Design, Development, and Validation of a Whole-Body Vibration Measurement Device

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Measurements of whole-body vibration are fundamental to access and evaluate comfort levels and possible injury development in the human being. International standards such as ISO 2631 and ISO 10326 are dedicated to the measurement and validation of mechanical systems to access vibration levels. Nowadays, the traditional measurement devices require multiple components and so hence become highly bulky, do not allow autonomous data recording, and are expensive. Following the previously mentioned standards, the present research is focused on the design and validation of a new and economic whole-body vibration measurement device. The developed device, besides being capable to measure the whole-body vibration, allows the user to select multiple sample ratings, is capable to record data on a μSD card, is easily moved and adapted, and is autonomous and low cost. This device is composed of three main components: a tri-axial accelerometer, a protective metal case, and semi-rigid rubber disc. Shaker tests were conducted to evaluate the measurement capability of the whole system and the influence of each component on the vibration measurements. This article will introduce the design and development steps for the proposed system. Concerning the validation phase, its results will be discussed and analyzed. [DOI: 10.1115/1.4055191]

Keywords: analysis and design of components, devices, and systems, applied mechanics, applied mechanics simulation, design engineering, experimental mechanics, finite element analysis, instrumentation, measurement, mechanical engineering

1 Introduction

Human vibration is defined as the physical factor effect on the human body induced by mechanical energy transmission from oscillation sources. Car, bus, and train journeys represent vibration sources in normal daily life [1,2].

Vibration types are characterized according to the transmission path and been classified as whole-body vibration (WBV) or hand-arm vibration (HAV). The former is related to the vibration transmitted into the body by means of a supporting surface, and the latter is characterized by a local vibration transmitted to the hands and arms. Exposure to both types of vibration leads to negative health effects. Reported health risks from WBV include headache, fatigue, insomnia, and mainly lumbar, neck, and shoulder pain, while for HAV, effects such as white finger, Raynaud's phenomenon, carpal tunnel syndrome, and peripheral neuropathies are frequently reported. This way, considering the health risk and multiple vibration sources present in daily routine, it is fundamental to develop protective vibration methods. To do it, it is crucial to access the level and duration of vibration exposure [3–6].

ISO 2631 standard quantifies the WBV evaluation for nausea, health, perception, and comfort. This defines a frequency range between 0.1 and 80 Hz for the analysis when this affects the body as a whole and states that measurements must occur at the interface surfaces when the vibration transmission happens [7].

Traditional WBV equipment is constituted of three units, the measurement, the acquisition, and the record units. This traduces a system composed of a seat pad measurement unit, connected to DAQ system (comprised chassis and modules, and the number of modules depends on the number of seat pads) and acquisition unit, connected with a computer—record unit. For these systems, there is a need for a power supply that can be done by electricity or battery. Due to its high number of components, this system tends to become bulky, hard to adjust and adapt, and expensive. A second option present at the market connects the seat pad with reading equipment, which acts as a data logger and analyzer, presenting the results to the user after the experiments. However, this option only allows the use of one seat pad at a time, restricting the measurement position to one place. Both types of equipment present a high capability of sample frequency and guarantee synchronized data measurement. For the first equipment, a huge number of measurements can be performed at the same time, and it depends on the number of modules [8–12].

Based on the limitations of the existing systems, this study focused on the design, development, and validation of new equipment that is capable to access and record WBV and, if possible, HAV, allowing multiple uses and higher test flexibility. The system should obey requirements such as no need for an external power supply, autonomous recording, data logger, lower number of components, be a light system, easy to adapt and adjust, and be a low-cost system.

The developed device is composed of three components, a three-axial accelerometer, a protective metal case, and a semi-rigid rubber disc. Besides being capable of measuring both types of vibration, the device is capable to record data on a μSD card, is easily moved and adapted, and is autonomous and low cost. The equipment was developed following the standards ISO 10326—Mechanical vibration—Laboratory method for evaluating vehicle seat vibration, ISO 2631—Mechanical vibration and shock—Evaluation of human exposure to whole-body vibration, and ISO 5349—Mechanical vibration—Measurement and evaluation of human exposure to hand-transmitted vibration. Initially, pressure tests, on Autodesk Inventor software, were realized to verify the mechanical behavior of the components. Finally, shaker tests were conducted to validate the equipment. The influence of each component on the vibration measurements was studied, analysis of variance (ANOVA) statistical tests were performed, and frequency analysis was also realized [7,13,14].

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2 Equipment Design

According to ISO 2631, ISO 5349, and ISO 10326, a couple of rules need to be accomplished to create a vibration measurement system. Concerning the three-axial accelerometer, its setting must be rigid and protect from external shocks. This protector case should be housed in a semi-rigid rubber disc. In its turn, when assessing a HAV system, the protector case should be coupled to an adapter [7,13,14]. So, to design and develop a measurement system capable to fulfil the standards, three steps were taken. The first step consisted of the selection of the accelerometer. Second, a metal case was designed and numerically tested. Finally, a silicone rubber disc was produced.

2.1. Three-Axial Accelerometer: Characteristics and Selection.

The international standard ISO 2631 defines the necessary conditions and evaluation methods for access measurements and control of WBV. This states a vibration frequency range between 0.1 and 80 Hz as the ones necessary to measure and record for nausea, health, comfort, and perception analysis. To fulfill the enunciated requirement, the vibration measurements should be recorded using a sample rate equal to or higher than 200 Hz, respecting the Nyquist theorem and preventing aliasing that, consequently, leads to data loss [7].

ISO 5349 specifies the requirements for measuring and evaluating the vibration effects concerning hand-arm transmitted vibration. Vibration records should be comprehended on a frequency range between 8 and 1000 Hz. As mentioned previously, considering the data loss and Nyquist theorem, the sample rate should be equal to or higher than 2000 Hz [13].

For both standards, there is a need to access the vibration on three axes, and this way, only three-axial accelerometers should be considered [7,12].

Following the defined ISO standard conditions and the goal of the project, a set of characteristics were highlighted as an essential for the accelerometer, such as three axial, scale range between ±2 g and ±16 g, allowing sample rate of 200 Hz and 2000 Hz or above, allowing data record on a μSD card, low-power consumption, autonomous, and low cost.

PCE Instruments Company, a partner of the present project, kindly provided the PCE-VDL-24I Accelerometer. This three-axial accelerometer presented the following technical characteristics, scale range of ±16 g, sample rating between 0– and 2400 Hz, precision of ±0.24 g, resolution of 0.004 g, autonomous recording (32 GB μSD at 200 Hz sample rate records during 1d08h32min), Li-ion 3.7 V/500 mAh integrated battery, and postanalysis due to data export (CSV file). Once the accelerometer presented the pretended technical characteristics and complies with the standard requirements, it was selected as the measurement unit [15].

2.2. Protector Metallic Box Development and Numerical Validation.

ISO 2631 defines the conditions for vibration experimental tests: the vibration frequency range, measurement placement, and evaluation methods, and ISO 10326 concerns the measurement equipment. Therefore, this standard was defined as the base for the equipment design. It states that the accelerometer setting must be rigid and protected from external shocks. Thus, a protective metallic box was designed and validated [7,14].

The accelerometer should be allocated inside the box, so two different pieces were thought to form the metallic box, which will be closed using screws. Rigid fixation was guaranteed using a mounting plate, where the accelerometer was coupled. This plate ensures zero influence on the measurement results and provides magnetic imam allowing extra support on metal surfaces. An illustration of the accelerometer attached to the mounting plate is shown in Fig. 1.

Then, it was needed to design, validate, and produce the top of the protector metal case. This part of the box should prevent external shocks. Furthermore, concerning WBV tests, the protector case also needs to support and sustain the weight of a user without any damage to the accelerometer or influence on the vibration measurements. The proposed solution involves the development of an aluminum 6061 box, reinforced at the top and laterally. Figure 2 illustrates a combination of views and, so, it provides a better comprehension of the 3D box.

Finally, after design, it was necessary to validate the top of the metallic box. To fulfill this purpose, a pressure test was conducted resorting to a finite element analysis on AUTODESK INVENTOR software.

According to SAE J1384, a 75 kg mass should be used in place of a human when testing vibration equipment. To obtain a more elevated test margin and representation of people with a higher weight, the pressure test was performed with 0.001 MPa, which represents the exercised pressure of a 100 kg person seated on the box. Results, presented in Fig. 3, showed a maximum Von Misses stress of 0.07975 MPa, a maximum displacement of 8.935×10^{-5} mm, and 15 safety factors [3].

An aluminum 6061 top box was produced. This box has been demonstrated to be reliable, secure, and able to protect the accelerometer from external shocks.

2.3. Design and Production of the Silicone Rubber Disc.

According to ISO 10326-1—Part 1: Basic requirements, the accelerometer box should be placed in a semi-rigid mounting disc. This needs to present between 80 and 90 durometer units (A-scale), total diameter of 250 mm ±50 mm, and should interfere, as little as possible, on the dynamic properties between the passenger and seat interface [16,17].

Initially, the disc was designed on AUTODESK INVENTOR. Its diameter was set at 235 mm, while the height was defined to match the metal box high. To couple, the metal box a fit, with the metal box dimensions, was withdrawn from the center of the disc. By using 3D printing technology, a disc was produced to confirm its dimensions and metal box fit. After validated, the disc also served as a mold for the definitive production. Finally, following the

Fig. 1 Three-axial accelerometer attached on the mounting plate

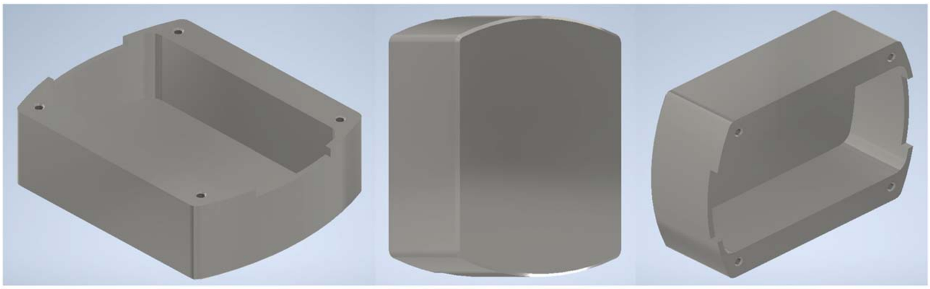

Fig. 2 Combination of multiple views obtained on AUTODESK INVENTOR

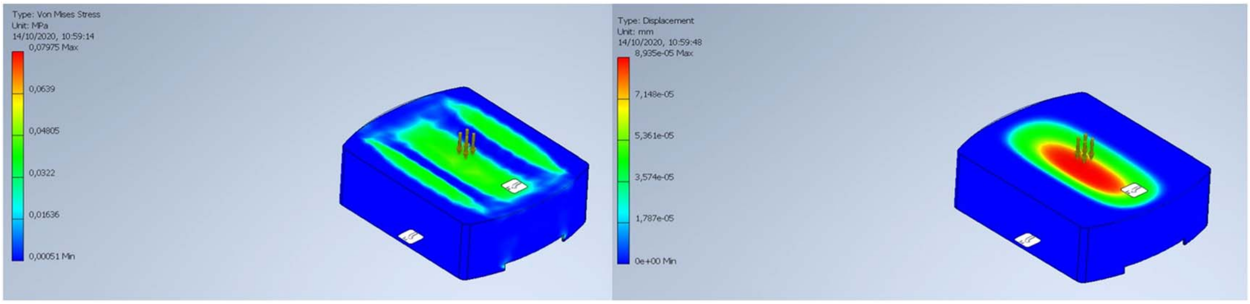

Fig. 3 Von Misses stress and displacement analysis for the 0.001 MPa pressure test

considerations of ISO 10326 and given the available materials, it was decided to produce the disc in silicone rubber 80 shoreA. Figure 4 shows the developed system, composed by the metallic box housed into the silicone disc.

This way, the necessary components were designed, validated, and produced. Experimental tests were conducted to validate the measurement capability of the system. It should be highlighted that, besides the accelerometer presents measurement capability for HAV, a new silicone equipment, capable to be adapted and adjusted to the arm or/and hand, should be designed, and produced to fulfill this purpose.

3 Experimental Tests and Validation

As described earlier, four different components were developed concerning the construction of a WBV measurement system. Thus, it was crucial to experimentally test and validate each one of them and the system as one. To examine if the developed system could be validated and used as a measurement and record acceleration system, the following experimental setup was made. Each equipment was attached to a vibrating base and set to record data. Equal vibration level was applied to each test. The obtained acceleration data were then studied using MATLAB software and statistically analyzed by resorting to an ANOVA test.

3.1. Materials and Methods. By using Brovind vibration equipment, a vibration measurement test was performed. Vibration levels were controlled by the CB controller. This one allows the regulation of vibration to ten levels. Attached to the controller were the vibrating base and container [18–20].

Initially, the equipment was fixed on the vibrating container and the test started. The vibration was set at level 0 for 1 min, and then, it was increased to level 1 for another minute and, finally, returned to level 0 for the last minute. The three axes (x, y, and z) of the accelerometer were fixed in the same position for all experiments. Each experiment was repeated three times for each configuration (accelerometer, mounting plate, metallic box, and rubber disc/developed system). Figure 5 shows examples of the experiments and axis configuration.

The results were obtained and analyzed using MATLAB coding. Mean, maximum, and minimum values were calculated for each test. Moreover, by grouping experiments by axis, the standard deviation was obtained. Once the accelerometer records in g's, the results are expressed in this measurement unit. An ANOVA

Fig. 4 Developed system, metallic box coupled with a silicone rubber 80 shoreA disc

Fig. 5 Experiments examples and axis configuration: (*a*) accelerometer, (*b*) mounting plate, (*c*) metallic box, and (*d*) rubber disc/full equipment

test was used to validate the developed equipment. This test determines the probability of whether the means of the different datasets are equal. Four ANOVA tests were performed. Each piece of equipment was observed and compared with the accelerometer, namely, the accelerometer/mounting plate, accelerometer/metallic box, and accelerometer/rubber disc, for studying the influence of the four components as a complete WBV measurement system. The null hypothesis was that the equipment's presented the same mean. If the *p*-value returns higher than 0.05, the means are equal otherwise, and they are considered different [21–23]. Once ISO 2631 specifies a frequency range (0.1–80 Hz) for WBV analysis, the frequency content was also observed.

3.2 Results.

Figure 6 shows the standard acceleration behavior observed in all tests. The experiments showed residual vibration during the first and last minutes, and initial peak, positive, and negative values were observed, which corresponds to the turn-on of the controller and increase of vibration up to level 1.

Table 1 presents the vibration mean, maximum, minimum, and standard deviation for the three-axis concerning the four different equipment configurations.

Concerning the *X*-axis, results showed a lower mean (−0.0024 g's) for both disc (complete equipment) and metallic box. The maximum mean was found for the mounting plate configuration (−0.0026 g's), while the accelerometer presented a mean of −0.0025 g's. The maximum vibration displayed a range between 0.3282 and 0.3283 g for all configurations, while the minimum vibration was approximately between −0.3438 and −0.3439 g. Figure 7 shows the mean results for the *X*-axis.

For the *Y*-axis, a lower mean (−0.0026 g) was presented for both accelerometer and disc configurations. The mounting plate and the metallic box configurations showed means of −0.0024 g and −0.0021 g, respectively. The maximum and minimum acceleration were found for the accelerometer, 0.2033 g and −0.2463 g. Figure 8 illustrates the mean results for the *Y*-axis.

Concerning the *Z*-axis, the higher mean was shown for the accelerometer (0.9642 g), while the lower one was presented for the metallic protector case (0.9626 g). Both mounting plate and disc found means of 0.9636 g's. The maximum vibration, 1.8362 g, was found for the accelerometer, while the minimum vibration, 0.0842 g, was established for the metallic box. Figure 9 portrays the mean results for the *Z*-axis.

The results per test exhibited the highest values for the accelerometer, with a mean of 0.3197 g, a maximum of 1.8362 g, and a minimum value of −0.3438 g. The other configurations presented similar results. The complete system results should be highlighted once it presented results as, a mean equal to 0.3195 g,

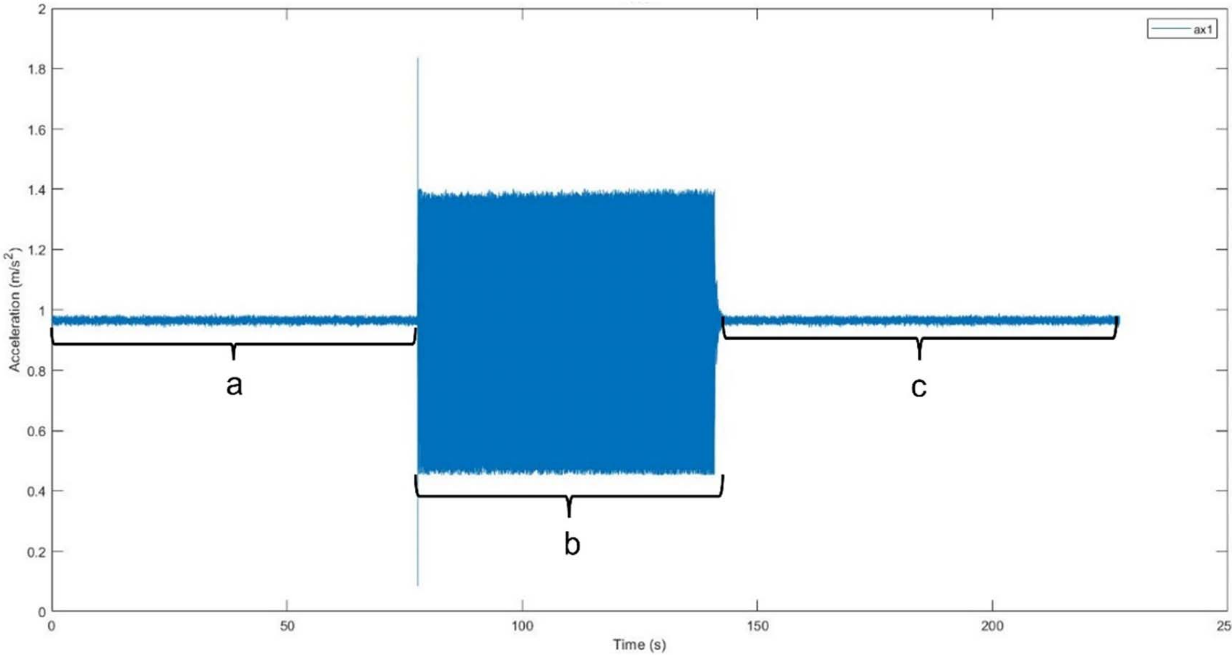

Fig. 6 Standard acceleration behavior: (*a*) level 0 vibration, (*b*) level 1, and (*c*) level 0

Table 1 Mean, maximum, minimum, and standard deviation results

	Mean (g)			Maximum (g)			Minimum (g)		
	X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
Accelerometer	−0.0025	−0.0026	0.9642	0.3283	0.2033	1.8362	−0.3438	−0.2463	0.0847
Mounting plate	−0.0026	−0.0024	0.9636	0.3283	0.2032	1.8358	−0.3439	−0.2462	0.0847
Metallic box	−0.0024	−0.0021	0.9626	0.3282	0.2031	1.8361	−0.3439	−0.2462	0.0842
Rubber disc /complete equipment	−0.0024	−0.0026	0.9636	0.3282	0.2032	1.8361	−0.3439	−0.2462	0.0845
Standard deviation	0.00018	0.00023	0.00090	0.00013	0.00013	0.00016	0.00012	0.00017	0.00017

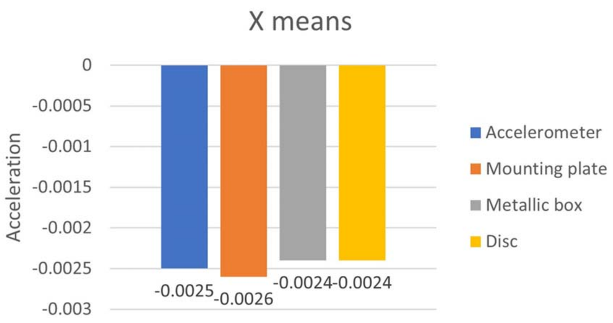

Fig. 7 Results concerning *X* means

a maximum value of 1.8361 g, and a minimum of −0.3439 g. The outcomes concerning per test and standard deviation are presented in Table 2.

An ANOVA statistical analysis was performed for the interaction between the primary element (accelerometer) and the other configurations. This way, differences in mean values for each test were statistically tested and further analyzed (see Table 3).

Likewise, an analysis of all configurations was also performed. Once the results were above 0.05, it can be assumed that all the means are similar; thus, the null hypothesis was not rejected, and therefore, the results showed significance.

The frequency analysis showed similar results for all axis and equipment configurations. Two main frequency peaks were found, an initial one around 4.49 Hz with an amplitude of

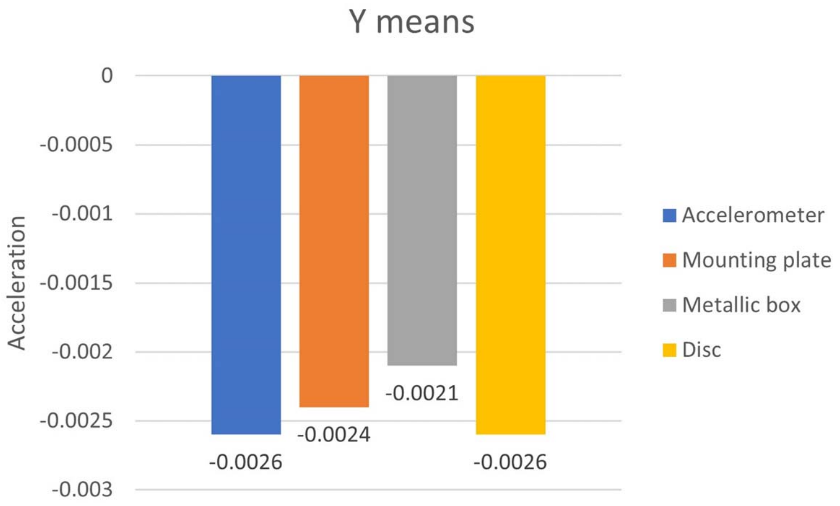

Fig. 8 *Y* means results

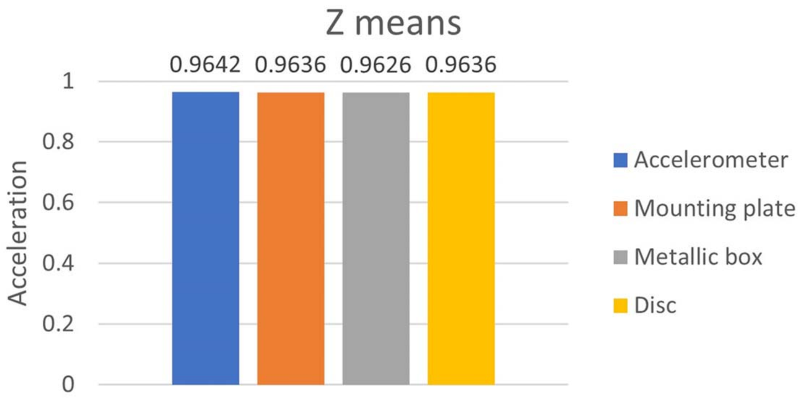

Fig. 9 *Z* means results

Table 2 Results per test

Component	Mean	Maximum	Minimum
Accelerometer	0.3197	1.8362	−0.3438
Mounting plate	0.3195	1.8358	−0.3439
Metallic box	0.3194	1.8361	−0.3439
Disc	0.3195	1.8361	−0.3439
Standard deviation	0.00013	0.00017	0.00005

Table 3 ANOVA statistical tests results

Comparison	p-Value
Accelerometer/mounting plate	0.3295
Accelerometer/METALLIC box	0.652
Accelerometer/full equipment	0.8025
All configurations	0.4872

0.03 Hz and a second of approximately 47.75 Hz and 0.40 Hz amplitude. Figure 10 illustrates an example of the obtained frequency content.

3.3 Discussion. Results have shown that the developed equipment could be validated for the proposed goal and, so, it can be used as a WBV measurement system.

Considering the results for the accelerometer as the reference ones, the other three configurations were compared with this one to study the influence of adding new components to the measurement equipment.

For the *X*-axis, differences of 0.0001 and 0.0002 g's on the mean values were found when comparing the accelerometer results with the mounting plate and the metallic box/disc, respectively. The maximum values were equal for both the accelerometer and mounting plate (0.3283 g). Regarding the metallic box and complete system, the obtained maximum was 0.3282 g, which corresponds to a difference of 0.0001 g compared with the reference values. Finally, the minimum value for the accelerometer was −0.3438 g, while for the other configurations, a gap of 0.0001 g was found (−0.3439 g).

Concerning the *Y*-axis, equal mean values were observed for accelerometer and full system components, −0.0026 g's. For both maximum and minimum values, results presented a difference of 0.0001 g. While the accelerometer showed a maximum of 0.2033 g and a minimum of −0.2463 g, the other equipment presented a maximum of 0.2032 g and a minimum value equal to −0.2462 g.

Z-axis presented the highest differences in the mean values. The accelerometer presented the highest mean (0.9642 g). Both mounting plate and disc showed a mean of 0.9636 g, which corresponds to a difference of 0.0006 g. However, concerning this parameter, the highest difference (0.0016 g) was observed for the metallic box. This component demonstrated a mean of 0.9626 g. Relatively to the maximum values, a gap of 0.0001 g was found between the accelerometer and both the metallic box and full system. The former presented a maximum of 1.8362 g, while the latter showed a 1.8361 g of maximum.

Minimum values were found for the *X*-axis, while the higher values were presented on the *Z*-axis. It should be highlighted that the higher and lower values of acceleration correspond to the beginning of level 1 vibration, in the second minute of the experiments. It was observed as an acceleration peak and then a transition for a constant vibration pattern. A possible explanation for the peak is related to the increase of vibration by the controller.

Analyzing the results per test, differences lower than 0.1% were obtained when comparing the components. Comparing the differences between the accelerometer and the mounting plate, an increase of 0.063% of the mean was observed. For the maximum and minimum values, an increase of 0.022% and decreasing of −0.029% were calculated, respectively. The minimum value decreasing was equal for all the components. For the accelerometer/metallic box interaction, increases of 0.094% and 0.005% were presented for both mean and maximum values. Finally, comparing the accelerometer with the disc, an increase of 0.073% was observed for the mean, while an increase of 0.005% was shown for the maximum value.

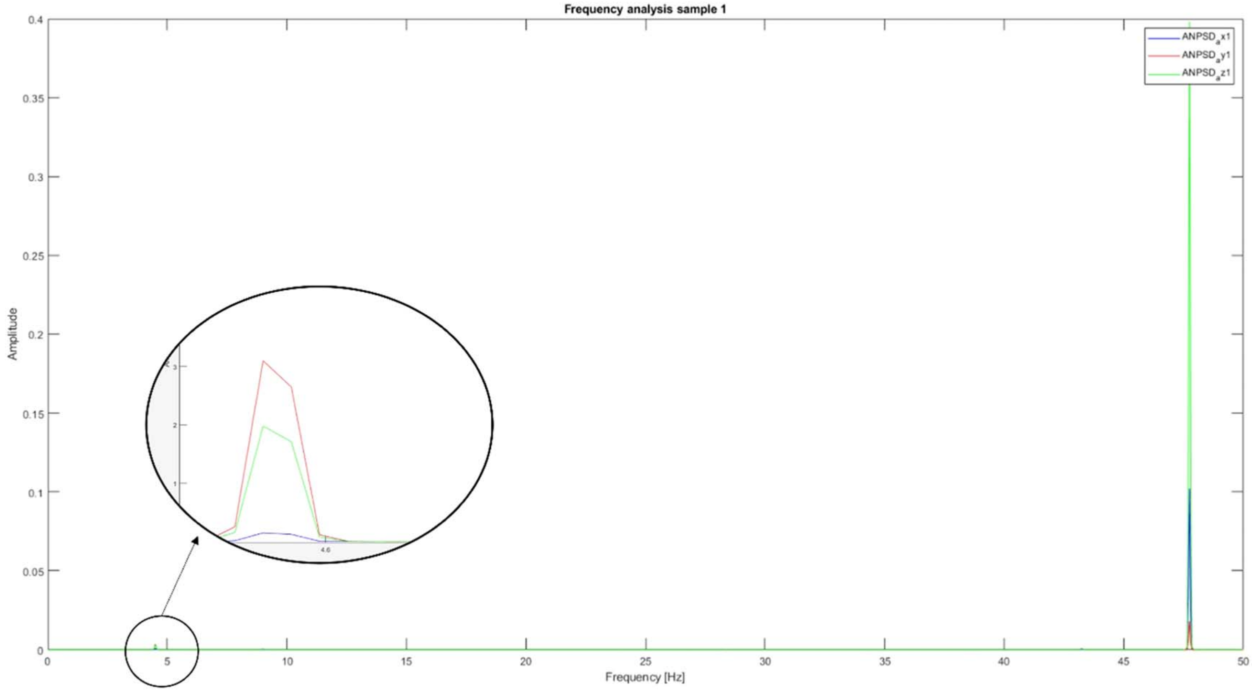

Fig. 10 Example of frequency content for experiment 1—full equipment

Relatively to both results per test and per axis, low standard deviations, under 0.0009, were found for all experiments. This observation probes the precision of the results and tests.

ANOVA tests showed that the means of the different components were equal and that the results are significant ($p > 0.005$). Two different ANOVA tests were performed. First, the components were individually compared with the accelerometer, and later, an ANOVA statistical test comprehending all equipment was performed to study the interaction of all tests and validate the designed equipment. The test that comprehended the accelerometer/complete system interaction presented the highest p-value, 0.8025, demonstrating this way, a strong connection between both means. Once this comparison occurs between the main equipment and the developed system, it should be considered the most important one.

ISO 2631 defines an interesting frequency ranging from 0.1 to 80 Hz for the analysis concerning nausea, comfort, perception, and health. The conducted experiments presented two main frequency peaks, around 4.49 Hz and 47.75 Hz, respectively. Studies concerning seat transmissibility have demonstrated that a vibration transmission peak occurs at approximately 4.3 Hz [24–26]. Therefore, frequencies close to this value assume high importance, which in the present results occurs at the first peak, 4.49 Hz. Concerning the second peak, it represents approximately the middle of the frequency range defined by the standard.

Considering all the presented results and observations, the equipment could be validated as a system for WBV measurement.

4 Conclusion

A new vibration measurement system was developed. Due to its sample rate range, the equipment is capable to take measures for both WBV and HAV. Concerning the WBV acquisition purpose, a metallic box and a silicone rubber disc have been designed, numerically validated, and produced. Besides the accelerometer presenting sample frequency capable to measure accelerations for HAV, a new silicone adaptor should be designed and produced to fulfill this purpose. Shaker tests were conducted on the designed equipment to ascertain its influence on vibration measurements as single equipment and as a complete system. Test results and ANOVA statistical analysis have demonstrated that the components do not influence vibration measurements. Moreover, a 0.8025 p-value shows that both developed equipment and accelerometer presented equal means. Frequency analysis showed two peaks, 4.49 Hz and 47.75 Hz, which represent the seat transmissibility and middle of the ISO 2631 frequency scale, respectively. Therefore, the developed system could be validated as equipment for WBV measurement and record.

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Conflict of Interest

There are no conflicts of interest. This article does not include research in which human participants were involved. Informed consent not applicable. This article does not include any research in which animal participants were involved.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

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