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PRELIMINARY STUDY OF AN ARDUINO CONTROLLED SHAKE TABLE TO LOW-FREQUENCY TEST

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Abstract

Modernity and advances in civil design are directed at increasingly tall and slender buildings, adding vibrations to structures that generate discomfort, being necessary to mitigate the amplitudes of vibrations produced by low-frequency excitations, characterized in these buildings. In this sense, for some time, experimental studies have been developed with the objective of investigating low-cost scale models, which allow a more detailed study of this type of phenomenon. In this paper, the experimental validation of a dynamic parameterization of low-frequency periodic base motion, considering one degree of freedom, with a synchronized electrodynamic system and controlled with Arduino microcontroller boards is presented. Developed using a small-scale homemade shake table, the system was applied to case studies as a control system using a simple pendulum. The necessary tools are presented to measure the system's responses over time; the dynamic response of the vibratory system can simulate several excitation frequencies. The results obtained in the proposed experimental tests are feasible, with satisfactory precision. The documented results can support an overview of the trend in the efficiency of vibrating table tests in the study of low-frequency vibration control.

Keywords: Shake Table, Arduino, Low-frequency, Control, Experimental Study.

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1 INTRODUCTION

Modernity and advances in civil engineering design are directed at increasingly tall and slender buildings, causing vibrations to structures that generate discomfort, being necessary to mitigate the amplitudes of vibrations produced by low-frequency excitations, characterized in these buildings. In this sense, experimental studies have been developed aiming to investigate low-cost scale models, which allow a more detailed study of this type of phenomenon.

Shaking tables are equipments widely used in engineering laboratories, in order to analyze the behavior of structures subjected to seismic actions [1,2]. Small-scale shake tables are widely used, due to its practicality and low-cost, to study the dynamic behavior of a dynamic system. You can find several manufacturers of this equipment for commercial purchase. Or you can also design a homemade one.

Experimental studies with pendulum elements are often used in literature for experimental studies of its nonlinear behavior, to identify oscillation frequency and damping properties, for example. As well, they are always present in basic physics disciplines, teaching science, engineering, and/or technology courses.

Huang [3] and Soeiro [4] define some types of dynamic actuators (known in laboratories as shakers) as a device used to induce vibration in a system, with controlled amplitude and frequency. It may be mechanical, electromagnetic, electrodynamic or hydraulic. Oliveira [5] stated that an electrodynamic actuator is the most common excitation mechanisms in vibration laboratories to simulate controlled excitation (sinusoidal, random and mechanical shock). The electrodynamic shakers can perform tests that identify important dynamic parameters such as: resonance frequencies, resistance to fatigue and product durability. The use of these actuators is very common due to the cost-benefit ratio and their load capacity of up to 30 kN with a frequency range of 5-20 kHz [6]. At this frequency range, it can be achieved displacements up to 25 mm [7]. But these industrial solutions can reach thousands of dollars.

Damci and Şekerci [8] compared the results of a homemade shake table with commercial ones with similar characteristics. The shake table was excited using a small-scale structure excited by a step motor actioned by *Arduino* microcontrollers, to precisely achieve the imposed base-motion. The use of small-scale shake tables is the most common way to perform vibration tests for industrial applications [9]. Liu *et al.* [10] stated that the shake table test has been increasingly used to study the dynamic responses of structures in these decades. And this device is a powerful tool for researchers and designers to examine dynamic system performance.

In this paper, the experimental validation of a dynamic parameterization of low-frequency periodic base motion, considering one degree of freedom, with a synchronized electrodynamic system and controlled with Arduino microcontroller boards is presented. Developed using a small-scale homemade shake table, the system was used to case studies like a control system using a simple pendulum. The necessary tools to measure the system's responses along time are presented; the dynamic response of the vibratory system can simulate several excitation frequencies. The results obtained in the proposed experimental tests are feasible, with satisfactory precision.

2 SHAKE TABLE

The shake table is a type of electrodynamic actuator capable of carrying out controlled displacements on a sliding table with prescribed amplitude and frequency. A schematic drawing of the shake table used in this work is shown in Figure 1.

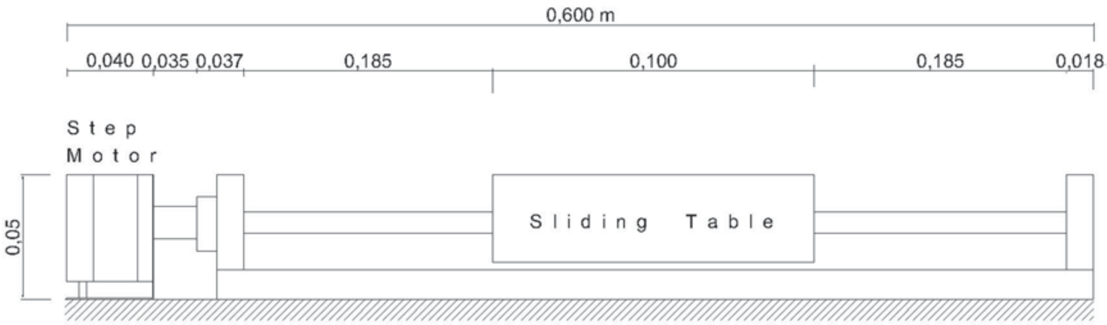

Figure 1 – Shaking Table Scheme

The shake table equipment, to generate and analyze electrodynamic excitation, is divided into two systems: movement of the mechanical system and data acquisition. For the mechanical system, a sliding platform is used to simulate the movement of seismic vibrations at low frequencies, a stepper motor as a source of mechanical force capable of generating potential energy, which allows the movement of the platform and a microcontrolled board that encodes the controlled movement to be transferred electronically to the stepper motor that transforms the force.

In this work, a handcrafted shaking table sampled was used (Figure 2). With base dimensions of 0.423 x 0.048 x 0.100 m, two axial axes (0.423 m) that serve as a guide and support, a trapezoidal spindle with 8 mm in diameter and an adaptation for the connection of the mechanical energy generator system, which is able to move the square iron base, with base dimensions of 0.100 x 0.100 m, that simulates a car.

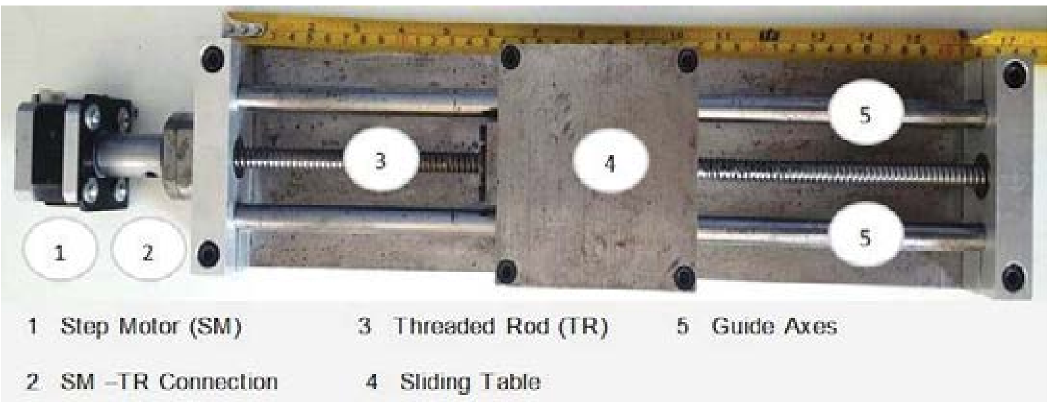

Figure 2 – Eletro-mechanical devices of Shake Table

The electro-mechanical actuator is a bipolar stepper motor bipolar *Nema 17* to perform very precise angular movements, in discrete or fractional steps, controlled by A4988 driver module [11]. The stepper motor *Nema 17* is a high torque motor with dimensions 42 x 34 mm, the equivalent rotation angle of 1.8° for a complete lap (a spin of 360°). To know the steps taken to complete a lap or revolution, what is known as PPR (steps per revolution or pulses per revolution), the following calculation is performed:

$$PPR = \frac{360°}{rotation\ angle} \tag{1}$$

$$PPR = \frac{360°}{1.8°} = 200\ steps\ per\ revolution \tag{2}$$

Stepper motors can be controlled in open loop, as they have a known position at all times [12] In this case the motor is connected to a microdevice controller, capable of controlling the interpolation of the flow current in stepper motors, controlling the size of the pulse. The slower the rotation, the larger the pulse size, smoothing the resulting movement of the motor. One of the main advantages of this device is being able to manually set the maximum output current, allowing the application of voltages above the motor's nominal value. The controller drive has a voltage regulator with an intelligent system that automatically adapts the decay mode, a thermal protector that shuts down allowing the temperature control and, a protection against cross currents that generates a reduced dissipation in the power and allows the immediacy in the precision.

To find the reduction in the size of the pulse, the complete cycles are divided into smaller steps, smoothing the movement of the motor, after all, the smaller the step, the greater the precision. The 1.8 ° angle can be divided up to 256 times, obtaining steps up to 0.007 degrees (1.8 x 0.007) or 51,200 micro steps. To establish communication with the engine it is using an Arduino Uno, which is the most popular microcontroller model and widely used for its simplicity, accessibility and low power consumption; the programming is done through the regular computer, connected by a USB port that establishes a communication link with the flash memory built into the Arduino, the USB socket also supplies power to the Arduino. The programming used is the C programming language and through execution in the integrated development environment (IDE) as explained by S. Monk [13] allowing one program to run at a time.

In Figure 3, the components of the mechanical system of the handmade vibrating table are sampled.

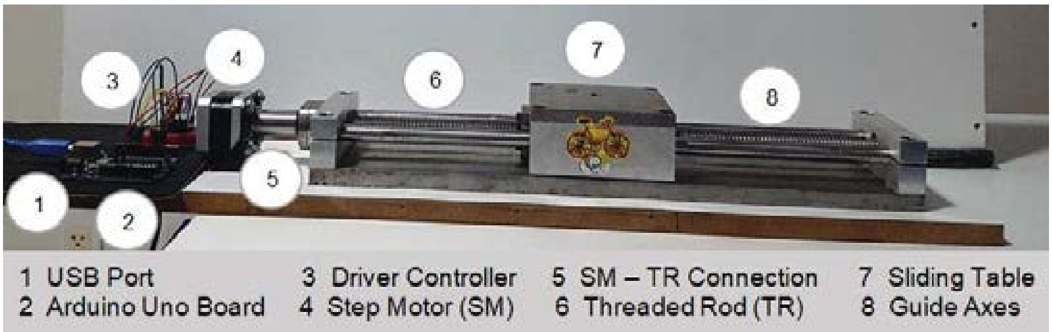

Figure 3 – Composition of the handmade shake table.

3 METHODOLOGY

Initially, the evaluation and behavior of the shaking table is carried out and then a simple pendulum excited by the table is analyzed.

For the movement of the vibrating table, energy is transformed using an electric motor, step-by-step, controlled by a potentiometer and a microcontroller, capable of directing the information from the programming code that allows excitation and rotation control to be carried out. Low frequencies in the range of 0.3 Hz and 2.1 Hz were considered, varying in steps of 0.2 Hz, verifying the limitations of displacement of the table in its maximum trajectory and minimum motor capacities. In order to guarantee greater reliability to the study [14], an appropriate number of repetitions were carried out for each study. In this sense, the number of repetitions of sixty-four (64) periods was considered for each operating mode of the engine in random order and in duplicate; also, it saves the life of the controller drive in function of thermodynamic capacity for the most rambling mode of the engine and the storage capacities of the data analysis program according to the resources available for the study.

The technique used in this study for data acquisition was video capture, performed using a Samsung-SM-G920A Smartphones camera, Android version 5.0.2, with resolution adapted to FHD (60fps) 1920x1080, and speed of 60 images for approximate seconds according to the instrument's specifications. Where the object of the center of analysis of differentiated color is identified that will facilitate and it was used a measuring tape that allows to carry out the necessary calibration on the screen in the data analysis software with the intention of guaranteeing the accuracy of the data under study. Figure 4 shows the image of the slide platform with the identification of the elements that allowed the object to be marked, calibrated, to locate the known points and the Cartesian axis, and to define the units considered.

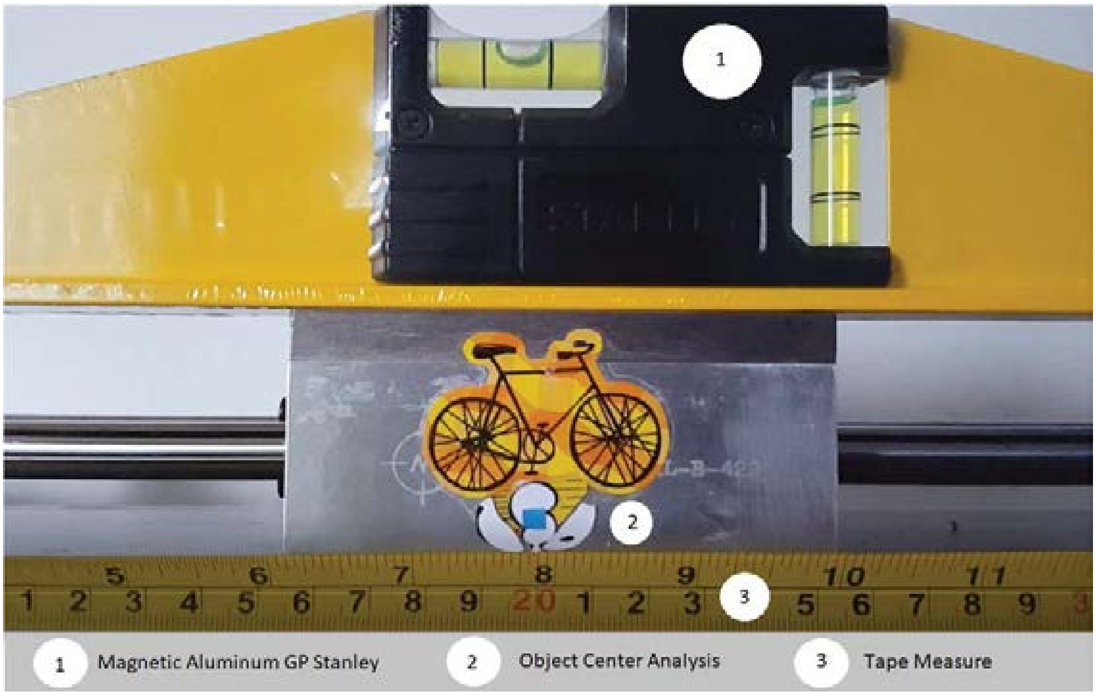

Figure 4 – Detail of sliding platform with follower point.

In this work, the free software Tracker is used to analyze the results (Figure 5), which was also used by Bezerra Jr. et al. [15] for their analysis of the results, they specified the software's capacity to measure several quantities in two-dimensional space, based on a standard established by the user. The software identifies the number of frames per second of the video in analysis, presenting the data and graphics corresponding to the study of physical phenomena, automatically and in real time, such as: displacements, velocities, accelerations, time, angular frequencies, among others, making it possible to carry out various analysis, such as comparing results, identifying discrepancies in movement patterns and analyzing performances. Bonventi Jr. and Aranha [16] describes that the software also allows you to make adjustments to various functions and even to build your own mathematical models.

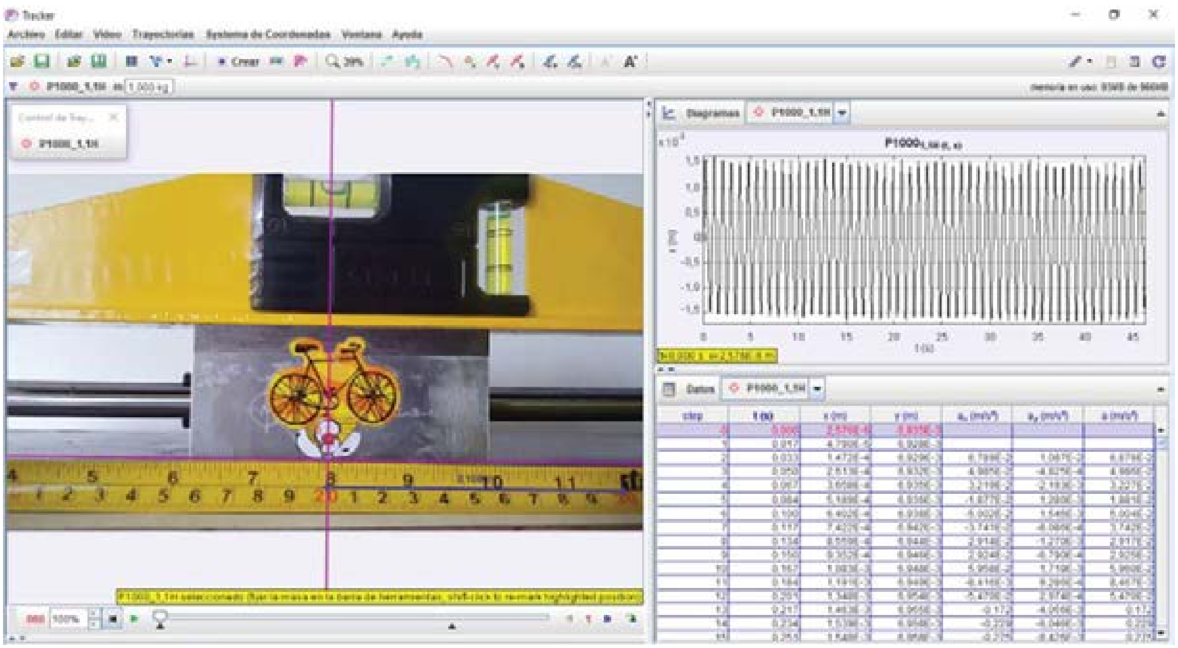

Figure 5 – Motion of sliding platform analyzed by Tracker software.

4 RESULTS

The results of the study consist of validating the movement of the vibratory table movement, and studying simple pendulum tests.

4.1 Validation of the Shake Table

The study of the motor oscillation movement for five (5) different configuration of the stepper motor + A4988 controller on the Arduino platform, Table 1, was performed.

Mode	Steps (PPRM)	Angular Speed (ω)	Motor Deceleration (%)
Full	200	1,85	-
Half	400	1,49	(20)
¼	800	1,07	(28)
1/8	1600	0,68	(36)
1/16	3200	0,39	(42)

Table 1 – Operating Parameters of the A4988 Controller on the NEMA motor rotational movement.

By enabling one of these operation modes of the stepper motor [11], the waveform obtained resembles the square wave, Figure 6. The precision of periodicity is observed. Figure 6 shows the experimental result of rotation of the stepper motor for modo mode, obtaining an oscillation frequency of 0.6 Hz and an average angular velocity amplitude of 2.62 rad / s, analogous to Brites, [17]. The experimental result was obtained through motion capture by video analyzed by the Tracker program.

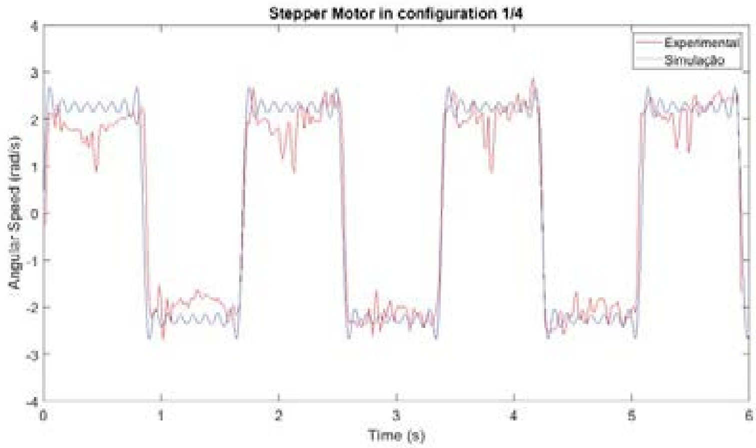

Figure 6 – Angular rotation of the stepper motor for the operation mode ¼.

For the validation of the movement of the shake table, the acceleration time history of the sliding platform is shown in Figure 7 showing a triangular waveform. As expected, a triangular wave-type displacement has the following shape as a series of Fourier:

$$x(t) = x_o \cdot \frac{8}{\pi^2} \sum_{i=0}^{N} \frac{(-1)^i}{n^2} \sin(n \cdot 2\pi f\, t) \tag{3}$$

where, $n = 2i + 1 = 1,3,5, \ldots$. Note that from the triangular wave, the square wave is obtained with the time derivative of the expression (3) referring to the velocity of movement of the platform and similar to the angular velocity of the stepper motor.

$$\mathrm{x(t)} = \mathrm{x_o} + \frac{8}{\pi^2} \sum_{\mathrm{i}=0}^{\mathrm{N}} (\mathrm{n} \cdot 2\pi \mathrm{f})^2 \cdot \frac{\mathrm{A}(-1)^{\mathrm{i}}}{(2\mathrm{n})^2} \sin(\mathrm{n} \cdot 2\pi \mathrm{f t}) \tag{4}$$

Figure 7 compares the experimental results and the simulated theoretical model regarding the acceleration of the platform. There is a gap between the experimental results and the theoretical model due to inaccuracies in the excitation frequency.

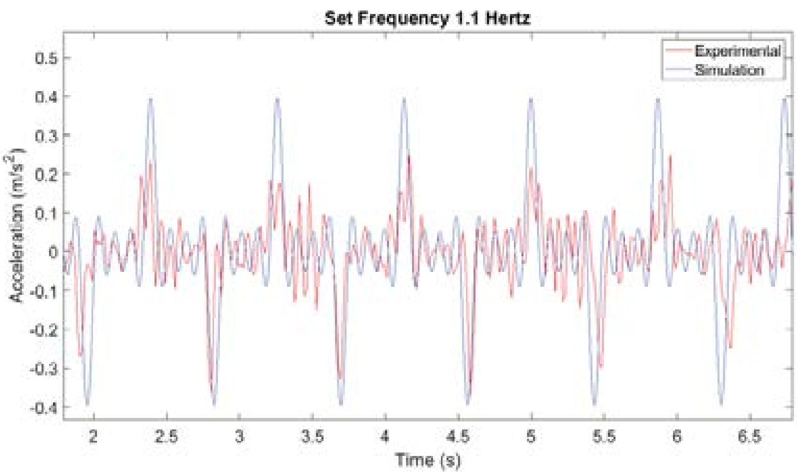

Figure 7 – Comparation of experimental data and analytical waveform of sliding platform acceleration

When analyzing the time-history acceleration of the platform in different directions, the Figure 8 shows the acceleration of the platform in the x-direction (parallel to the movement of the platform) and the y-direction (perpendicular to the movement of the platform) measured by a smartphone *Samsung-SM-G920A*, Version of *Android 5.0.2* and by the program *Tracker*. As expected, the platform response (in the x-direction) presents the expected waveform for acceleration, as Figure 8. The acceleration in the x-direction is ten times greater than the acceleration in the y-direction (perpendicular) demonstrating a good relationship signal-to-noise ratio for this frequency $1{,}1\ Hz$. These parasitic accelerations are due to noise mainly due to small clearances in the linear platform mechanism.

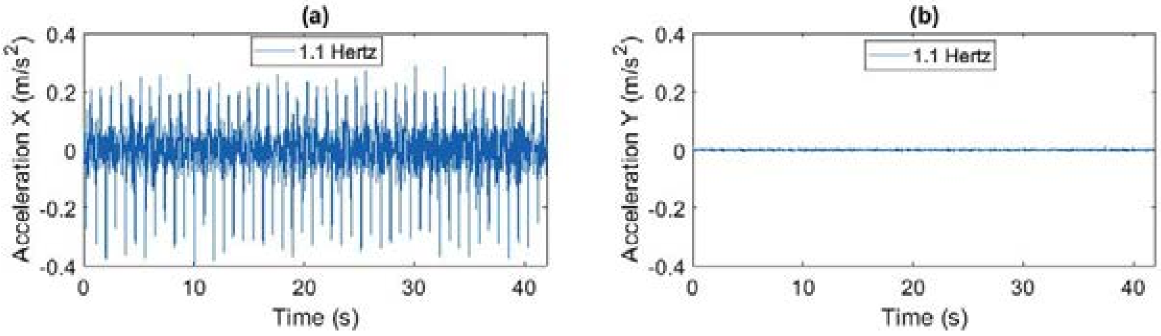

Figure 8 – Time history acceleration of the platform to the excitation frequency $\mathbf{1,1}\ \boldsymbol{Hz}$.
(a) Steering acceleration-X (b) Steering acceleration -Y.

When analyzing the experimental results for other excitation frequencies, the shake table shows signs of acceleration with different magnitudes depending on the number of steps of the stepper motor. A series of experimental measurements of the acceleration of the platform for excitation frequencies between $0{,}3\ Hz$ to $2{,}1\ Hz$ for a range of $0{,}2Hz$. Only the results are presented for the frequencies of $0{,}3Hz$ (Figure 9), $0{,}7Hz$ (Figure 10) e $1{,}7Hz$ (Figure 11). The results show good signal-to-noise ratios for frequencies above $0{,}5Hz$. Due to mechanical gaps, failures in the platform support, and inaccuracies in the stepper motor action, the acceleration signal for low frequencies is less than the noise for low frequencies ($f \leq 0{,}5Hz$).

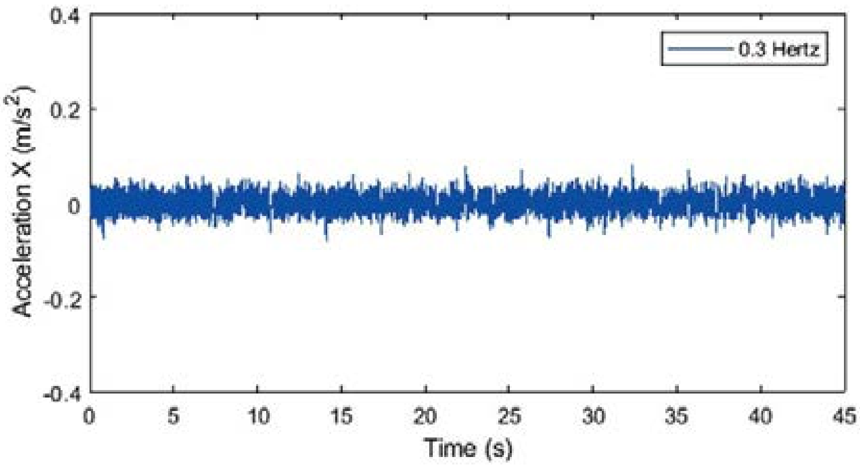

Figure 9 – Time history acceleration in the X-direction for the excitation frequency 0.3 *Hz*.

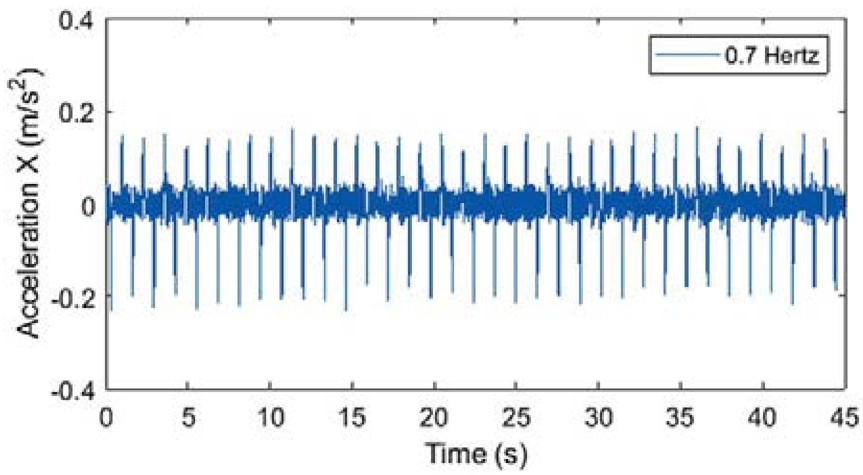

Figure 10 - Time history of acceleration in the X-direction for the excitation frequency 0.7 *Hz*.

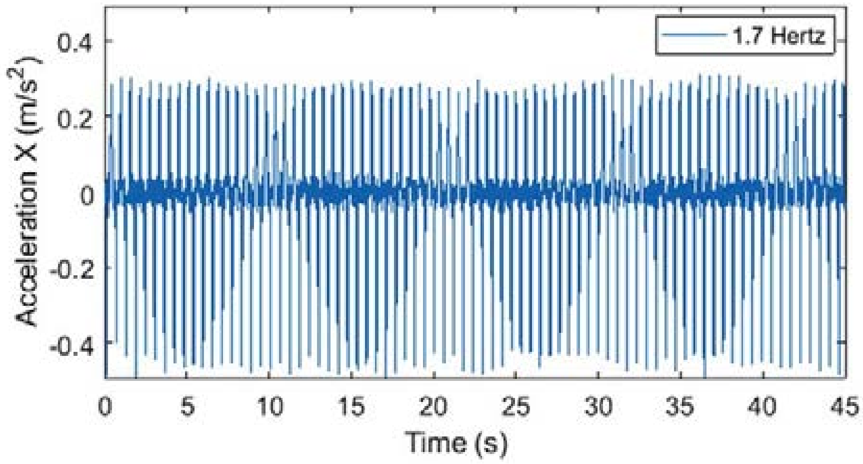

Figure 11 - Time history acceleration in the X-direction for the excitation frequency 1.7 *Hz*.

The analysis in the frequency domain of the temporal signals results in a spectrum of acceleration amplitudes for the excitation frequencies de 0,9 Hz (Figure 12), 1,2 Hz (Figure 13) e 2,1 Hz (Figure 14). The frequency peaks are observed for the respective fundamental frequencies f_n and its odd harmonics $f_i = if_n$ $(i = 1,3,5, \dots)$, accordingly the expression of the Fourier series (1).

$$f(t) = a_0 + \sum_{n=1}^{\infty} a_n \cdot \cos(n\omega_0 t) + b_n \cdot \sin(n\omega_0 t) \tag{5}$$

where, Fourier coefficients are obtained through the temporal expressions $a_0 = \frac{1}{T_0}\int_{t_1}^{t_1+T_0} f(t)\,dt$, $a_n = \frac{1}{T_0}\int_{t_1}^{t_1+T_0} f(t) \cdot \cos(q\omega_0 t)\,dt$, $b_n = \frac{2}{T_0}\int_{t_1}^{t_1+T_0} f(t) \cdot \cos(q\omega_0 t)\,dt$; t_1 is a temporal arbitrary instant [18]. The amplitude spectrum has even symmetry and the phase spectrum has unique symmetry. When evaluating the acceleration spectra, it is found discrete spectra containing a number of harmonics integer multiples of the signal fundamental frequency.

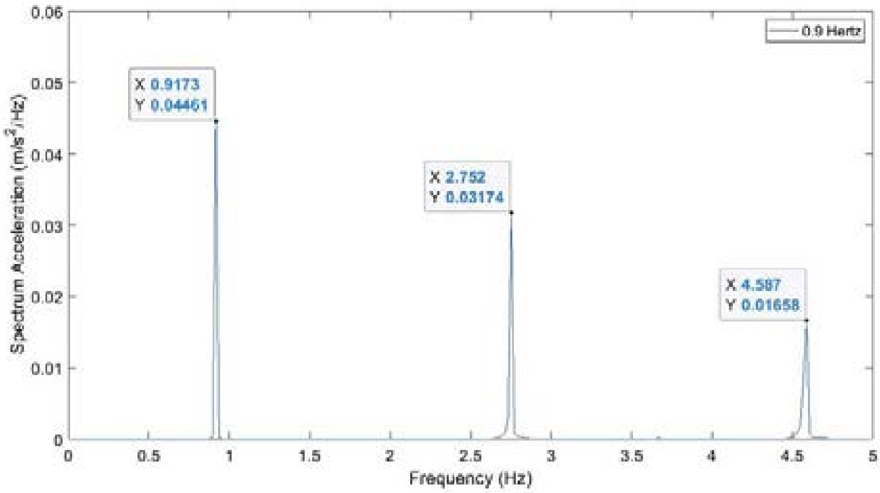

Figure 12 - Spectral response from acceleration to excitation frequency 0.9 *Hz*.

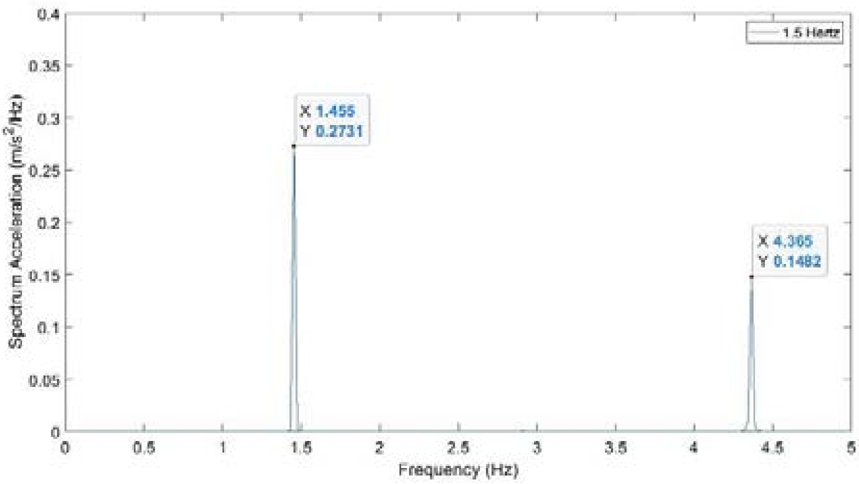

Figure 13 - Spectral response from acceleration to excitation frequency 1.5 *Hz*.

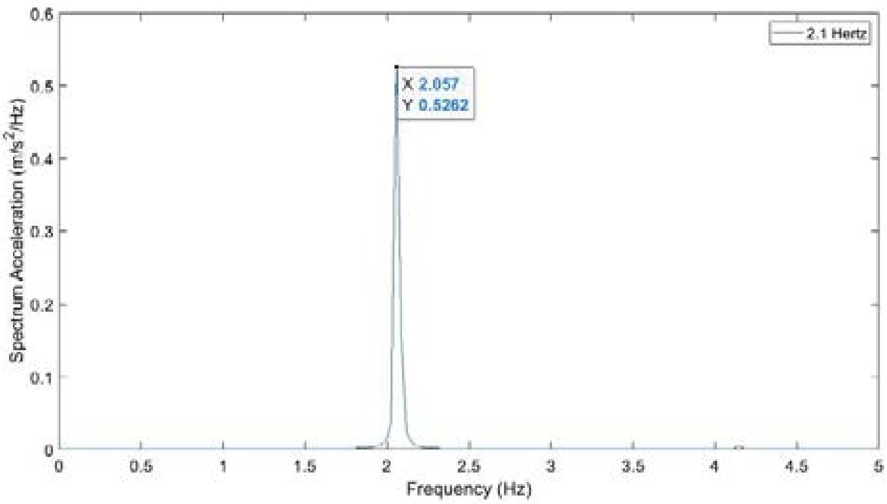

Figure 14 - Spectral response from acceleration to excitation frequency 2.1 *Hz*.

4.2 Free Pendulum Vibration Test

In order to study a practical application of the platform, it was studied the dynamic behavior of a simple pendulum (Figure 15) with length $l = 0{,}255\ m$ between the contact point and the mass center of the small sphere of mass $m = 0{,}04101\ g$, considering local gravity acceleration in Brasilia DF-Brazil (15°45'43''S 47°52'25''W) $g = 9{,}7808439\ m/s^2$. Using motion capture by video with the Tracker software, the dynamic behavior of the simple pendulum is studied.

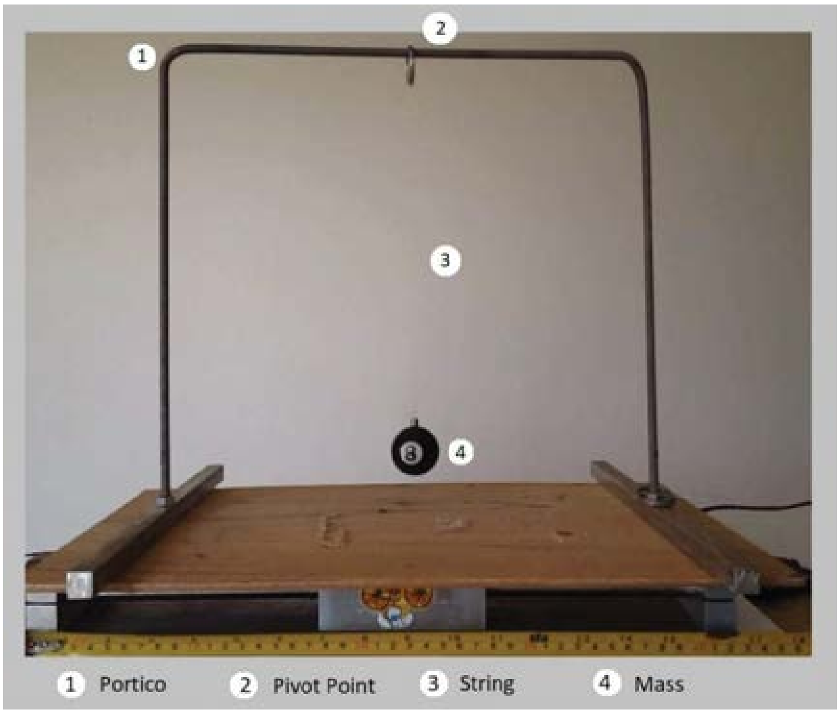

Figure 15 – Simple Pendulum

At first, the preliminary results to determine the behavior of the pendulum's amortization are presented, varying the amplitude of the sphere's displacement in small angles and considering the approximation $sin\,\theta \cong \theta$ acceptable. The initial movement is generated carefully and searching that the effects of air displacement can be minimized.

The motion equation of the pendulum can be written as:

$$\ddot{\theta}+2\xi\omega_n\dot{\theta}+\omega_n^2 \sin\theta=0 \quad (5)$$

where θ is the angle of the pendulum, the period of undamped linear oscillation is $T_o = 2\pi/\omega_n = 2\pi\sqrt{L/g}$, it is function of local gravity acceleration g and pendulum length L, assuming that $\sin\theta \approx \theta$, and the exact oscillation period T It is given by [19]:

$$T=T(\theta)\approx T_o\left[1+\frac{1}{16}\theta^2+\frac{11}{3072}\theta^4+\frac{173}{737280}\theta^6+\ldots\right] \quad (6)$$

Providing an initial disturbance, Figure 16 presents the comparison of the experimental response of the simple pendulum obtained by motion capture in the *Tracker* and the result of the theoretical model obtained by numerical simulation with MatLab software. In this case, the amplitude of displacement of the pendulum mass is of 0.2094 rad. There is a certain similarity in the temporal results of the angular position of the mass between the theoretical models and the experimental result. The damping model needs to be improved.

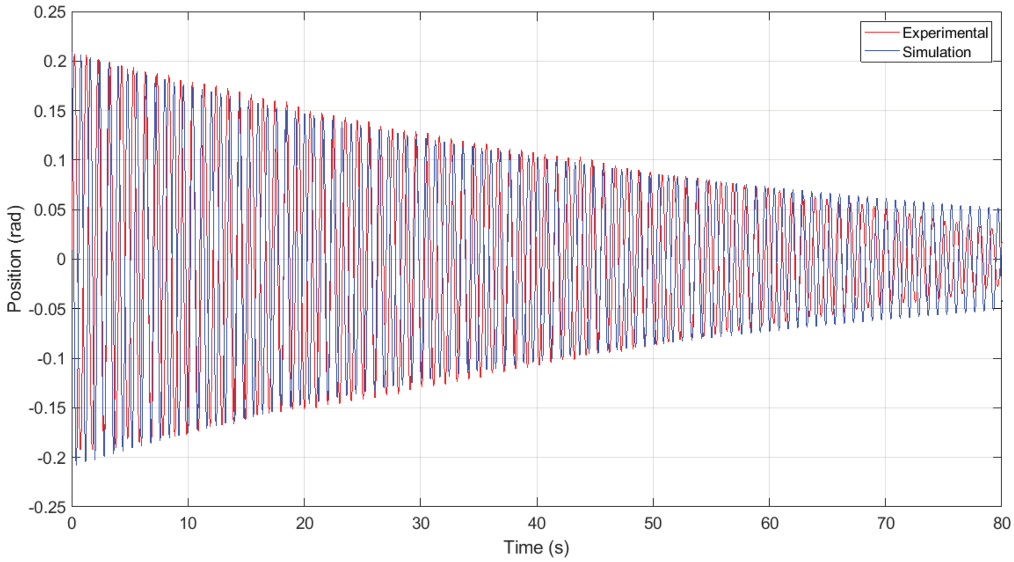

Figure 16 – Damped Response of the Simple Pendulum: Experimental results x numerical simulation.

The period of experimental oscillation is compared as a function of the angle of oscillation of the simple pendulum according to the expression (6). Figure 17 presents a comparison between the theoretical results with the experimental period extracted from the temporal response. The experimental results show an evolution close to the theoretical solution and an evolution dependent on the maximum period of oscillation angle.

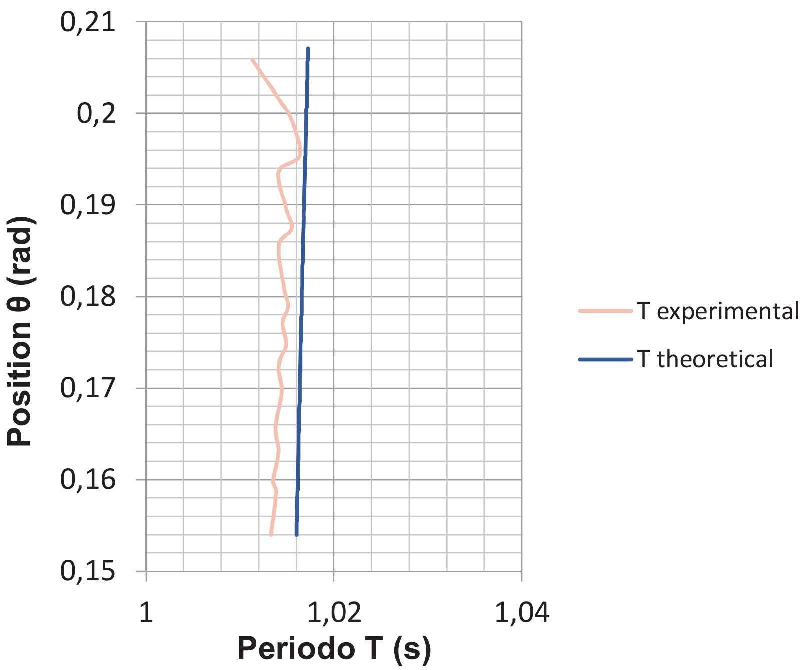

Figure 17 - Period Relationship - Position of a Simple Pendulum

5 CONCLUSION

This work performs an experimental study of a low-frequency handcrafted electrodynamic shake table. Initially, the validation of the shake table dynamic is done using video motion capture through Tracker software for experimental frequencies between 0.3 and 2.1 Hz. The dynamic displacement, velocity, and acceleration of the shake table platform are compared to analytical solution achieving reasonable agreement. Finally, the free vibration of a simple pendulum motion is acquired through video motion capture. The experimental data is compared to theoretical models that show a good agreement with reasonable accuracy.

The authors suggest carrying out future work to verify and adapt the study, based on the results obtained in the validation of the shake table, the study of the dynamic response of a simple pendulum, or coupled pendulums, or of a tuned liquid column damper (TLCD).

6 ACKNOWLEDGMENTS

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