Desing and Validation of a Low-cost Educational Impact Hammer for Modal Analysis Studies

Moisés dos Santos[1], Vitor F. de Carvalho [1], Leonardo Avane[1], Leonardo G. Siveri[1], Hugo S. Idagawa[1], Renato L. Pilan[1]

[1]*Faculdade de tecnologia SENAI "Roberto Mange".*
Rua Pastor Cicero Canuto de Lima, 71, São Bernardo, 13036-210, São Paulo, Brazil.
moises.santos16512@gmail.com, vitor.frutuoso@senaisp.edu.br, leonardoavane@gmail.com, Leonardosiveri@yahoo.com.br, hugo.sakai@sp.senai.br, renatopilan@yahoo.com.br

Abstract. Modal analysis is a technique used to identify the dynamic properties of structures, such as natural frequencies, vibration modes and damping. This analysis is essential to predict structural behavior under different excitation conditions and to ensure the integrity and safety of projects. Among the instruments that perform modal tests, the impact hammer is generally used, however the commercial models available on the market are expensive, which makes them difficult for educational institutions with limited budget to access. Thus, this work developed an impact hammer designed to measure the excitation impact force in small to medium-sized structures which will also perform modal analysis. The objective was to create an economically viable and more accessible alternative when compared to the equipment available on the market. Furthermore, the project serves as a didactic kit, facilitating the teaching and understanding of the principles related to structural vibration. In order to perform the appropriate measurements, the hammer has a load cell, seismic mass and analog electronics, this allows the measurement of impact forces and perform the frequency response analysis of a body. Additionally, this instrument was developed through machining, which allowed the creation of an internal cavity to house the components. The handle was produced using stainless stell, designed to internally incorporate the electronic circuits for the system to operate. Calibration was performed using Bump Test and based on Newton's Second Law, using the previously determined seismic mass and the acceleration of gravity as a reference. To this end, a device was built that standardizes the acceleration applied to the system, allowing repetitions and controlled impacts. Moreover, in each test, the electrical voltage generated by the compression of the piezoelectric cell was analyzed. The final validation of the system was an experiment in which a clamped steel bar was subjected to impact excitation. The results achieved were satisfactory when compared with the theoretical model of the bar and with data obtained from a commercial instrument, ensuring accuracy with an error of 5.03%.

Keywords: Impact hammer, bump test, impact force, modal analysis.

1 Introduction

Modal analysis is a technique used to identify dynamic properties of structures, such as natural frequencies, vibration modes, and damping. This analysis is essential for predicting object behavior under different conditions and ensuring the integrity and safety of projects. Among the instruments used for these tests is the impact hammer, whose main function is to create impacts on objects or structures to analyze their behavior. In modal testing, impacts allow for the identification of the frequency at which a body vibrates most intensely, which is essential for designing and analyzing its dynamic characteristics.

According to Rao [1], whenever the natural vibration frequency of a machine or structure coincides with the external operating frequency, a fault called resonance occurs, resulting in excessive deflections and failures. Due to the undesirable effects that vibration can cause, vibration testing is a standard procedure in the design and development of large engineering systems. Despite its harmful effects, vibration can be used in a variety of

applications, such as earthquake simulations and geological surveys.

The main objective of this project is to develop an impact hammer composed of an accelerometer, a piezoelectric transducer, a seismic mass, and an analog circuit. The device's manufacturing cost is lower than that of a commercial impact hammer. This aims to democratize access to structural dynamics practices in educational institutions. Finally, this work validated the system in a laboratory to ensure the accuracy and reliability of the data collected.

2 Methodology

The impact hammer, in simple terms, is a hammer equipped with a piezoelectric transducer, seismic mass, and an analog circuit. Its purpose is to excite a structure to be tested, enabling the identification of the dynamic properties of the stimulated body. According to Lee [2], it is important to determine physical parameters through depth measurement for structural analysis and maintenance. Now, with the advent of more sensitive depth sensors, other methods exist for determining the physical properties of structural elements and materials. These can be calculated through sound tests, rather than static tests alone. The impact hammer test is an experimental method for obtaining dynamic information through sound testing.

The piezoelectric transducer, together with the seismic mass, forms the system's accelerometer. Accelerometers are sensors that measure the acceleration of a body upon impact, for example. According to Levinzon [3], piezoelectric accelerometers with integrated electronics represent a large class of vibration sensors that incorporate in a single closed housing, a piezoelectric transducer as the mechanical part and the integrated electronics as the electrical part.

2.1 Impact hammer construction

The impact hammer design was based on commercial models already used and validated in modal tests, aiming to combine construction simplicity and precision. All components used were previously modeled in SolidWorks 2023 software, which allowed for the simulation of the positioning of the internal elements and optimization of the assembly's center of mass, ensuring geometric balance, which was essential for ensuring greater stability of the hammer during impacts, especially during the experimental validation stages. The hammer is divided into two main parts: the hammer head (composed of the interchangeable tip and the accelerometer) and the handle. The tip is made of solid material and has a threaded end that allows it to be replaced. The accelerometer is located on the opposite side, consists of a housing that contains the seismic mass and the piezoelectric transducer. The tip and the housing are interconnected by a fine-pitch thread, ensuring proper alignment and stability between the parts. The handle was made using a tubular structure, which houses the electronic circuit of the hammer.

After the modeling stage, the components were manufactured, and the hammer was assembled The piezoelectric transducer material chosen was quartz crystal. According to Stefanescu [4], quartz transducers differ from other sensing techniques because they are active elements (called self-generating sensors), do not require a power supply, and the deformation required to generate an electrical signal is small. Another advantage of this type of sensor is the system's high-frequency response, making them suitable for measuring dynamic forces such as oscillations, impact, or high-speed compression and tension. Another important characteristic of quartz crystal is the accuracy of sample measurements. Compared to other transducer types, the typical total uncertainty for this type of transducer ranges from 0.3% to 1%. Below Fig. 1 shows the final assembly of the hammer:



Figure 1 – Impact hammer.

2.2 Experimental validation

In order to determine the impact force of the hammer, a structure was built to perform standardized impact tests, ensuring repeatability and control of the variables involved. Below, Fig. 2 shows the structure of the impact hammer and the setup for carrying out the tests.

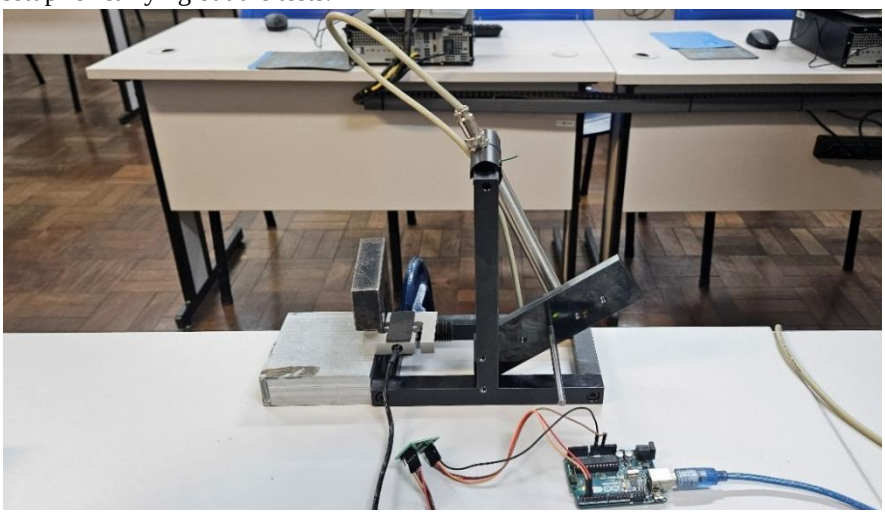


Figure 2 – Measurement structure and setup.

For each impact, the voltage emitted by the transducer was recorded . To achieve greater accuracy, multiple tests were performed under the same conditions, reducing potential experimental variations and noise. The sensitivity of the impact hammer is expressed as:

$$S = \frac{mV}{F} \tag{1}$$

In Which "S" represents sensitivity, "V" represents the emitted voltage (Volts), and "F" represents the impact force (Newtons). This relation is the proportionality between the mechanical deformation of the piezoelectric wafer and the applied impact force, as discussed by Levinzon [3], but adapted for the prototype and used in calibrations of piezoelectric transducers with integrated electronics.

The structure was designed to ensure alignment between the hammer and the test specimen, and to make the hammer perform the simple pendulum movement, so that the hammer's impact force could later be calculated during calibration.

2.3 Impact force

During the impact hammer calibration stage, it is necessary to determine the impact force exerted on the test specimen. For this purpose, the simple pendulum model was used on a theoretical basis, which approximates the movement executed by the hammer during the calibration phase.

According to Rao [1], a vibrating system generally includes a means of storing potential energy (spring or elasticity), a means of storing kinetic energy (mass or inertia), and a means of gradual energy loss (damper). The vibration of a system involves the alternating transfer of potential energy to kinetic energy and from kinetic energy to potential energy. If the system is damped, a certain amount of energy is dissipated in each vibration cycle. Considering a simple pendulum, its gravitational potential energy is described as:

$$Epg = mgl(1 - \cos\theta) \tag{2}$$

Considering the law of conservation of energy, where all potential energy is converted into kinetic energy at the lowest point of the movement, the eq. is obtained:

$$Ep = Ek \tag{3}$$

Substituting the equation for the potential energy of the simple pendulum into the equation for the law of conservation of energy and isolating the velocity, we obtain the following eq.:

$$V = \sqrt{2gl(1 - \cos \quad \theta)} \tag{4}$$

In which "V" is the velocity, "g" is gravity, "l" is the length of the hammer handle, and "θ" is the initial angle at which the hammer falls onto the structure. This gives the hammer's velocity when the angle is 0°, during the falling motion. Using the velocity obtained, the impact force is calculated using adapted Newton's Second Law:

$$F = m \cdot \frac{\Delta v}{\Delta t} \tag{5}$$

Where "m" is the mass of the impact hammer, "ΔV" is the velocity of the hammer at the moment of impact, and "Δt" is the duration of the impact. This allowed us to determine the impact force for each test based on the pendulum kinematics and the geometric parameters of the experimental system.

2.4 Results

For data processing, a frequency spectral acquisition and analysis system was used, capable of recording the dynamic response of the structure as a function of the excitation force applied by the developed impact hammer. This system, based on the design proposed by Carvalho [5], allowed for accurate signal collection during testing. After data acquisition, the collected data were processed and passed through a digital filter according to the Proaks method [6], where it was passed through the first-order Butterworth band-pass, where the lowcut frequency used was 0.36 Hz and the highcut frequency was 10 Hz, in order to minimize the noise and preserve the spectrals.

Furthermore, using the developed test structure, it was possible to determine and compare the data collected with the commercial load cell. The tests were performed by releasing the hammer from different inclination angles 15°, 25°, 35°, and 45° as shown in Tab. 1.

Table 1. Comparison between calculated and measured values

Impact angle (°)	Theorical force (N)	Measured force (N)	Error (%)
15	2,07	2,06	0,42
25	3,43	3,74	8,25
35	4,77	5,12	6,77
45	6,07	6,37	4,68

Figure 4 presents the results of consecutive impact tests performed at different inclination angles. Each curve represents the force values measured and by the load cell for each angle. The data exhibits excellent repeatability, with low dispersion between the impacts, confirming the stability if the system. Moreover, the proximity between the curves indicates high precision of the developed hammer, demonstrating consistent performance.

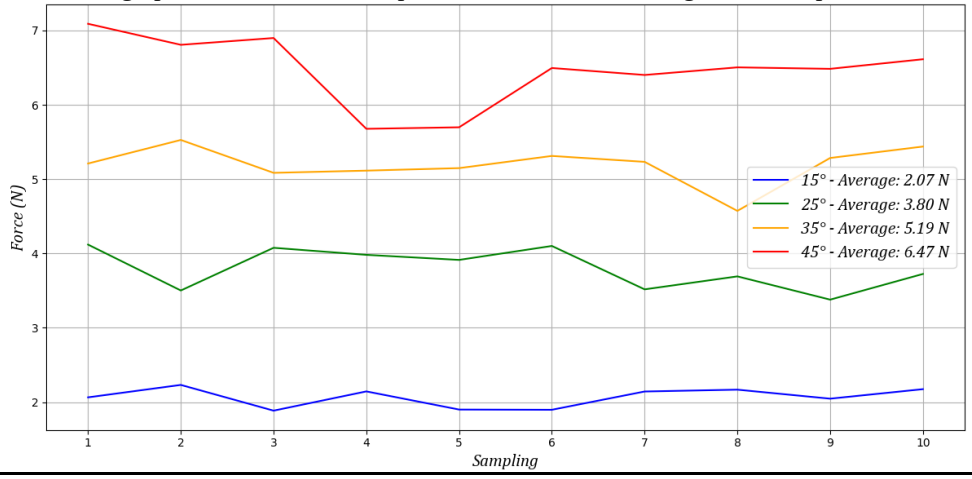


Figure 4 - Graph of collected samples

3 Conclusions

This work presented the design, construction, and experimental validation of a low-cost educational impact hammer intended for modal analysis of small and medium-sized structures. The prototype, developed through precision machining processes, integrated a piezoelectric transducer, a seismic mass, and analog circuitry for dynamic force measurement. The calibration and validation tests performed at different inclination angles revealed that the measured impact forces closely followed the theoretical predictions obtained from the pendulum model. The mean deviation between theoretical and experimental values was 5.03%, confirming both the accuracy and consistency of the system. Furthermore, the results exhibited excellent repeatability, reinforcing the mechanical stability of the test structure and the reliability of the data acquisition system, ensuring that the instrument can be reliably used for the excitation of structures in modal analysis. In addition to its technical performance, the prototype achieved its educational objective by providing an accessible and replicable tool that enables practical learning of vibration and structural dynamics principles areas often limited by the high cost of commercial equipment. Thus, the developed impact hammer stands out as a viable, precise, and educationally valuable alternative to commercial models, expanding experimental possibilities in teaching and research in mechanical and structural engineering.

Acknowledgements. The authors thank SENAI São Paulo for their assistance and participation in the Grupo de Pesquisa em Engenharia Elétrica, Eletrônica, Automação e Reindustrialização. The author thanks OPTIMA Machinery Brazil for its support during the development of the project, in addition to the collaboration and provision of resources contributing to the quality of the work.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] RAO, Singiresu S. “Vibrações Mecânicas”. 4th ed. São Paulo. Pearson Education do Brasil, 2012.
[2] LEE, Eun-Taik. “Pediction of the Physical Properties of a Structural Member by the Impact Hammer Test”. MDPI, 17 August 2022. Available at: https://www.mdpi.com/1424-8220/22/18/6762.
[3] LEVINZON, Felix. “Piezoelectric accelerometers with integral electronics”. New York, NY, USA: Springer International Publishing, 2015.
[4] STEFANESCU, Dan M. “Handbook of Force Transducers: Principles and Components”. Berlin: Springer, 2011.
[5] CARVALHO, Vitor F. “Validation of an In-House developed acquisition system using a commercial acquisition system and the theoretical model of a clamped beam”. Alagoas, Brazil. XLVCILAMCE, 2024.
[6] PROAKIS, John G.; MANOLAKIS, Dimitris G. Digital Signal Processing: Principles, Algorithms and Applications. 4. ed. Upper Saddle River, Pearson Education, 2014.