedded flat beam was excited by a pulse and after the acquisition and processing of the acceleration data the result was obtained in the frequency domain. Using the half power bandwidth method, the parameters for the flat beam could be obtained. Replacing the parameters found by the half-power bandwidth method in equation 9, a mathematical model was obtained that represented the variation in amplitude over time for the flat beam. To verify the performance of the model, it was necessary to simulate it under operating conditions, in which there is an answer that allows comparing with the experimental output of the system. For this, the mathematical model and the experimental bench were excited with the same input signal (pulse of the same amplitude) and the responses were compared. To tune the simulated response to the experimental response, a gain in the damping rate was implemented. After the tuning of the mathematical model was carried out, we proceeded to carry out its validation. For this, the model was simulated without any additional adjustment and a comparison was made with the data measured and collected in tests different from those used in the development and tuning of the model (Aguire, 2000).

RESULTS AND DISCUSSION

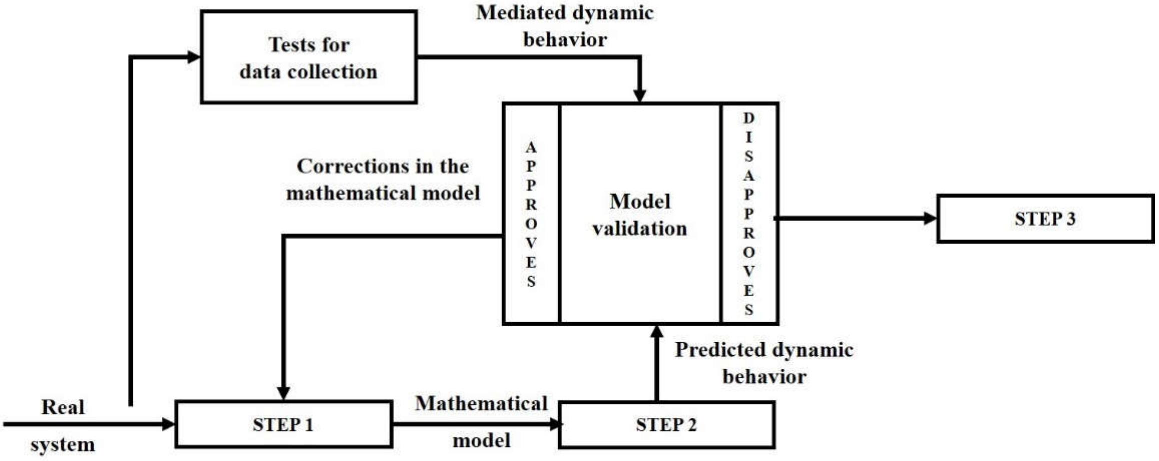
Estimation of the damping rate of the flat beam embedded in the experimental bench: During the test, the embedded flat beam was excited by pulse and after the acquisition and processing of the acceleration data the result was obtained in the frequency domain shown in figure 18. Analyzing the results in figure 18 and using the method of half power bandwidth, the parameters for the flat beam shown in figure 17 were obtained, which are shown in table 1 (figure 19). Substituting the parameters in table 1 in equation 9, equation 13 is obtained, which represents the variation in amplitude over time for the flat beam shown in figure 17. To verify the performance of the model presented by equation 13, it was necessary to perform a simulation under operating conditions, in which we have the answer that allows to compare with the experimental output of the system. For this purpose, the equation 13 model and the experimental bench were excited with the same input signal (pulse of the same amplitude) and the following response, shown in figures 21 and 22, was observed.



(a) (b)

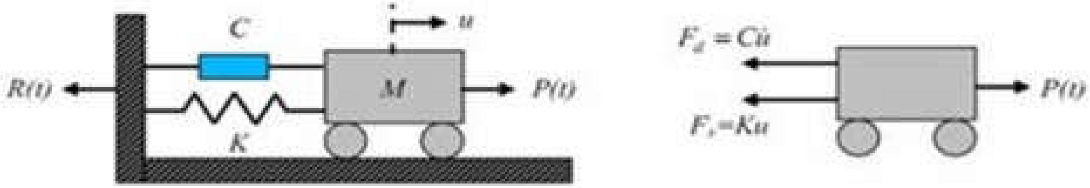
Source: Correia (2017, p. 9)

Figure 1. (a) Embedded flat beam system model; (b) Analogous model of a linear oscillator with 1 degree of freedom



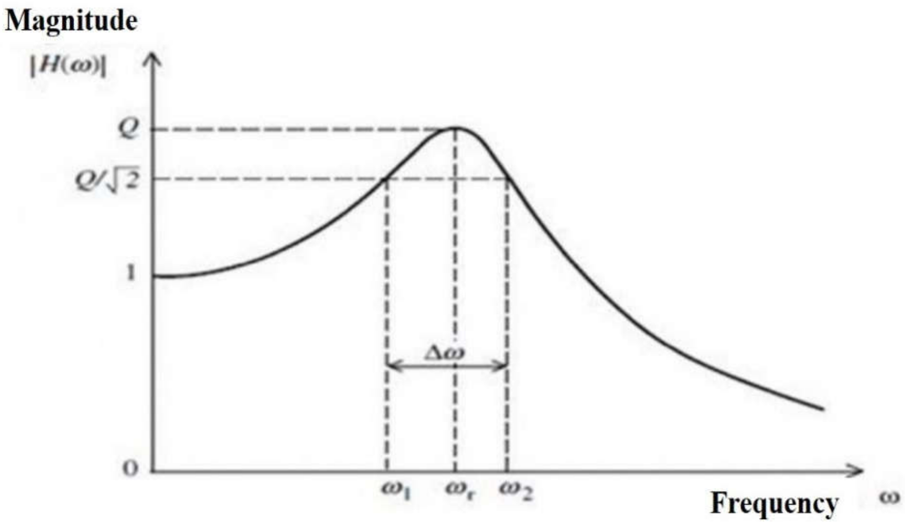
Source: Nascimento (2004, p. 14).

Figure 2. Steps to obtain a dynamic model



Source: Correia (2017, p. 9).

Figure 3. Model a proposed mass, spring and shock absorber system.

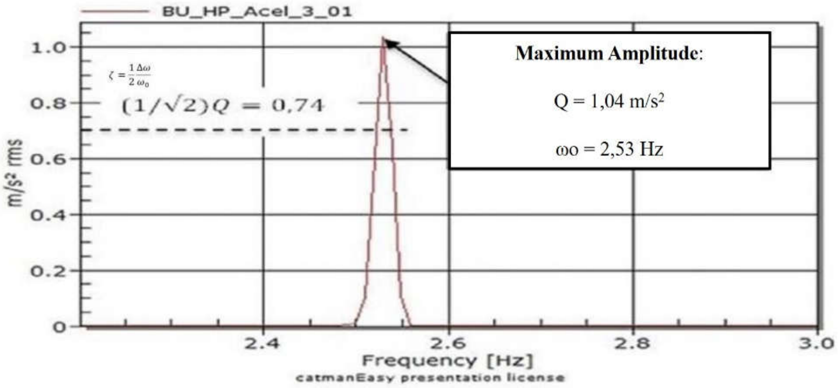


Source: Cossolino *et al* (2010, p. 10).

Figure 14. Bandwidth method for determining damping in a system with 1 degree of freedom

Source: data collected by the authors.

Figure 17. Experimental bench with an embedded flat beam



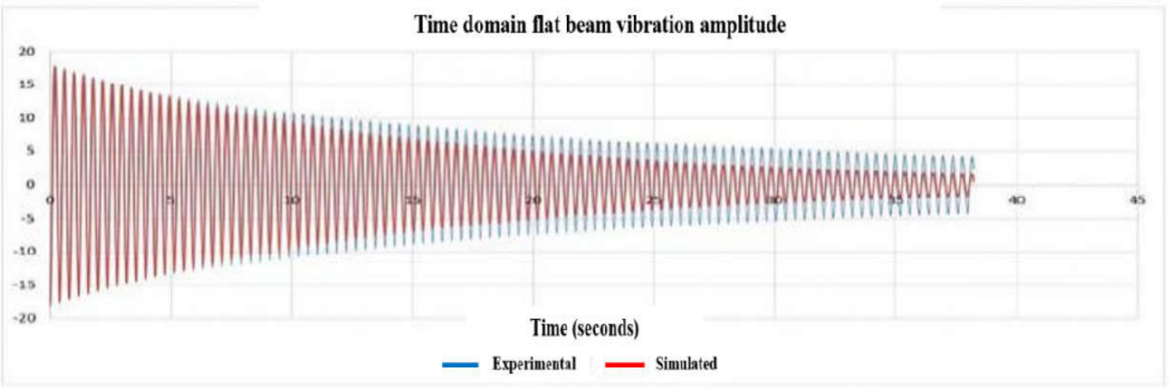
Source: data collected by the authors.

Figure 18. Response in the frequency domain after the flat beam is excited by a pulse.

Table 1. Estimated parameters for the flat beam

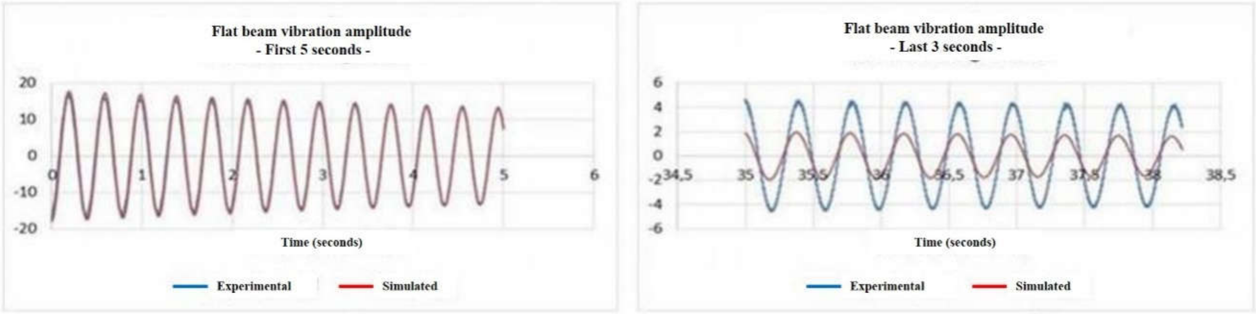
Parameters	Symbology	Value	Value
System natural frequency	$\square_0$	2,53 Hz	15,90 rad/s
Frequency before natural in the range of (1 / (√2)) * Q	$\square_1$	2,52 Hz	15,83 rad/s
Frequency after natural in the range of (1 / (√2)) * Q	$\square_2$	2,54 Hz	15,96 rad/s
Frequency Delta	$\Delta\square = \square_2 - \square_1$	0,02 Hz	0,13 rad/s
Damping rate	$\zeta = \frac{1}{2}\frac{\Delta\omega}{\omega_0}$	0,00395	0,00395

Source: data collected by the authors.



Source: data collected by the authors.

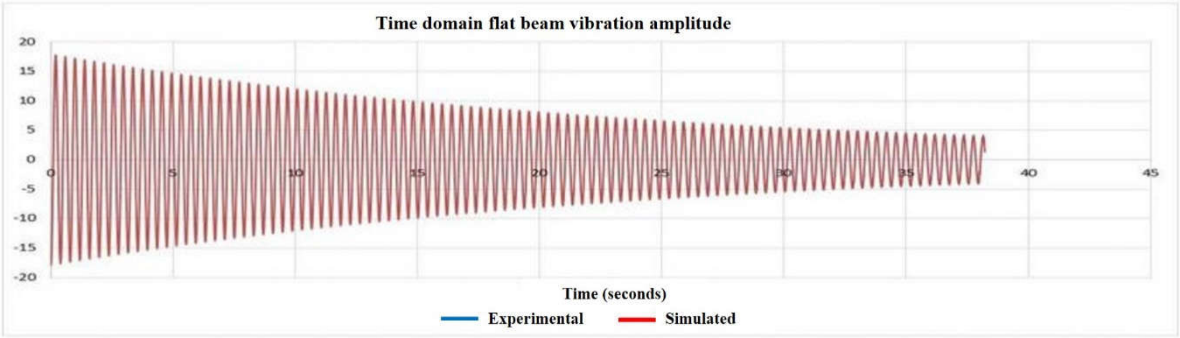
Figure 20. Vibration amplitudes measured experimentally and simulated from the estimated model



(a) (b)

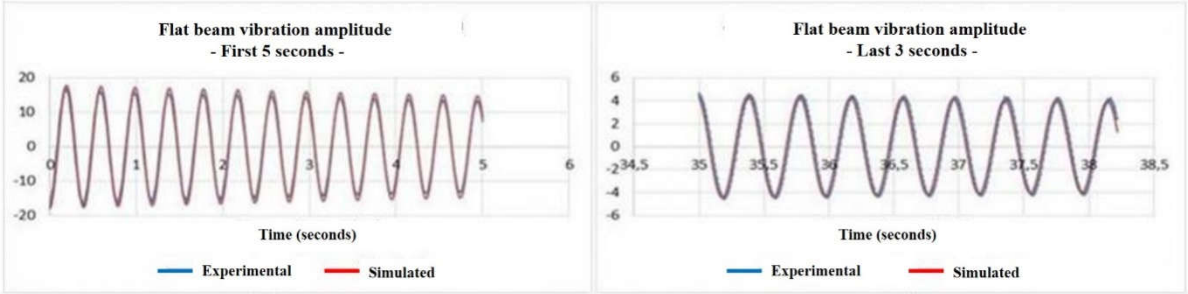
Source: data collected by the authors.

Figure 21. (a) First 5 seconds of experimental x simulated data; (b) Last 3 seconds of the experimental x simulated data.



Source: data collected by the authors.

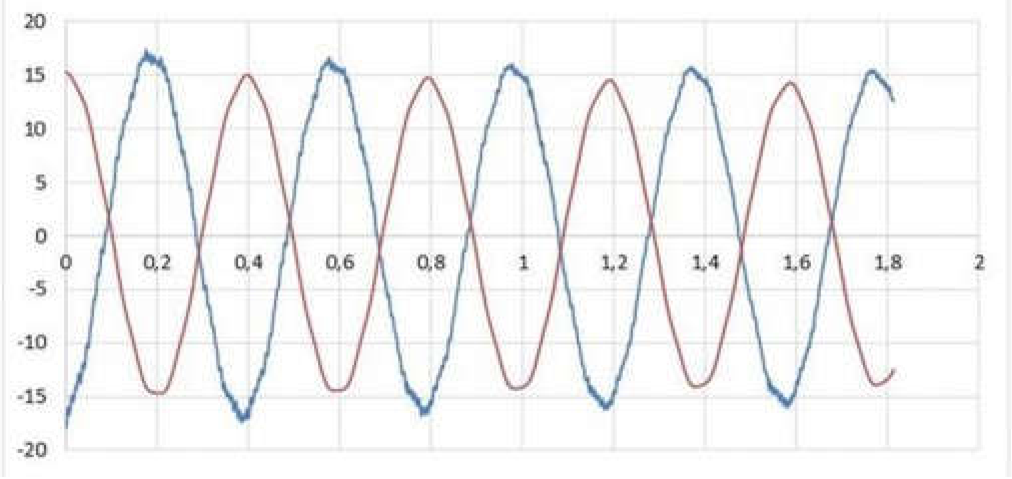
Figure 22. Vibration amplitudes measured experimentally and simulated from the tuned model



(a) (b)

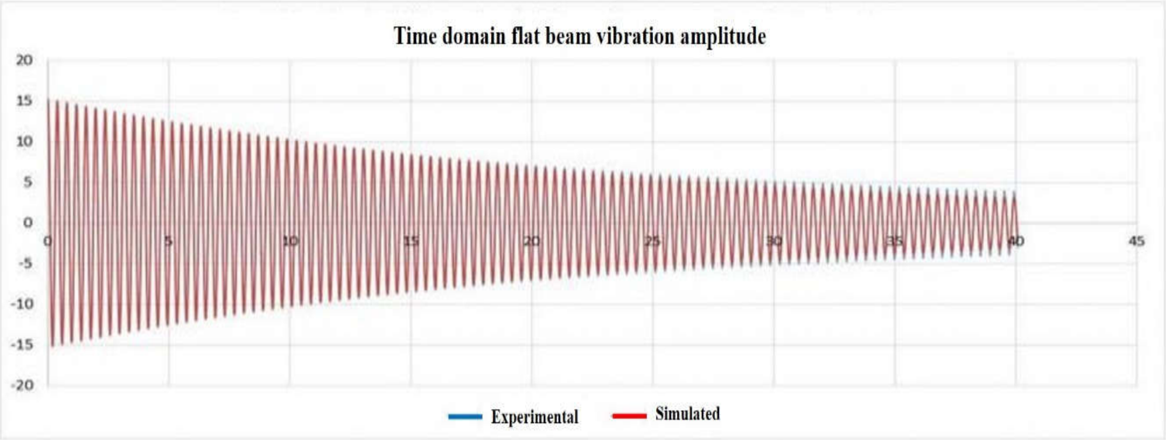
Source: data collected by the authors.

Figure 23. Tuned model: (a) First 5 seconds of experimental x tuned data; (b) Last 3 seconds of experimental x tuned data.



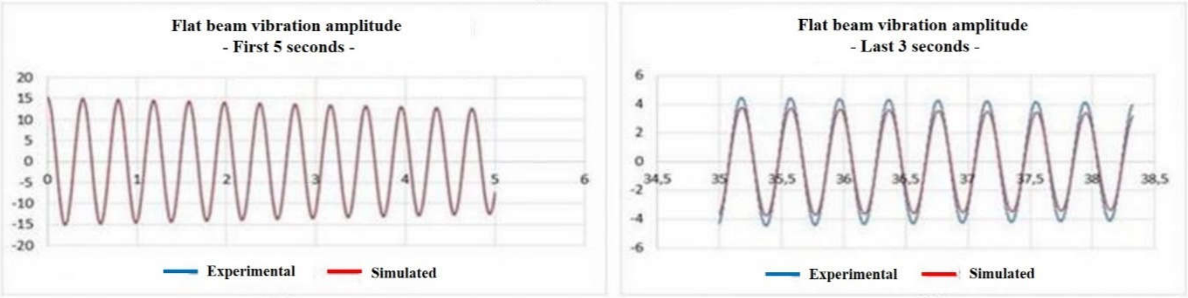
Source: data collected by the authors.

**Figure 25. System responses used for model estimation and validation
In blue, parameter estimation data; in red, model validation data**



Source: data collected by the authors.

Figure 26. Measured and simulated vibration amplitude signal for validation of the adjusted model.



(a) (b)

Source: data collected by the authors.

Figure 27. Validation of the Model: (a) First 5 seconds of the experimental data x tuned (b) Last 3 seconds of the experimental data x tuned

It can be seen in figures 21 and 22 that the simulated response has the same shape as the experimental response but needs adjustments. Basically, it is noticed that the simulated response is more cushioned than the experimental response. Therefore, to tune the simulated response with the experimental response, the simulated response must be made less dampened in the presence of an excitation signal, by implementing a gain in the damping rate. After carrying out some simulations, it was reached that this gain should be equal to 0.63 and the new damping rate is *psi* (tuned) = 0.63 *psi*. Figures 23 and 24 show the simulated response with the gain acting. It can be seen in figures 23 and 24 that the gain added to the damping rate improved the identification of the system's output.

Model Validation: Figures 23 and 24 make it clear that equation 14 was effective in adjusting the model's output to the experimental data obtained but does not guarantee that the model is valid for situations other than shown in figure 23. For this reason, there is a need to validate the model. For this, the model must be simulated without any additional adjustment and compared to data measured and collected in tests different from those used in the development and tuning of the model (Aguire, 2000). To validate the model represented by equation 14, another data collection was performed, with an amplitude of the input pulse and phase different from that used for estimation, as shown in figure 26. Figures 27 and 28 show the results of the new test, as well as the simulation of the model in this condition. The figure suggests that the model can represent well the behavior of the flat beam embedded with the characteristics shown in figure 17.

Final consideration

This work also presented a methodology for making a didactic bench for simulating the vibratory effects in 1 degree of freedom system, followed by the estimation of its parameters. The half power bandwidth method was used to estimate the damping rate of a 1 degree of freedom vibratory system. From the estimated parameters, a model was obtained and tuned, which resulted in an equation that represents the system of a 2 "x 3/16" x 1m flat bar with a mass of 675g installed at the end in balance and instrumented by a PCB model 352C65 piezoelectric accelerometer. It concluded with the validation of this model using acquired data not used in the estimation. The created bench proved effective for didactic use in the training of control and automation engineering professionals.

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