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Instrumentation for vibration measurement for comfort evaluation in motor vehicles

Instrumentação da medição de vibrações para avaliação de conforto em veículo automotor

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ABSTRACT

The global automotive industry has always sought to improve the safety and comfort quality of its vehicles, recognizing that providing an exceptional experience to the users is crucial for market progress and ensuring the safety and well-being of the passengers. In this context, the relentless pursuit of this goal makes it relevant to explore the adverse effects that may arise through the use of automotive vehicles. This paper outlines the initial steps to create a methodology focused on measuring, analyzing, and monitoring mechanical vibrations caused by a vehicle prototype developed at the Universidade Federal de Santa Maria (UFSM), Cachoeira do Sul campus, RS. This approach aims not only to achieve safety and comfort standards but also to contribute to the constant evolution of the automotive industry by providing a more comprehensive understanding of the impacts of mechanical vibrations on occupants.

Keywords: Mechanical vibrations; Vehicle comfort; Whole body vibrations

RESUMO

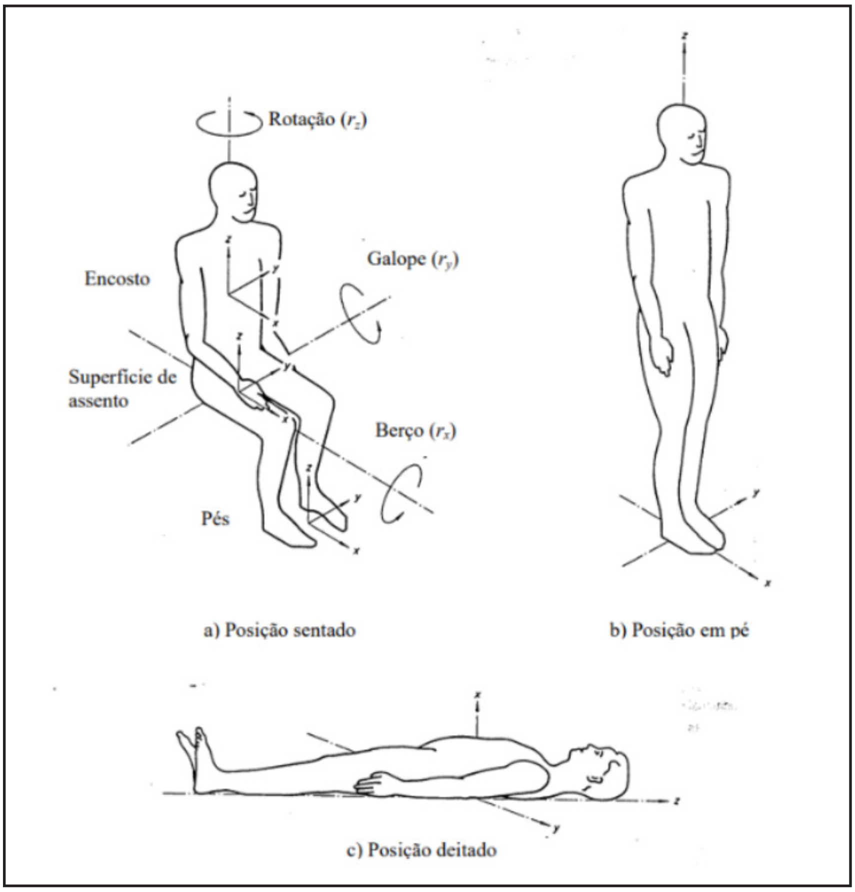
A indústria automobilística global sempre buscou aprimorar a qualidade da segurança e do conforto de seus veículos, reconhecendo que proporcionar uma experiência excepcional aos ocupantes é crucial para o progresso do mercado e para garantir a segurança e bem-estar dos passageiros. Nesse contexto, a busca incessante por esse objetivo torna relevante a exploração minuciosa dos efeitos adversos que podem surgir com a utilização de veículos automotivos. Este capítulo delineia os passos iniciais na criação de uma metodologia voltada para a medição, análise e monitoramento das vibrações mecânicas provocadas por um protótipo veicular desenvolvido na Universidade Federal de Santa Maria (UFSM), campus Cachoeira do Sul, RS. Essa abordagem visa não apenas atender aos padrões de segurança e conforto, mas também contribuir para a constante evolução da indústria automobilística, proporcionando uma compreensão mais abrangente dos impactos das vibrações mecânicas nos ocupantes.

Palavras-chave: Vibrações mecânicas; Conforto veicular; Vibrações de corpo inteiro

1 INTRODUCTION

Whole Body Vibrations (WBV), as widely recognized in international medicine (Skroder et al., 2020), are about the transfer of vibrations to the human body. This transfer occurs when a person is standing, sitting, or lying on a surface that generates and transmits these vibrations. ISO 2631-1 (1997) standard establishes specific guidelines for the measurement of WBV, defining the x, y, and z axes as longitudinal, lateral, and vertical, respectively. These guidelines provide a standard for assessment, ensuring a consistent and accurate approach to measuring bodily vibrations.

Figure 1 – Coordinate system of the three body axes



Source: ISO 2631-1 (1997)

As we can see, the upward figure illustrates the orientations of the three axes (x, y, z) according to different positions of the human body (Holanda et al., 2020). It is observed that the z-axis is often associated with higher accelerations, in comparison to the x and y axes (Araya-Solano & Medina-Escobar, 2020). Exposure to Whole Body Vibrations (WBV) in the z-direction is influenced by terrain imperfections and obstacles.

As highlighted by Langer et al. (2015), off-road vehicles such as tractors, forklifts, cranes, and backhoes tend to expose operators to significantly higher levels of Whole Body Vibration (WBV) in the z-axis. This is due to the rotational movement of these vehicles when navigating holes and obstacles in the ground. On the other hand, the seat height and wheel track width influence the magnitude of the acceleration transmitted to the operator in the y-axis direction. Thus, the condition of the terrain surface plays a crucial role in determining the level of vibration exposure in the y and z axes.

The automotive industry has been undergoing significant changes and innovations for the past three decades. These changes include not only the introduction of Toyota's production system but also the standardization of microelectronics and improvements in safety standards, with a constant flow of new technologies, designs, and models (1996 apud Vickery; Carvalho 2008). This pursuit of new technologies and innovations is not only aimed at gaining a competitive advantage in the market but also at ensuring that the company provides a quality product, aiming to guarantee the safety, comfort, and performance of its automobiles for consumers (Candelo et al. 2022).

However, there are problems that still persist, mainly caused by the popularization of automobiles and how they have become an almost obligatory means for carrying out daily activities. One of these phenomena is exposure to mechanical vibrations, which, although seemingly harmless at first, can cause severe health problems when exposed to them over medium to long periods. Professor Massimo Bovenzi (2010, p. 1), cites according to the European Union's mechanical vibration directive, that Whole Body Vibrations (WBV) are defined as “mechanical vibration which, when transmitted to the whole body, poses risks to the health and safety of workers, especially lumbar morbidity and spinal injuries”. Exposure to WBVs can not only cause problems in the spine but also various similar symptoms experienced by drivers, truck drivers, and operators of cargo vehicles such as the development of chronic headaches, muscle pain, and vascular problems (Massimo, 2010; Massimo et al. 2017). In critical cases, such as exposure of pregnant women to prolonged doses of WBV, complications in pregnancy can occur, compromising the health of the woman. One of the most common reactions is gestational diabetes and preeclampsia, which defines high blood pressure in the period before 20 weeks of pregnancy (Holanda et al., 2020).

In order to create a methodology for measuring WBVs, the use of a vehicle prototype was conceived, which, while traveling on a rolling track, simulates in a controlled environment the oscillations to be studied in the WBV phenomenon. This prototype implemented a MEMS accelerometer, which, through an open-source microcontroller in an AD converter, conditions the signals obtained by the sensor and converts these signals from analog to digital. Subsequently, the obtained values are processed and stored by a portable device or computer. The accelerometer is a device sensitive to loads, in which an instantaneous change in voltage caused by the movement of the internal springs of the sensor produces a voltage at the output terminals of the accelerometer, which is proportional to the applied acceleration (Khandpur, 2020).

For the measurement of risks associated with exposure to WBV, the Vibration Dose Value (VDV) and the “A(8)” are calculated, referring to the daily exposure to vibrations over a period of 8 hours. These variables estimate, depending on various tabulated parameters, whether the individual’s exposure to WBV can pose risks to their health (Bovenzi et al., 2017).

The purpose of this paper is to establish a reference model for the quantification and comparison of vibrations generated by a vehicle prototype (VP). To achieve this goal, we have developed a methodology divided into four distinct parts: 1) introduction, 2) data collection, 3) processing, and 4) comparison with a reference material.

2 HARDWARE DESCRIPTION OF THE PROTOTYPE

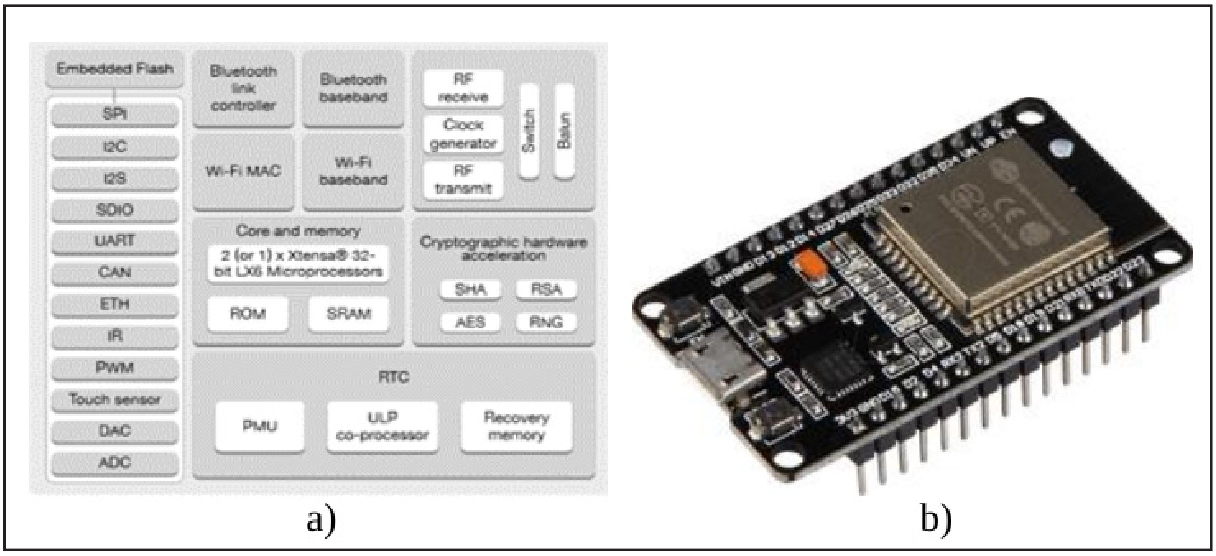
The implemented prototype has three main modules: Control Module, Sensing Module and Communication Module.

The Control Module is composed by the Micro-controller Unit (MCU) that executes the digital algorithm for vibration measurement. The MCU receives the vibration from the Sensing Module and uses some digital signal processing tools to filter and provide a correct measurement. The MCU uses an algorithm to calculate the Fast Fourier Transform (FFT) and a detailed analysis in the vibration frequency domain is evaluated.

2.1 CONTROL MODULE

An ESP32 series MCU from the manufacturer Espressif® was used as the main element of the control module. Its processing speed, memory capacity and peripherals made this MCU appropriate for the application, with advantages such as good performance, robustness, and reliability. The functional internal blocks of the ESP32 micro-controller board are illustrated in Figure 2.

Figure 2 – a) Functional Blocks Diagram of the ESP32 control module, b) ESP32 control card



Source: datasheet esp32

The characteristics of the ESP32 MCU used for processing are described below:

1) CPU: This MCU integrates two 32-bit Xtensa LX6 microprocessors and operates at processing speeds of up to 160 MHz. It has a 16-bit and 24-bit instruction set that supports digital signal processing functions and 32 interrupt vectors that can generate internal or external interrupt routines from 70 different sources.

2) Internal Memory: it has 520 KB of RAM, integrated ROM of 448 KB and 16 KB in the RTC (Real TimeClock). In addition, it supports up to 8 MBytes of external SPI RAM.

3) I²C Communication Interface: it has two physical I²C buses that can be configured as slaves or masters, in standard 100 Kbit/s mode or 400 Kbit/s fast mode. Used to connect external peripherals to the MCU. It supports 5 MHz frequencies depending on the configuration of the SDA data line with pull-up resistors and 7-bit and 10-bit addressing modes. This interface was necessary in the project to communicate the control module with the sensing module.

4) PWM Output Port: the ESP32 MCU has output 16 channels for pulse width modulation, which is used to control motors and smart lights. Internally it is composed of synchronous or independent timers and a dedicated capture module that detects external events by flank or logical level change with exact timing.

5) Wi-Fi Wireless Connectivity: it has Wi-Fi and Bluetooth functions with implemented TCP/IP Internet protocol and 802.11 b/g/n full wireless communication protocol that offers a Basic Services Set (BSS) and a network administrator.

2.2 SENSING MODULE

The main element of the detection module was an Inertial Measurement Unit (IMU) based on the MPU6050 sensor of InvenSense MotionApps™ devices. This sensor combines a 3-axis gyroscope and a 3-axis accelerometer on the same chip, manufactured with MEM technology. This device integrates a Digital Motion Processor

(DMP) capable of performing complex motion capture algorithms of 9 degrees of freedom.

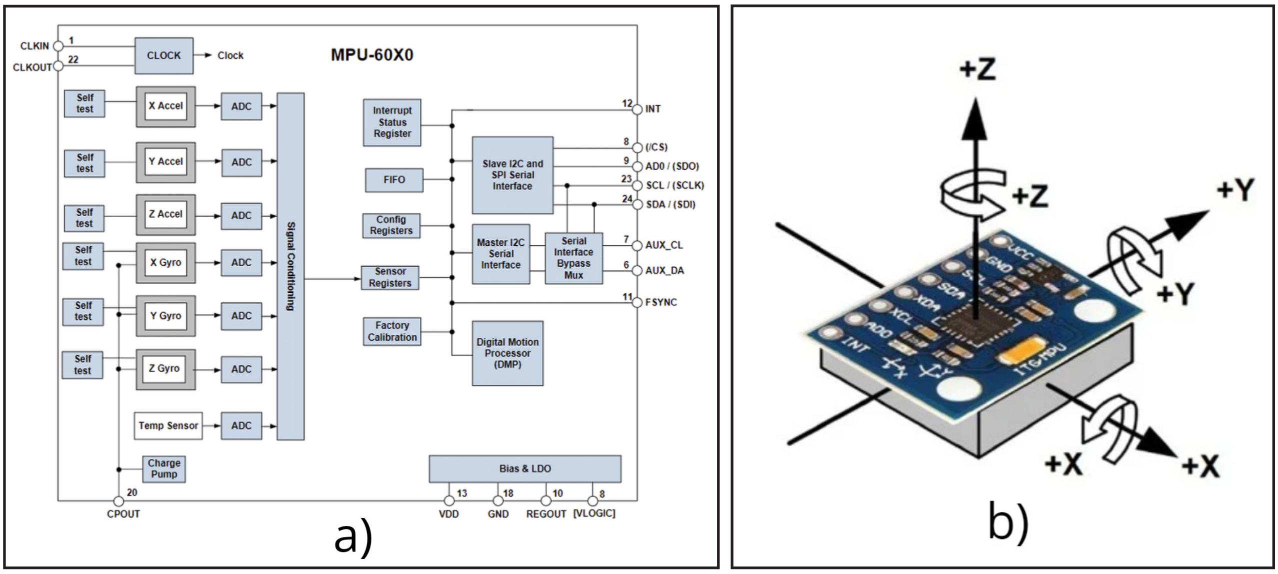
It communicates through the I²C interface compatible with the MCU of the control module and has the *i2cdevlib* library for immediate use. This sensor incorporates a 3.3V voltage regulator and it was connected in parallel through pull-up resistors connected to the Data and SCL pins of the I²C bus between the MCU and the IMU for direct use.

For accurate capture of fast and slow movements, it has a programmable scale range of 250/500/1000/2000 degrees/sec for the gyroscope and 2g/4g/8g/16g for the accelerometer. It can be configured to transmit data at rates of up to 400KHz. For the application, the sampling rate of the accelerometer and gyroscope was set at 8KHz.

The gyroscope of the IMU detects the velocity of the angle in the three directions and the accelerometer detects the angular acceleration.

The sensor was mounted on a card and connected directly to the control module through the I²C pins as a slave mode, and its access was made by interruption. Figure 3 shows the internal architecture of the IMU and the orientation of its recommended physical installation.

Figure 3 – a) Block diagram of the IMU MPU6050, b) Axes Orientation of the MPU 6050



Source: researchgate e arduinoomega

This sensor was chosen due to its availability in the market and the electronics industry, as well as its high level of sensitivity and reliability. Considering that, according to Oliveira et al. (2016), the maximum acceleration peaks produced by an off-road vehicle prototype for competitions were 21.0 m/s^2, it is expected that higher acceleration peaks will be encountered in this paper, which involves the use of a less advanced vehicle prototype. To compensate for this increase, a sensor that operates in larger ranges was selected. It is estimated that it would be necessary to work in the ranges of 2 to 4 g to fully meet the demand. Since this accelerometer can work in accelerations of 2, 4, 8, up to 16 g (where gravitational acceleration g = 9.81 m/s^2), the accelerometer will cover all possible vibrations experienced by the off-road vehicle.

2.3 COMMUNICATION MODULE

This module establishes a remote connection between the control module and a device connected to the Internet, such as the PC or a mobile phone, which acts as a visualization module. The communication module uses the Wi-Fi wireless.

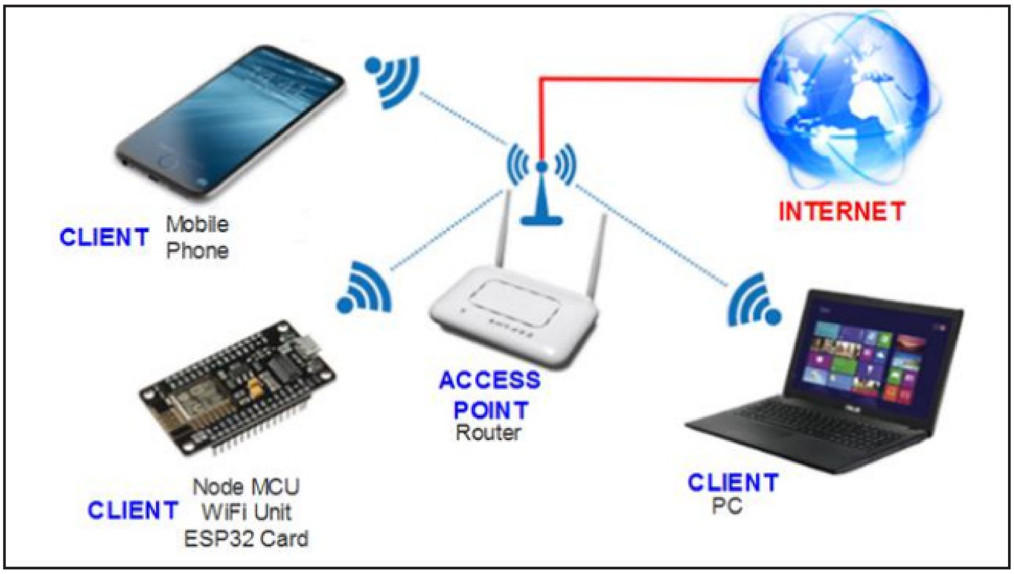
Communication block of the control module to connect the MCU node to the Internet with a PC. The MCU node is connected to an existing access point of a Wi-Fi network that is known as a station mode connection (STA). The wireless communication architecture in STA mode is shown in Figure 4.

When the connection is established, two events are presented to the ESP32, SYSTEM_EVENT_STA_CONNECTED that indicates that it has connected to an access point and SYSTEM_EVENT_STA_GOT_IP that indicates that an IP has been assigned with the server of the access point.

This connection was used to transmit the vibration signal from the control module to other client devices that connect to the same access point as the PC or smartphone, taking advantage of the fact that the access point is connected to the Internet (router).

In Station mode, the MCU node was connected to an Access Point, such as a router with its network name SSID (Service Set Identifier) . In this mode, the MCU Node is integrated into the Wi-Fi network as a server/client, being able to interact with the rest of the devices that form it. The ESP8266WiFi.h library was used to establish and manage the connection. The WiFi.begin() function connects to the access point at a baud rate of 115.000.

Figure 4 – STA architecture communication module



Source: Blog Eletrogate

For connection management such as reconnection, disconnection or verification of the connection status was used the WiFi.reconnect() function. Also, to get information about the connection, such as the MAC or IP address, was used the WiFi.macAddress() command.

2.4 MICRO SD CARD SHIELD

For optimization in the measurement procedure, it is envisioned that data acquisition should be performed first, followed by its analysis. Therefore, a device for data storage is necessary. In parallel with the sensor, a Micro SD Card reader module has been connected.

Figure 5 – Micro SD Card reader module

Source: MakerHero

2.5 TEST BENCH

As the calibration and initial tests cannot be performed on the vehicle prototype due to its complexity, a test bench has been devised. This test bench will utilize an audio generator to generate vibrations at a known frequency. These vibrations will be used as initial measurements of the model and provide an indication of the accelerometer's reliability.

3 PROCESSING OF COLLECTED DATA

There are different formats for processing data, one of them being a data logger programmed in Python based on the collected information, which gathers the features obtained by the sensor, organizes it, and sends it to an Excel spreadsheet. Through functions available on this platform, we can generate graphs comparing frequency over time.

As a parallel option, there is the methodology used in Oliveira's work (2023, p. 53), in which the data is supplied by the ESP32 and stored on the microSD card. Subsequently, data processing is carried out using Octave/Matlab® software. At this point, we can check for any issues in the measurement process. Using this data, we can create graphs showing how the main aspects change over time.

With the resulting values, the Fast Fourier Transform (FFT) function is applied, allowing us to obtain the average frequency of the acquired data. It is also relevant to calculate the power spectral density for each frequency range using the PSD (power spectral density) method.

Equation 1. Fast Fourier Transform equation.

$$F(\omega) = \int_{-\infty}^{\infty} f(t) e^{-i\omega t} dt \tag{1}$$

Equation 2. Equation of Power spectral density.

$$PowerSpectrumDensity = \frac{Power\ Spectrum}{\Delta f} \tag{2}$$

Equation 3. Equation PSD.

$$Power = |X[k]|^2 \tag{3}$$

Where $X[k]$ = Frequency component amplitude.

4 ANALYSIS AND COMPARISON WITH THE REFERENCE MATERIAL

4.1 VIBRATION SYSTEMS

Taking the mass-spring system as the basic vibration operating system, as it possesses one degree of freedom, we only need one axis along which it displaces to determine its position. Considering it as an isolated system without any external force or damping applied to it, we can observe, through the analyzed force, the free vibration of the spring without any alteration in its amplitude.

According to Inman (2018), if we consider a single force "F" acting on a mass "m" attached to a spring with elastic constant "k", we can reduce the sum of the forces in a single direction as follows:

Equation 4. Hooke's Law, disregarding friction.

$$mx''(t) = -kx(t) \tag{4}$$

Analyzing the motion of the spring over time, Inman (2018) describes this motion as periodic. We can describe the position using the following equation:

Equation 5.

$$x(t) = Asin(\omega_n t + \phi) \tag{5}$$

If we differentiate x(t) with respect to time "t" to obtain "dx/dt", we can find the velocity as a function of time.

Equation 6.

$$x'(t) = \omega_n Acos(\omega_n t + \phi) \tag{6}$$

Differentiating the equation a second time, taking the velocity and differentiating with respect to time, we can obtain the acceleration x"(t).

Equation 7.

$$x''(t) = -\omega_n^2 A sin(\omega_n t + \phi) \quad (7)$$

4.2 METHODS OF EVALUATION

In order to relate the previously obtained data to improvements in comfort and safety, an approach was conducted through a systematic literature review with the purpose of seeking similar parameters for comparison and standardization. As a result, two quantitative methods of vibration assessment were obtained: Method A(8) and the Vibration Dose Value (VDV) parameter.

4.2.1 A(8) METHOD

In many studies, the most common method for assessing vibration exposure has been the calculation of Daily Exposure, known as A(8), or Normalized Exposure Resultant Acceleration (NREA). This method represents the continuous equivalent acceleration over an 8-hour working period. (Holanda et al., 2020).

Equation 8.

$$A(8)_{max} = (\sum_i a_{\omega i(max)}^2 \times \frac{t_{di}}{T_{(8)}})^{1/2} \; (ms^{-2} r.m.s.) \quad (8)$$

Given that $a^2_{w(max)}$ is the root mean square (RMS) frequency-weighted acceleration in a triaxial plane.

Equation 9.

$$r.m.s = \left[\frac{1}{T}\int_{0}^{T} a_{\omega}^{2}(t)dt\right]\left(m.s^{-2}\right) \tag{9}$$

(Bovenzi et al. 2017)

4.2.2 VDV parameter

The Vibration Dose Value (VDV) is calculated using the fourth power vibration dose method, considering the x, y, or z axes.

Equation 10.

$$VDV_{max} = \left[\int_{0}^{T} a_{\omega(max)}^{4}(t)dt\right]\left(ms^{-1.75}\right) \tag{10}$$

We consider a4w(max) as the root mean square (RMS) frequency-weighted acceleration in a triaxial plane.

Equation 11.

$$r.m.q = \left[\frac{1}{T} a_{\omega}^{4}(t)dt\right]\left(m.s^{-2}\right) \tag{11}$$

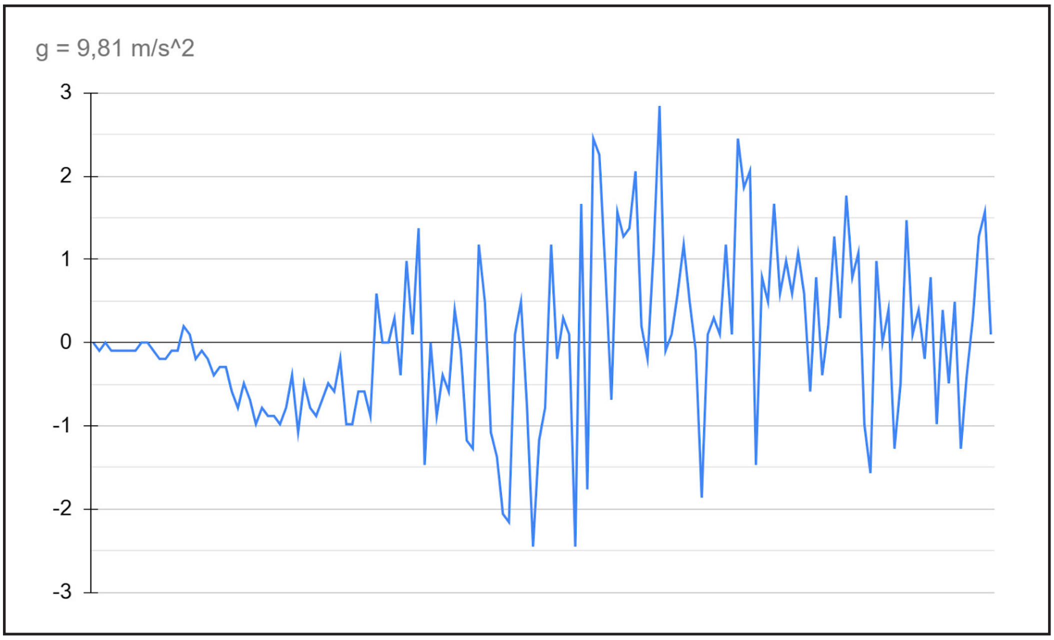
(Bovenzi et al. 2017)

5 VALIDATION PROCEDURE AND RESULTS

The MEMS accelerometer MPU-6050, in conjunction with the ESP32 module, was subjected to mechanical vibrations caused by the ground and obstacles on the road, with the aim of simulating the stresses that could be imposed during circulation. After data collection and analysis, the MEMS accelerometer recorded peaks of 27.91 ± 0.10

m/s² (equivalent to 2.845 ± 0.01025 g with uncertainty, as specified in the datasheet). These values stood out, especially in situations of passing over speed bumps and abrupt obstacles.

Figure 5 – Graph of initial tests of the MPU-6050 accelerometer



Source: Author's own work

Comparing the results collected from reference materials, which described peaks around 21m/s², we can see that the prototype is capable of reaching the estimated values for the measurement.

6 CONCLUSIONS

The prototype system for measuring vibrations aimed at vehicle comfort, using a MEMS accelerometer, presented promising results in seeking an effective method to measure mechanical shocks. This system met the demands and scope of the project, proving to be a viable option for implementation.

The methodology outlined in this project aims to serve as a foundation for future researchers to understand the potential of MEMS accelerometers and realize the feasibility of conducting vibration tests, regardless of the project's premises. Such an approach expands the possibilities of developing a control methodology applicable to companies and regulatory bodies for supervision and safety.

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