POLITECNICO MILANO 1863

School of Industrial and Information Engineering

Master of Science in Mechanical Engineering

Effects of 3D whole-body vibration on the response time measured in a psychomotor vigilance task

Supervisor: Prof. Marco Tarabini

Co-Supervisors: Eng. Stefano Marelli

Eng. Andrea Mazzoleni

Eng. Cristina Ferrario

M.Sc. thesis by

Teenu Arjun Ravi

ID: 10688809

Yuvan Sathya Ravi

ID: 10681728

Academic Year 2020/2021

Acknowledgement

It is a pleasure to acknowledge our deepest thanks to everyone who supported us throughout the course. First and foremost, we owe our profound gratitude to our supervisor Prof. Marco Tarabini and our co-supervisor Eng. Stefano Marelli for their valuable guidance and pragmatic supervision provided throughout the period of the thesis work. Their guidance for pursuing our work with the highest levels of scientific integrity has been a constant source of inspiration throughout our thesis. They ensured a better comfort at the workplace. We would like to extend our thanks to co-supervisors Eng. Andrea Mazzoleni and Eng. Cristina Ferrario for their timely help and guidance throughout our thesis work. We would like to extend our profound gratitude all the members of Department of Mechanical Engineering, Politecnico di Milano who provided us with sufficient knowledge throughout our academics.

Table of Contents

List of figures

List of tables

Abstract

The effects of multi-axis Whole-Body Vibrations (WBV) on the response time of a human body in psychomotor vigilance task (PVT) have been studied in this thesis. The 3D shaker had total harmonic distortion smaller than -5 dB and cross talk lower than 0.5 along the three axes when operated at an amplitude of around 1 m/s^2. To study the effects of WBV on response time of human body, a WBV – PVT experiment protocol is designed and validated on 12 male and 13 female subjects. Male subjects on an average responded at 151 (45) ms when they were not exposed to vibration and upon exposure to WBV, their mean response time increased to 172 (61) ms. In the case of female subjects, the mean response time without vibration was 187 (41) ms and the same during WBV exposure was 205 (44) ms. For both male and female subjects the mean response time increased upon exposure to WBV. Bonferroni pairwise comparison test results assessed that there was a statistically significant difference in mean response times between WBV conditions and non-vibration conditions. The subjects felt more discomfortable when the WBV was transmitted vertically to the body (along Z axis) as male subjects rated a discomfort of 3.0 (1.2) (with 5 being very uncomfortable) and female subjects rated 2.8 (1.2) when the vibration was along Z axis.

1. Introduction

1.1 Whole-Body Vibrations

Whole-Body Vibrations (WBV) are mechanical oscillations transmitted to the human body over a range of amplitudes and frequencies. These mechanical oscillations are transmitted to the human body through a contact surface in the form of sinusoidal vibrations. Vibration-induced accelerations can influence the human body. People experience distinct types of whole-body vibration in their daily life, most commonly through a seat of a vehicle or while walking. In some public transportation, people are exposed to vibration when standing. The human body experiences WBV in various postures such as the standing posture (legs straight, knees bent), seated posture (relaxed, crouched, tensioned), etc. To help understand and evaluate the potential detrimental effects of vibration exposure, various cognitive tests can be used which measure reaction time and reasoning ability. This thesis will focus on the effects of Whole-Body Vibration on the response time of human body. To test the human response to WBV, an electro-mechanical excitation system is used to simulate a vibrating environment.

1.2 Effects of vibration on human body

A regular exposure to Whole-Body Vibrations during the day-to-day activities can have some serious health effects on the human body. In this section, the negative as well as some positive effects created on human bodies due to WBV exposure at various levels are studied. The major effects of WBV are related to musculoskeletal pain due to fatigue in the back, neck, hands, shoulders, and hips of the human body [1]–[6]. J. Kiiski et al., [7] assessed the vibration-induced accelerations at the ankle, knee, hip, and lumbar spine. Subjects felt some discomfort specifically between 20 and 25 Hz vibration frequencies when the amplitude was 0.5 mm or greater (the platform peak acceleration was between 0.8 and 7.5 G). In addition, some subjects had numbness in the feet at 3-mm amplitude and 40-Hz frequency (the platform peak acceleration was 19 G) and mild heel pain [7].

D. Chadefaux et al., [8] studied the WBV effects during stationary and propelled walking. Comparing stationary walking with propelled walking, higher transmissibility as well as apparent mass were obtained during the Stationary Walking experiments than during the Propelled Walking experiments. The apparent mass is higher when standing in neutral position than with knee bent which indicates that bending the knees induces higher damping of the vibrations especially through the muscular activation. WBV transmissibility decreased with the distance from the driving point and with the frequency of the vibration. The phase of the apparent mass demonstrated that the human body, above 5 Hz, acts as an energy dissipator and not as a solid mass [8].

Apart from musculoskeletal disorders, occupational exposure to WBV may also contribute to the development of peripheral and cardiovascular disorders and gastrointestinal problems. In addition, there are more recent data suggesting that occupational exposure to vibration may enhance the risk of developing prostate cancers [9].

The inclination of a seat backrest influences sitting comfort. In a transport environment, the inclination of the backrest will also influence the vibration transmitted to the body and the vibration discomfort experienced by passengers and by drivers. With a backrest inclined to 30° or 60°, less weight is supported at the seat and more weight is supported at the back [10], [11].

As predicted by current standards, a backrest can increase discomfort caused by high frequencies of vibration. However, a backrest can reduce discomfort caused by low frequencies, with the benefit depending on the frequency and direction of oscillation and backrest height [12]. To counteract increased discomfort with a greater number of shocks, H. V. C. Howarth, and M. J. Griffin [13] proposed using the vibration dose value, which provides useful predictions of the reduction in shock magnitude.

According to S. Waugh et al., [14] Occupational exposure to vibration may result in DNA damage and alterations in cell signaling pathways that have significant effects on cellular division.

An association between deterioration of manipulative dexterity and neurovascular symptoms in the fingers of hand-transmitted vibration (HTV) workers has been found.

There was evidence for a significant relation between loss of precise manipulation and exposures to hand-transmitted vibration and ergonomic risk factors [15].

T. Nilsson et al., [16] in their systematic review and meta-analysis observed that workers who are exposed to HAV have an increased risk of vascular and neurological diseases compared to non-vibration exposed groups.

Whole-body vibration (WBV) training has been proposed as a time-efficient exercise intervention for the improvement of cardiovascular health by enhancing the Heart rate variability (HRV). WBV training appears to be a useful therapeutic intervention to improve cardiac autonomic function in different populations, through decrease in sympathovagal balance [17], [18].

C. Bosco et al., [19] conducted a study focusing on evaluating the acute responses of blood hormone concentrations and neuromuscular performance following whole-body vibration (WBV) treatment. It was demonstrated that there was a significant increase in the plasma concentration of testosterone and growth hormone, whereas cortisol levels decreased. An increase in the mechanical power output of the leg extensor muscles was also observed. Neuromuscular efficiency and jumping performance also improved. The study suggested that WBV influences proprioceptive feedback mechanisms and specific neural components, leading to an improvement of neuromuscular performance.

1.3 WBV for seated subjects

People who are involved in professions which demand travelling for long hours such as truck drivers are exposed to Whole-Body Vibrations in the seating position most of the time. Here, the effects related to the exposure of WBV for seated subjects are discussed. M. S. Khan and J. Sundstrom [20] conducted a survey, measuring the vibrations at five positions around a passenger seat above the bogie during normal service, two-thirds of the 330 passengers reported difficulties in performing sedentary activities such as reading and writing due to vibration and shocks. The vibration discomfort is higher in the vertical direction in all the positions except for the backrest but the vibration discomfort for the backrest is higher in the longitudinal direction. The discomfort indexes (ISO, Wz) were shown to be highest in the vertical direction in all positions (seat-pan, armrest, table, and floor) except at the backrest where the longitudinal direction showed the highest discomfort values.

Among the factors that affect the seat transmissibility such as age, gender, physical characteristics, backrest contact, and magnitude of vibration, subject age was the strongest predictor of the resonance frequency evident in vertical seat transmissibility at resonance [21]. The transmissibility of the seat at 12 Hz depended on subject age, body mass index, and gender. Although subject weight was strongly associated with apparent mass, weight was not strongly associated with seat transmissibility. Increased age was associated with an increased resonance frequency and increased seat transmissibility at resonance. This suggests that we need to use subjects of appropriate age when measuring the transmissibility of seats. The resonance frequency in the vertical seat transmissibility, and the transmissibility of the seat at resonance, increased when subjects contacted the seat backrest.

A study focusing on the effect of WBV on the apparent mass of the body for seated subjects concluded that the relative movement between the vibrating platform and the feet reduced the measured apparent mass of the body at frequencies below resonance [11]. The effect depended upon the amplitude of the vibration and the amount of contact between the legs and the platform. The resonance frequency and the apparent mass at frequencies above resonance both increased with the use of a backrest, an erect posture, and increased muscle tension. Therefore, we can say that the use of a backrest influences the apparent mass of the body and the resonance frequency [10], [11].

According to Y. Matsumoto and M. J. Griffin [22], [23], as an effect of the vertical seat vibration, the lumbar spine, and the lower thoracic spine, tended to bend in the region around L1, where the spine may deform in an S-shape. The thoracic spine tended to rock about the lower thoracic spine with slight bending along the full length of the thoracic spine. Both motions were coupled with the bending motion of the lower spine. Pitch motion of the pelvis also occurred at the resonance frequency, although the pitch resonance of the pelvis occurred at higher frequencies. Any axial motions along the spine were not dominant at the principal resonance frequency near 5 Hz.

1.4 WBV for standing subjects

For standing subjects, the Whole-Body Vibrations have some different effects when compared to the effects of WBV on seated subjects. The literature available related to the effects of WBV on standing subjects (in different standing postures) are studied and reported in this section. Y. Matsumoto and M. J. Griffin [24] conducted a study on the measurement of the apparent masses and transmissibilities at the first and eighth thoracic and fourth lumbar vertebrae (T1, T8, and L4), at the right and left iliac crests and at the knee. The influence in the magnitude of posture and vibration of the human subject in standing position subjected to vertical WBV has been investigated. During experimentation, different motions of the body measured with different postures of the human leg such as in one leg, normal and leg bent positions have been taken. The peak resonance frequency for apparent mass in different postures of the leg such as for normal posture, it was found to be 5.5 Hz, for legs bent posture, the resonance frequency was 2.75 Hz and in the one leg posture, the frequency was 3.75 Hz. The dynamic response has been measured using two methods i.e., driving-point frequency response and transmissibility. For normal posture, a resonance frequency of apparent mass declined from a frequency of 6.75 to 5.25 Hz, also increased in the magnitude of vibration from 0.125 to 2.0 m/s^2.

There is the presence of non-linearities in the response of the human body to WBV. M. Tarabini et al., [25] conducted a study focusing on non-linearities in the response of the human body to WBV. It was concluded that the contributions of the non-linear terms to the apparent mass are negligible and the biodynamic response to vertical WBV is affected by the vibration magnitude for frequencies above 10 Hz. The procedure for the identification of the origins of non-linear effects consists of the computation of the apparent mass using the Welch approach and the H1 estimator of the transfer function.

A study [26] focused on the effects of vertical WBV on the human body shows that the frequency range which is classified as highly sensitive ranges from 4 to 8 Hz, but at frequencies above 16 Hz, there is a decrease of sensitivity. This is consistent across several studies related to resonance frequencies exposed to WBV [24], [26]. Observing the difference between the vibrations affecting standing and sitting persons, vibrations while standing are felt half as sensitively as while sitting because the ankles in the region of the lower extremities absorb the transmission of vibrations to the trunk [26].

O. Thuong and M. J. Griffin [27] investigated the vibrations in fore-and-aft, lateral, and vertical directions. The effect of the direction of vibration on the discomfort of standing people exposed to 4 Hz vibration differs from that of seated people. With vibration stimuli of 6 s duration, standing people are more sensitive to 4 Hz fore-and-aft vibration than to 4 Hz lateral vibration, due to greater postural instability during fore-and-aft vibration. The same was studied in the seated subjects and found that in lateral direction forces were small in magnitude [28].

We can use mathematical models to measure the WBV response of a standing human body. A study [29] focused on the linear lumped-parameter model of the human body in standing posture when subjected to WBV in the vertical direction and for experimentation, a model with 1 and 2 degrees of freedom was considered. Three different postures have been used as a normal standing posture, a one-leg posture, and a leg bent posture. With the changes in values of stiffness and damping ratios in models by fixing the masses, the effect in the magnitude of vibration and changes in the position on apparent mass was represented. It has been found that vibration is transmitted from structure to human body, while the human body is supported or is contacted with vibrating structures.

A study [30] was conducted on the apparent mass and cross-axis apparent mass of standing subjects during exposure to vertical whole-body vibration in five different postures such as upright, knees bent, lordotic, knees more bent, and anterior lean. It was found that the increase in muscle tension causes non-linear characteristics to be less clear.

Baker and Mansfield [31] investigated the effects of WBV horizontally using 16 human subjects when subjected to random vibration conditions up to 4 Hz in two different standing positions. With an increase in the magnitude of vibration, the time required to complete the task was also increased. While comparing both the postures, the performance of the human subject was better on the Y axis rather than vibration on the X axis.

Muir et al., [32] described that WBV devices have been used to treat injuries and musculoskeletal diseases. The main objective was to determine the extent to which acceleration has been transmitted by WBV devices to the standing human subject. A laboratory test was conducted on 6 healthy human subjects in standing posture on a WBV device using accelerometers mounted on the skin to measure the transmissibility to the cranium and the tibia. With the increase in frequency, transmissibility declines non-linearly. Results suggested that the magnitude of vibration has a damaging effect on physiologic systems.

Shibata [33] proposed “multiply scale factors” to find the discomfort arising for both standing and seated human subjects while exposed to WBV in the tri-axial directions over the frequency range that lies between 1 to 20 Hz. The results have been observed that standing human subject is more sensitive to vertical and seated human subjects has been sensitive to both lateral and fore-and-aft vibration conditions.

1.5 Cognitive tasks

Cognitive tasks are used to assess the mental capability of a subject and the way it processes information. They are an effective way to determine the brain capacity and damage or impairment.

Exposure to WBV also correlates to longer reaction times to both audible and visual stimuli and may also disrupt the ability to sustain attention [34], [35]. A common task that measures the speed at which subjects respond to a visual or tactile stimulus is the psychomotor vigilance test (PVT), also known as reaction time test. It is a simple task in which the subject must respond to a simple visual or mechanical stimulus. This task is commonly used to test sleep depravity, fatigue, and alertness in people [36], [37]. Another common task used to test cognitive performance is the Stroop test that measures the delay of reaction time between congruent and incongruent stimuli.

1.6 Vibration tests

In this study, vibration tests are used in such a way that Whole-Body Vibrations are given to human subjects and their cognitive behaviors during the WBV exposure are analyzed. To achieve this, cognitive tests are performed on human subjects while they are exposed to WBV. In this way, it is possible to study if the WBV influences the cognitive behavior of human beings.

1.7 Objectives of this thesis work

The objective of this thesis work is to study the effects of Whole-Body Vibrations on response time measured in a psychomotor vigilance task. For this purpose, an existing electro-mechanical excitation system (a 3D shaker) is used. The shaker excites in three different axes (X, Y, Z) at various controllable excitation amplitudes and frequencies, thereby transmitting sinusoidal vibrations to human subjects standing on the shaker. Then the performance of the excitation system is analysed, and the results are discussed and reported. To acquire the response time of human subjects, an Arduino based PVT device has been used. Experiments were carried out on 12 male and 13 female subjects, acquiring response times and comfort perception under 24 different sinusoidal WBV conditions. The methodology of the experiment, the device and tools used are reported. Then, statistical analyses are performed on anthropometric data, reaction times and comfort survey. Finally, conclusions and discussions of possible further developments on this study are reported.

2. Method

2.1 Three degrees of freedom electromechanical excitation system

An electro-mechanical excitation system as shown in Figure 2.1 is used to impose multi-axis vibrations to a human subject in a standing position. The excitation system is a multi-axial shaker since it can produce mechanical oscillations along the three degrees of freedom (X, Y, Z) [6]. Apart from vibrating individually in the three axes, the shaker can produce mechanical oscillations in all the three axes simultaneously. Therefore, it is possible to acquire multiaxial responses.

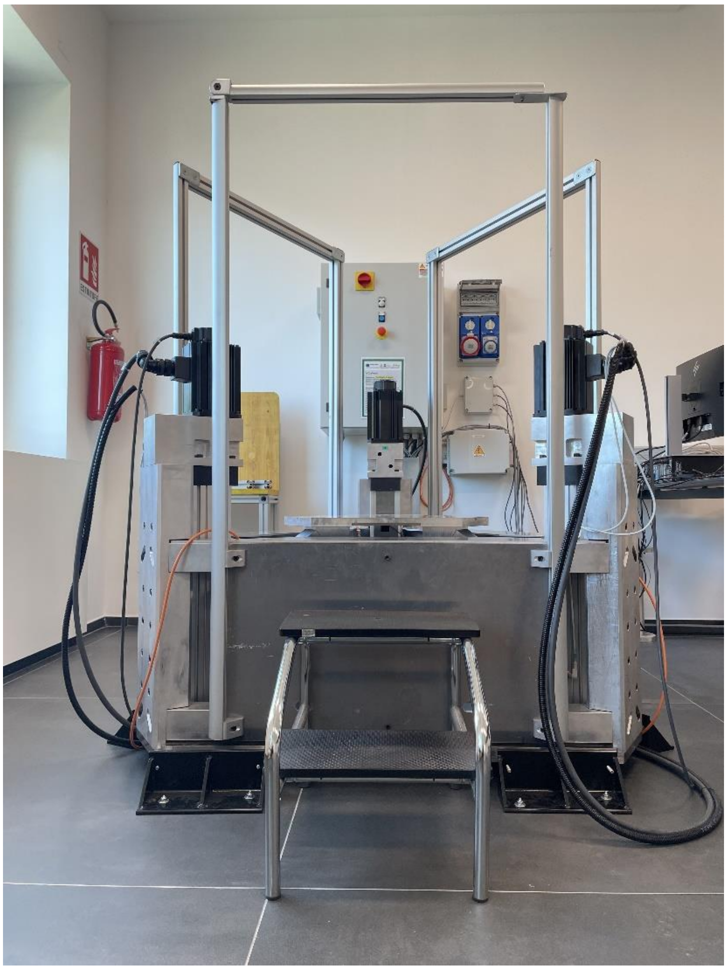


Figure 2.1 Electro-mechanical excitation system

2.1.1 Design

The excitation system is based on the linear delta configuration and is designed to expose standing subjects to vibration along three perpendicular axes (X, Y, Z), with an excitation bandwidth of at least 30 Hz and a maximum vibration amplitude of ± 30mm along the vertical direction and ± 20mm along the horizontal directions. The system is based on the parallel manipulator geometry mechanism. The delta robot actuator configuration contributes to the three degrees of freedom (DOF) of the shaker. The vibrating platform with a person on it can reach an acceleration of 5 m/s^2 along the three axes. The maximum weight carried by the shaker is defined as 200 kg, which corresponds to the apparent mass in the vertical direction of a standing subject weighing 100 kg subjected to vertical vibrations at the resonance frequency of 5–6 Hz.

2.1.2 Control system

To perform experiments with human subjects standing on the shaker, the system should be capable of generating a controlled mechanical oscillation. The 3D shaker can be controlled majorly in terms of its excitation amplitude, frequency, and axis of vibration by a control program developed by Trio Sistemi Misure. Figure 2.2 depicts the home page of the control program used for the 3D shaker.

Figure 2.2 Control program Home page

The mechanical oscillations of the 3D shaker could be controlled in terms of its acceleration or displacement. It is possible to set the initial position of the 3D shaker in the three principal axes (X, Y, Z). It is also possible to control the gain value of the excitation signal. The 3D shaker could be turned on or off based on the control button in this page of the control program.

The generator page of the control program as shown in Figure 2.3 is used to provide the parameters of excitation for the 3D shaker. In this page, it is possible to provide the excitation amplitude, axis of vibration and excitation frequency as inputs to the 3D shaker. It is possible to select more than one axis in order to perform multi-axis vibration simultaneously. Operations such as start and stop of the vibration with the entered parameters are also performed on this page.

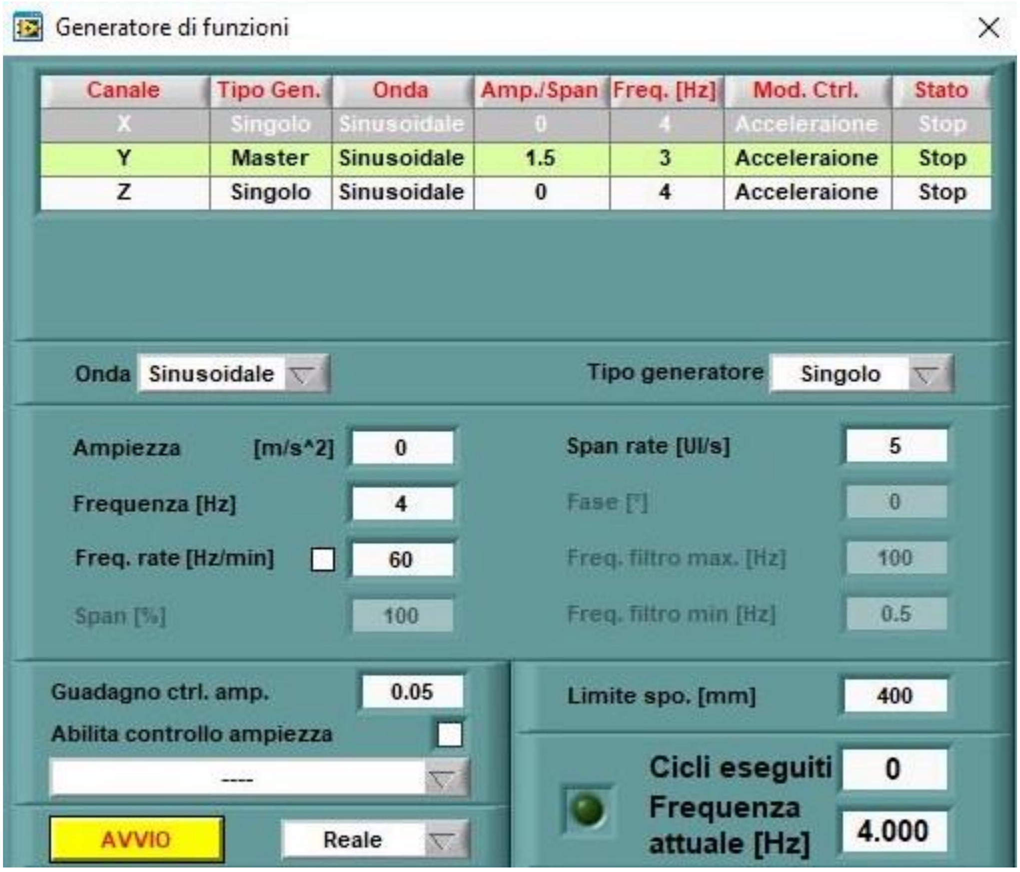


Figure 2.3 Generator page of control program

2.2 Performance analysis of the 3D shaker

This section explains the tests conducted aimed at evaluating the performances reached by the 3D shaker. The acquisition systems used, and the methodologies applied are reported. Vibration tests are conducted aimed at evaluating the performances reached by the 3D shaker.

2.2.1 Acquisition system

To measure the acceleration signals coming from the vibrating 3D shaker, a triaxial accelerometer as shown in Figure 2.4 is used. The triaxial accelerometer can measure the accelerations in all the three directions (X, Y, Z). The accelerometer is mounted on the vibrating platform of the 3D shaker and connected to the channel of a National Instruments 9234 acquisition board as shown in Figure 2.5

Figure 2.4 Tri-axial accelerometer by PCB Piezotronics

Figure 2.5 NI 9234 acquisition board

Sinusoidal harmonic excitations were then provided to the vibration platform of the 3D shaker. The excitation is provided in all the three directions (X, Y, Z) and their corresponding acceleration signals were acquired and saved. The acquired signals are processed using "Measlab", a signal processing software developed in Labview. The test was performed both with a person standing on the vibration platform and on an idle platform without any person standing on the platform to see if the abovementioned conditions influence the performance of the excitation system. Accelerations along the three axes (X, Y, Z) were measured with the following parameters.

Table 2.1 3D Shaker vibration and signal acquisition parameters

Vibration amplitude [m/s^2]	1
Vibration frequencies [Hz]	3, 5, 10, 15
Signal acquisition time [s]	60
Sampling rate [Hz]	2048

The acquired signals are processed in Measlab and the time domain signals of all the three axes were analysed. The RMS values of the signals are also computed in Measlab.

2.2.2 Harmonic analysis

To evaluate the performance of the harmonic signals coming from the 3D shaker, Crosstalk (CT) and Total Harmonic Distortion (THD) of the acceleration signals are computed. Crosstalk is computed to evaluate how an acceleration signal coming from one principal vibration axis affects the signals in the other two axes. Total Harmonic Distortion is computed to measure the distortion present in a signal during excitation along the three axes (X, Y, Z).

The Crosstalk between the axis of vibration and the remaining two axes is computed from the acquired data to check if there is a crosstalk in signals between the vibration platform and the base of the shaker. In this way, it is possible to check if the vibration given to the platform affects the base of the 3D shaker. To check this, three monoaxial accelerometers were used. As depicted in Figure 2.6, one accelerometer was placed on the platform and two were placed in the base of the shaker.

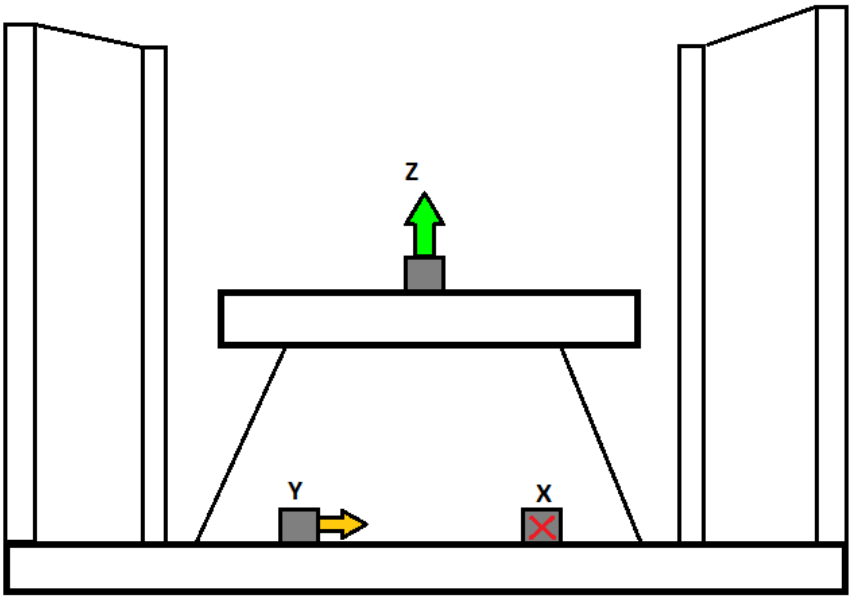


Figure 2.6 3 Monoaxial accelerometers used. One on the platform and two on the base of the shaker

CT is computed in MATLAB® software based on the following formulae.

Crosstalk in Y and Z axes (CT_y and CT_z) when excitation is along X axis:

$$CT_y = \frac{RMS_Y}{RMS_X}$$

$$CT_z = \frac{RMS_Z}{RMS_X}$$

Crosstalk in X and Z axes (CT_x and CT_z) when excitation is along Y axis:

$$CT_x = \frac{RMS_X}{RMS_Y}$$

$$CT_z = \frac{RMS_Z}{RMS_Y}$$

Crosstalk in X and Y axes (CT_x and CT_y) when excitation is along Z axis:

$$CT_x = \frac{RMS_X}{RMS_Z}$$

$$CT_y = \frac{RMS_Y}{RMS_Z}$$

Total harmonic distortion (THD) on the acquired acceleration data has been computed using MATLAB® for all the signals. The THD is computed and analysed to measure the distortion of the harmonics of the signal from the fundamental frequency. To compute THD, the RMS of the signals and the excel data of the time signals are taken from Measlab software. Then, the time signals are recreated in MATLAB® from the excel data taken from Measlab. Then, using MATLAB®'s inbuilt function to compute THD (thd(x)), the THD of the signals are computed and analysed.

The 3D shaker was then fixed to the ground using six supports as shown in Figure 2.1 and the performances of the 3D shaker are analysed again in terms of its Crosstalk and THD before starting the WBV experiments on human subjects. This time, to compute the Crosstalk, a single triaxial accelerometer was placed on the vibrating platform (Figure 2.7) to check if the sinusoidal harmonic signal given along one axis affects the harmonic signals of the other two axes.

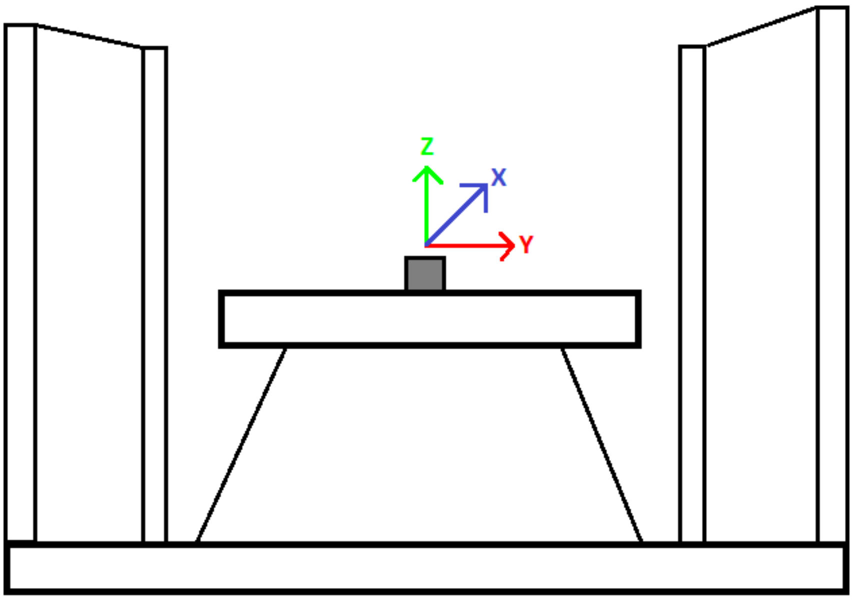


Figure 2.7 A single triaxial accelerometer mounted on the platform

Two different vibration amplitudes (0.5 and 1 m/s^2) and five different excitation frequencies (1 Hz to 5 Hz) as shown in Table 2.2 were selected for the test. The signal was acquired for 120 s and processed in Measlab software as done before.

Table 2.2 Vibration parameters to perform harmonic analysis after grounding the 3D shaker

Amplitude [m/s^2]	Frequency [Hz]
0.5	1
0.5	2
0.5	3
0.5	4
0.5	5
1	1
1	2
1	3
1	4
1	5

Once the data were acquired, the analyses done before grounding the shaker to evaluate the performance of the system are repeated. Time signals, Crosstalk analysis and analysis of THD are done in the same way as before, but this time with the vibration data acquired after fixing the 3D shaker to the ground.

The same analyses of Crosstalk and THD are repeated with a human subject standing on the vibrating platform during the WBV – PVT experiment. This time, the analyses are done for an amplitude of 1 m/s^2 and 6 different excitation frequencies for all the three axes of vibration (X, Y, Z).

2.3 Psychomotor-vigilance task device

A Psychomotor Vigilance Task (PVT) device (Figure 2.8) with a WEMOS D1 R1 mini controller (Figure 2.9) has been used to provide the stimulus for human subjects. The device contains two LED (Light Emitting Diode) lights in blue and green colours. The response time of the human subject is recorded when the PVT device provides a stimulus to the subject. The stimulus is provided in the form of a green LED (Light Emitting Diode) light.

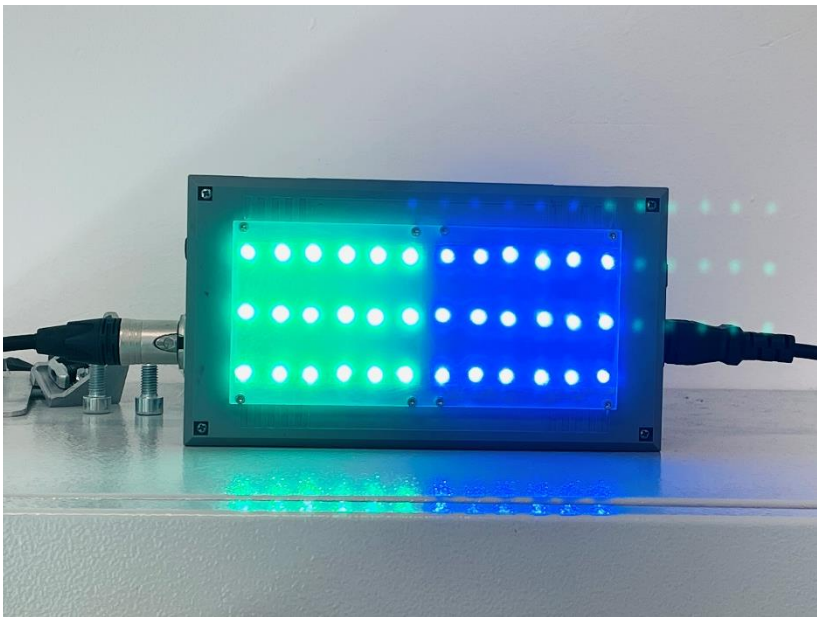


Figure 2.8 PVT Device

Once the subject responds to the green LED illumination, the next stimulus happens in a time interval known as Inter-Stimulus Interval (ISI). Four different intervals (250 ms, 500 ms, 750 ms, 1000 ms) were chosen for the test. The choice of these four values of ISI was based on a study conducted by Ishimatsu et al., [38] at National Institute of Occupational Safety and Health, Japan. The PVT device provides the stimuli 112 times with a randomly generated ISI sequence for each condition. Thus, it is possible to acquire 112 response times. The working of the PVT device is designed in such a way that for each condition, the device gives the stimuli in random Inter-Stimulus Intervals of the four fixed time intervals.

The controller used to run the test was Arduino® WEMOS D1 R1 mini (Figure 2.9) that will provide the stimuli, measure the reaction time, and send via Wi-Fi the results of each trial to a computer, where the data will be processed. The control program containing 415 lines of code has been written in Arduino® Integrated Development Environment. The program contains multiple blocks of codes for the WEMOS controller to execute various processes. Initial block of program contains the code for the controller to establish a Wi-Fi connection and connect with the computer. Then the program is coded to read and accept the user inputs from MATLAB® software and provide corresponding blue and green colour LED lights in the PVT device.

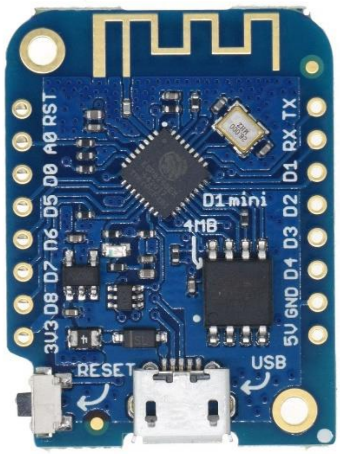


Figure 2.9 WEMOS D1R1 mini controller

The various inputs given by the user in MATLAB® includes operations such as giving the number of trials needed for the experiment, starting the blinking of the LED lights based on the random Inter-Stimulus Interval, saving the response data, proceeding with the next trial, exit and resetting the PVT device, etc. These inputs are read by the Wemos controller through the established Wi-fi connection. Once the inputs are given by the user in MATLAB®, the device produces 112 stimuli for the human subjects to respond. The subject should respond by pressing a button, which will be held in their hand while standing on the platform in a neutral standing position. Upon pressing of the button by the subject, the controller records the time elapsed between the illumination of the stimulus and the subject pressing the button and sends the recorded response time information to display in the MATLAB® screen of the PC as shown in Figure 2.10. Between two successive blinks of the green LED from the PVT device, a given time interval (i.e., ISI) is present, that can be equal to 250, 500, 750 or 1000 ms.

```
T: 1    98       R: 282.68 ms
T: 1    99       R: 190.72 ms
T: 1    100       R: 206.55 ms
T: 1    101       R: 277.56 ms
T: 1    102       R: 201.31 ms
T: 1    103       R: 144.77 ms
T: 1    104       R: 273.07 ms
T: 1    105       R: 267.77 ms
T: 1    106       R: 286.72 ms
T: 1    107       R: 352.96 ms
T: 1    108       R: 332.88 ms
T: 1    109       R: 600.59 ms
T: 1    110       R: 174.91 ms
T: 1    111       R: 169.72 ms
T: 1    112       R: 187.20 ms

Press 1 to continue with Trial 2 OR type Q to save and quit...
1
The Test will start in 4,5s ...
Test start
T: 2    1      R: 8781.46 ms
T: 2    2      R: 178.02 ms
T: 2    3      R: 3091.88 ms
T: 2    4      R: 15394.81 ms
T: 2    5      R: 272.09 ms
```

Figure 2.10 Response times displayed in MATLAB® screen

The WEMOS will be fixed on a PCB board housed in a 3D printed plastic case. This case is presented in Figure 2.11. Four holes are used to fix the PCB board with the WEMOS and the required connections. The aperture is used to connect the power supply to the WEMOS.

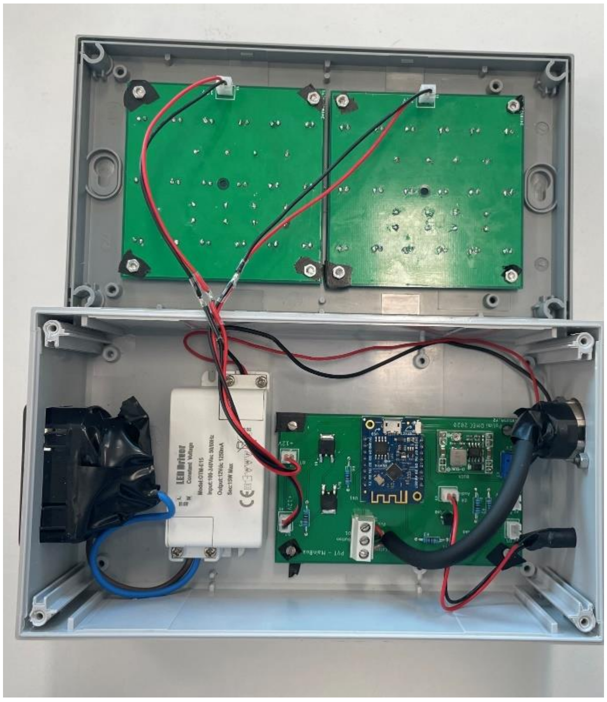


Figure 2.11 Case to place the WEMOS controller and its connections with the PCB board

2.4 Experiment design

A cognitive test experiment was performed on human subjects to assess the effect of WBV on the response time of human beings. A Psychomotor Vigilance Task (PVT) device as shown in Figure 2.8 was used to measure the response time for the test. The setup for the experiment and further details are presented in the following sections, The design of the device used to run the PVT test has also been explained.

2.4.1 WBV conditions

The human subjects participating in the experiment are exposed to Whole Body Vibrations of various frequencies with a fixed amplitude of 1 m/s^2. The RMS of the sinusoidal WBV is set to 0.7 m/s^2. The subjects are exposed to WBV of six different octave frequencies and two Baseline (0 Hz i.e., without vibration) conditions. Table 2.3 contains information about the 24 different WBV – PVT test conditions. The excitation frequencies selected for the experiment are 1.5 Hz, 2 Hz, 3.15 Hz, 5 Hz, 8 Hz and 12.5 Hz. Among the two Baseline conditions, the first Baseline condition is set before the six vibration conditions and the second Baseline condition is set after the six vibration conditions. These six vibration conditions and two baseline conditions are repeated in all the three axes (X, Y, Z) for each subject.

Table 2.3 WBV – PVT test vibration conditions

Session	Axis	Frequency [Hz]	Condition
1	BASELINE	0	BL
	X	1.5	1
	X	2	2
	X	3.15	3
	X	5	4
	X	8	5
	X	12.5	6
	BASELINE	0	BL
2	BASELINE	0	BL
	Y	1.5	7
	Y	2	8

Session	Axis	Frequency [Hz]	Condition
	Y	3.15	9
	Y	5	10
	Y	8	11
	Y	12.5	12
	BASELINE	0	BL
3	BASELINE	0	BL
	Z	1.5	13
	Z	2	14
	Z	3.15	15
	Z	5	16
	Z	8	17
	Z	12.5	18
	BASELINE	0	BL

2.4.2 Human subjects

To perform a study on the effect of Whole-Body Vibrations on response time when standing in an upright position, 25 human subjects, aged between 18 and 40 years participated with their consent and full willingness. The consent form to participate in the WBV- PVT test experiment has been attached in the annexure. The participants are not eligible if the individual

- has been previously diagnosed by a physician to have diabetes, vibration-induced pathologies, or a concussion
- suffers from motion sickness
- has had a lower body musculoskeletal injury in the previous 6-months

If agreed to participate, each participant was asked to provide their anthropometric data such as height, weight, and date of birth. The personal anthropometric data of the participants were processed with proper care according to the EU regulations. The information on the processing of personal data has been attached in section iv) of the annexure. 12 male subjects and 13 female subjects participated in the experiment.

2.4.3 Experiment protocol

A protocol to perform the experiment has been designed. Each WBV condition lasts for around 3 minutes and 30 seconds. The experiment is performed in three different sessions with each session lasting for around 36 minutes. Each session consists of acquisition of response times in six different randomized WBV conditions with two Baseline response acquisitions (before and after the exposure to WBV), totalling to 8 conditions per session. A schedule to perform the experiment in three sessions, for all the 25 subjects has been created. An example of schedule of a single session for the WBV – PVT experiment of a subject is given in Table 2.4. In each session, the vibration conditions (axis and frequency) are randomized.

Table 2.4 An example schedule for a single experiment session

DAY	AXIS	FREQ [Hz]	INDEX	CONDITION
1	BL	0		1
	Y	3.15	9	2
	X	8	5	3
	Y	12.5	12	4
	X	12.5	6	5
	X	5	4	6
	Y	8	11	7
	BL	0		8

In each session, the subject should perform a task of responding to a visual stimulus while being exposed to WBV. The corresponding data related to 112 response times (against 112 stimuli) are acquired and saved. After each session, the subject is provided a break of one minute to relax from their standing position before starting to respond to the stimulus from the PVT device for the new vibration condition. After each session of 36 minutes, the subject will be given a break of a minimum of one day before starting the next 36 minutes session in a different day. The total experiment will be conducted in a span of 3 days for a total time of 108 minutes for each subject. The entire workflow done in a single experiment session has been depicted in Figure 2.12. Figure 2.13 shows a human subject responding to the visual stimulus during the experiment.

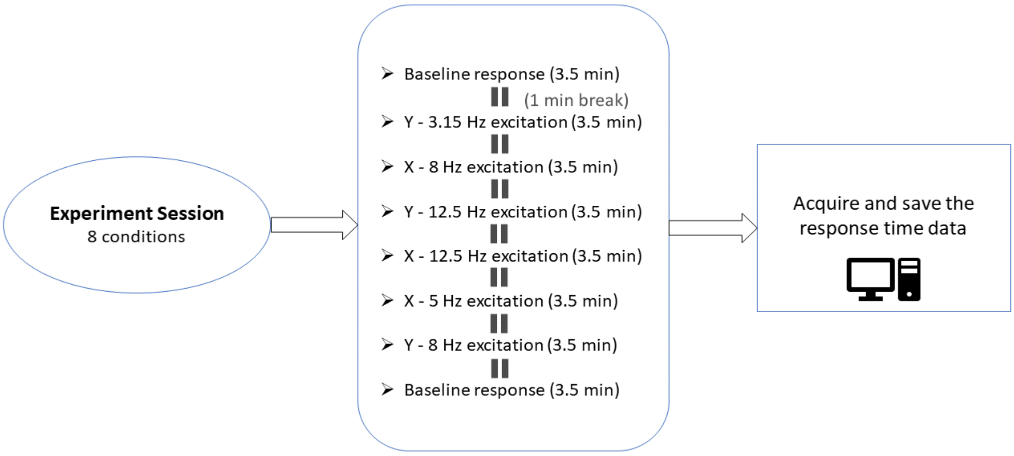


Figure 2.12 Sample workflow of an experiment session

Figure 2.13 A subject responding to the stimulus

At the end of each condition, a survey is taken from each subject. The survey contains two questions. In the first question, the subject is asked to report a rating of discomfort caused due to the WBV. The subject rates the discomfort in a scale of 1 to 5 with 1 being not uncomfortable and 5 being very uncomfortable. In the second question, the subject is asked to report a level of confidence in the accuracy of their responses (from 0 - completely unconfident to 100 - completely confident). This survey form contains the above-mentioned two questions for the six different excitation conditions. The survey forms must be filled for each subject for each condition.

At the end of each session, the button connected with the PVT device and the supports fixed in the 3 DOF electro-mechanical excitation system were sanitized. The protocol to perform the WBV – PVT test and collect the data has been reported in section ii) of the Annexure.

For further analysis, the data (response times of each session) acquired were saved in an array as a *.mat file in the computer according to the naming convention mentioned in the Data collection protocol.

2.5 Data analysis

2.5.1 Export data for statistical analysis

Once the data from the WBV – PVT experiment are collected, multiple statistical analyses were performed on the collected data using "Minitab®," a statistical data analysis software. The software contains tools to input the data, analyse the data statistically and identify trends and patterns. The data collected from the experiment contained anthropometric information such as Weight, Height, Body Mass Index, and Age along with the Response Time of the subject. Also, the data of the discomfort survey are collected. These experiment data were organized and separated into two groups based on the sex of the subject. Group 1 contains experiment data of male subjects and Group 2 contains experimental data of female subjects. The data were exported as a *.csv file and imported into Minitab® for further statistical analysis.

2.5.2 Descriptive statistics

The descriptive statistics such as Mean, Standard deviation, Variance are calculated on the subjects' anthropometric data such as height, weight, BMI, and age for the Baseline vibration condition of the experiment. These descriptive statistics are computed for male subjects and female subjects separately. Based on the computed statistics of male and female subjects, the trends are analysed to comment on the anthropometric data of the subjects participated in the experiment.

The descriptive statistics such as mean and standard deviation are calculated also on the survey data collected from the 25 subjects. The survey data collected during the experiment is saved in an excel file. These excel data are converted into a comma separated value file (*.csv) and then sent as an input to Minitab® separately for the two groups (Group 1 - male subjects; Group 2 - female subjects).

First, the survey data on discomfort rating given by Group 1 for the six different excitation frequencies (1.5 – 2 – 3.15 – 5 – 8 – 12.5 Hz) are taken and the mean value of discomfort rating given by the 12 male subjects and their corresponding standard deviation from the mean value are calculated for the six frequencies. Then the calculated mean and standard deviations are plotted in the form of a bar plot. The same procedure is done on the discomfort data of Group 2 and on the combined data of Group 1 and Group 2 as well. After plotting the bar plots as described above, the plots are analysed looking for any specifics such as higher or lower discomfort felt by the subjects at a specific frequency of excitation or looking for any trend among the plots that could be observed. The results of the analysis are discussed for male and female subjects and as a comparison between male and female groups of subjects as well. The results and discussions are reported in section 0

Then, the survey data on the confidence in the accuracy of the male subjects' responses for the six different excitation frequencies are imported into Minitab®. The mean value of confidence in accuracy given by the 12 male subjects and their corresponding standard deviation from the mean value are calculated for the six different frequencies. Then the calculated mean and standard deviations are plotted in the form of a bar plot. The same procedure is done on the accuracy confidence data of Group 2 and on the combined data of Group 1 and Group 2 as well. After plotting the bar plots as described above, the plots are analysed looking for any specifics such as higher or lower confidence in accuracy felt by the subjects at a specific frequency of excitation or looking for any trend among the plots that could be observed. Like the analysis done on the data of the discomfort ratings, the results of the analysis of confidence in accuracy data are discussed as a comparison between male and female groups of subjects and for individual groups of subjects as well.

2.5.3 Two samples t-test

A two samples t-test on the anthropometric data of the subjects participated during the experiment has been performed using Minitab® tool. The t-test is done to determine whether a statistically significant difference in terms of average exists between the male and female groups of data. Group 1 represents the data of male subjects and Group 2 represents the data of female subjects. The test contains two variables. One variable is the anthropometric data to be compared between the two groups of data and the other variable is the Group (male or female subjects). Based on the result of the p-value obtained during the test, a conclusion is reached on whether there is a statistically significant difference between male and female subjects.

2.5.4 Creation of a data structure with sorted conditions for each subject

Initially, the response time data from all the three sessions are loaded and 3 different cases were created for each subject. For each subject, the data are loaded in such a way that in each data set, there are two information. It includes the response times from the 3 sessions and their corresponding randomly generated vector of sequences (i.e., ISI in a random order).

In Case 1, the data acquired from all the sessions are structured as Baseline, X, Y, Z axis respectively for each subject. This Case 1 data is referred as Raw data. (i.e., data without any filtering). This data is plotted as Response time against the Number of clicks (i.e., number of stimuli) as shown in Figure 3.28.

All the time, the raw data cannot be used for further analyses due to several reasons. One such reason is the late or incorrect response by the subjects to the stimulus which gives a response time of more than 3 s. Sometimes due to overheating or excessive usage of the device, there is a possibility of a delay in stimulus from the PVT device. Because of these reasons, it is required to filter the acquired raw data to perform a correct and fair analysis without any inappropriate response time data.

In Case 2, the first filtering is done on the acquired data. The data containing response times over 1 s are removed and plotted as Response time against the Number of clicks as before along with their mean ± standard deviation marked in the plot as shown in Figure 3.31.

In Case 3, to analyse the data in a closer range, a further filtering of the data is done. The data is filtered based on two limit conditions. On the data from previous case (Case 2), the limit condition is applied where all data containing response times less than 50 ms and greater than 2.5 standard deviations from the mean response time were removed, respectively as previously done by Maeda et al. [38]

The above-mentioned operations of loading the raw data and applying three layers of filters are done in MATLAB®. For each subject, a total of 810 lines of code, which includes all the 3 cases has been written in MATLAB®.

For each subject all these cases are structured using struct array. For example, in subject 1 there are three cases named as C1, C2, C3. In each case, there is the response time and vector of sequence data of Baseline and X, Y, Z axis. In each of the three axes, there are 6 different frequency conditions, respectively. Then, all the 25 subjects are structured together in a single MATLAB® file named as PVT_DATA.m. This MATLAB® file could be used to access the data of any subject and any axis. A schematic representation of the WBV – PVT experiment data Structure is shown in Figure 2.14.

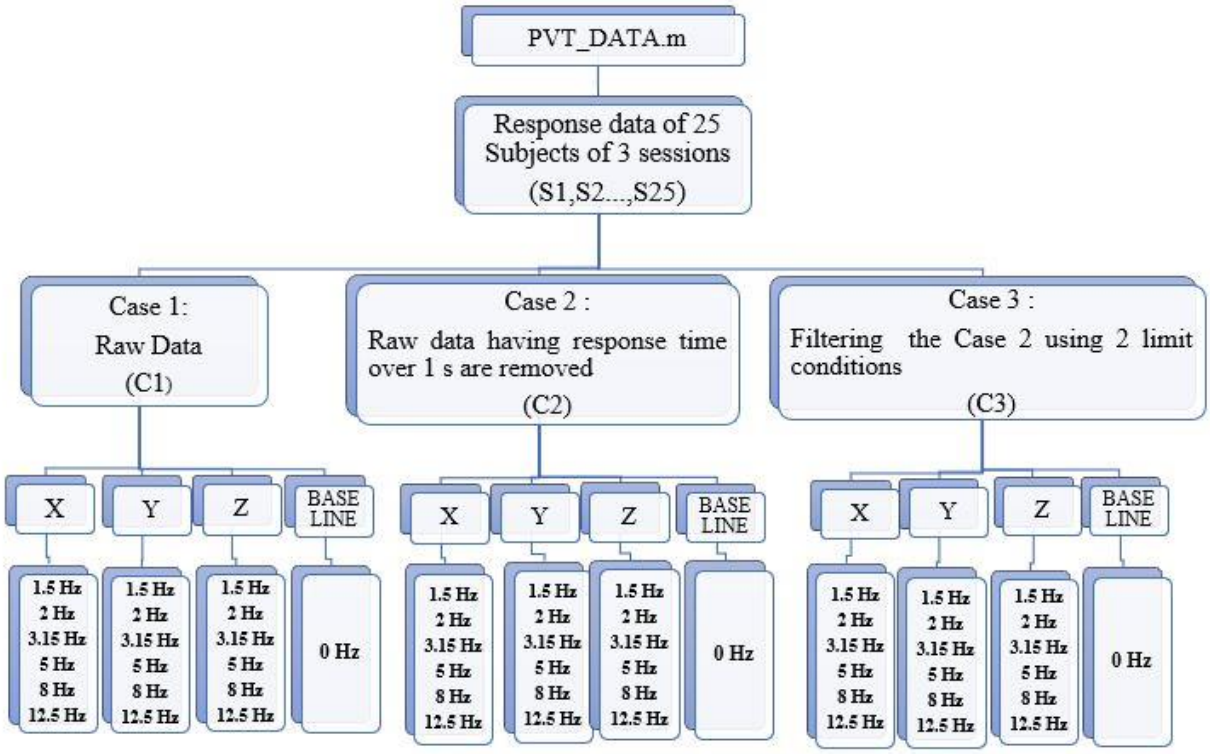


Figure 2.14 PVT_DATA STRUCTURE

2.5.5 Comparison of Response Times before and after WBV exposure

To observe the response time of the subjects, before being exposed to WBV and after the exposure to WBV, a comparison test on the response times of the subjects has been performed. This comparison test is performed in order to observe if the WBV exposure has had an effect on the Baseline response time of the subjects. In the study of low intensity WBV conducted by Gobbi. M et al. [39], the measured variables having a very high deviation (St Dev of around 100 units) from the mean value were filtered and removed. Therefore, referring to [39], it is reasonable to select the response time data set obtained after Case 3 filtering, since Case 3 filter removes response time data having a very high variability as mentioned in section 2.5.4. This comparison has been done in three tests. One test each has been done for Group 1 (male subjects), Group 2 (female subjects) and for all the 25 subjects (i.e., Group 1 + Group 2), respectively. All the Baseline response time data of both the male and female subjects are compiled together, with one variable indicating the group (Male/Female) of subjects and another variable indicating the pre- or post-vibration Baseline condition.

The compiled RT data is given as an input to Minitab®. To measure the statistical significance, a repeated measure analysis of variance (ANOVA) was performed on the data with the within-subject factor of Time (pre- and post-WBV) and the between-subject factor of Group (Group 1 vs. Group 2). Post hoc tests were performed by applying Bonferroni's correction for the significance threshold. Measures of effect size were provided in terms of partial eta-square (Partial η^2) (For Partial η^2, a value of 0.01 was considered as a small effect, 0.06 medium effects and 0.14 large effects [39]). The equation to compute the effect size (Partial η^2) is given by

$$\text{Partial } \eta^2 = \frac{Adj\ SS_{variable}}{Adj\ SS_{variable} + Adj\ SS_{error}}$$

Then, the comparison test was performed using Bonferroni Pairwise Comparisons tool in Minitab®. The mean response time of pre-vibration Baseline condition and post-vibration Baseline condition are computed. Based on the computed mean response times, bar plots are plotted comparing the pre-vibration Baseline condition and post-vibration Baseline condition. This comparison is done for Group 1, Group 2 and also on the combination of Group 1 + Group 2 data as well.

2.5.6 Mean response time analysis

The mean response time of both male and female subjects was computed for both baseline and WBV conditions. This computation was done on the response time data obtained after Case 2 filtering in which the raw data that had response times under 1 s were filtered and removed. The data obtained after Case 3 filtering has 2 layers of limit conditions, whereas the raw data might contain some inappropriate response times as mentioned in section 2.5.4. Therefore, it is reasonable to consider the response time data set obtained after Case 2 filtering for further analyses of response times. The computed mean response times are plotted for both male and female subjects. Based on the computed average response time, it was studied if WBV affects the response time of the human subjects. The results are discussed in section 3.3

2.5.7 Statistical analysis of mean Response Time data

The response time of each WBV condition is compared with the Baseline conditions for both male and female subjects, respectively. RT data obtained after Case 3 filtering has been selected for the same reason as mentioned in Section 2.5.5. This comparison test was performed using Bonferroni Pairwise Comparisons tool in Minitab®. This test was performed to identify the WBV conditions that have a statistically significant difference with the Baseline condition. All the response time of both male and female are categorised into "RT" and the baseline conditions and WBV conditions are categorised under "CONDITIONS" and finally male and female subjects into "GROUP". All the details are compiled in *.csv format and imported in Minitab® and the analysis is performed for a combination of GROUP×CONDITION variables, separately for male and female subjects.

3. Results and discussion

3.1 Shaker performance

The shaker performance was analysed in three stages. Initially the shaker was not fixed to the ground and its performance was analysed. Then the shaker was fixed to the ground using supports and its performance was analysed. Finally, during the WBV – PVT experiment, the performance of the 3D shaker was analysed with a subject standing on the grounded shaker and undergoing experiments. During each performance analysis of the 3D shaker, its corresponding time-domain signals, Crosstalk and THD plots were computed and analysed.

3.1.1 Shaker Ungrounded – Time Domain Analysis

On analysing the time domain signals for all the excitation frequencies on an idle platform, it could be seen that when vibrated along a particular direction, the signals of the other two directions are very low in amplitude (around 0.1 m/s^2) as shown in Figure 3.1. So those comparatively low amplitude signals can be concluded as noise.

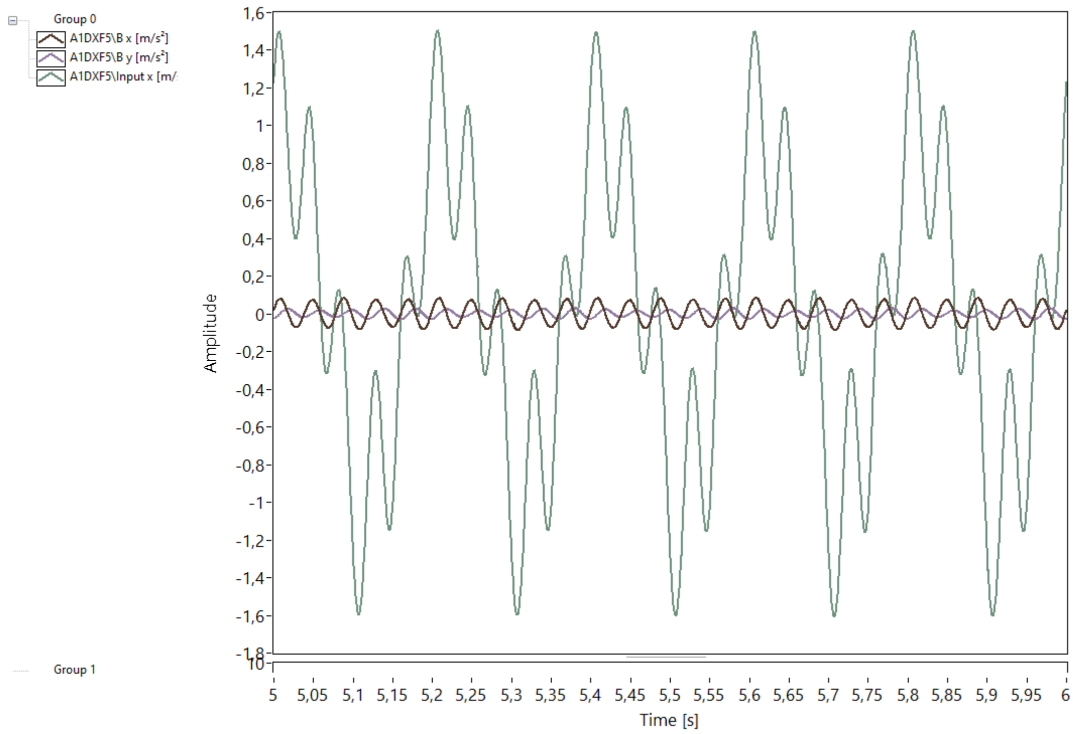


Figure 3.1 Time signal of one of the vibration conditions with an idle platform when the shaker was not grounded

When the vibrations were measured with a person standing on the platform as seen in Figure 3.2, the amplitudes of the vibrations are slightly lesser (around 1.4 m/s^2) when compared to the amplitudes of the platform vibrating in idle condition (around 1.5 m/s^2) without any person standing on it. This could be because when a mass is added to the platform, the vibration is damped by the mass, which causes a reduction in amplitude of around 0.1 m/s^2. Looking at the trend of the signals, it could be said that the motions in all three directions are in phase.

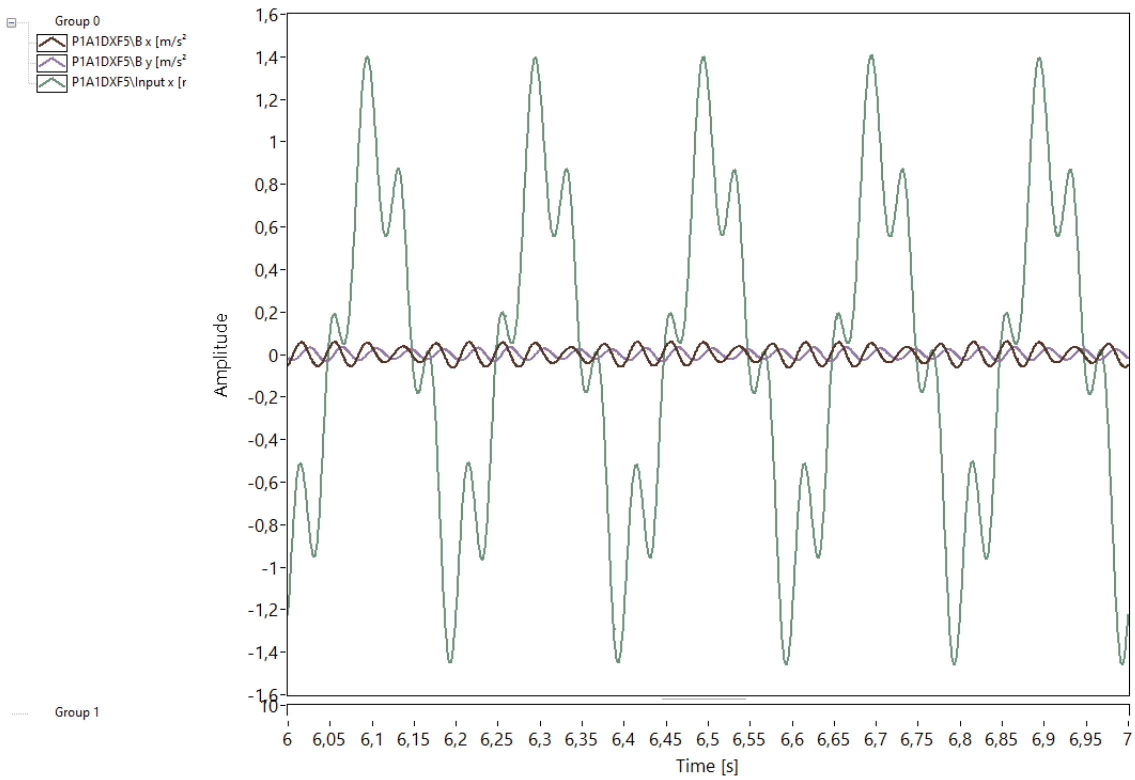


Figure 3.2 Time signal of one of the vibration conditions with a person standing on the platform when the shaker was not grounded

3.1.2 Shaker Ungrounded – Crosstalk analysis

The following plots shows the Crosstalk values of the acceleration signal both with vibration in an idle platform and with a person standing on the ungrounded platform.

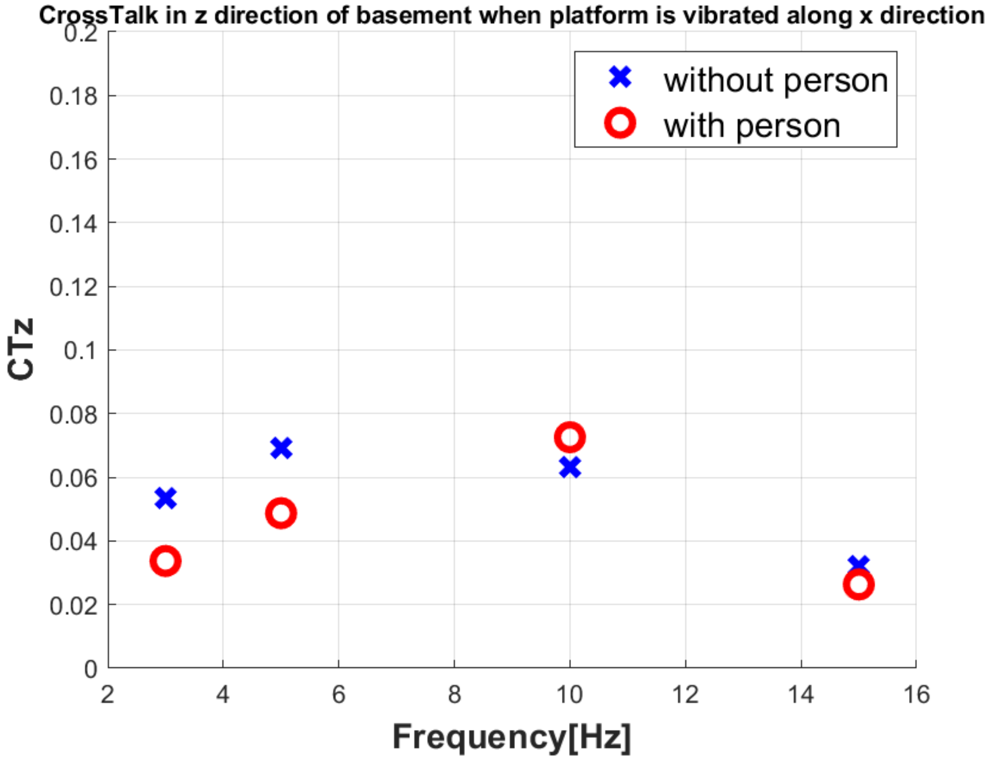


Figure 3.3 CT_z when vibration along X axis

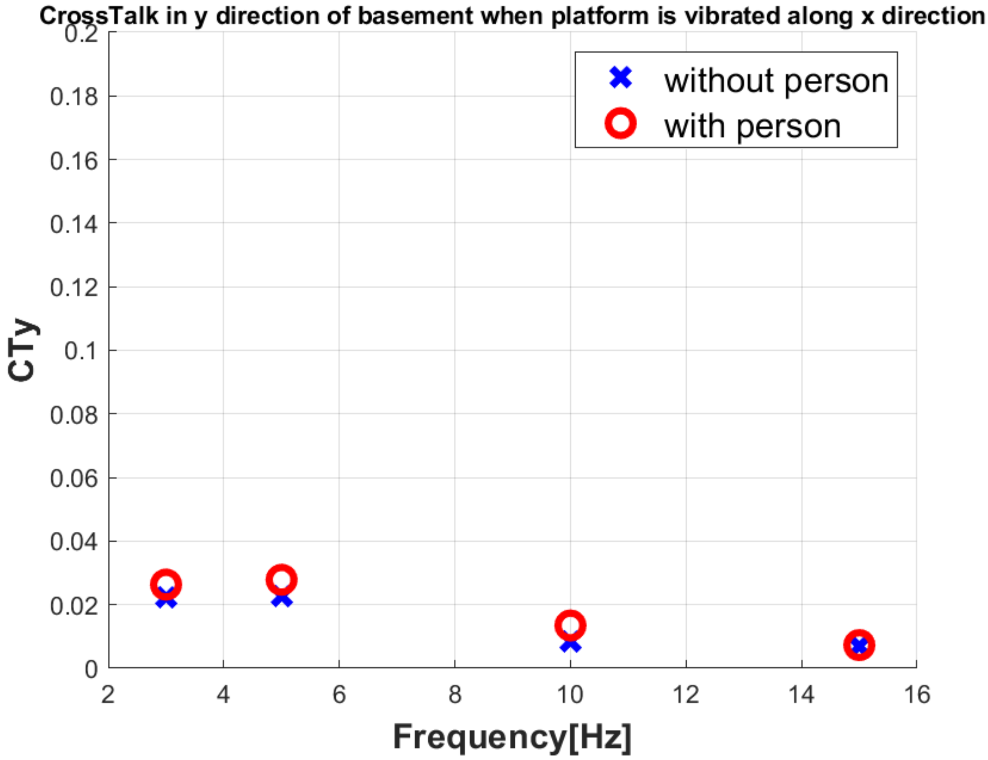


Figure 3.4 CT_y when vibration along X axis

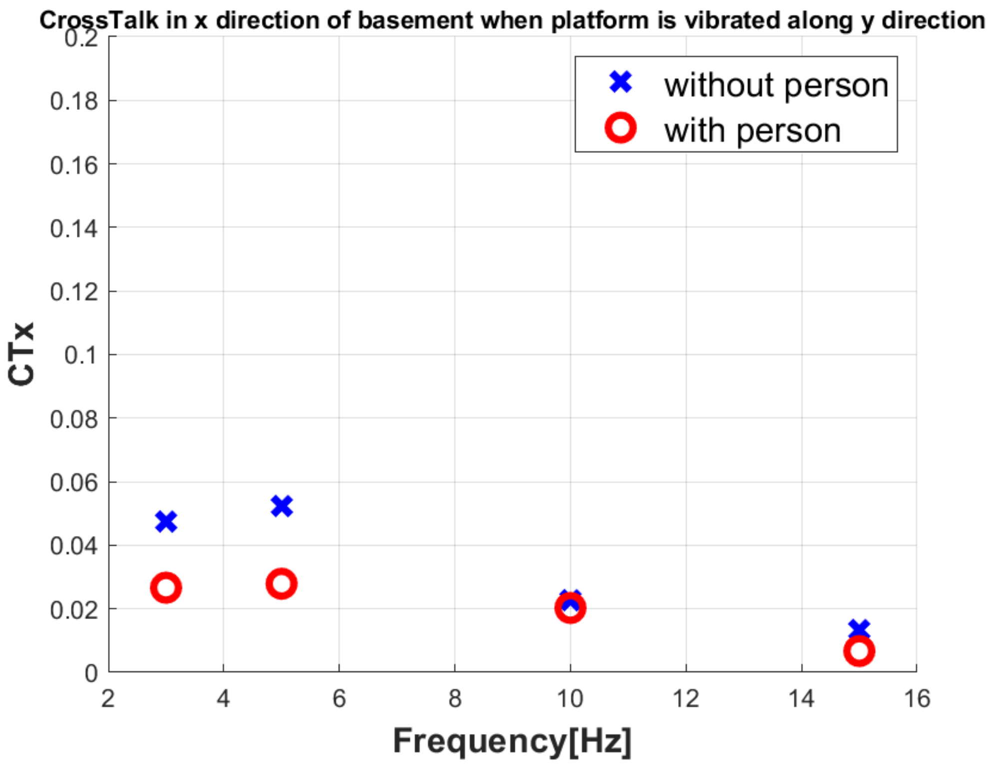


Figure 3.5 CT_x when vibration along Y axis

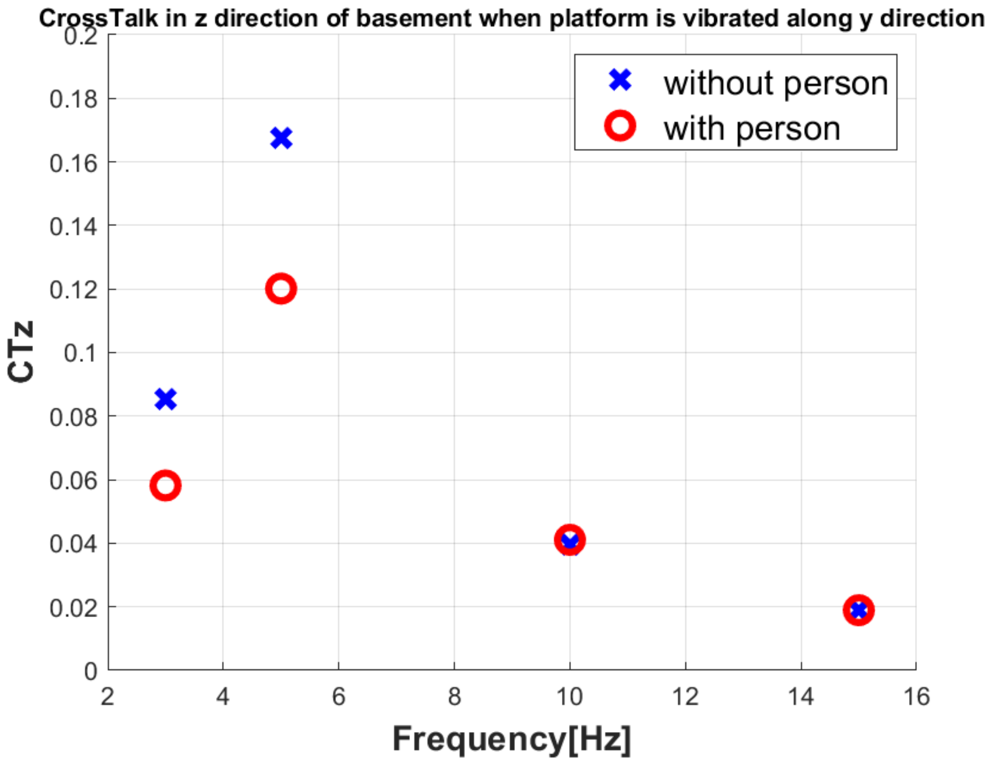


Figure 3.6 CTz when vibration along Y axis

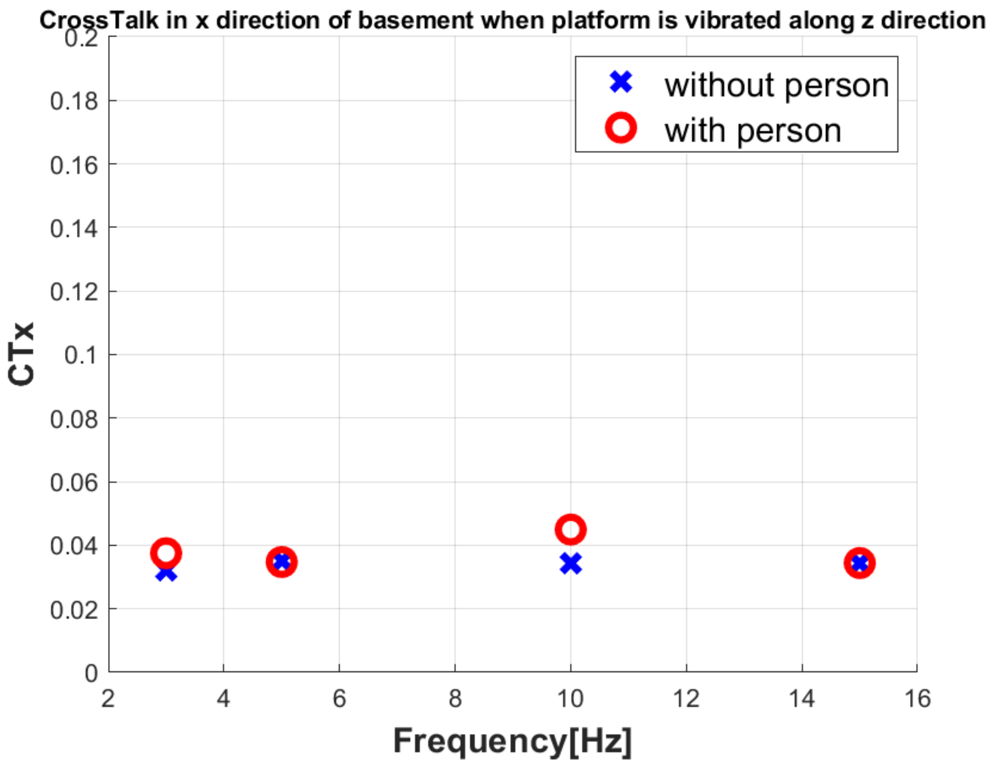


Figure 3.7 CT_x when vibration along Z axis

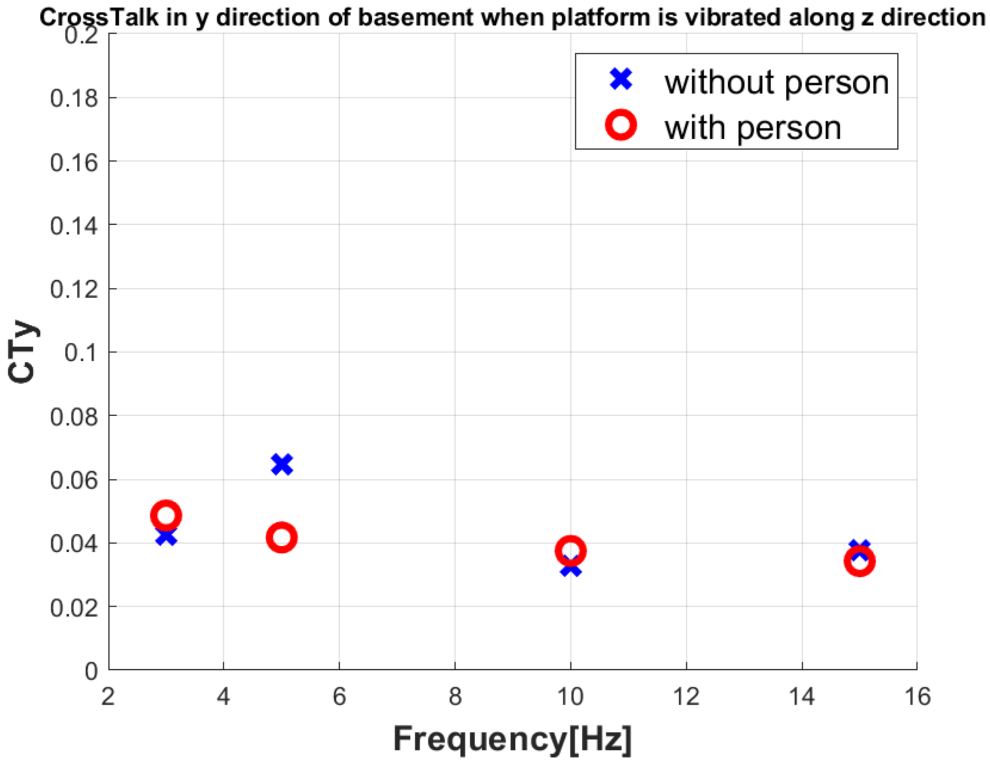


Figure 3.8 CT_y when vibration along Z axis

Observing the Crosstalk values in the above plots (from Figure 3.3 to Figure 3.8), there is a maximum CT value of 0.168 when vibrated along Y axis (Figure 3.6). Apart from this, it could be said that when the platform is vibrated along any of the three axes, the Crosstalk values of the vibrations in the basement of the 3D shaker are lower than 0.1. Therefore, it could be said that the vibrations (along X, Y, Z axes) provided to the platform of the shaker does not affect the base of the shaker. Also, when a person stands on the platform does not make much of a difference as the Crosstalk values of without person and with person cases are close to each other. In some cases, it could even be observed that a person standing on the platform improves the performance of the 3D shaker by reducing the Crosstalk as in Figure 3.5 and Figure 3.6.

3.1.3 Shaker Ungrounded – Total Harmonic Distortion analysis

Total harmonic distortion (THD) on the acquired acceleration data has been computed using MATLAB® for all the signals. The THD is computed and analysed to measure the distortion of the harmonics of the signal from the fundamental frequency. The THD plots computed for all the three axes are reported below.

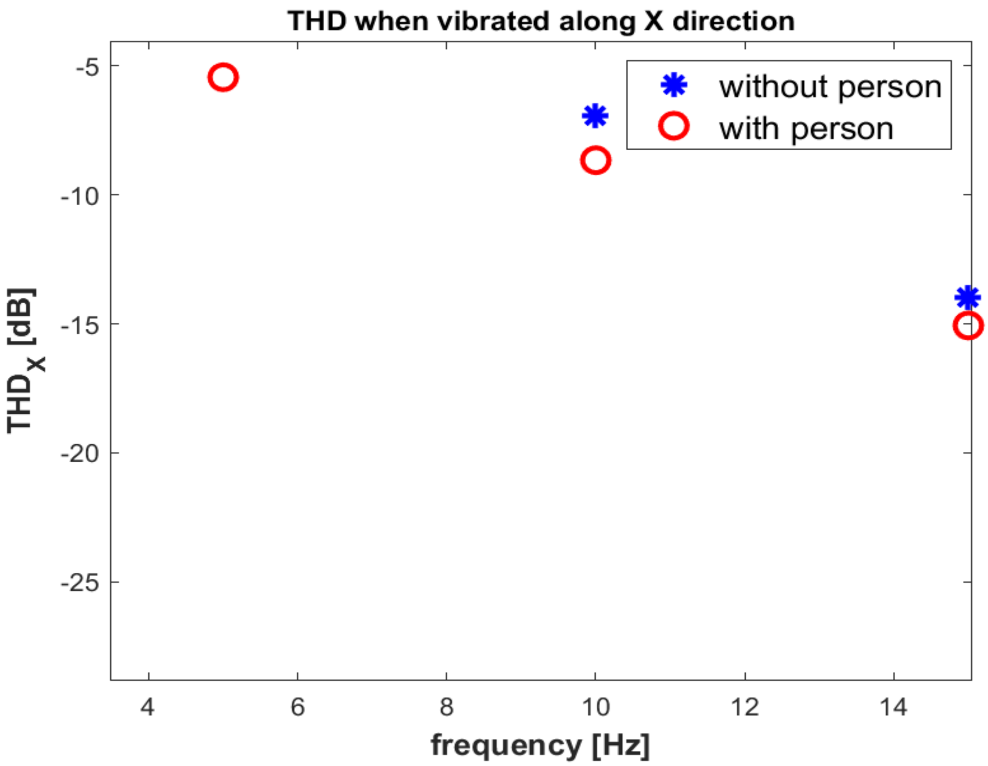


Figure 3.9 THD when vibration along X axis

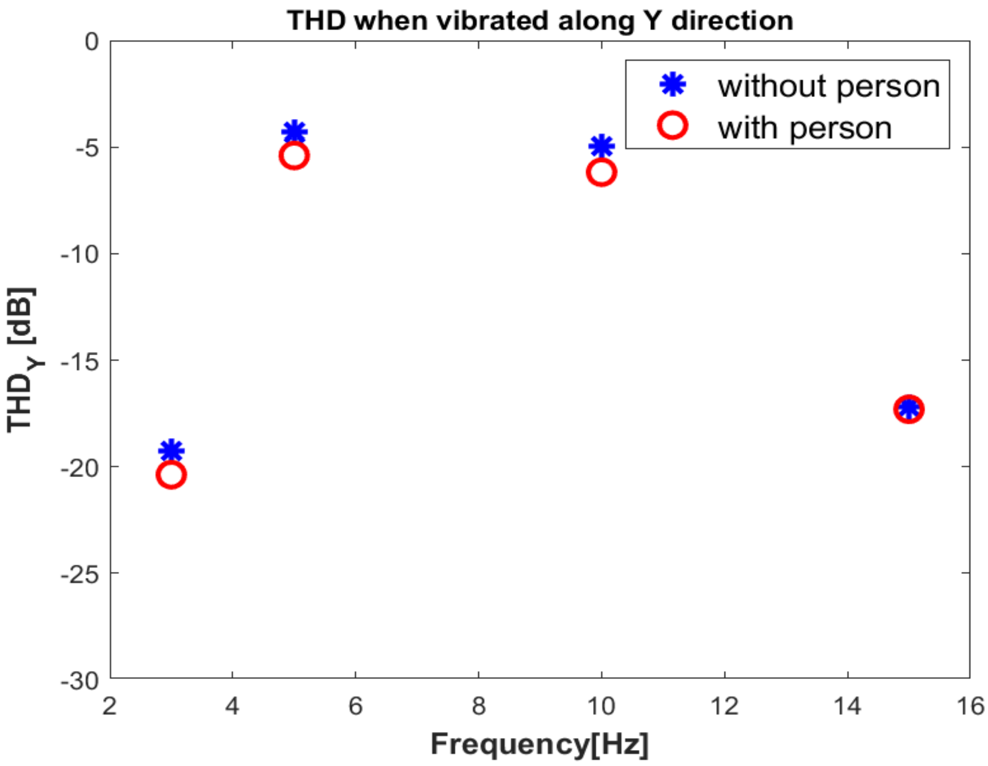


Figure 3.10 THD when vibration along Y axis

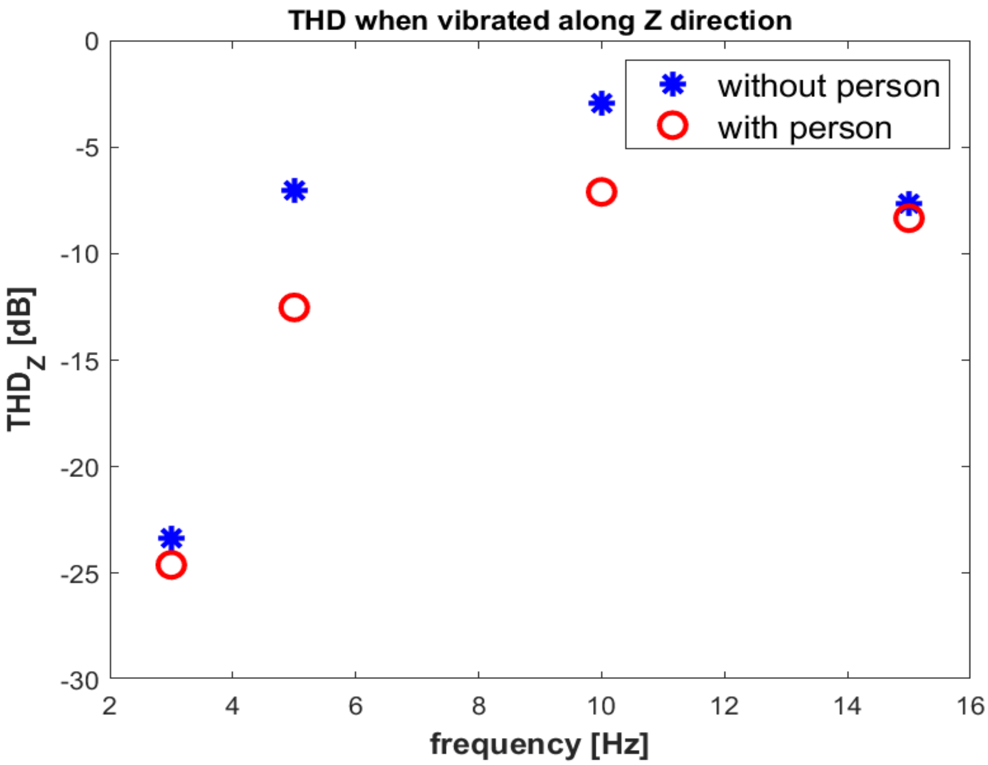


Figure 3.11 THD when vibration along Z axis

As observed from the above plots (from Figure 3.9 to Figure 3.11), it could be seen that for most of the vibrating conditions, the THD values are extremely high (greater than -5 dB) especially at excitation frequencies of 5 and 10 Hz. These THD values indicates that there is a significant amount of distortion in the other two directions when a sinusoidal vibration is given in any one of the directions. In some cases, THD values which are close to -1dB indicates that there is more noise than the input signal. So, there are conclusive evidence to suggest that the vibration on the plate is not uniform while imposing a vibration in the platform along an axis. Because of this high distortion (which are close to -1 dB), it was decided to fix the 3D shaker to the ground. The 3D shaker was fixed to the ground (Figure 2.1) using six angle plates made of steel in the base of the machine.

3.1.4 Shaker Grounded – Time Signal Analysis

Initially, the acceleration signals in time domain were visualized and analysed. No significant discrepancies were found in the time signals. A sample plot of the acceleration signal in time domain is reported in Figure 3.12

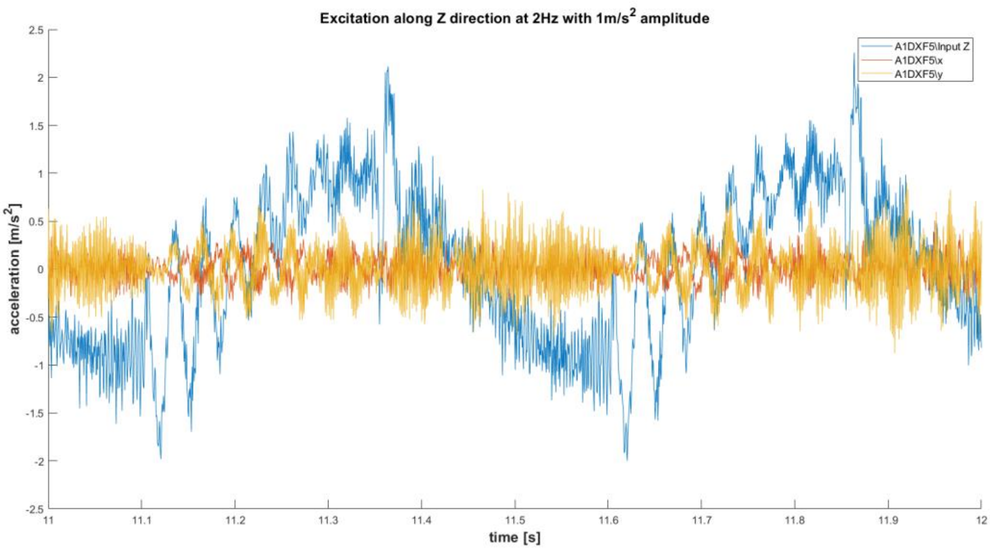


Figure 3.12 Time signal when vibration along Z direction at 2 Hz with 1 m/s^2 amplitude

3.1.5 Shaker Grounded – Crosstalk Analysis

After grounding the shaker, Crosstalk were computed to check if the harmonic sinusoidal excitation along one axis affects the signals of the other two axes. Crosstalk computation was performed in MATLAB® with the method as explained in section 3.1.2 with excitation along all the three axes (X, Y, Z). The plots are reported below.

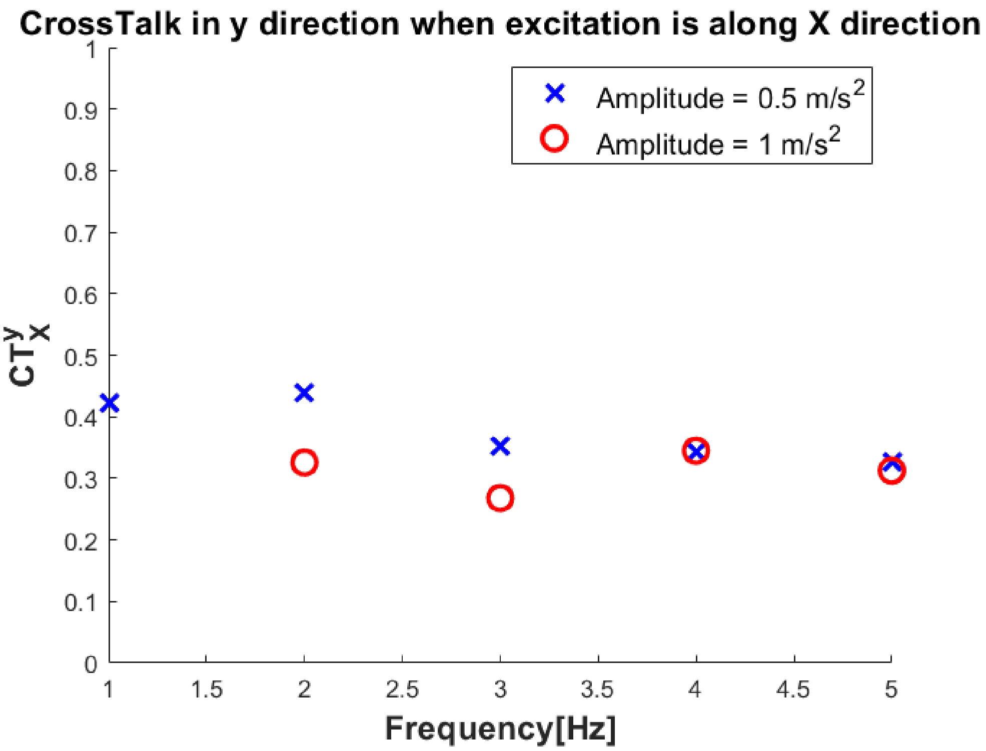


Figure 3.13 CT_y when vibration along X axis

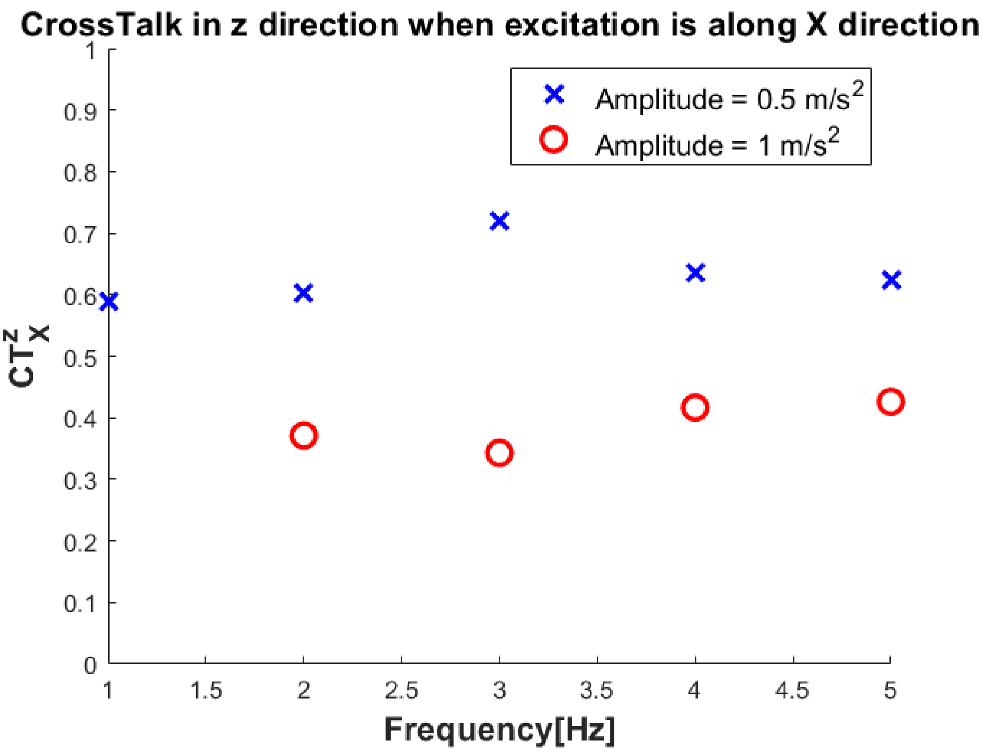


Figure 3.14 CT_z when vibration along X axis

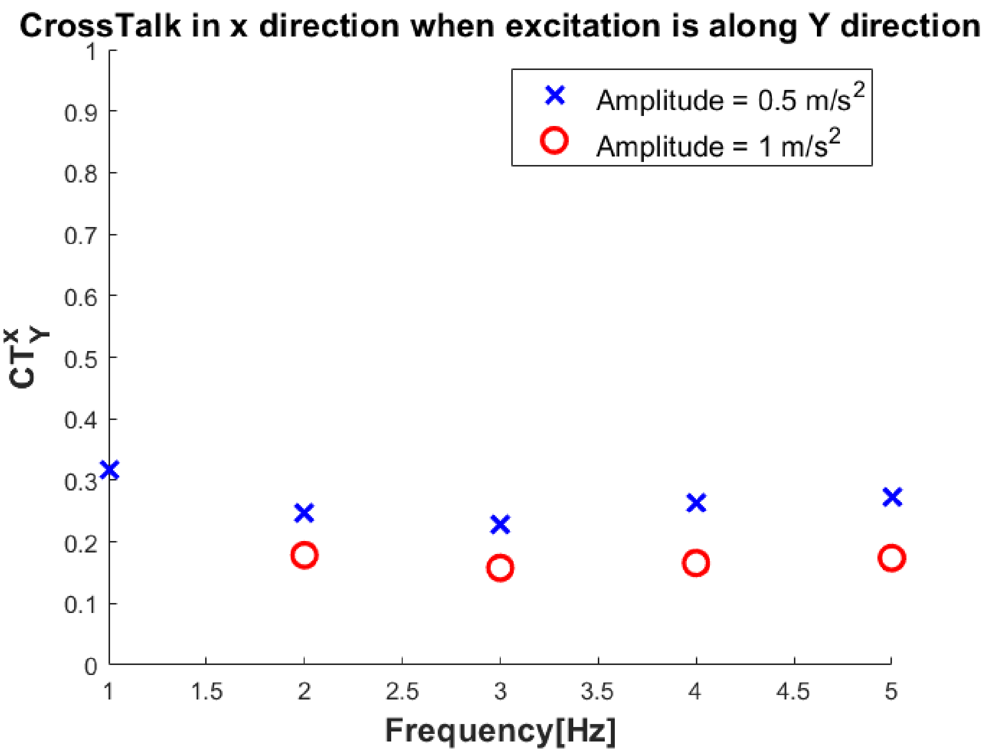


Figure 3.15 CT_x when vibration along Y axis

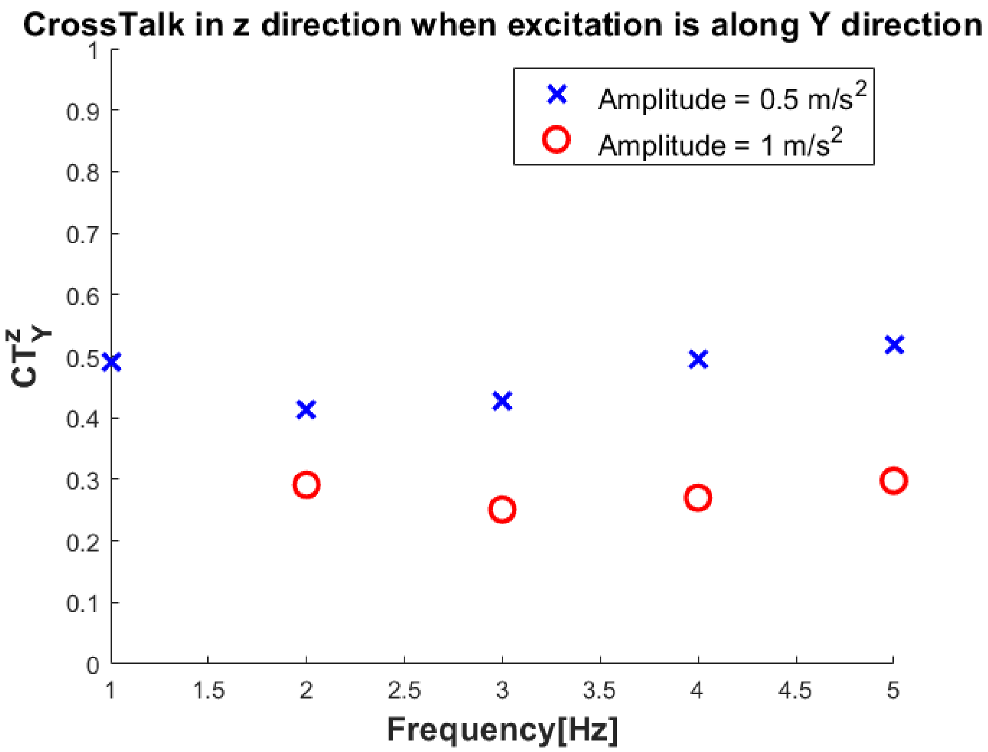


Figure 3.16 CT_z when vibration along Y axis

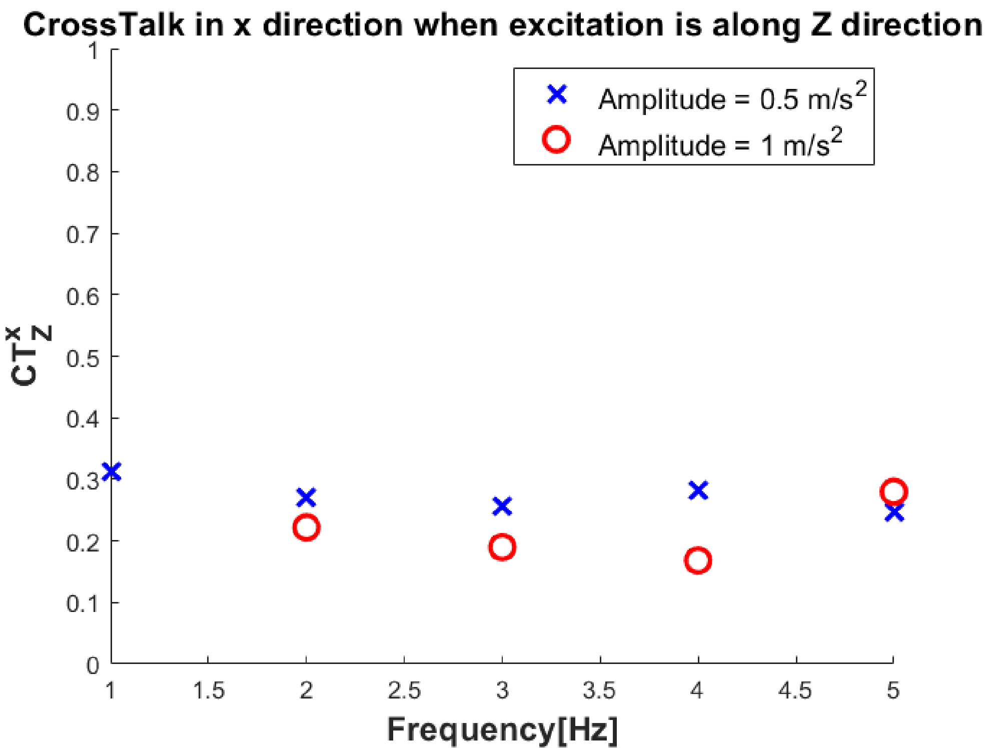


Figure 3.17 CT_x when vibration along Z axis

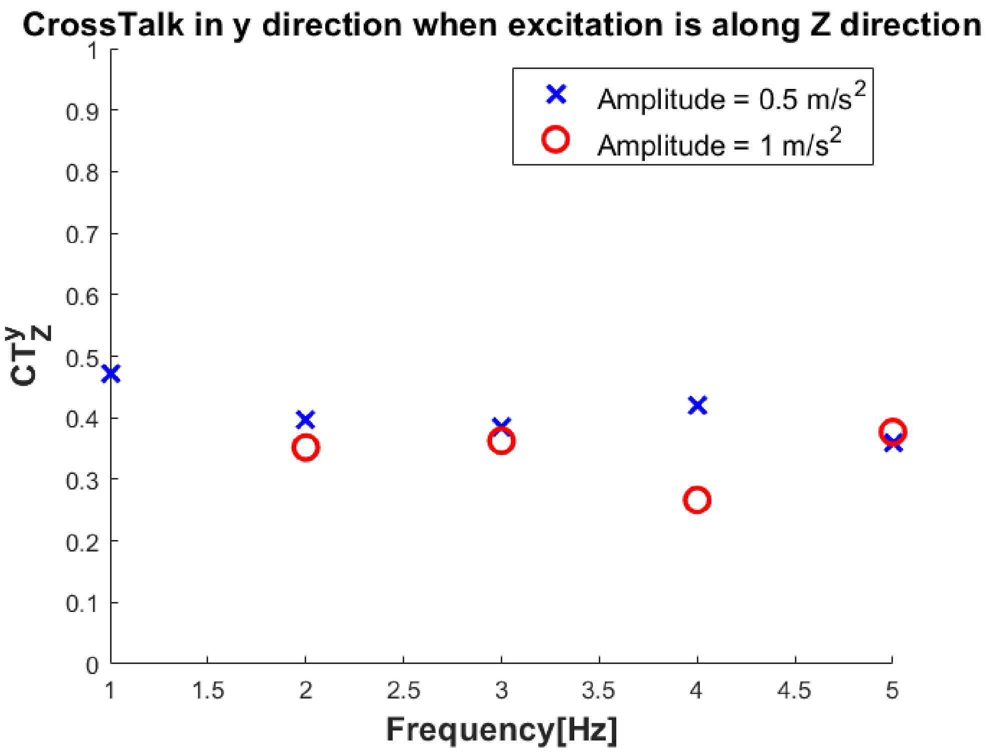


Figure 3.18 CT_y when vibration along Z axis

By observing the CT plots (from Figure 3.13 to Figure 3.18), we can see a better performance of the shaker in terms of the CT values when the system is excited at a higher amplitude of 1 m/s^2 when compared with exciting the system at 0.5 m/s^2. Higher CT values can be observed when the system is excited at an amplitude lower than 1 m/s^2. With this observation, we can conclude that with the current setup of the machine, it is better to avoid amplitudes lower than 1 m/s^2 such as 0.5 m/s^2 while producing vibrations in the 3D shaker.

3.1.6 Shaker Grounded – THD Analysis

The Total Harmonic Distortion (THD) was computed in MATLAB® using the same method as reported in section 3.1.3 by fixing the machine to the ground. The THD plots for all the three axes are reported below.

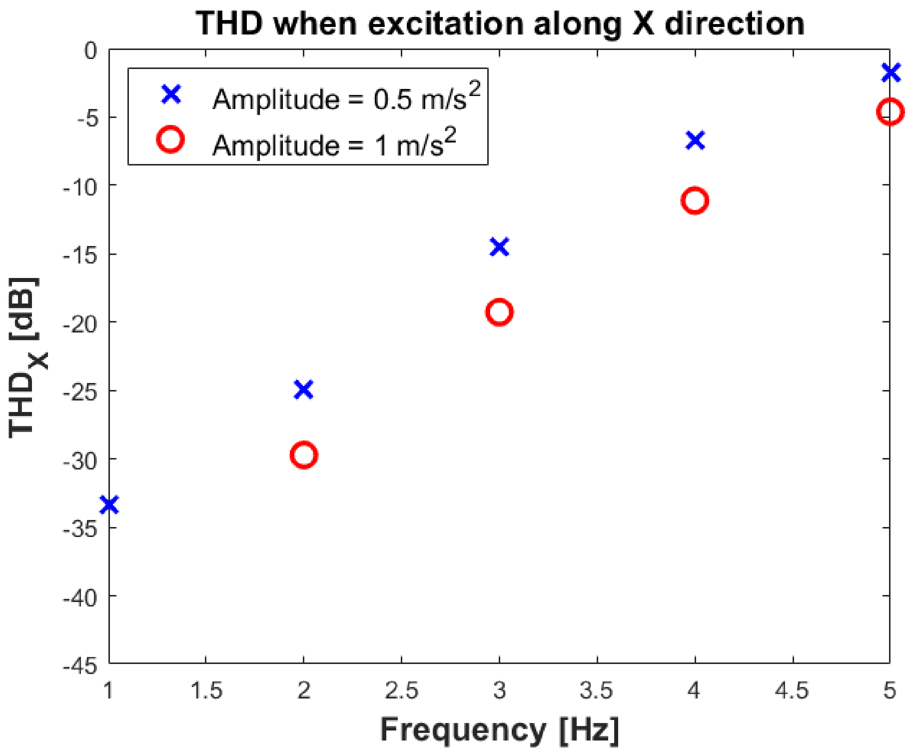


Figure 3.19 THD when vibration along X axis

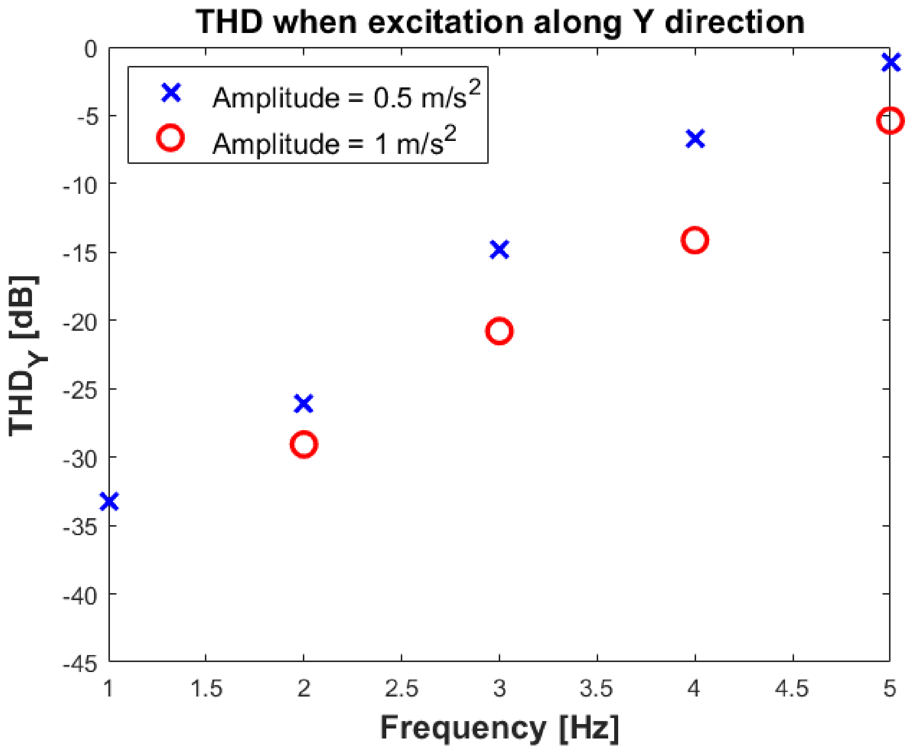


Figure 3.20 THD when vibration along Y axis

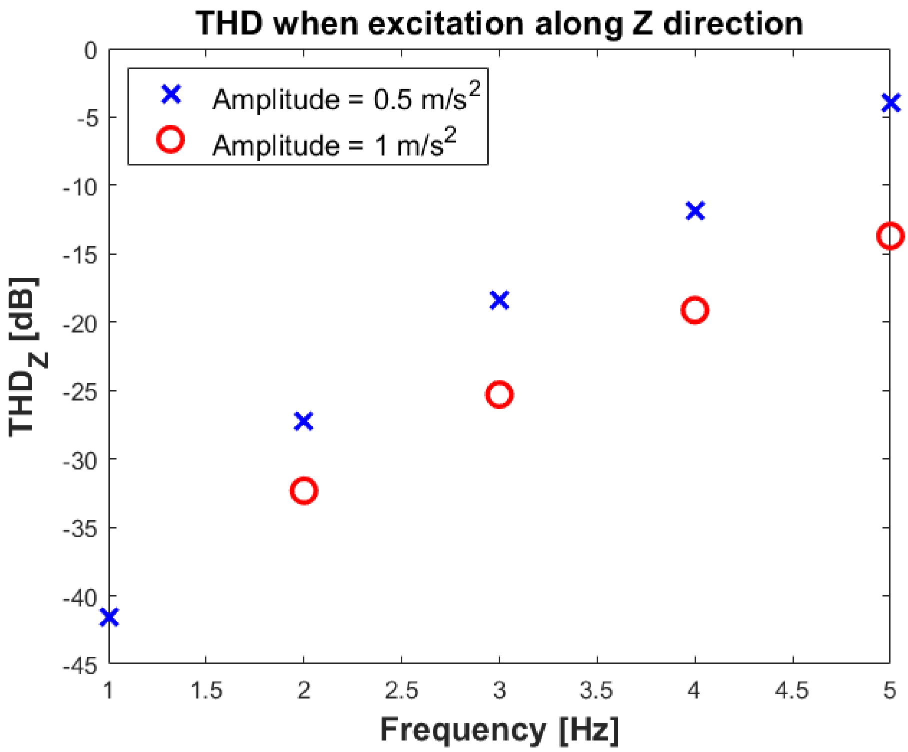


Figure 3.21 THD when vibration along Z axis

Looking at the THD plots (from Figure 3.19 to Figure 3.21), a linear increase of distortion could be observed as the excitation frequency is increased. THD values close to -5 dB has been observed as the excitation frequency nears 5 Hz. This could be because the resonance frequency of the excitation system is around 5 Hz [6], as a consequence when the excitation frequency reaches close to the resonance frequency of the system, a higher distortion of the signal (THD more than -5 dB) occurs. Like the observation during Crosstalk analysis, a better performance of the system in terms of THD can be seen when the excitation is given at an amplitude of 1 m/s^2, since at this amplitude we get THD values close to or lesser than -20 dB for most of the vibrating conditions. As a result of this, similar to the conclusion reached in section 3.1.5, it is better to operate the 3D shaker at amplitudes close to 1 m/s^2.

3.1.7 Shaker Grounded with Subject – Crosstalk Analysis

The following plots shows the Crosstalk computed when a human subject underwent the WBV – PVT experiment. The Crosstalk were computed in MATLAB® in the same method as explained before with excitation along all the three axes.

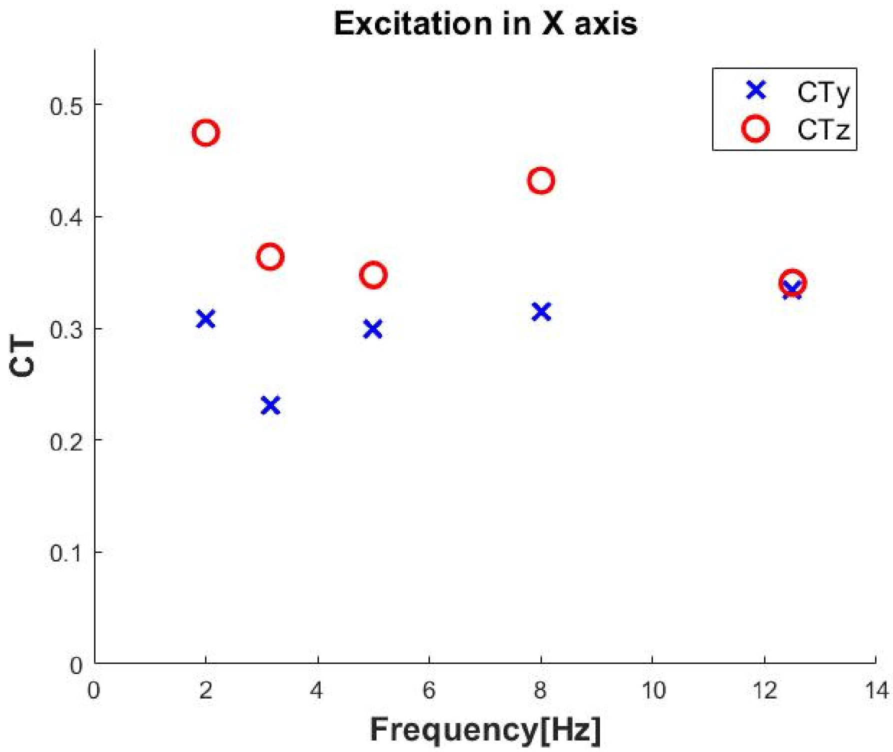


Figure 3.22 Crosstalk when vibration along X axis

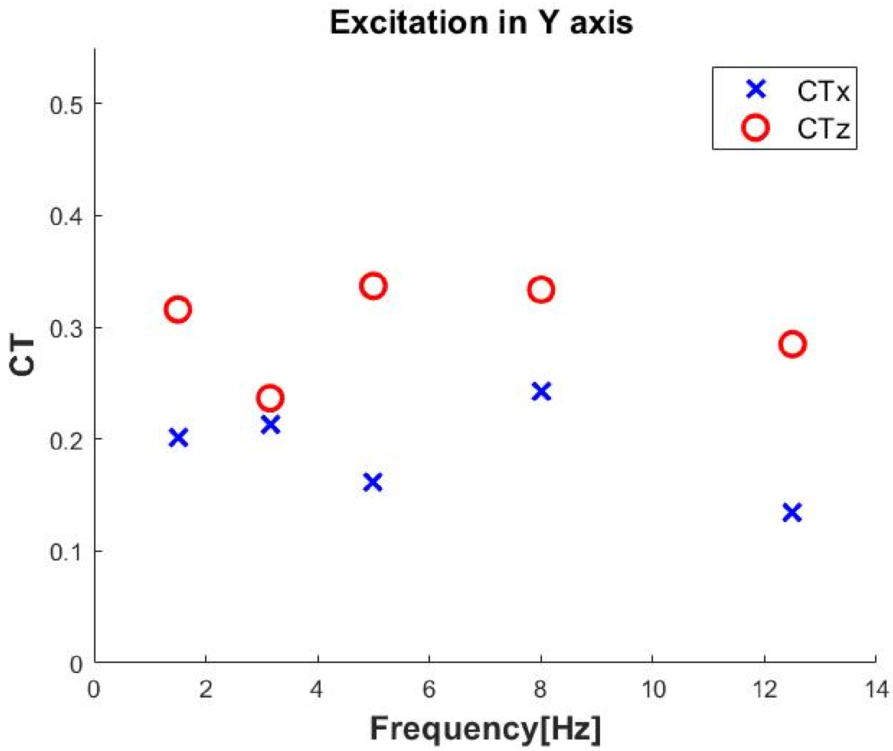


Figure 3.23 Crosstalk when vibration along Y axis

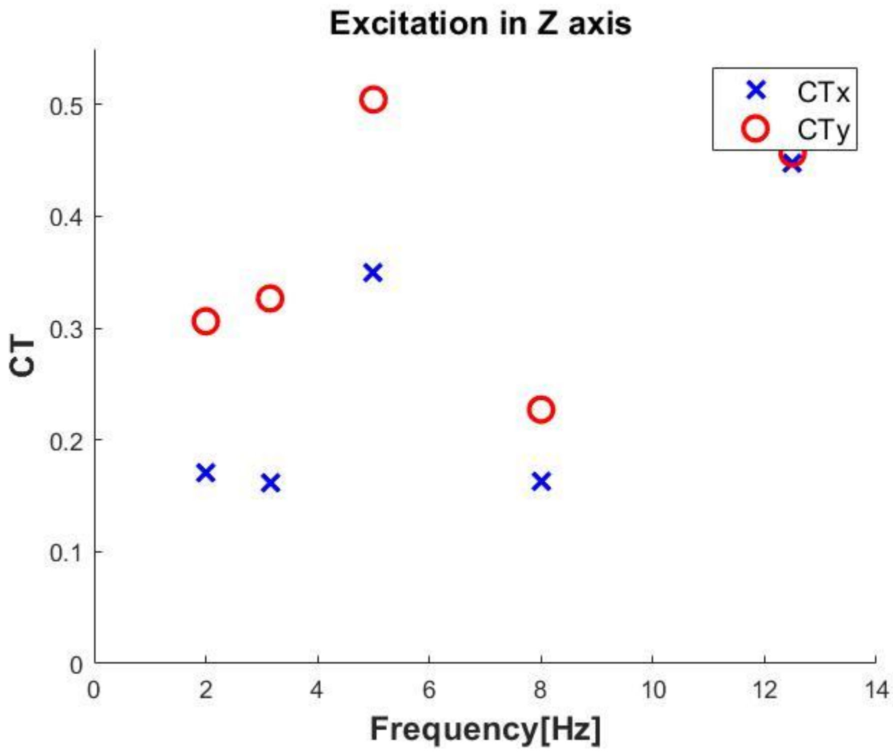


Figure 3.24 Crosstalk when vibration along Z axis

Looking at the CT plots (from Figure 3.22 to Figure 3.24) it could be observed that when the excitation is along X axis with a subject standing on the vibrating platform, there is no significant variability in Crosstalk values between the other two axes (Y and Z). The values of CT_y and CT_z are consistent and are between 0.2 and 0.5 for all the six excitation frequencies. When the excitation is along the Y axis with the subject, the Crosstalk in the other two axes (CT_x and CT_z) are consistent between 0.2 and 0.5 for all the frequencies except during vibration at 2 Hz, where the CT values are higher than 0.5. When the vibration was along Z axis, the Crosstalk values (CT_x and CT_y) are between 0.2 to 0.6.

3.1.8 Shaker Grounded with Subject – THD Analysis

The following plots shows the computed THD when the WBV – PVT experiment was conducted with a human subject. The THD were computed in MATLAB® in the same method as explained before with excitation along all the three axes.

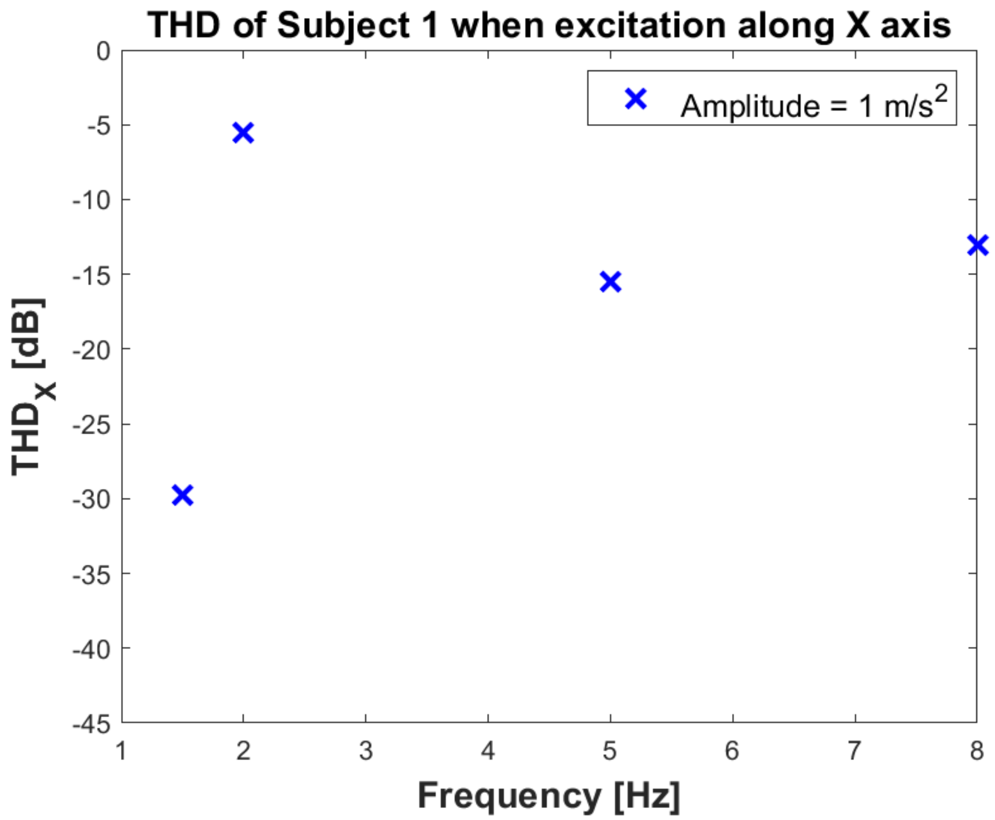


Figure 3.25 THD when vibration along X axis

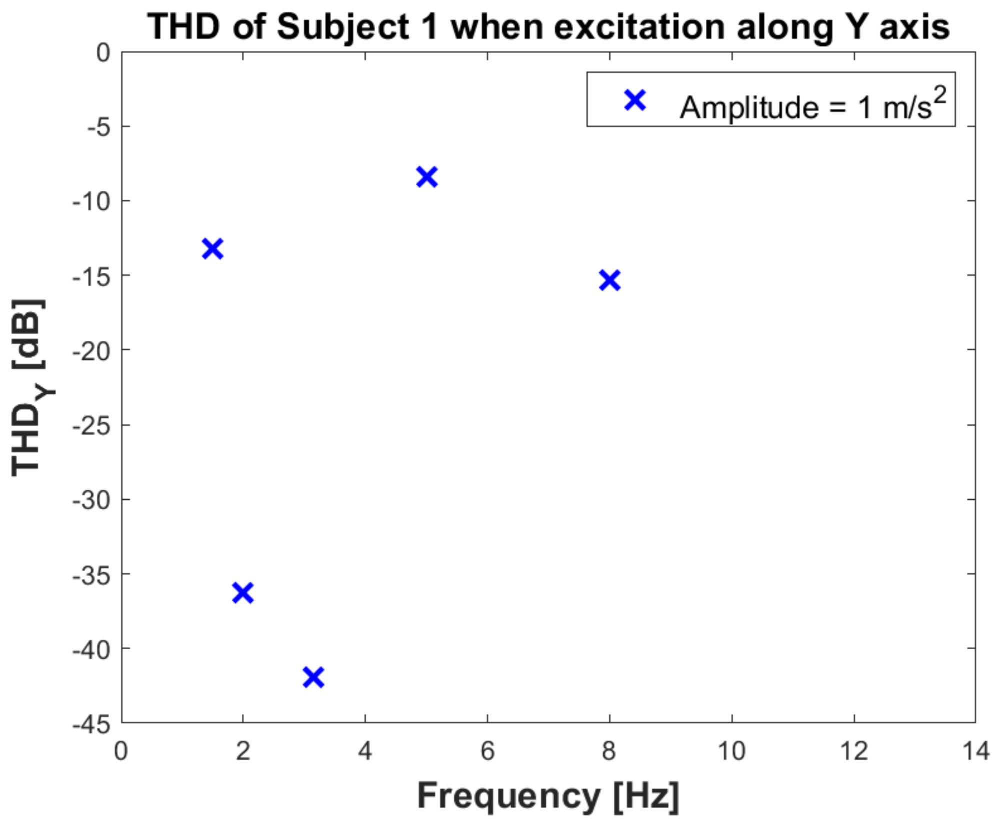


Figure 3.26 THD when vibration along Y axis

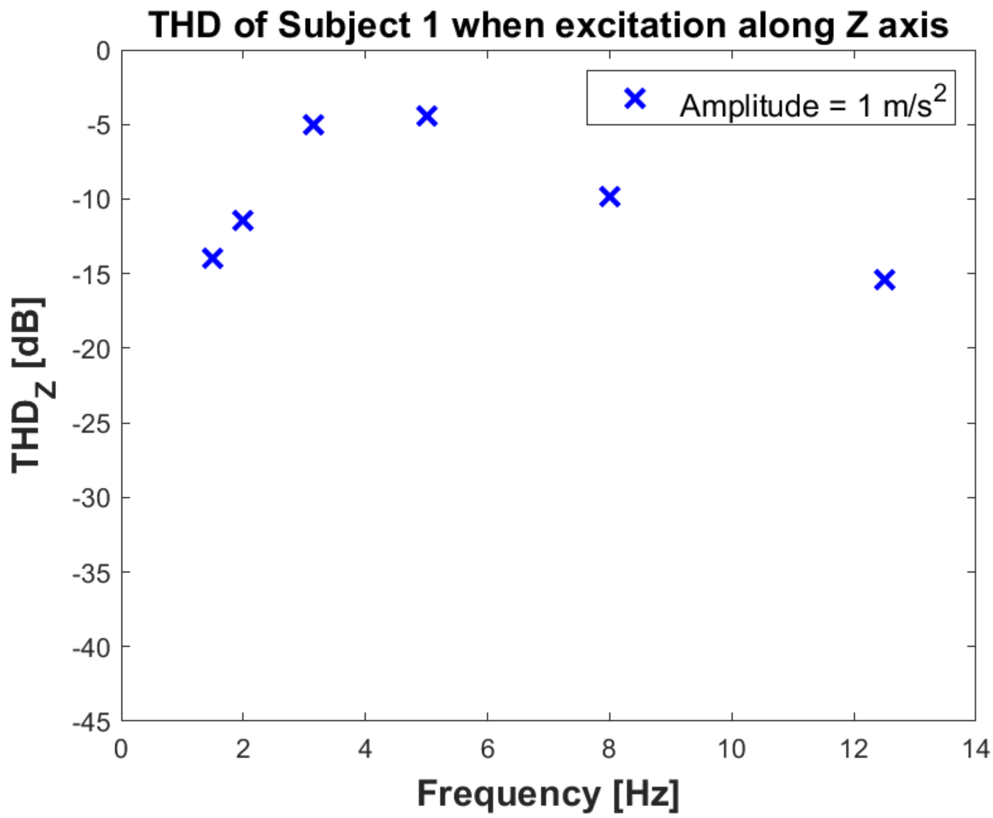


Figure 3.27 THD when vibration along Z axis

On observing the THD plots (from Figure 3.25 to Figure 3.27) with a subject on the 3D shaker, it could be seen that when excited along X axis, a THD close to -5 dB was observed at an excitation frequency of 2 Hz. When the excitation is along Y and Z axes, higher distortions (around -5 dB) were observed at an excitation frequency of 5 Hz. In any of the axis, as the excitation frequencies are increased to more than 5 Hz, their corresponding THDs were lower when compared to 5 Hz. More distortion of the signal at 5 Hz could be because the resonance frequency of the system is at around 5 Hz as explained in section 3.1.6.

3.2 Descriptive statistics on anthropometric data

The descriptive statistics such as Mean, Standard deviation, Variance are calculated for the Baseline vibration condition of the experiment. These descriptive statistics are computed on the anthropometric data such as weight, height, BMI, and age separately for both male and female subjects.

Table 3.1 Descriptive statistics of male subjects

Variable	Mean	SE Mean	StDev	Variance	Minimum	Median	Maximum
Weight [kg]	73.167	0.139	12.510	156.492	55	71.5	105
Height [m]	1.77	0.000538	0.0483	0.00233	1.7	1.755	1.88
BMI [kg/m^2]	23.417	0.0432	3.88	15.078	18	22.5	34
Age [years]	26.583	0.0437	3.926	15.412	23	25	39

Table 3.2 Descriptive statistics of female subjects

Variable	Mean	SE Mean	StDev	Varianc e	Minimum	Median	Maximum
Weight [kg]	59.154	0.0845	7.902	62.445	45	58	74
Height [m]	1.61	0.000635	0.0594	0.00352	1.5	1.63	1.73
BMI [kg/m^2]	22.769	0.0279	2.606	6.794	19	23	28
Age [years]	25.308	0.0203	1.897	3.598	21	26	29

By observing Table 3.1 and Table 3.2, it could be said that male subjects have higher average weight (73.17 kg) and height (1.77 m) when compared with the ones of female subjects (59.15 kg and 1.61 m). It could be observed that female subjects are more consistent in terms of weight as female subjects have lesser standard deviation and variance (7.902 and 62.445) in terms of weight when compared with male subjects (12.51 and 156.492). The average age of male subjects is 26.6 years and that of female subjects is 25.3 years.

3.2.1 Two samples t-test on anthropometric data

Table 3.3 to Table 3.6 show the results of the t-test conducted on the anthropometric data of the subjects such as Weight, Height, BMI, and Age. The t-test has been done comparing Group 1 and Group 2 as the two samples as mentioned in section 2.5.3.

t-test on Weight

Table 3.3 Results for t-test done on Weight of the subjects

Group	N	Mean [kg]	StDev [kg]	SE Mean [kg]	Differe nce [kg]	95% CI for Difference	T-Value	DF	P-Value
1	8064	73.2	12.5	0.14	14.013	(13.693, 14.332)	85.99	13416	0.00
2	8736	59.15	7.90	0.085					

t-test on Height

Table 3.4 Results for t-test done on Height of the subjects

Group	N	Mean [m]	StDev [m]	SE Mean [m]	Difference [m]	95% CI for Difference	T-Value	DF	P-Value
1	8064	1.77	0.0483	0.00054	0.16	(0.158369, 0.161631)	192.24	16541	0.00
2	8736	1.61	0.0594	0.00064					

t-test on BMI

Table 3.5 Results for t-test done on BMI of the subjects

Group	N	Mean [kg/m^2]	StDev [kg/m^2]	SE Mean [kg/m^2]	Difference [kg/m^2]	95% CI for Difference	T-Value	DF	P-Value
1	8064	23.42	3.88	0.043	0.6474	(0.5466, 0.7483)	12.58	13938	0.00
2	8736	22.77	2.61	0.028					

t-test on Age

Table 3.6 Results for t-test done on Age of the subjects

Group	N	Mean [years]	StDev [years]	SE Mean [years]	Difference [years]	95% CI for Difference	T-Value	DF	P-Value
1	8064	26.58	3.93	0.044	1.2756	(1.1812, 1.3701)	26.47	11422	0.00
2	8736	25.31	1.90	0.020					

By observing the P-Value of the two-sample t-test in all the anthropometric data such as the subjects' weight, height, BMI, and age, it could be seen that there is a significant difference between the male and female subjects in terms of their average values (since $p < 0.01$). This suggests that the Null hypothesis can be neglected. This test also validates our method to analyse the experiment data by separating into male and female sets of data.

3.3 Mean Response Time data analysis

3.3.1 Response Time data visualization

The response time data for the 25 subjects were collected and plotted against the number of clicks of 112 as explained in section 2.5.4. Figure 3.28 shows the raw response time data of a subject. As it could be seen from the plot, all the responses of this subject were under 1 s. Similar to this, most of the subjects had response times less than 1 s.

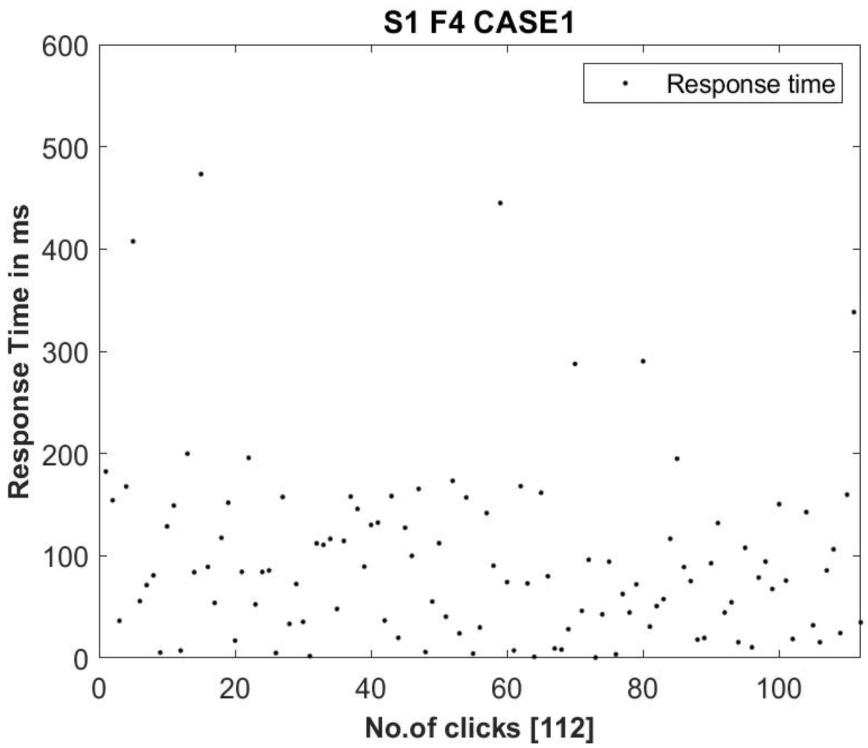


Figure 3.28 Raw response time data without any filters applied

But, among the collected data there were few cases which had some response times more than 1 s. The reason for response time more than 1 second was discussed in section 2.5.4. One such example of a raw data plot is shown below in Figure 3.29, where the response data above 1 second is circled in red. This justifies the decision to filter the acquired raw data before proceeding with further analysis.

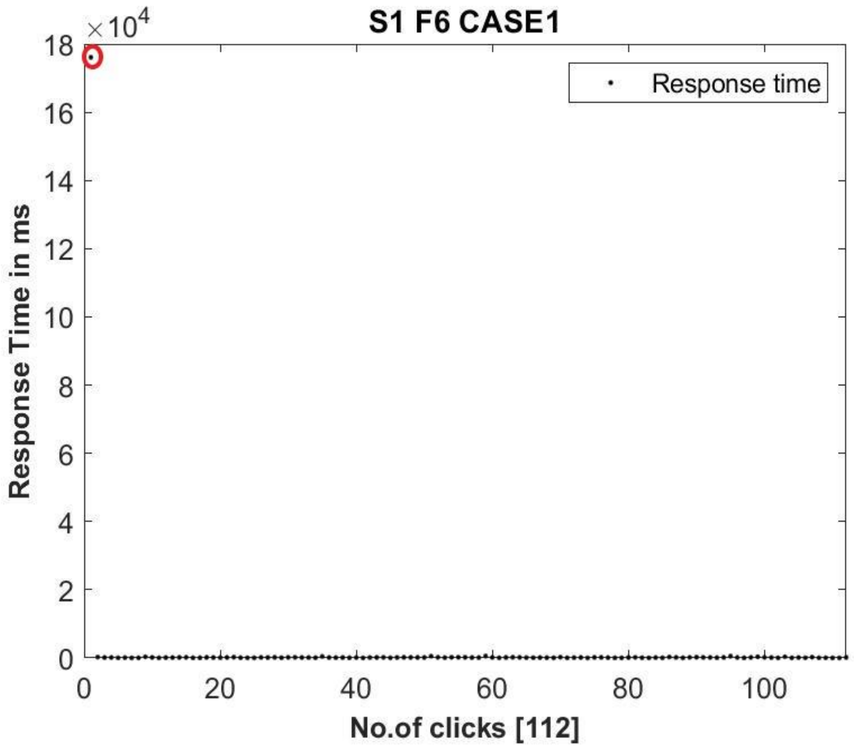


Figure 3.29 Visualization of a sample data where a response time was greater than 1 second (circled in red)

By filtering the data, we can get a trend that helps us to find the actual behaviour of the subjects. The excessive response times that were greater than 1 second were removed from the data and the mean and standard deviation was plotted for each vibration condition and baseline conditions for all the 25 subjects as explained in section 2.5.4

Figure 3.30 and Figure 3.31 shows the plots (for 2 different vibration conditions) of the response time data obtained after applying a filter to remove response times more than 1 s. Figure 3.30 shows the plot obtained after applying the filter to Figure 3.28. Comparing Figure 3.30 and Figure 3.28, it could be seen that both the plots are exactly similar and have the same number of response time data (112 RT). Figure 3.31 shows the plot obtained after applying the filter to Figure 3.29. Comparing Figure 3.31 and Figure 3.29, it could be seen that Figure 3.31 has lesser responses than Figure 3.29, because data with response times more than 1 s were filtered and removed as discussed in section 2.5.4.

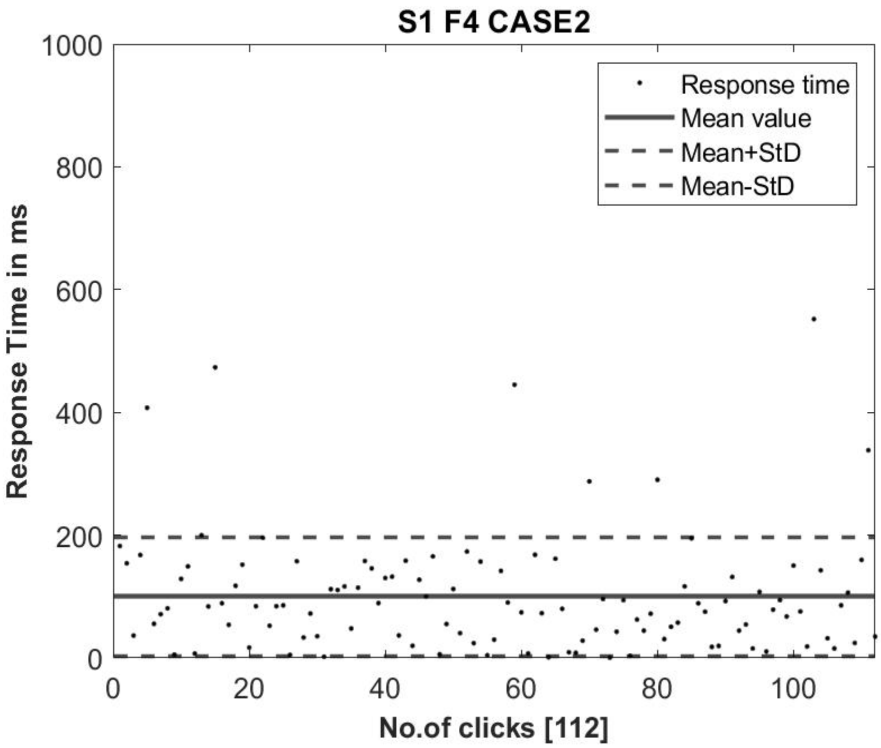


Figure 3.30 Visualisation of the data after removing response times over 1 s

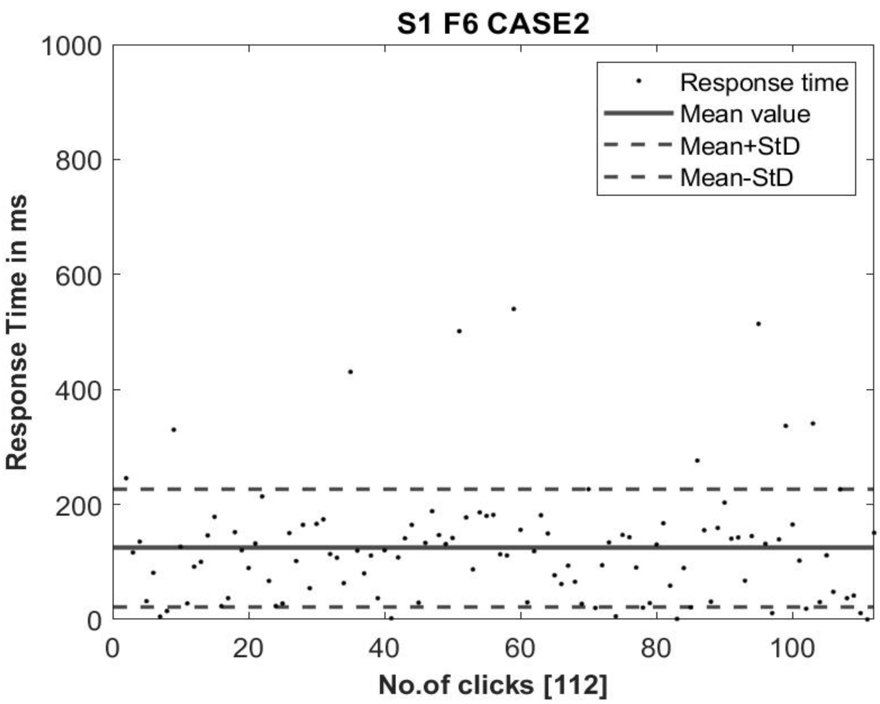


Figure 3.31 Visualisation of the data after removing response times over 1 s

On further filtering the data using the 2 limit conditions as specified in section 2.5.4, the response times greater than 2.5 times the standard deviation and response time under 50 ms were removed as shown in Figure 3.32 and Figure 3.33. As a consequence of this filtering, there is a change in the mean value and standard deviation. There is a change in the mean value from Case 2 (Figure 3.30 and Figure 3.31) to Case 3 which is marked in red (Figure 3.32 and Figure 3.33).

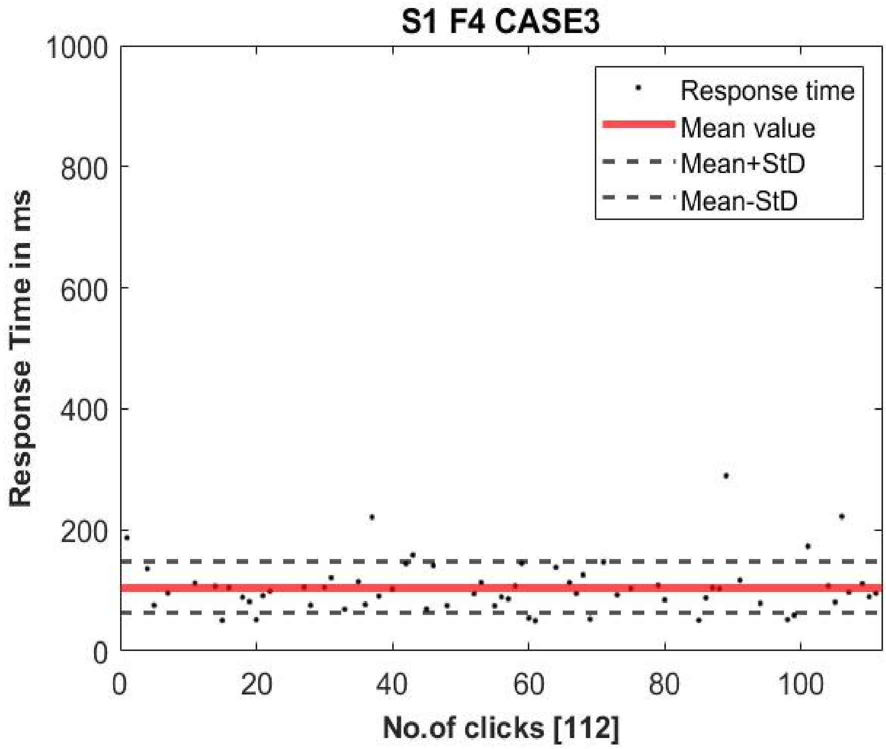


Figure 3.32 Visualisation of the data after further filtering using 2 limit conditions

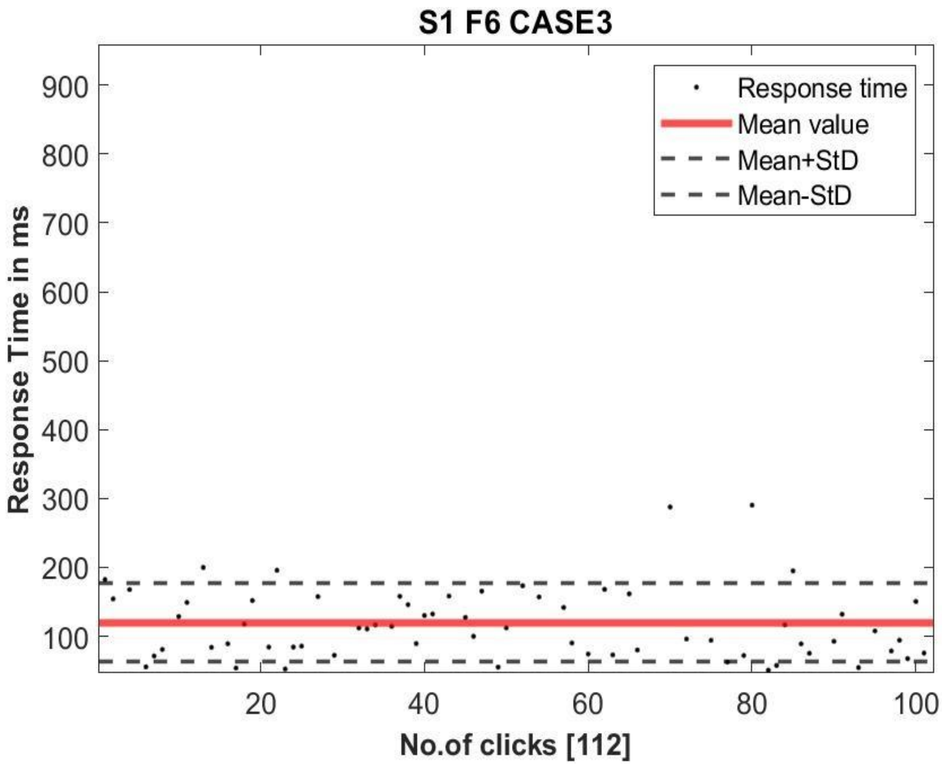


Figure 3.33 Visualisation of the data after further filtering using 2 limit conditions

For the compared figures (Figure 3.30 vs Figure 3.32 ; Figure 3.31 vs Figure 3.33) there was around a 5.20 % and 3.57 % increase and decrease in mean value from Case 2 to Case 3 at 5 Hz and 12.5 Hz, respectively. This increase and decrease in percentage of mean values is because of the filtering and removal of response times.

3.3.2 Comparison of Response Time before and after WBV exposure

The Table 3.7 shows the analysis of variance of Response time with variables as Group, Time and a combination of Group×Time. Observing the partial η^2 values, variables Group and Time have effect size (0.012 and 0.004, respectively) larger than that of the combination of Group and Time variable (4.77e-04). Also, looking their corresponding p-values, variables Group, Time, and combination of Group×Time have p-values ($p = 0.00$, $p = 1.07\text{e-}14$, and $p = 7.62\text{e-}03$, respectively) less than 0.1. Hence, it could be said that these variables are statistically significant in terms of the mean RT. Therefore, it is reasonable to analyse separately the pre and post-WBV mean reaction times for Group 1 and Group 2 of subjects.

Table 3.7 Analysis of Variance

Variable	P-Value	Partial η^2
GROUP	0.000	0.012
TIME	1.07e-14	0.004
GROUP×TIME	7.62e-03	4.77e-04

The results of Bonferroni simultaneous test results for differences of means in terms of Group, Time, and Group×Time are reported in Table 3.8 to Table 3.10.

(Note: Group 1 indicates male subjects, Group 2 indicates female subjects, Time 0 indicates pre-vibration Baseline condition and Time 8 indicates post-vibration Baseline condition)

Table 3.8 Bonferroni Simultaneous Tests for Differences of Means between male and female subjects

Difference of GROUP Levels	Difference of Means	Simultaneous 95% CI	T-Value	Adjusted P-Value
2 - 1	16.20	(13.87, 18.54)	13.62	0.00

Table 3.9 Bonferroni Simultaneous Tests for Differences of Means between pre and post WBV conditions

Difference of TIME Levels	Difference of Means [ms]	Simultaneous 95% CI	T-Value	Adjusted P-Value
8 - 0	-9.21	(-11.54, -6.87)	-7.74	1.07e-14

Table 3.10 Bonferroni Simultaneous Tests for Differences of Means between Group×Time

Difference of GROUP×TIME Levels	Difference of Means	Simultaneous 95% CI	T-Value	Adjusted P-Value
(1 8) – (1 0)	-6.03	(-10.71, -1.36)	-7.74	0.004
(2 8) – (2 0)	-12.38	(-16.57, -8.19)	-7.80	4.08e-14

Looking at the P-values and T-values from Table 3.8 and Table 3.9, it could be said that there is a significant difference in terms of means between the compared groups, because $p < 0.01$ for variables Group and Time. Therefore, null hypothesis can be neglected.

Figure 3.34 shows the comparison of RT between pre-vibration Baseline condition and post-vibration Baseline condition for male subjects.

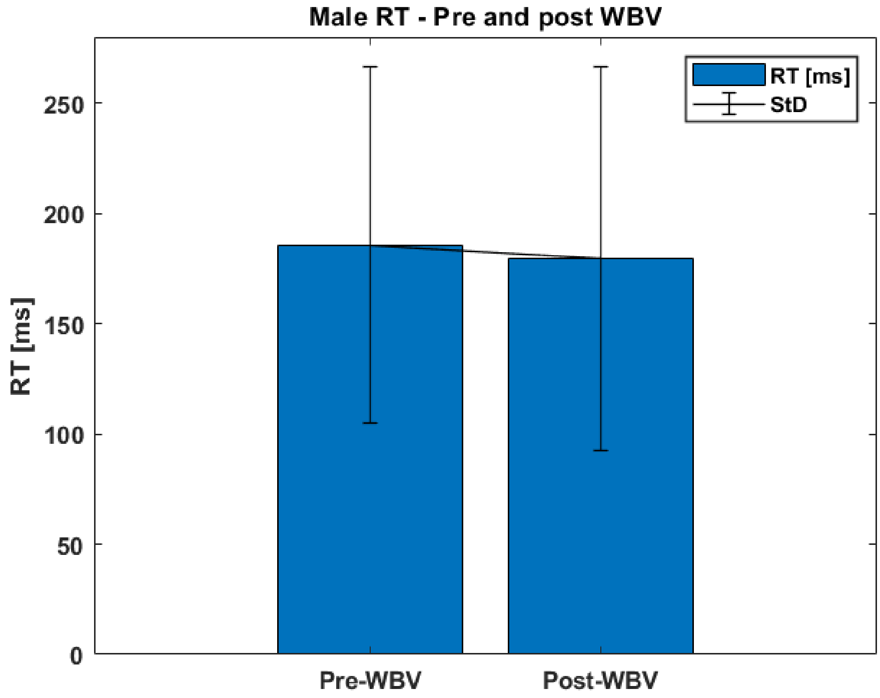


Figure 3.34 Pre and post WBV RT for male subjects

From fig, it could be seen that the male subjects responded on an average at 185.63 ms before being exposed to WBV and at 179.60 ms after being exposed to WBV. There has been a 3.25 % reduction in response time after the exposure to WBV.

Figure 3.35 shows the comparison of RT between pre-vibration Baseline condition and post-vibration Baseline condition for female subjects.

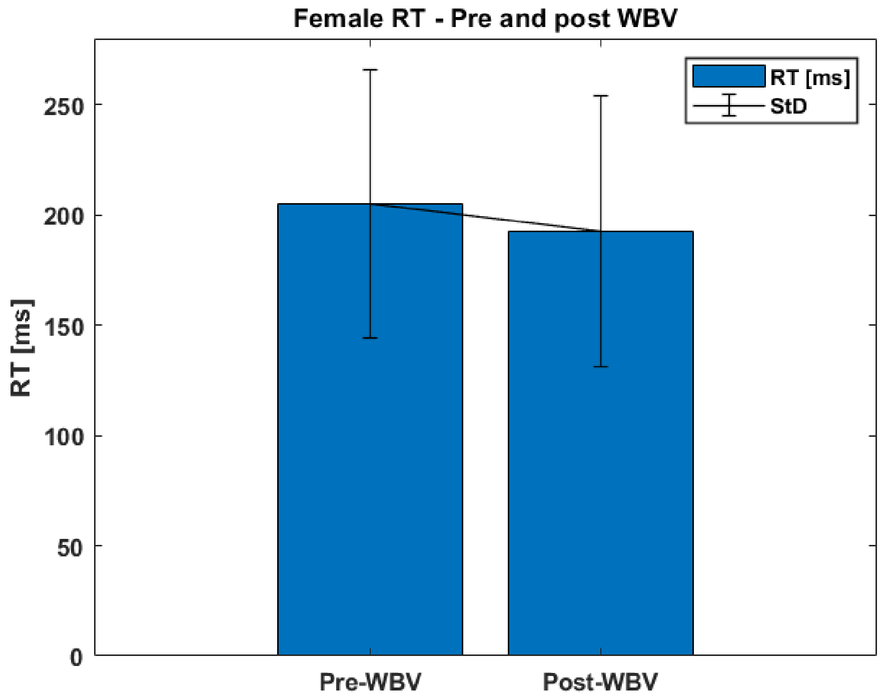


Figure 3.35 Pre and post WBV RT for female subjects

The female subjects responded on an average at 205.01 ms before being exposed to WBV and at 192.63 ms after being exposed to WBV. Unlike male subjects, there is a larger (6.04 %) reduction in response time after being exposed to WBV. Comparing Figure 3.34 and Figure 3.35, it could be observed that female subjects took longer time to respond than male subjects.

Figure 3.36 shows the comparison of RT between pre-vibration Baseline condition and post-vibration Baseline condition for all the 25 subjects. The average response time before being exposed to WBV was 195.32 ms and the average RT after being exposed to WBV was 186.12 ms. Overall, there is a 4.71 % reduction in RT after being exposed to WBV.

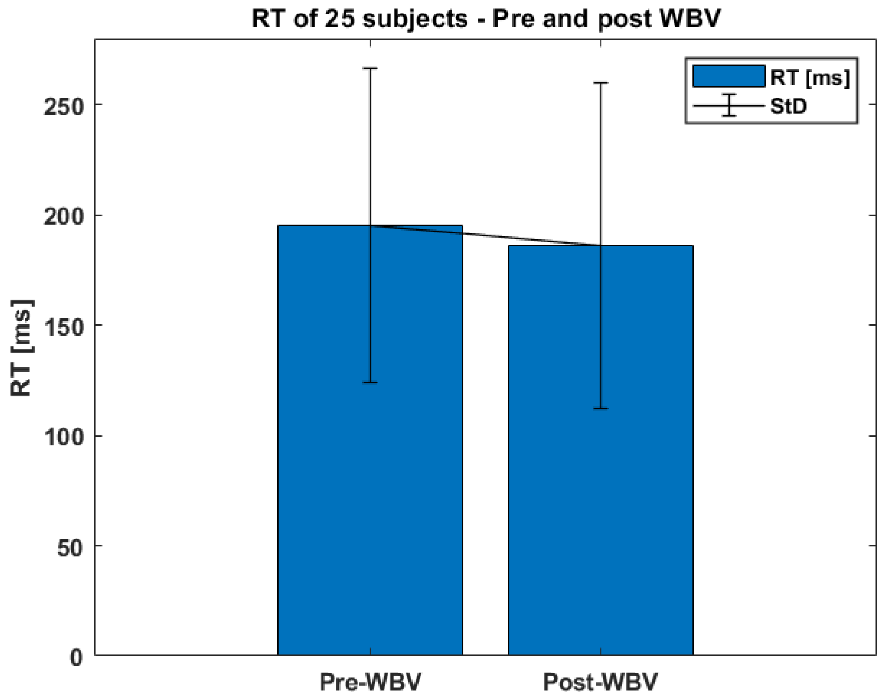


Figure 3.36 Pre and post WBV RT for the 25 subjects

A reduction of the response time in the Post-WBV Baseline conditions for both the Groups indicates that the subjects did not feel any fatigue after the exposure to WBV. The subjects got used to responding to the visual stimuli over the course of the PVT test and as a result of this learning effect, the subjects responded faster during Post-WBV Baseline condition which was performed as a last condition at the end of each session.

3.3.3 Comparison of Response Time data acquired without and with WBV

The bar plots of mean response times for both male and female subjects are shown in Figure 3.37 and Figure 3.38. The bar plot compares the baseline and WBV conditions, respectively.

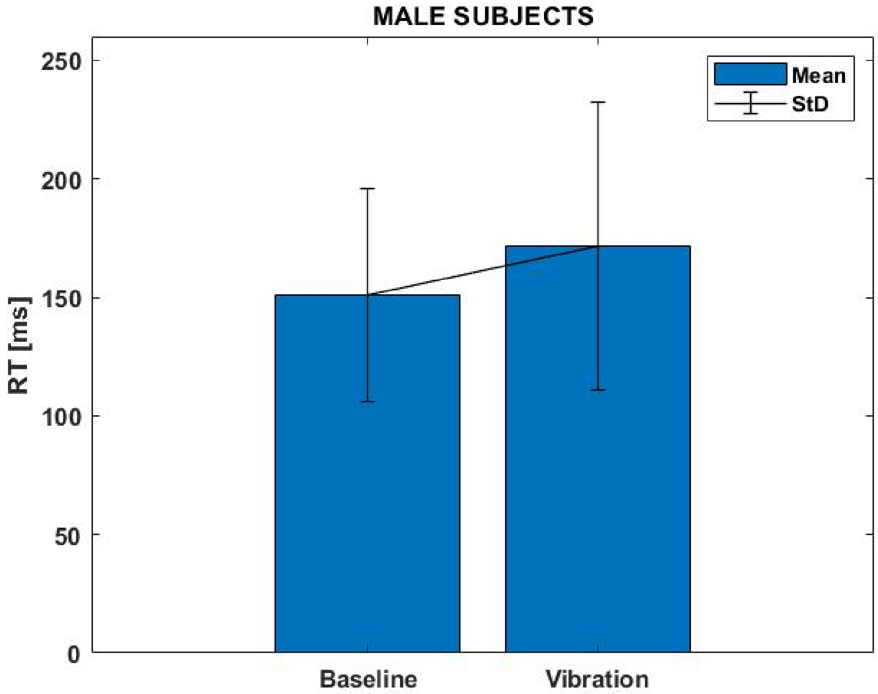


Figure 3.37 Comparison of mean response time of male subjects between WBV and Baseline conditions

By analysing Figure 3.37, it could be observed that male subjects, on an average responded in 150.98 (44.78) ms during Baseline condition, whereas when they were exposed to WBV, their average response time increased to 171.54 (60.89) ms. There is nearly a 13.62% increase in mean response time during WBV condition with respect to Baseline condition. This indicates that male subjects took comparatively more time to respond to the stimuli upon exposure to WBV. This significant increase in response time could be because of the exposure to WBV. As a result, it could be said that for male subjects, there was a high variability (20.56 ms) in terms of mean response times upon exposure to WBV.

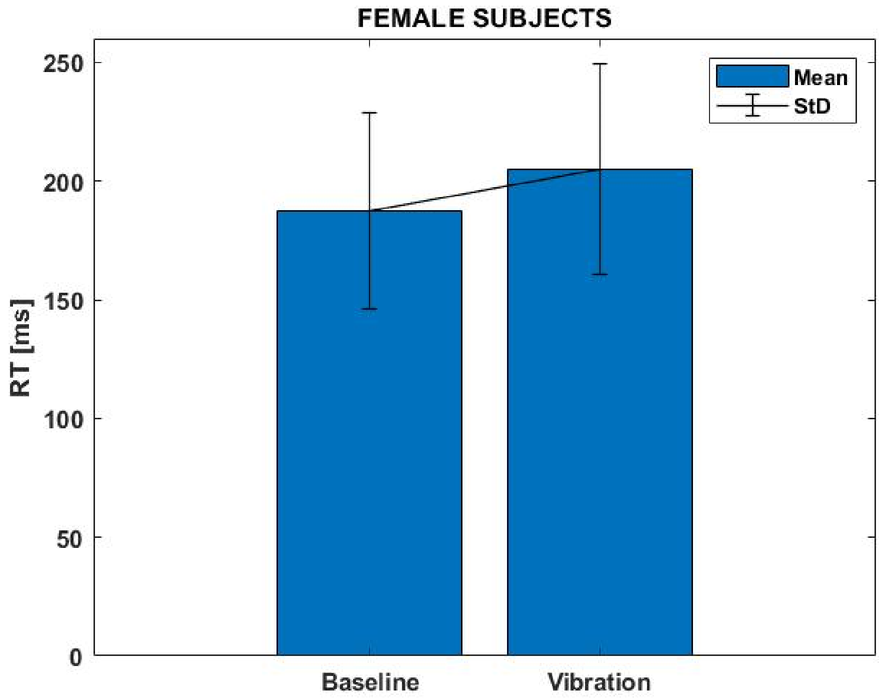


Figure 3.38 Comparison of mean response time of female subjects between WBV and Baseline conditions

Analysing Figure 3.38, female subjects also showed significant variability in responding to the stimuli in WBV and Baseline conditions. During the Baseline condition, female subjects on an average responded at 187.34 (41.39) ms, and during WBV conditions, the average response time was 205.13 (44.44) ms. An increase of 9.5% in mean response time upon exposure to WBV could be observed. This increase in mean response time could be attributed to WBV exposure.

Comparing Figure 3.37 and Figure 3.38, it could be observed that female subjects, on an average took longer time than male subjects to respond. There was around 17.83% difference in average response times between male and female subjects due to WBV exposure. In general, male subjects were faster to respond to the stimuli, but both male and female subjects took longer time to respond upon exposure to WBV.

Table 3.11 and Table 3.12 shows separately for male and female subjects, the WBV conditions that have a statistically significant difference with the Baseline condition. The statistical significance has been determined based on the p-values ($p < 0.05$ indicates a statistically significant difference among the compared groups).

(Note: The vibration conditions (frequency and axis) have been mentioned in Table 2.3)

Table 3.11 Bonferroni Simultaneous Tests for Differences of Means between Group×Condition for male subjects

Difference of GROUP×CONDITION	Difference of Means [ms]	Adjusted P-Value
(M C1) - (M BL)	-13.53	3.53E-07
(M C4) - (M BL)	-11.75	6.01E-05
(M C6) - (M BL)	-19.48	7.00E-16
(M C7) - (M BL)	-11.81	7.88E-05
(M C9) - (M BL)	-10.16	3.10E-03
(M C11) - (M BL)	-15.34	2.69E-09
(M C12) - (M BL)	-10.46	1.48E-03
(M C13) - (M BL)	-11.24	1.24E-04
(M C14) - (M BL)	-19.06	1.80E-15
(M C15) - (M BL)	-16.64	1.19E-11
(M C16) - (M BL)	-16.31	4.59E-11
(M C18) - (M BL)	-9.07	1.69E-02

Table 3.12 Bonferroni Simultaneous Tests for Differences of Means between Group×Condition for female subjects

Difference of GROUP×CONDITION Levels	Difference of Means [ms]	Adjusted P-Value
(F C11) - (F BL)	-12.25	0.000
(F C14) - (F BL)	-7.47	0.092
(F C16) - (F BL)	-7.82	0.047
(F C18) - (F BL)	-9.92	0.000

Observing the tables, it could be said that for male subjects, 14 different WBV conditions have a statistically significant difference in terms of RT with the Baseline conditions. Whereas for female subjects, only 4 WBV conditions have statistically significant difference when compared with Baseline conditions. This could be because male subjects have a higher standard deviation in their response times when compared with female subjects as seen in Figure 3.37 and Figure 3.38. Therefore, from the results of this section, it could be said that there is a statistically significant difference in terms of response time between Baseline and WBV conditions.

3.4 Descriptive statistics on experiment survey data

3.4.1 Discomfort rating

Figure 3.39 contains for the six different excitation frequencies, the mean value of the rate of discomfort and their corresponding standard deviation from the mean value for male subjects.

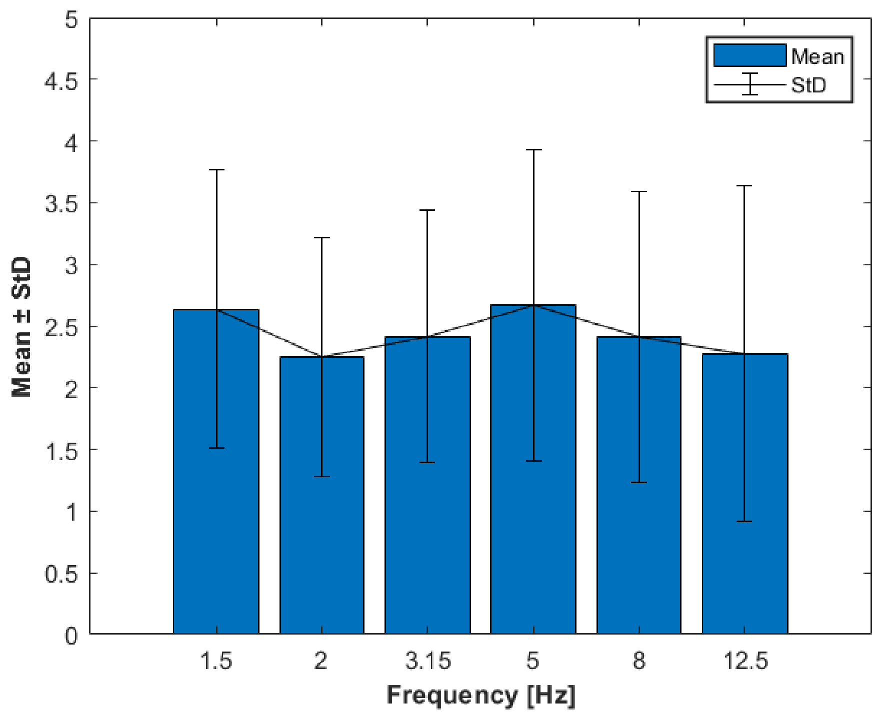


Figure 3.39 Mean discomfort rating of male subjects for the six excitation frequencies

The highest mean value of discomfort rating was at 5 Hz (2.667), which indicates that the male subjects faced the worst discomfort at this frequency. The discomfort was least at 2 Hz excitation. By observing the bar plot, it is reasonable to say that male subjects felt more discomfortable when the platform is excited at 1.5 Hz, 5 Hz and 8 Hz. The resonance frequency of the human body is at around 5 Hz [24]. Therefore, we could conclude that when the subjects are exposed to WBV at frequencies close the resonance frequency of the human body (e.g., 5 Hz, 8 Hz), the rate of discomfort caused due to WBV increases.

Figure 3.40 shows for the three different excitation axes (X, Y, Z), the mean value of the rate of discomfort and their corresponding standard deviation from the mean value for male subjects.

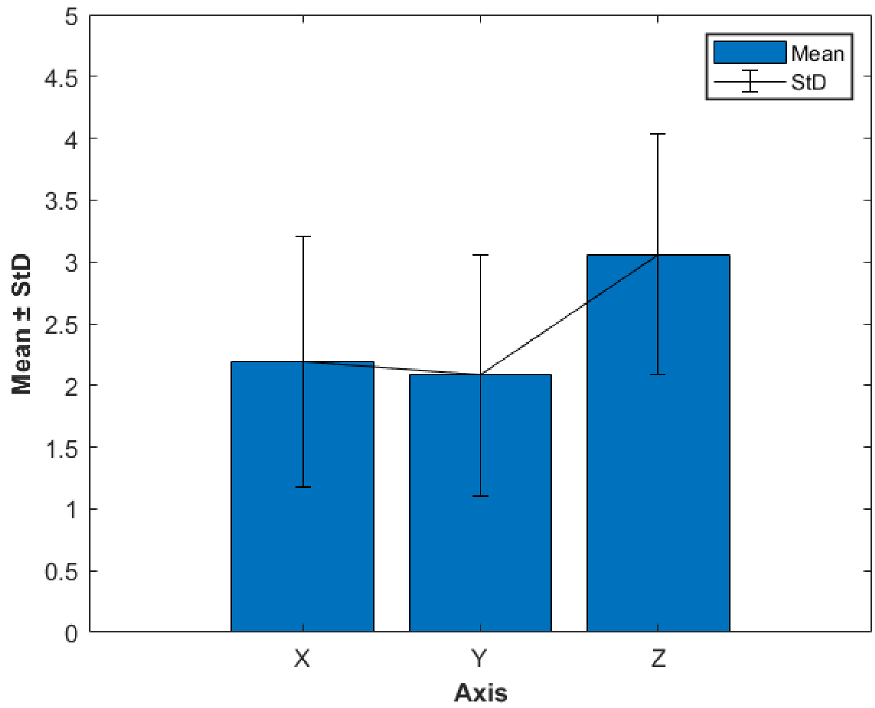


Figure 3.40 Mean discomfort rating of male subjects for the three axes

Looking at the mean discomfort ratings among the three axes for male subjects, it is evident that the subjects felt the most discomfort when vibration is along Z axis since the vibration along Z axis has the highest mean discomfort rating value (3.056). As it could be seen from the above plot, the male subjects felt similar range of discomfort when the vibration is along X and Y axes. The subjects felt least discomfortable when the vibration was along Y axis (mean value of 2.083). When the vibration is along the Z axis, it is transmitted vertically into the human body, who is in a neutral standing position. This could explain the reason the subjects felt significantly higher amount of discomfort when the vibration was along the Z axis.

Figure 3.41 contains for the six different excitation frequencies, the mean value of the rate of discomfort and their corresponding standard deviation from the mean value for female subjects.

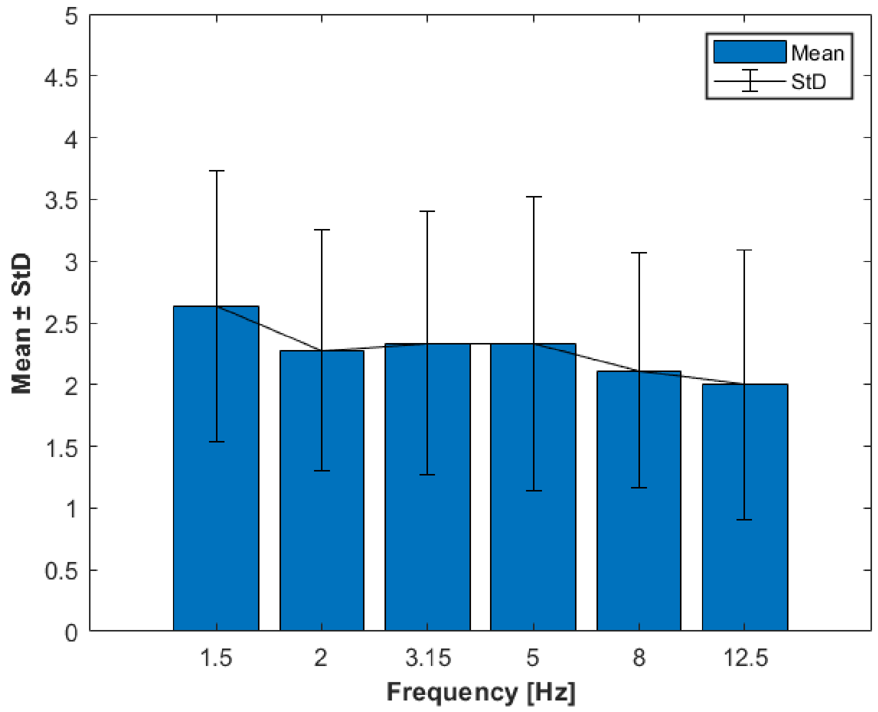


Figure 3.41 Mean discomfort rating of female subjects for the six excitation frequencies

The highest mean value of discomfort rating was at 1.5 Hz (mean value of 2.6), which indicates that the female subjects faced the worst discomfort at this frequency. The discomfort was least at 12.5 Hz excitation. By observing the bar plot, it is reasonable to say that the female subjects felt more discomfortable when the platform is excited at 1.5 Hz, 3.15 Hz and 5 Hz. The discomforts at 3.15 and 5 Hz are due to the excitation close to the resonance frequency of the human body. The highest discomfort at 1.5 Hz could be because at a lower frequency (around 1.5 to 3 Hz), there is a high displacement of the excitation platform (around ±10 mm of displacement along the vibration axis). As a consequence of these high displacements caused at low vibrating frequencies, the subjects felt more discomfortable at excitation frequencies from 1.5 Hz to 3 Hz. By looking at the bar plot, this seems reasonable because, at the highest excitation frequency of 12.5 Hz, the subjects felt more comfortable which could be because of a small displacement (less than ±2 mm) along the vibrating axis at this high frequency of 12.5 Hz.

Figure 3.42 contains for the three different excitation axes (X, Y, Z), the mean value of the rate of discomfort and their corresponding standard deviation from the mean value for female subjects.

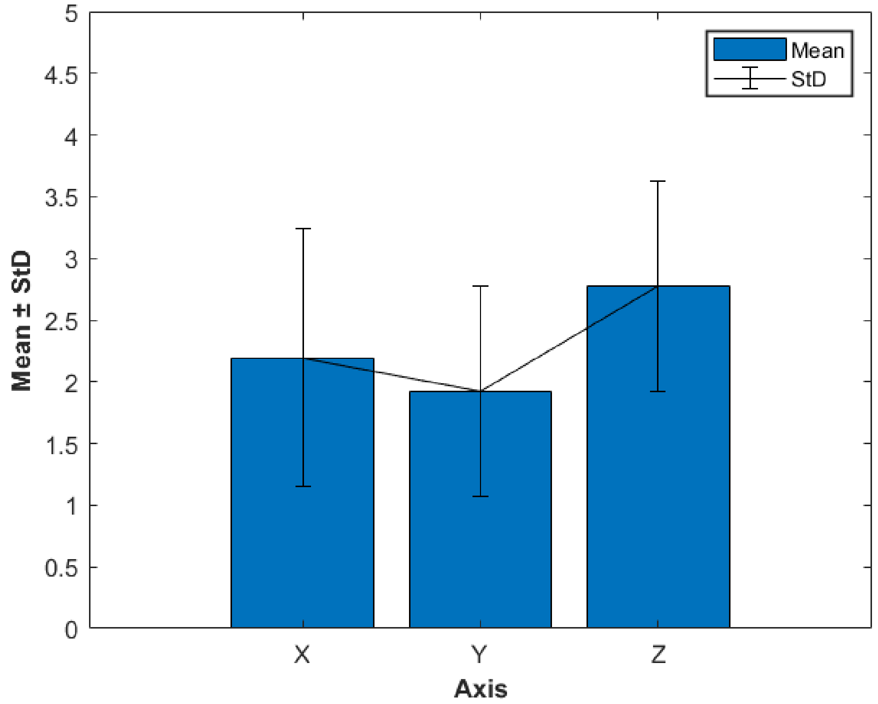


Figure 3.42 Mean discomfort rating of female subjects for the three axes

Looking at the above plots, it could be concluded that like the results of male subjects, the female subjects also felt the highest level of discomfort when the vibration is along the Z axis (with a mean value of 2.778). The female subjects felt a similar range of discomfort when the vibration is along X and Y axes. Like the male subjects, the female subjects also felt least discomfortable when the vibration was along Y axis (mean value of 1.917). Comparing the plots of male subjects and female subjects (Figure 3.40and Figure 3.41) for their mean value of discomfort ratings when vibrating along the three axes, it could be concluded that female subjects felt less discomfortable when compared with the male subjects even when the vibration is along Z axis.

3.4.2 Confidence in accuracy

Figure 3.43 contains for the six different excitation frequencies, the mean value of the confidence of accuracy in the responses and their corresponding standard deviation from the mean value for male subjects.

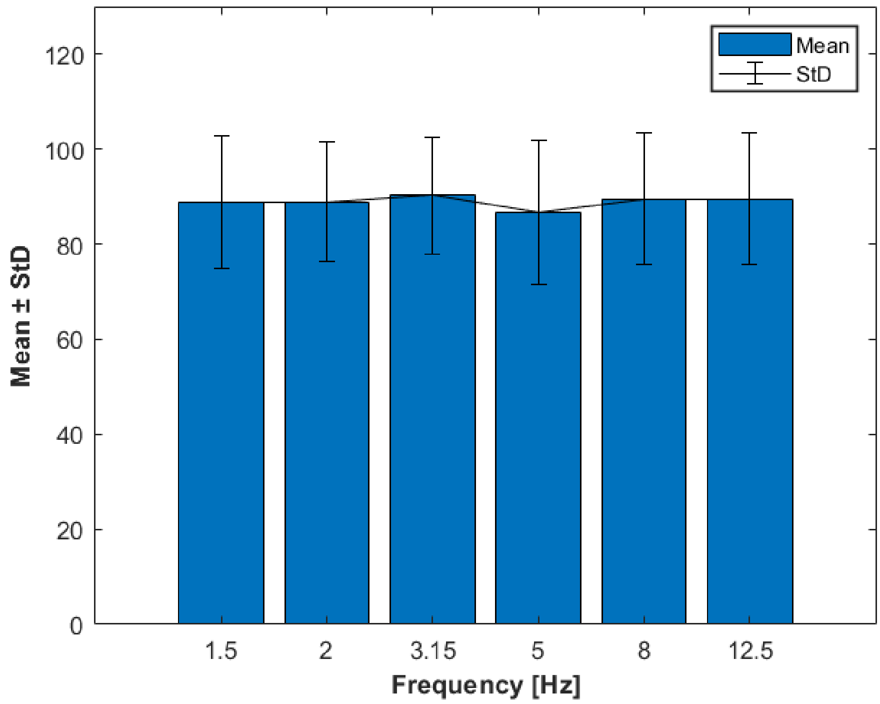


Figure 3.43 Mean confidence in accuracy of responses of male subjects for the six excitation frequencies

Figure 3.44 contains for the three different excitation axes (X, Y, Z), the mean value of the confidence of accuracy in the responses and their corresponding standard deviation from the mean value for male subjects.

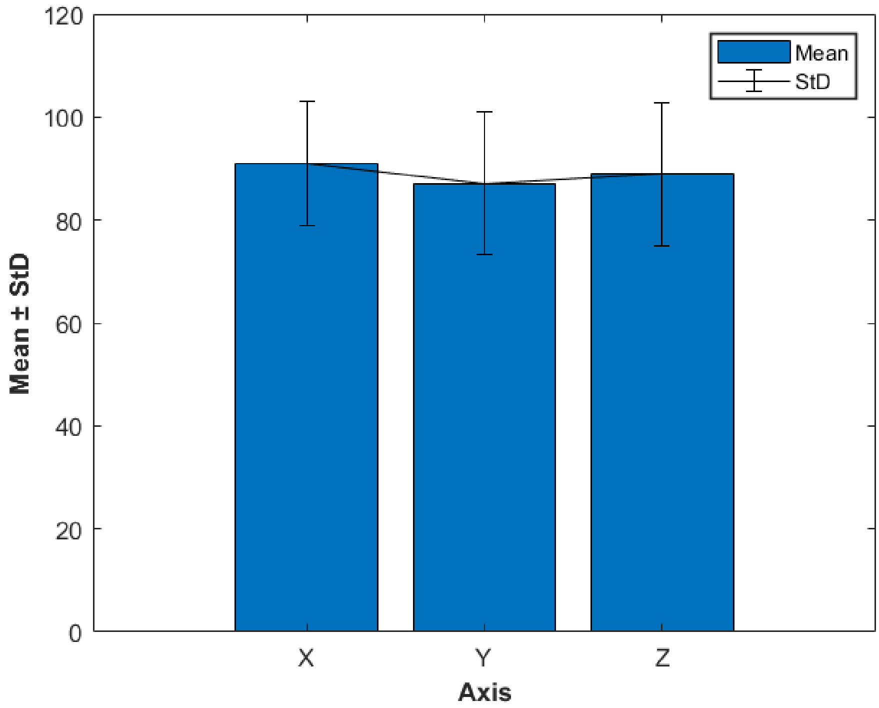


Figure 3.44 Mean confidence in accuracy of responses of male subjects for the three axes

Figure 3.45 contains for the six different excitation frequencies, the mean value of the confidence of accuracy in the responses and their corresponding standard deviation from the mean value for female subjects.

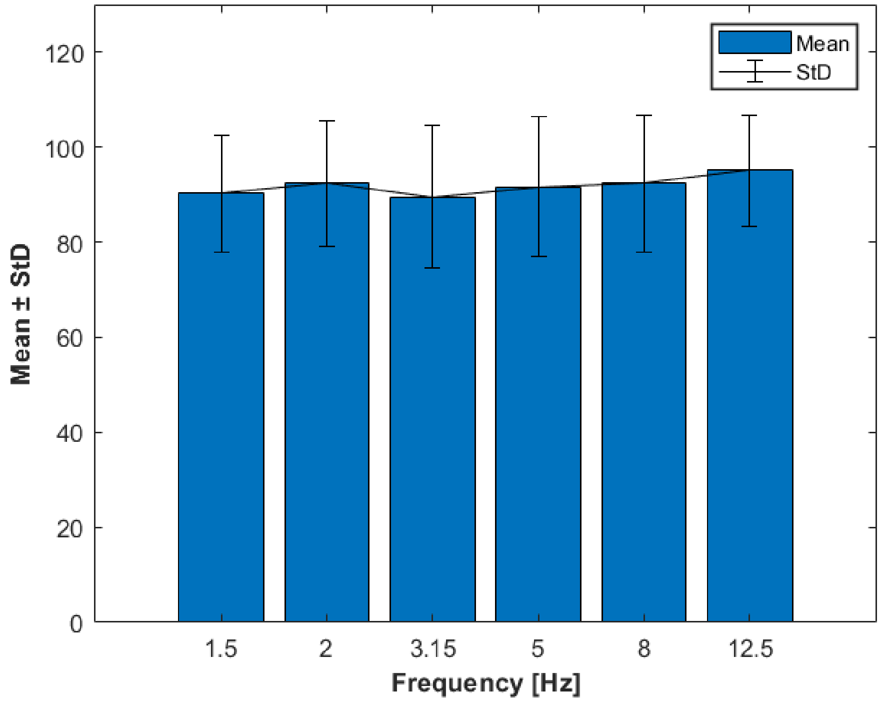


Figure 3.45 Mean confidence in accuracy of responses of female subjects for the six excitation frequencies

Figure 3.46 contains for the three different excitation axes (X, Y, Z), the mean value of the confidence of accuracy in the responses and their corresponding standard deviation from the mean value for female subjects.

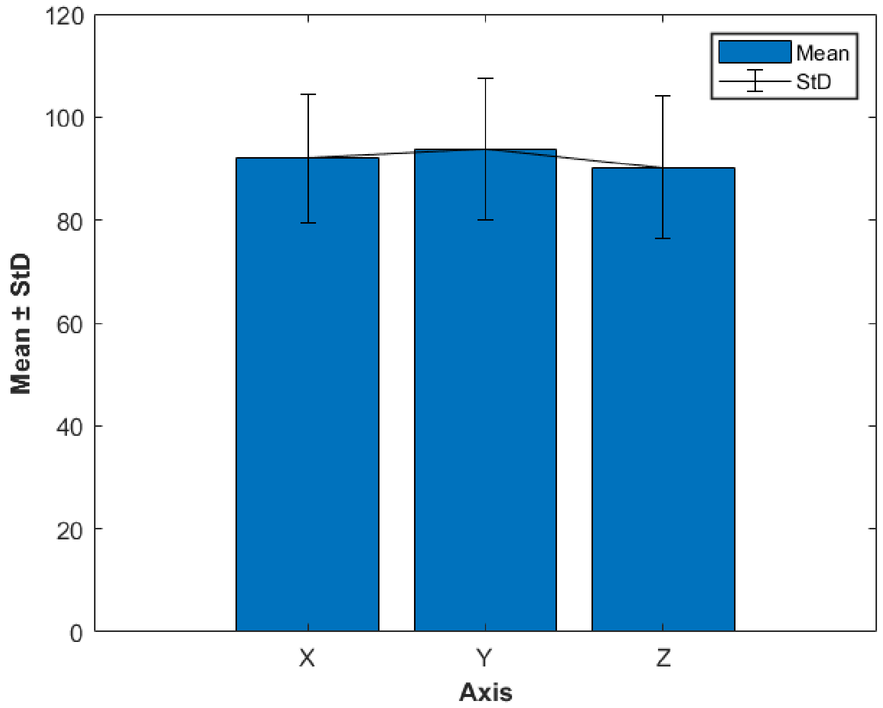


Figure 3.46 Mean confidence in accuracy of responses of female subjects for the three axes

Analysing the above plots (Figure 3.43 to Figure 3.46), it could be seen that there is no significant variability of accuracy in the responses for both male and female subjects. Analysing the plots in Figure 3.43 and Figure 3.45, we can observe a slight decrease in the accuracy of the responses at excitation frequencies of 3.15 Hz and 5 Hz. Therefore, it could be said that when the subjects felt discomfort with the WBV, their corresponding accuracy of responses are affected slightly.

4. Conclusions and future developments

4.1 Conclusions

In this thesis, the performance of the 3D shaker has been analysed, a Whole-Body Vibrations experiment on human subjects was designed and conducted to acquire the cognitive response of the human subjects and then the corresponding experiment data were analysed to test the effect of WBV on the response time.

From the preliminary performance analysis of the 3D shaker, it could be concluded that there was more noise than the input signal when a sinusoidal harmonic vibration is given to the 3D shaker, since the Total Harmonic Distortion was between -5 dB and -1 dB. As a result of this, the 3D shaker was fixed to the ground using mechanical supports. From the analysis of the 3D shaker, which was fixed to the ground, it could be concluded that the 3D shaker could be operated at an amplitude of around 1 m/s^2 for the experiments, since at this amplitude, the shaker exhibited a THD of around -20 dB and Crosstalk less than 0.4, which indicates that the shaker is rigid enough when a sinusoidal vibration is applied on the vibrating platform. Upon analysing the distortion in the 3D shaker with a human subject standing on it and undergoing an experiment, it could be concluded that when the excitation frequencies are higher than 5 Hz (e.g.: 8 Hz, 12.5 Hz), the distortion of the 3D shaker was around -15 dB.

A PVT experiment to study the response times of human subjects exposed to WBV was designed and the experiment protocol was validated. The experiment was conducted on 25 human subjects (12 male and 13 female) for 24 different WBV conditions and their corresponding response time data were collected and analysed.

A two-samples t-test on the anthropometric data of the subjects indicated a lower p-value ($p < 0.01$). Therefore, it could be concluded that there is a statistically significant difference between male and female subjects. Hence, male and female subjects were analysed separately in terms of their response times.

For both male and female subjects, there was a reduction in Baseline response time (4.9% and 2.95%, respectively) after the WBV exposure. It could be concluded that, in the post-WBV condition, the subjects did not feel any fatigue and got used to responding to the stimuli over the course of the experiment time and so there was a slightly faster response in the post-WBV condition.

Male subjects took 151 (45) ms to respond to the stimuli during Baseline condition and 172 (61) ms during WBV conditions. Whereas female subjects responded in 187 (41) ms during Baseline condition and 205 (44) ms during WBV conditions. It could be concluded that both male and female subjects, on an average took comparatively longer time to respond when they were exposed to WBV. It could be concluded from the Bonferroni pairwise comparison test results that for male subjects, there was a statistically significant difference between the Baseline condition and vibration conditions for all the 18 WBV conditions except C2 (X axis - 2 Hz), C5 (X axis - 8 Hz), C8 (Y axis - 2 Hz) and C10 (Y axis - 5 Hz). Whereas for female subjects, there was a statistically significant difference between the Baseline condition and C11 (Y axis - 8 Hz), C14 (Z axis - 2 Hz), C16 (Z axis - 5 Hz) and C18 (Z axis – 12.5 Hz) WBV conditions. In general, male subjects were faster to respond to the stimuli.

From the statistical data analysis of the discomfort rating survey collected from the WBV – PVT experiment, it could be concluded that the male subjects felt most discomfortable at the excitation frequency of 5 Hz (mean discomfort rating of 2.7) and the female subjects felt most discomfortable at the excitation frequency of 1.5 Hz (mean discomfort rating of 2.6). Analysing the discomfort survey data among the three axes of vibration, both male and female subjects unanimously felt most discomfortable when the vibration was at Z axis as male subjects rated the discomfort as 3.0 (1.2) and female subjects rated the discomfort as 2.8 (1.2). This could be because the main resonance of the human body is along Z axis.

4.2 Future developments

Currently, when the shaker is operated at around its resonance frequency, there is a higher distortion (around -15 dB) of the signal. It is possible to improve the performance of the 3D shaker in terms of its Total Harmonic Distortion. The shaker could be fixed to the ground in a more rigid manner by fixing also the columns of the shaker to the ground. It is possible to design and use a light weight vibrating platform, which can make the displacement of the platform smoother. This can also shift the resonance of the shaker.

In this thesis, the experiments were performed by limiting the amplitudes to around 1 m/s^2. In future, it could be experimented with various vibration amplitudes over the three axes. Currently, the gain value of the harmonic signal for each vibration condition was set with an empirical method. It is possible to have a better control of the 3D shaker by fixing an optimal gain value for over a range of frequencies along the three axes.

Upon using the PVT Device for longer times (more than 60 minutes), the device overheats, and as a consequence, sometimes produces wrong stimuli. Then this data has to be removed during the filtering phase. Therefore, if it is possible to make the PVT device more robust by adding a cooling fan to remove the heat generated.

As an effect of WBV, the response time measured using PVT has been studied in this thesis. In the future, the effects of WBV on the cognitive ability of human body could be studied by conducting various other identification experiments such as Stroop test or Colored Numbers Test.

References

[1] L. E. Charles, C. C. Ma, C. M. Burchfiel, and R. G. Dong, “Vibration and Ergonomic Exposures Associated With Musculoskeletal Disorders of the Shoulder and Neck,” *Saf. Health Work*, vol. 9, no. 2, pp. 125–132, 2018, doi: https://doi.org/10.1016/j.shaw.2017.10.003.

[2] M. Bovenzi and C. T. J. Hulshof, “An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain (1986–1997),” *Int. Arch. Occup. Environ. Health*, vol. 72, no. 6, pp. 351–365, 1999, doi: 10.1007/s004200050387.

[3] M. Bovenzi, “Low back pain disorders and exposure to whole-body vibration in the workplace,” *Semin. Perinatol.*, vol. 20, no. 1, pp. 38–53, 1996, doi: https://doi.org/10.1016/S0146-0005(96)80056-5.

[4] M. Bovenzi, “Health effects of mechanical vibration,” *G Ital Med Lav Erg.*, vol. 27, no. 1, pp. 58–64, 2005.

[5] M. Bovenzi, “Health risks from occupational exposures to mechanical vibration,” *Med. Lav.*, vol. 97, no. 3, pp. 535–541, 2006, [Online]. Available: http://europepmc.org/abstract/MED/17009691.

[6] P. Marzaroli, A. Albanetti, E. Negri, H. Giberti, and M. Tarabini, “Design and Testing of a 3-DOF Robot for Studying the Human Response to Vibration,” *Machines* , vol. 7, no. 4. 2019, doi: 10.3390/machines7040067.

[7] J. Kiiski, A. Heinonen, T. L. Järvinen, P. Kannus, and H. Sievänen, “Transmission of Vertical Whole Body Vibration to the Human Body,” *J. Bone Miner. Res.*, vol. 23, no. 8, pp. 1318–1325, Aug. 2008, doi: https://doi.org/10.1359/jbmr.080315.

[8] D. Chadefaux, A. P. Moorhead, P. Marzaroli, S. Marelli, E. Marchetti, and M. Tarabini, “Vibration transmissibility and apparent mass changes from vertical whole-body vibration exposure during stationary and propelled walking,” *Appl. Ergon.*, vol. 90, p. 103283, 2021, doi: https://doi.org/10.1016/j.apergo.2020.103283.

[9] E. Young, N. Kreiger, J. Purdham, and A. Sass-Kortsak, “Prostate cancer and driving occupations: could whole body vibration play a role?,” *Int. Arch. Occup. Environ. Health*, vol. 82, no. 5, pp. 551–556, 2009, doi: 10.1007/s00420-009-0403-z.

[10] B. Basri and M. J. Griffin, “Predicting discomfort from whole-body vertical vibration when sitting with an inclined backrest,” *Appl. Ergon.*, vol. 44, no. 3, pp. 423–434, 2013, doi: https://doi.org/10.1016/j.apergo.2012.10.006.

[11] T. E. Fairley and M. J. Griffin, “The apparent mass of the seated human body: vertical vibration,” *J. Biomech.*, vol. 22, no. 2, pp. 81–94, 1989.

[12] G. F. Beard and M. J. Griffin, “Discomfort of seated persons exposed to low frequency lateral and roll oscillation: Effect of backrest height,” *Appl. Ergon.*, vol. 54, pp. 51–61, 2016, doi: https://doi.org/10.1016/j.apergo.2015.11.010.

[13] H. V. C. Howarth and M. J. Griffin, “Subjective reaction to vertical mechanical shocks of various waveforms,” *J. Sound Vib.*, vol. 147, no. 3, pp. 395–408, 1991, doi: https://doi.org/10.1016/0022-460X(91)90488-6.

[14] S. Waugh, M. L. Kashon, S. Li, G. R. Miller, C. Johnson, and K. Krajnak, “Transcriptional Pathways Altered in Response to Vibration in a Model of Hand-Arm Vibration Syndrome,” *J. Occup. Environ. Med.*, vol. 58, no. 4, 2016, [Online]. Available: https://journals.lww.com/joem/Fulltext/2016/04000/Transcriptional_Pathways_Altered_in_Response_to.5.aspx.

[15] F. Rui, F. D’Agostin, C. Negro, and M. Bovenzi, “A prospective cohort study of manipulative dexterity in vibration-exposed workers,” *Int. Arch. Occup. Environ. Health*, vol. 81, no. 5, pp. 545–551, 2008, doi: 10.1007/s00420-007-0256-2.

[16] T. Nilsson, J. Wahlström, and L. Burström, “Hand-arm vibration and the risk of vascular and neurological diseases—a systematic review and meta-analysis,” *PLoS One*, vol. 12, no. 7, p. e0180795, 2017.

[17] A. Wong and A. Figueroa, “Effects of whole-body vibration on heart rate variability: acute responses and training adaptations,” *Clin. Physiol. Funct. Imaging*, vol. 39, no. 2, pp. 115–121, Mar. 2019, doi: https://doi.org/10.1111/cpf.12524.

[18] M. Cardinale and J. Wakeling, “Whole body vibration exercise: are vibrations good for you?,” *Br. J. Sports Med.*, vol. 39, no. 9, pp. 585 LP – 589, Sep. 2005, doi: 10.1136/bjsm.2005.016857.

[19] C. Bosco *et al.*, “Hormonal responses to whole-body vibration in men,” *Eur. J. Appl. Physiol.*, vol. 81, no. 6, pp. 449–454, 2000, doi: 10.1007/s004210050067.

[20] M. S. Khan and J. Sundstrom, “Effects of Vibration on Sedentary Activities in Passenger Trains,” *J. Low Freq. Noise, Vib. Act. Control*, vol. 26, no. 1, pp. 43–55, Mar. 2007, doi: 10.1260/026309207781487448.

[21] M. G. R. Toward and M. J. Griffin, “The transmission of vertical vibration through seats: Influence of the characteristics of the human body,” *J. Sound Vib.*, vol. 330, no. 26, pp. 6526–6543, 2011, doi: https://doi.org/10.1016/j.jsv.2011.07.033.

[22] Y. Matsumoto and M. J. Griffin, “Non-Linear Characteristics in the Dynamic Responses of Seated Subjects Exposed to Vertical Whole-Body Vibration ,” *J. Biomech. Eng.*, vol. 124, no. 5, pp. 527–532, Sep. 2002, doi: 10.1115/1.1499959.

[23] Y. Matsumoto and M. J. Griffin, “MOVEMENT OF THE UPPER-BODY OF

SEATED SUBJECTS EXPOSED TO VERTICAL WHOLE-BODY VIBRATION AT THE PRINCIPAL RESONANCE FREQUENCY," *J. Sound Vib.*, vol. 215, no. 4, pp. 743–762, 1998, doi: https://doi.org/10.1006/jsvi.1998.1595.

[24] Y. Matsumoto and M. J. Griffin, "Dynamic response of the standing human body exposed to vertical vibration: influence of posture and vibration magnitude," *J. Sound Vib.*, vol. 212, no. 1, pp. 85–107, 1998.

[25] M. Tarabini, S. Solbiati, G. Moschioni, B. Saggin, and D. Scaccabarozzi, "Analysis of non-linear response of the human body to vertical whole-body vibration," *Ergonomics*, vol. 57, no. 11, pp. 1711–1723, Nov. 2014, doi: 10.1080/00140139.2014.945494.

[26] J. Herterich and H. Schnauber, "The Effects of Vertical Mechanical Vibration on Standing Man," *J. Low Freq. Noise, Vib. Act. Control*, vol. 11, no. 2, pp. 52–61, Jun. 1992, doi: 10.1177/026309239201100204.

[27] O. Thuong and M. J. Griffin, "The vibration discomfort of standing people: Relative importance of fore-and-aft, lateral, and vertical vibration," *Appl. Ergon.*, vol. 43, no. 5, pp. 902–908, 2012, doi: https://doi.org/10.1016/j.apergo.2011.12.011.

[28] N. Nawayseh and M. J. Griffin, "Non-linear dual-axis biodynamic response to vertical whole-body vibration," *J. Sound Vib.*, vol. 268, no. 3, pp. 503–523, 2003, doi: https://doi.org/10.1016/S0022-460X(03)00254-2.

[29] Y. Matsumoto and M. J. Griffin, "Mathematical models for the apparent masses of standing subjects exposed to vertical whole-body vibration," *J. Sound Vib.*, vol. 260, no. 3, pp. 431–451, 2003, doi: https://doi.org/10.1016/S0022-460X(02)00941-0.

[30] G. H. M. J. Subashi, Y. Matsumoto, and M. J. Griffin, "Apparent mass and cross-axis apparent mass of standing subjects during exposure to vertical whole-body vibration," *J. Sound Vib.*, vol. 293, no. 1, pp. 78–95, 2006, doi: https://doi.org/10.1016/j.jsv.2005.09.007.

[31] W. D. R. Baker and N. J. Mansfield, "Effects of horizontal whole-body vibration and standing posture on activity interference," *Ergonomics*, vol. 53, no. 3, pp. 365–374, Mar. 2010, doi: 10.1080/00140130903402242.

[32] J. Muir, D. P. Kiel, and C. T. Rubin, "Safety and severity of accelerations delivered from whole body vibration exercise devices to standing adults," *J. Sci. Med. Sport*, vol. 16, no. 6, pp. 526–531, 2013, doi: https://doi.org/10.1016/j.jsams.2013.01.004.

[33] N. Shibata, "Subjective response of standing persons exposed to fore-aft, lateral and vertical whole-body vibration," *Int. J. Ind. Ergon.*, vol. 49, pp. 116–123, 2015, doi: https://doi.org/10.1016/j.ergon.2015.01.012.

[34] D. D. Stamenković, V. M. Popović, and M. A. Tirović, "Operator's reaction

time prolongation induced by whole-body vibration," *FME Trans.*, vol. 42, no. 4, pp. 297–304, 2014.

[35] Z. Zamanian, A. Nikravesh, M. R. Monazzam, J. Hassanzadeh, and M. Fararouei, "Short-term exposure with vibration and its effect on attention," *J. Environ. Heal. Sci. Eng.*, vol. 12, no. 1, p. 135, 2014, doi: 10.1186/s40201-014-0135-1.

[36] M. Basner, D. Mollicone, and D. F. Dinges, "Validity and sensitivity of a brief psychomotor vigilance test (PVT-B) to total and partial sleep deprivation," *Acta Astronaut.*, vol. 69, no. 11, pp. 949–959, 2011, doi: https://doi.org/10.1016/j.actaastro.2011.07.015.

[37] L. In-Soo, B. W. A., A.-I. Sonia, and D. J. E., "Number of Lapses during the Psychomotor Vigilance Task as an Objective Measure of Fatigue," *J. Clin. Sleep Med.*, vol. 06, no. 02, pp. 163–168, Apr. 2010, doi: 10.5664/jcsm.27766.

[38] K. ISHIMATSU, N. SHIBATA, and S. MAEDA, "Effects of whole-body vibration on visual information processing(Summary of Awarded Presentation at the 27th Annual Meeting)," 基礎心理学研究, vol. 28, no. 1, pp. 179–180, 2009, doi: 10.14947/psychono.KJ00005878696.

[39] M. Gobbi *et al.*, "Low-Intensity Whole-Body Vibration: A Useful Adjuvant in Managing Obesity? A Pilot Study," *Appl. Sci.*, vol. 11, no. 11, p. 5101, May 2021, doi: 10.3390/app11115101.

Appendix

i) 3D shaker – Working manual

WORKING MANUAL FOR THE 3-DOF ELECTRO-MECHANICAL EXCITATION SYSTEM

Introduction

This working manual describes the procedure to operate the electro-mechanical excitation system (3D Shaker) for characterization of the response of the human body to multiaxial vibrations.

Initial setup

1. Turn on the main power supply by rotating the switch. This supplies power to the panel (box) in which the wires of the 3D-shaker are connected.

2. Turn on the power supply in the panel by rotating the switch in the box.
3. Turn on the RT3 controller.
4. Turn on the PC which relates to the RT3 controller.
5. Release the emergency stop push button present in the panel(box) by rotating the button in counter clockwise direction.
6. Release the emergency stop push button present in the RT3 controller.
7. Launch the "Ctrl 3Gdl" application in the PC. This application is used to control the parameters of the vibration in the shaker.

Operations in the application

Initial phase [The setup]:

8. Once the application is open, import the previously saved "Test ezio 20191104.cfg" configuration file into the control program.
9. Check for any warnings or alarms in the "Allarmi" section. Any warning or error is displayed by a red colour circle. Fix them (if any) and click on Reset button. Make sure that all the circles are green in colour before proceeding.

1: Control program home window

10. Before starting the machine, a thorough visual inspection of the shaker should be made. The shaker should not have any obstacles or other unwanted foreign objects in its working space. The platform should be free and there should not be

any person standing on the platform or near the shaker. Also check for the cables are connected properly.

11. Once the visual inspection is done, click on the “Abilita marcia” button (the button turns green from yellow) in the application to start the motors of the shaker.
12. Set the origin (initial position) for the shaker by entering the coordinate positions of the three axes (x, y, z) in the “SetPoint posizione” section. It is possible to move the platform up to a maximum of 18mm each axis. Beyond the maximum limit it does not function.
13. The “Retro posizione” section shows the measured real time values of the position of the platform.
14. It is possible to control the shaker in its acceleration or its displacement. Select the required mode of control from the “Modalità Controllo” section.
15. Enter the required Gain value in the “Gain Master” section. (Preferably 25% to for a better control).

Second Phase [Input Values]:

16. To enter the parameters of vibration, navigate to Generatore → Generatore. A new window opens.

2: Configuration window

- For each axis, the required type of wave can be selected from the “Onda” option.
- The values of the amplitude and Frequency can be entered manually in their respective fields. A maximum of 30 Hz frequency can be used in the shaker.
- The platform can be vibrated in all the three axes individually and in a combination of any two or three axes.
- To begin the oscillation with the entered parameters, click on “AVVIO” button.
- To oscillate only in any one of the axes, select the required axis and choose ‘Singolare’ in the “Tipo generatore” section, then enter the other parameters and click on “AVVIO”. The platform will oscillate only in the selected axis.
- To oscillate the platform in two or three axes, one axis must be set as Master and the other axes should be set as Slave in the “Tipo generatore” section.

Third phase [Visualisation]

- To visualize the signal, navigate to Visualizzazione → Oscilloscopio. A new window opens where we can view the time signal and its corresponding spectrum.
- The signal can be viewed in any range. The range can be entered manually.
- Two different signals can be viewed in the Oscilloscope graph in two different channels. The user can choose to view the signal in any of the channels.
- The user can acquire the signal for any sampling frequency and observation time and save the acquisition data as a *.dat file in the PC.

ii) WBV – PVT test Data Collection Protocol

<u>STEPS:</u>

1. **When recruiting participants, ask them to wear comfortable shoes**

2. **Ask the participant to read over and sign the consent form (x2)**
   a. Explain the general data collection process to them
   b. Confirm the eligibility of the participants. Participants are eligible if:

- Male/Female
- Aged 18 - 40

   c. Participants are NOT eligible if:
      i. Diagnosed by a physician to have diabetes.
      ii. Diagnosed by a physician to have vibration-induced pathologies.
      iii. Diagnosed by a physician to have a concussion.
      iv. Suffer from motion sickness.
      v. Have had a lower body musculoskeletal injury in the previous 6-months.
      vi. Do not have normal or corrected-to-normal vision.
      vii. Have color vision defects.

3. **Assign a unique participant ID # (identification number) to the participant. Write the number on the consent form. File the consent form in a secure location. In all future files and documents refer to the participant only by his/her unique ID#**

4. **Collect participant's personal information and write his/her ID number on each page of the participant package**

5. **Ask the participant to stand on the vibrating platform in a neutral position, holding the button of the PVT device in one of his/her hand comfortably**

6. **Collect WBV data**

1.. Each subject will be asked to do 1 session per day for three days.
2.. One session is composed of eight conditions with fixed vibration amplitude (1 m/s^2), random axis of vibration (X, Y or Z) and random frequency (1.5 – 2 – 3.15 – 5 – 8 – 12.5 Hz)
3.. For each condition, 112 response times and their imposed acceleration signal will be acquired.

4.. At the end of each condition the participant will report a rating of discomfort from WBV (from 1, not uncomfortable to 5, very uncomfortable) and a confidence in the accuracy of their responses (from 0, completely unconfident to 100, completely confident).

7. **Confirm all data files have been saved**
   a. **Save data using the following file naming convention:**
      i. MATLAB® session (.mat):
         1. S 'subject #' S 'session #' _ 'code' (e.g., S1S1_010403020907.mat). Code is a 12-character string, where each couple of characters is the index of the condition, between 01 to 18.

      ii. Measlab test (.mlp):
         1. S 'subject #' 'axis' F 'frequency #' (e.g., S1ZF015)
      iii. The survey is saved in a form created in Microsoft Forms saving each response with the name equal to the MATLAB® file.

Assign the participant an ID number

Date:	Time:
Participant Number:	

Collect the participant's personal data

Height (cm):
Mass (kg):
Date of Birth (dd/mm/yyyy):

Required Devices

Device #	Device name	Device Position Description
1	Tri-axial accelerometer	Placed on the vibrating platform
2	Psychomotor Vigilance Task device	Placed at a position where the participant can easily see while standing on the vibrating platform. The button of the PVT device is given to the participant

Photograph

Take a picture of the participant in standing upright position, holding the button of the PVT device

Position Required	Example Description
Participant's neutral standing position	Ask the participant to stand in their natural position with the head looking forward and one of their hands holding the PVT device button comfortably
• **Note**: The position should be comfortable, and the participant should be balanced. This will be the same position they will be asked to hold for repeated exposures of vibration when standing on the platform.	

<u>Experimental Protocol for Vibration Measurements</u>

1. **Before starting the vibration protocol confirm the following:**
    - Consent form has been signed
    - Personal data has been recorded
    - Accelerometer is fixed on the vibrating platform and a button of the PVT device is given to the participant (pictures were taken)
    - Participant is comfortable with the standing position (Position picture has been taken)
    - Shaker and the PVT device are setup and ready for the experiment

2. **Participant readiness**

- Explain the general protocol to the participant
- Let the participant feel the vibration once before starting the official data collection
- Ask the participant if he/she has any questions before starting

3. Vibration Transmissibility Measurement

The experiment is done in 3 days. The step-by-step procedure to perform the experiment and acquire the data is given below:

randaxis = random number from 1 to 3 (1 =X, 2 = Y, 3 = Z).

vectorfreq = [1.5 – 2 – 3.15 – 5 – 8 – 12.5].

randvec = seven element vector with random numbers from 1 to 6 (i.e. [1 4 3 5 2 6]).

<u>SESSION 1</u>

Run the PVT program in MATLAB® to acquire 8 conditions. Call the test as S1S1 (session 1, subject 1).

<u>Condition 1: (3.5 minutes)</u>

- Set a Baseline frequency of 0 Hz
- Allow the participant to step on the platform
- Start PVT.

<u>Break 1: (1 minute)</u>

- Stop the excitation system
- Allow the participant to step off the platform and relax

For loop (X = randvec) {

<u>Condition X: (3.5 minutes)</u>

- Allow the participant to step on the platform
- Modify the excitation frequency to vectorfreq (X) Hz and start the excitation system along **randaxis**

- Start PVT

Break: (1 minute)

- Stop the excitation system
- Allow the participant to step off the platform and relax
- Ask the survey

}

End loop

Condition 8: (3.5 minutes)

- Allow the participant to step on the platform
- Set a Baseline frequency of 0 Hz.
- Start PVT

Session end:

- Allow the participant to step off the platform
- Ask the survey

Repeat the same procedure for Session 2 and Session 3.

4. Data check

Verify all the files are saved with the correct participant ID # and their corresponding file names

5. Comfort questionnaire

Ask the participant if the vibration exposure was comfortable to him/her and record their feedback

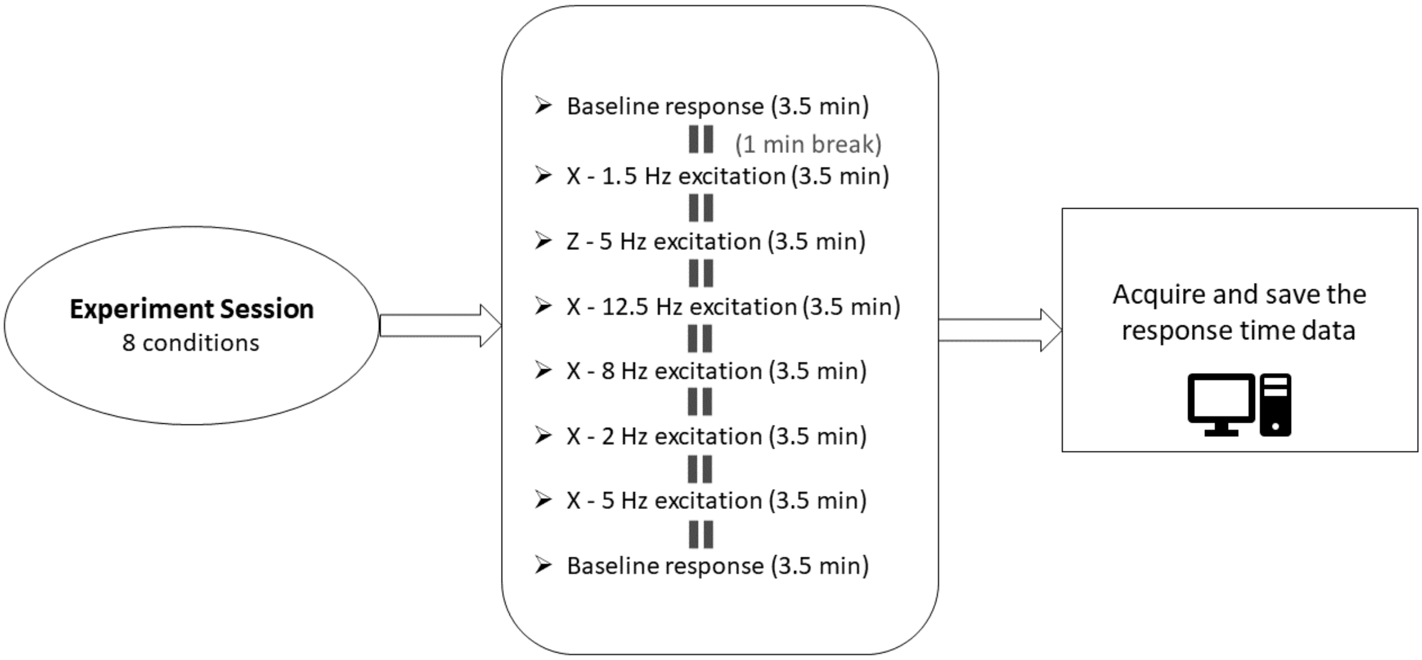
6. Thank the participant

- Ask the participant if they have any questions
- Thank the participant for their time
- The participant can leave the laboratory

7. **Sanitization of the setup**

Experiment workflow:

An example experiments workflow of a participant undergoing the PVT-WBV test in a session:



The experiment is performed for 8 different conditions in 1 session with a random frequency and axis in each condition.

iii) WBV – PVT test Consent form

ID _______

CONSENT FORM

Effect of whole-body vibration on response time of a standing person

I, __________________________, am interested in participating in the study on the effect of whole-body vibration on response time when standing in an upright position with Stefano Marelli, Cristina Ferrario, Andrea Mazzoleni, Teenu Arjun Ravi, Yuvan Sathya Ravi under the supervision of Professor Marco Tarabini, Mechanical Engineering Department at Politecnico di Milano. The purpose of this study is to determine how the response time is affected by the transmission of vibration from the feet to the whole body, when standing on a multi-axis excitation system in an upright position.

I understand that I am eligible to participate if I am aged between 18 and 40

I understand that I am NOT eligible to participate if

7. I have been previously diagnosed by a physician to have diabetes, vibration-induced pathologies, or a concussion
8. I suffer from motion sickness
9. I have had a lower body musculoskeletal injury in the previous 6-months
10. I don’t have normal or corrected-to-normal vision.
11. I have color vision defects.

If I agree to participate, I will be asked to provide my height, weight and date of birth. I understand I will be exposed to three sessions with acquisition of 112 response times while standing on a vibration platform.

Each session will consist of eight conditions. Each condition has fixed vibration amplitude (1 m/s^2), a random axis of vibration (X, Y, or Z), and variable frequency (0 – 1.5 – 2 – 3.15 – 5 – 8 – 12.5 – 0 Hz). Each condition lasts for 3 minutes, and 30 seconds of acquisition followed by 60 seconds of rest, equal to 28 minutes of vibration in a total session time of 36 minutes.

During every 3 minutes and 30 seconds of acquisition I will be exposed to vibration like what I might feel while travelling in a train or while driving a car, or I will not be exposed to any vibration. After each session of 36 minutes, I will be given a break of 1 day before starting the next 36 minutes session in the next day. I understand the total experiment will be conducted in 3 days with a total time of 108 minutes (1 hour and 48 minutes).

I have been informed that only members of the research team will have access to the data collected. **My participation is strictly voluntary,** and I am free to withdraw from the study at any moment without any penalty. I have received assurance from the researchers that all data collected will remain strictly confidential. My individual results will not be reported. All collected data will be coded with a participant number and stored in a locked filing cabinet (in the Human Vibration lab under the supervision of Prof. Marco Tarabini) or on a password secured laptop that only members of the research team will have access to. After a period of 7 years, paper documents collected will be shredded, and all electronic files will be destroyed (unless I give consent for the data to be stored in a vibration database).

I understand that I will receive no immediate benefit from my participation.

There are two copies of this consent form; one, which the researcher keeps and one that I keep.

If I have any questions or concerns about the study or about being a participant, I may contact:

PhD. Stefano Marelli

E-mail: stefano1.marelli@polimi.it

Professor Marco Tarabini

e-mail: marco.tarabini@polimi.it

If I have any questions or concerns surrounding the ethical conduct of the study, I may contact the Research Ethics Committee at comitatoetico@polimi.it

If I would like to receive a copy of the study, I can email PhD. Stefano Marelli or Prof. Marco Tarabini anytime.

By signing below, I agree to participate in this study.

I agree my vibration data can be stored in a vibration database and does not have to be destroyed after 7-years:

YES	Check if you agree

Participant's Signature: ____

Date: ______________________________

Thank you for your participation.

iv) WBV – PVT test Informativa Privacy

INFORMATION ON THE PROCESSING OF PERSONAL DATA PURSUANT TO ART. 13 OF EU REGULATION N° 679/2016 OF 27 APRIL 2016

Short description of the research project

The objective of this study is to measure how Whole-Body Vibration (WBV) affects the reaction time of cognitive vigilance while standing in a multi-axis vibrating platform. The duration of the vibration exposure is not intended to create fatigue, but rather to permit brief WBV exposure with cognitive testing, observing the effects of WBV on response time. Each subject will be asked to do 1 session per day for three days. Each session consists of eight conditions. Each condition has fixed vibration amplitude (1 m/s^2), random axis of vibration (X, Y and Z) and variable frequency (0 – 1.5 – 2 – 3.15 – 5 – 8 – 12.5 – 0 Hz). Each condition lasts for 3 minutes, and 30 seconds of acquisition followed by 60 seconds of rest, equal to 28 minutes of vibration, which is far below the upper limit of published studies and industry standards (ISO-2631). 24 different trials of Psychomotor Vigilance Test (PVT) during standing vibration will be conducted. In each trial, there will be 112 reaction tests and a total of 896 reactions test per session. The total study should last 108 minutes, with 36 minutes for a single session. If at any time during the testing, the subject wished to withdraw his consent, the test will be interrupted, and all associated data will be destroyed.

Research Project Leader: Prof. Marco Tarabini.

In terms of art. 13 of the GDPR (General Data Protection Regulation), EU Regulation n°. 679/2016 of 27 April 2016, we hereby provide the following information:

Data Controller:

Politecnico di Milano - Managing Director, delegated by the pro-tempore Rector - e-mail: dirgen@polimi.it.

In-house data processing manager

Prof. Marco Tarabini - Data will be processed by other authorised processors, instructed for this purpose in accordance with the current norm.

Data protection Officer and points of contact

Dr Vincenzo Del Core - privacy@polimi.it Tel.: 0223999378

Purpose of the data processing

Your personal data will only be processed as part of and for the purposes of the "Effects of Whole-Body Vibration on response time during standing in Healthy Subjects" research project referred to above.

Such data will be gathered and processed for the purposes of executing said research project, making use of: Cognitive reaction times during standing; both with and without vibration using a PVT testing device.

Legal basis and nature of conferral of data

The legal basis for this processing, in terms of art 6, 1st comma, lett. a) of the Regulation, is to be found in your free and optional consent.

Taking part in the project is optional. However, conferral of the data required is essential for the study to be carried out, and refusal to grant the same will mean that you will not be able to take part.

Data processing methods and nature of conferral of data

The data will be processed using computerised and telematic tools, with organisational and processing logics correlated only for the purposes of the research and, in any case, in a way that is able to guarantee the security and confidentiality of the same, in conformity to the current norm.

Audio and video recordings of verbal interactions can be transcribed, kept, computerised, and gathered for scientific purposes only. In such cases, the Politecnico di Milano undertakes to:

- Have the data processed by specifically appointed researchers.
- See to subsequent processing and saving phases involving the data gathered, in a way that does not directly identify the persons involved, making all information anonymous.
- Communicate any data processed and/or saved in anonymous form, in a database that will be accessible to all those taking part in the research project.
- Disseminate the responses provided, only in an aggregated and/or anonymous manner.

Communication and dissemination

Where personal data is to be communicated and/or disseminated (for example by means of scientific publications, congresses, seminars, lessons, etc.) it will, in any case, be rendered anonymous beforehand, and processed in an aggregated manner, to exclude any possibility of identifying the minor.

We wish to state that, where recordings are found to be socially appreciable or usable for presentations at scientific research and conference events, they may, with your consent, be communicated and/or disseminated,

We also wish to state that communication or dissemination of the data described above will only take place, with your consent, after assessing its pertinence, and will not go beyond processing for the purposes of gathering, or where non-publication of the findings from verbal interactions will have a negative effect on the quality of the research / study. A recording of verbal interactions and/or transcribing of their content may be communicated to those taking part in the project and may be disseminated / published (e.g., in scientific magazines, on the internet, or in databases accessible by other researchers).

Finally, we wish to state that, with your consent to communicate and/or disseminate audio/video recording of verbal interactions, implies granting a non-exclusive license, without a time limit and for the entire world that can be transferred to third parties, for using the images. This license includes the rights contained in articles 12 and following of Law n° 633/1941 including, by way of example but not exhaustively, the right of publication, right of reproduction in any way or form, right of transcription, editing, adaptation, processing and reduction; the right to communicate and distribute to the public, including the rights of projection, transmission, and diffusion, also in summary and/or reduced form, using any technical means, the right to keep a copy of the images, also in electronic format and on any technological support that is known or invented in the future, for the purposes and limits defined above. The use of the images does not give any right to compensation. In any case, this excludes the use of a portrait that may cause prejudice to the honour, reputation, or decorum of the person in the portrait, photographed, or recorded.

Period of retention of the Data

The data gathered will be used by means of computerised and telematic tools and will be kept only for the time strictly necessary for transcribing the contents and rendering it anonymous, and, in any case, for not more than 2 years.

Rights of the data subjects

As the person involved, you may, at any time, as the Data Controller for:
Confirmation of the existence or otherwise of personal data pertaining to you.

Access to your personal data and information related to the same, correction of imprecise data or addition to incomplete data, deletion of personal data pertaining to you (when one of the conditions occurs that are indicated in art. 17, paragraph 1 of the Regulation, and in accordance with the exceptions provided for in paragraph 3 of said article); limitation of processing of your personal data (when one of the cases applies that are indicated in art. 18 paragraph 1, of the Regulation), transformation into an anonymous form or blockage of data processed illegally, including that which does not need to be stored for the purposes for which said data was collected or processed at a later time.

As the person involved you have the right to oppose, in part or entirely:

For legitimate reasons, the processing of personal data concerning you, even if related to the purpose for which the data was collected.

Processing of personal data pertaining to you, for the purposes of sending promotional material in training initiatives and cultural events of the Politecnico di Milano.

These rights can be exercised by contacting privacy@polimi.it.

If you believe that your rights have been violated by the controller and/or a third party, you have the right to lodge a complaint with the Authority for the Protection of Personal data, and/or another competent controlling authority in terms of the Regulation.

CONSENT TO THE PROCESSING OF PERSONAL DATA

I ....

born in ………………… on..............................

resident in ....

address..

height ……. (cm)

weight. ………(kg)

Subject ID _______ having perused the notification in terms of art. 13 of the GDPR (General Data Protection Regulation), EU Regulation n° 679/2016 of27 April 2016 authorizes the Politecnico di Milano to process the personal data of the minor in terms of the " Effects of Whole-Body Vibration on response time during standing in Healthy Subjects"   project, for the purposes indicated in the notification above.

Consents   does not consent

to processing of their data, even of a particular nature, for the purposes of statistical

and scientific research, in the ways and for the purposes described [taking part in the project].

Consents does not consent

to processing of their data, even of a particular nature, for the purposes of statistical

and scientific research, including the communication and dissemination of interviews, in the ways and for the purposes described [dissemination of the interviews, without identifying data].

Consents does not consent

the use and publication, by means of al/ technical devices, or the images recorded and the possibility that the recording may be the subject of public representation, by way of shows, publications on the web and in social networks, downloading, or dissemination of optical or magnetic supports.

Place and date........................

(Legible signature)

v) WEMOS – Installation and connection procedure

Installation procedure of WEMOS D1 MINI in Arduino IDE

1. Download and install Arduino IDE
2. Go to the website: https://docs.wemos.cc/en/latest/d1/d1_mini.html
3. Under Documentation, click on CH340 Driver, select your version, download it and install it
4. Under Tutorials, in the previous page, click on " Get started with Arduino [D1/D1 mini series] "
5. Under Installing Hardware package, select esp8266 package with version specified in the Arduino sketch.
6. Under Contents -> Installing options: -> Using board Manager.
7. Follow the instructions
8. Start Arduino and open the Preferences window.
9. Enter https://arduino.esp8266.com/stable/package_esp8266com_index.json into the File>Preferences>Additional Boards Manager URLs field of the Arduino IDE. You can add multiple URLs, separating them with commas.
10. Open Boards Manager from Tools > Board menu and install esp8266 platform.
11. Select your ESP8266 board (LOLIN(WEMOS) D1 R2 & mini) from Tools > Board menu after installation).
12. Connect wemos to a USB port of your device through a USB-USB micro cable.
13. Go to Tools > Port and select the COMx (if you have just one device connected, you will see just one port)
14. You are ready to modify the Arduino sketch for wemos.

How to use the device with MATLAB®

1. Power on the device.
2. Connect to Wemos hotspot Wifi "PVT-Test-Net", password: "VBlab_PVTTest".
3. Open MATLAB® file "PVT_Test_Manager.m" in MATLAB®
4. Run the MATLAB® script.
5. Follow the instruction on MATLAB® popup or command window