

Ministry of Education

Technical University of Construction Bucharest

Doctoral School

**Partial theoretical and experimental research on the
validation of biomechanical models of the human
body subjected to the action of mechanical
vibrations**

(Scientific research report no. 3)

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Introduction

The general objective of the doctoral thesis is to start research that makes possible new perspectives in the field of vibration measurement in the points of interest of the human body for people who by nature of the job are subject to mechanical vibrations, the transmission and monitoring of this data in real time via GPRS.

Starting from the biomechanical modeling scheme of the interaction between the human body and the machine with which it works and considering the fact that for a spatio-temporal machine model with one degree of freedom, a differential equation can be written that describes the dynamic behavior while cannot have a solution written as a relationship of the system characteristic x exciting force type, it is found necessary to perform an analysis in the frequency domain which results in the determination of some quantities by applying the Fourier transform to a set of data collected by the acquisition system with the help of Matlab instructions.

Thus, a device model will be conceived and designed that will use the integrated processing platform (Arduino) on which vibration measurement sensors (accelerometers) will be positioned, the results of which can be collected, transmitted and displayed in real time via GPRS.

The asset tracking device with GPS / GLONASS, GSM connectivity and autonomous battery, is able to collect GPS coordinates and transmit them via GSM/GPRS to the VPS for the purpose of performing permanent data storage in a MySQL database or viewing them in real time in a web page directly on the laptop.

The obtained data can be viewed on any mobile phone running Android +4.2 and on any laptop running Windows, OS X by means of a Python language script.

Considering the need for data to be analyzed, the entire device was designed and the components that ensure the capture and transmission of this data were dimensioned.

The components were chosen: 3D sensor, accelerometer & gyroscope, microcontroller, SD module, GPS/GSM/GPRS module, accumulator module, battery with the technical characteristics suitable for operation according to needs and obtaining relevant data sets.

For each individual component, the mode of operation was described as well as the mandatory technical characteristics.

Once the data capture and transmission system was dimensioned, it was mounted on a subject and experimental determinations were made in two concrete situations, namely

determinations without the use of equipment that works with vibrations and determinations with the use of two equipments: compactor plate, respectively impact drill.

Determinations without the use of vibration equipment were made by mounting the system on the subject and recording data while the subject was walking down a ladder and while the subject was moving on a flat surface, respectively. The obtained results were processed and represented graphically.

The determinations for the situation in which an equipment that works with vibrations is used were made with the use of two equipments: compactor plate, respectively impact drill. Similarly, the determinations were made by mounting the system on the subject and recording the data when the subject uses a compactor plate, respectively a percussion drill with defined technical characteristics. The obtained results were processed and represented graphically.

The graphical representations thus obtained were compared with the results of previous studies. In future research, other types of equipment that produce vibrations during work will be used in order to optimize the calibration of the experimental setup in order to obtain results as close as possible to the results presented in the specialized literature.

1. Biomechanical modeling

The biomechanical modeling of the interaction between the human body and the machine it works with consists of going through the following stages shown in the block diagram below [fig. 1.]

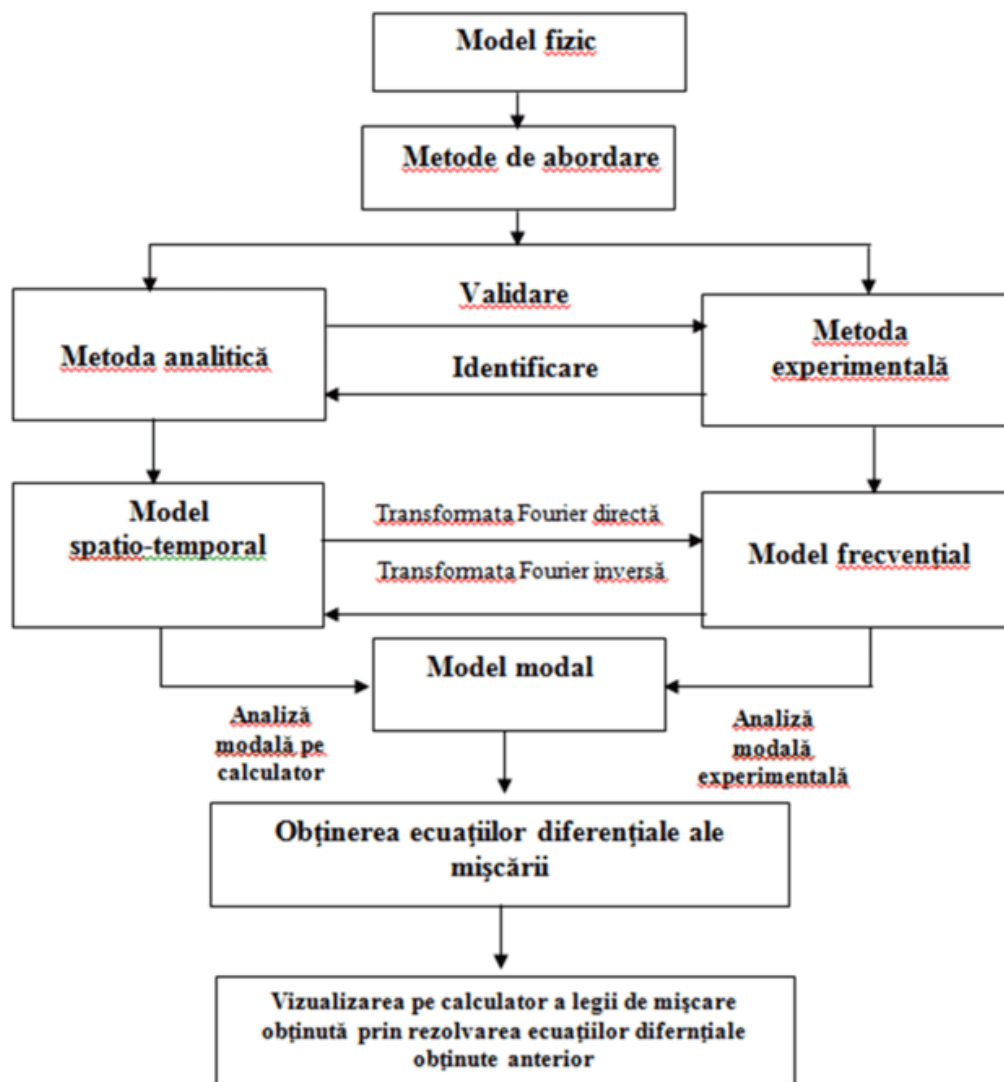


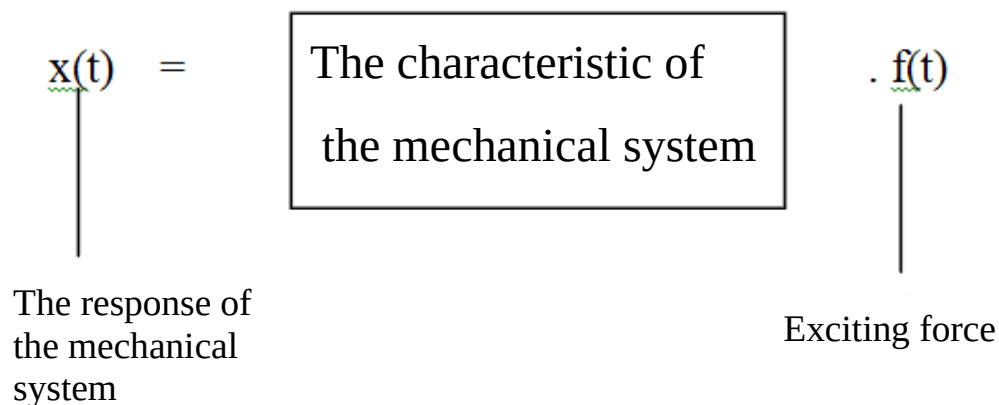
Fig. 1. Block diagram

2. The frequent model

For a spatio-temporal machine model with one degree of freedom, the differential equation that describes the dynamic behavior in time can be written in the form:

$$m\ddot{x} + c\dot{x} + kx = f(t) \quad (1)$$

Analyzing the solution of this differential equation, we find the impossibility of obtaining a relation of the form:



It follows from here the need to carry out an analysis in the frequency domain.

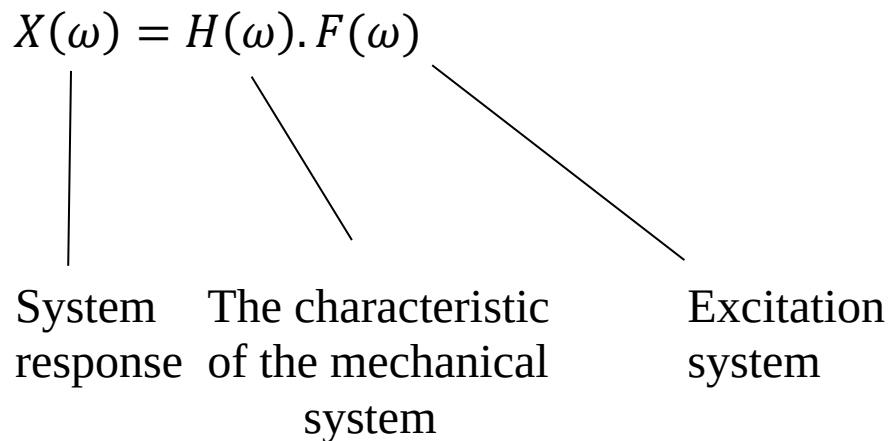
For strength $f(t)$ this can be written in the form:

$$f(t) = F(\omega)e^{i\omega t} \quad (2)$$

Putting the solution of the differential equation (1) in the form:

$$x(\omega) = X(\omega) \cdot e^{j\omega t} \quad (3)$$

For a pulse ω or for a frequency $f = 2\pi/\omega$ we get the relationship:

$$X(\omega) = H(\omega) \cdot F(\omega)$$


The diagram shows the equation $X(\omega) = H(\omega) \cdot F(\omega)$ at the top. Three lines extend downwards from the terms: a vertical line from $X(\omega)$ to the label 'System response', a diagonal line from $H(\omega)$ to the label 'The characteristic of the mechanical system', and another diagonal line from $F(\omega)$ to the label 'Excitation system'.

The quantities $X(\omega)$ and $F(\omega)$ that were introduced by relations (2) and (3) are obtained by applying the Fourier transform to the quantities $\mathbf{x(t)}$ and $\mathbf{f(t)}$ according to the relations below:

$$X(\omega) = \int_{-\infty}^{\infty} x(t) \cdot e^{-j\omega t}$$

$$F(\omega) = \int_{-\infty}^{\infty} f(t) \cdot e^{-j\omega t}$$

The Fourier transform is applied to a set of data collected by the data acquisition system using Matlab instructions:

```
{d,s} = xlsread('C:\Users\acer\Desktop\coapsa.xlsx');
t = d(:,1)*1E-3;           % convert 'seconds' to 'milliseconds'
v = d(:,2);                % Voltage (?)
L = length(t);
Ts = mean(diff(t));        % Interval (sec)
Fs = 1/Ts;                 % Frequency
Fn = Fs/2;                 % Frequency
vc = v - mean(v);          % Component ('0 Hz')
FTv = fft(vc)/L;           % Fourier transform
Fv = linspace(0, 1, fix(L/2)+1)*Fn; % Frecquenct vector (Hz)
lv = 1:length(Fv);         % Index Vector
figure(1)
plot(Fv, abs(FTv(lv))*2)
grid
xlabel('Frecventa (Hz)');   % Abscisa
ylabel('Amplitudine (g)'); % Ordonata
title('Grafic Laba');      % Graph title
```

3. The data acquisition system that will be used in the doctoral thesis

The general objective of the thesis consists in starting some research that makes possible new perspectives in the field of vibration measurement in the points of interest of the human body for people who by the nature of the job are subject to mechanical vibrations, the transmission and monitoring of this data in real time via GPRS.

The main results of the work will consist in the conception and design of a device model that will use the integrated processing platform (Arduino), which is already purchased. Vibration measuring sensors (accelerometers) will be positioned on this platform, the results of which can be collected, transmitted and displayed in real time via GPRS.

The asset tracker with GPS / GLONASS, GSM connectivity and autonomous battery, is able to collect GPS coordinates and transmit them via GSM/GPRS to the VPS.

The device is suitable for applications where it is necessary to determine the location of objects.

Various hardware modifications allow the connection of several external sensors (digital sensors, analog sensors) such as: temperature, speed, acceleration, rpm, force in different points of interest for the human body.

To start a communication (data capture), the main board (master) first establishes the connection with the microcontrollers (slaves), using a frequency lower than or equal to the maximum frequency that the slave devices support. The master then selects the desired slave and begins the data capture process, with the data being transmitted to a VPS (Virtual Private Server) for the purpose of permanently storing the data in a MySQL database or viewing it in real time in a web page directly on your laptop.

The obtained data can be viewed on any mobile phone running Android +4.2 and on any laptop running Windows, OS X [fig. 3.1.] by means of a Python language script [fig. 3.2.].



Fig. 3.1. Data visualization

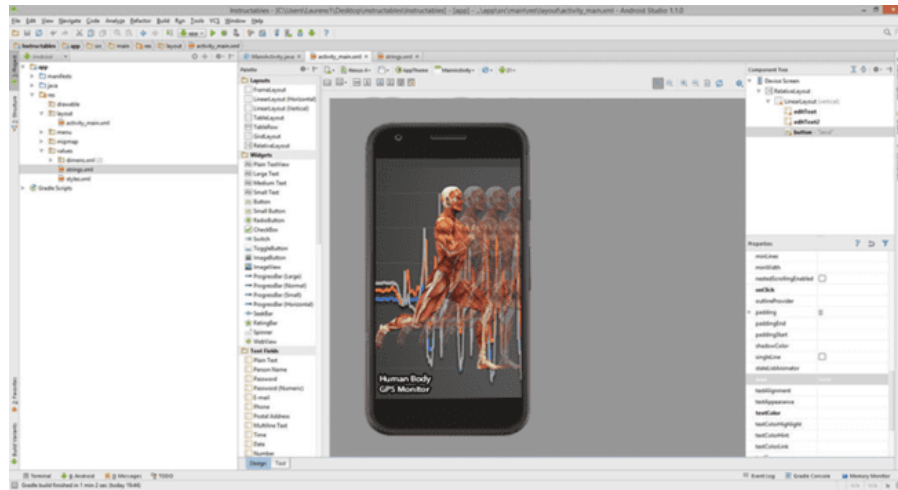


Fig. 3.2. Vizualizarea datelor

The components that were used to capture and transmit data [fig. 3.3.]:

1. 3D sensor, accelerometer & gyroscope;
2. Microcontroller:
3. SD mode:
4. GPS/GSM/GPRS mode;
5. Accumulator Module;
6. Battery.

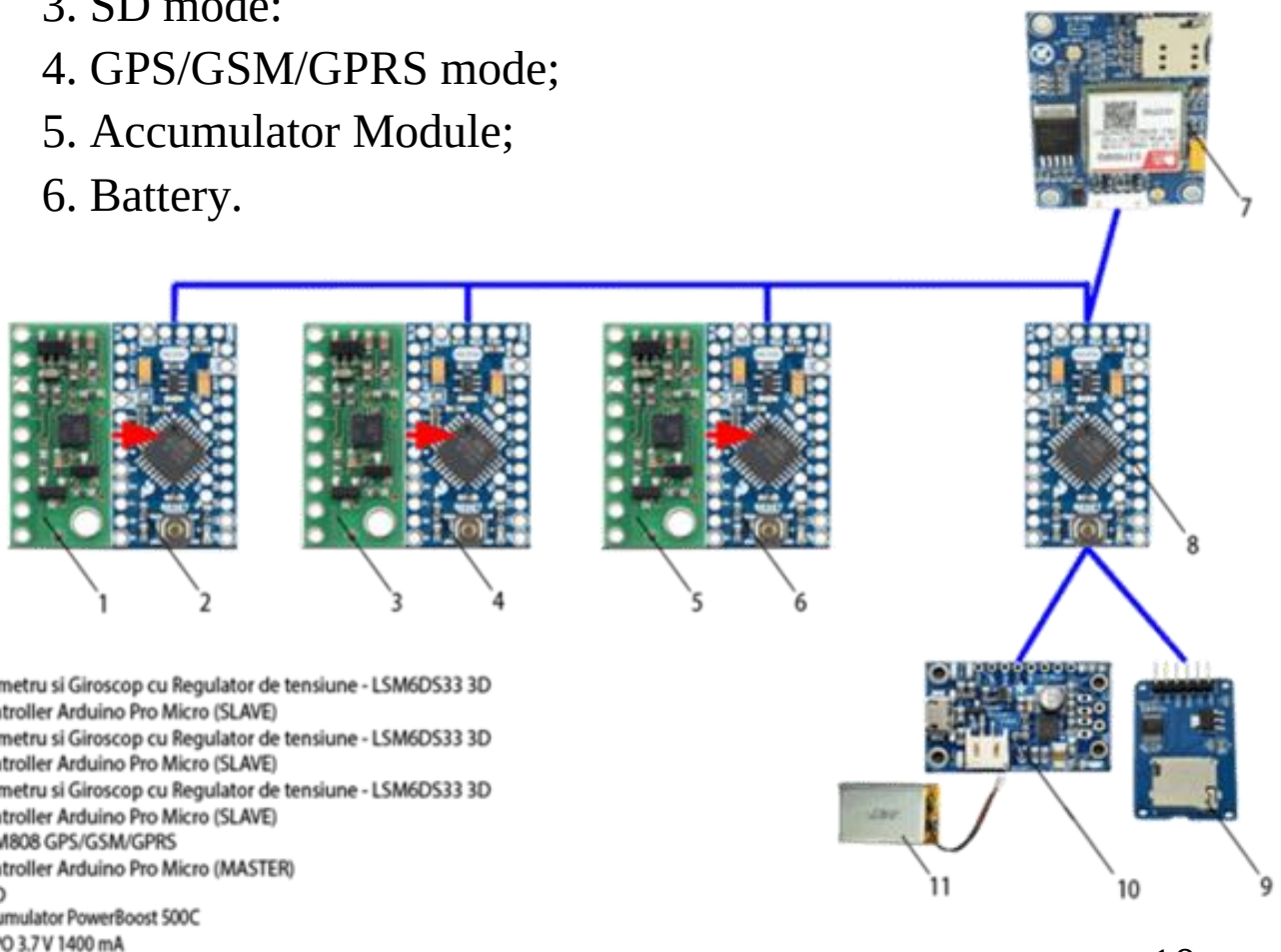


Fig. 3.3. Componente folosite

3.1. 3D sensor, accelerometer & gyroscope

3.1.1. 3D sensor

The sensor used in this project is the LSM6DS33 tri-axial accelerometer working in series (I2C).

Therefore, the microcontroller (master) periodically takes the data from it. It must take into account that the data provided by the sensor is measured exactly once for each sensor one after the other during sampling.

In other words, the microcontroller must read data from all sensors periodically, without losing or oversampling data from each accelerometer.

3.1.2. Accelerometer & gyroscope

LSM6DS33 [fig. 3.4.] combines a 3-axis digital accelerometer and a 3-axis gyroscope.

The sensor provides six independent acceleration and rotational speed readings whose sensitivity can be set in ranges of ± 2 g until ± 16 g and ± 125 ° / s until ± 2000 ° / s, available via I2C and SPI interfaces.

The LSM6DS33 includes a 3.3V voltage regulator and an integrated level shifter that allows operation from 2.5V to 5.5V.

Technical specifications:

- Dimensions: 22.8 x 10 x 2.5 mm;
- Weight: 0.6g;
- Interface: I2C, SPI;
- Minimum operation voltage: 2.5V;
- Maximum operation voltage: 5.5V;
- Measurement range (accelerometer): ± 4 , ± 8 , ± 12 and ± 16 g (gauss);
- Measuring range (gyroscope): ± 125 , ± 245 , ± 500 , ± 1000 , sau ± 2000 ° / s;
- Current consumed: 2mA.



Fig. 3.4. Accelerometer LSM6DS33

3.2. Microcontroller

The Arduino Pro Micro microcontroller was chosen for this project [fig. 3.5.]. The programming language used is C++. By combining the LSM6DS33 accelerometer with the Arduino Pro Micro microcontroller, it was aimed to obtain a very high accuracy of the data. Power consumption was the main factor that was considered when choosing the

appropriate microcontroller. Considering the fact that the whole system must be mounted on a subject (man), the power consumption must be low so that the system can be used for a long time without the need for additional weight for the whole system to be recharged by a powerful power source.

Technical specifications:

- Operating voltage: 5V;
- Pins I/O: 12;
- Pins PWM: 5 (from the I/O ones);
- Pins ADC: 4 (from the I/O ones);
- Communication: SPI and UART;
- Flash memory: 32kB (8 being occupied by the bootloader);
- Operating frequency: 16MHz.

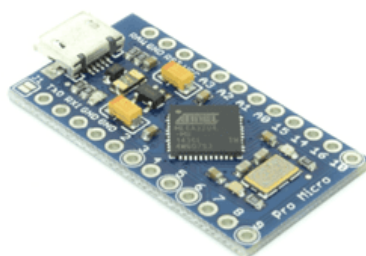


Fig. 3.5. Microcontroller Arduino

3.3. SD Module

The module [fig. 3.6.] is a MicroSD compatible adapter that can be used to write and read MicroSD cards through the ISP interface.

Technical specifications:

- Micro SD Card support ($\leq 2\text{GB}$);
- Micro SDHC Card ($\leq 32\text{GB}$);
- Supply voltage: $4.5\text{V} \sim 5.5\text{V}$;
- Maximum current: 200mA ;
- The communication interface: SPI;
- Dimensions: $42\text{mm} \times 24\text{mm} \times 12\text{mm}$;
- Weight: 5g .



Fig. 3.6. SD Module

3.4. GPS/GSM/GPRS mode

The SIM808 module [fig. 3.7.] combines GSM/GPRS technology with Global Positioning System (GPS) in a small chip. The communication logic level for the board's UART communication interface can be both 3.3V and 5V.

Technical specifications:

- Supply voltage: 5V – 18V;
- Quad-band 850/900/1800/1900MHz;
- GPRS multi-slot class 12/10;
- Bluetooth: compatible with 3.0 + EDR;
- Small consumption;
- Operating temperature: -40°C ~ 85°C.

Technical specifications of GPRS:

- GPRS class 12: max. 85.6 kbps;
- Support PBCCH;
- PPP-stack;
- CSD until 14.4 kbps;
- USSD.



Fig. 3.7 GPS/GSM/GPRS module

3.5. Battery Module

PoweBoost 500C [fig. 3.8.] is the perfect way to feed the project. It includes a battery recharging circuit, capable of recharging the battery after a long run. This converter can be powered from a 3.7V LiIon / LiPoly battery to provide an output voltage of 5.2V DC. The PowerBoost 500C contains TI's TPS61090 converter. This chip detects low battery, has an internal 2A switch, synchronous conversion, excellent efficiency and operates at high frequencies up to 700KHz.



Fig. 3.8. Battery module

3.6. Battery

Battery type LIPO 3.7 V [fig. 3.9.], 1400 mA. Ideal for powering the Arduino Pro Micro microcontroller.

Technical specifications:

- Charging voltage: 4.2V;
- Nominal voltage: 3.7V;
- Maximum charging current: 700 mAh;
- Maximum discharge current: 1400 mAh;
- Dimensions: 50 x 34 x 8mm;
- Weight: 27g.



Fig. 3.9. Battery

4.4. Data acquisition system mounted on a subject

In the following image [fig. 4.1.] the location of the components of the procurement system given on the subject as well as its scheme is presented.

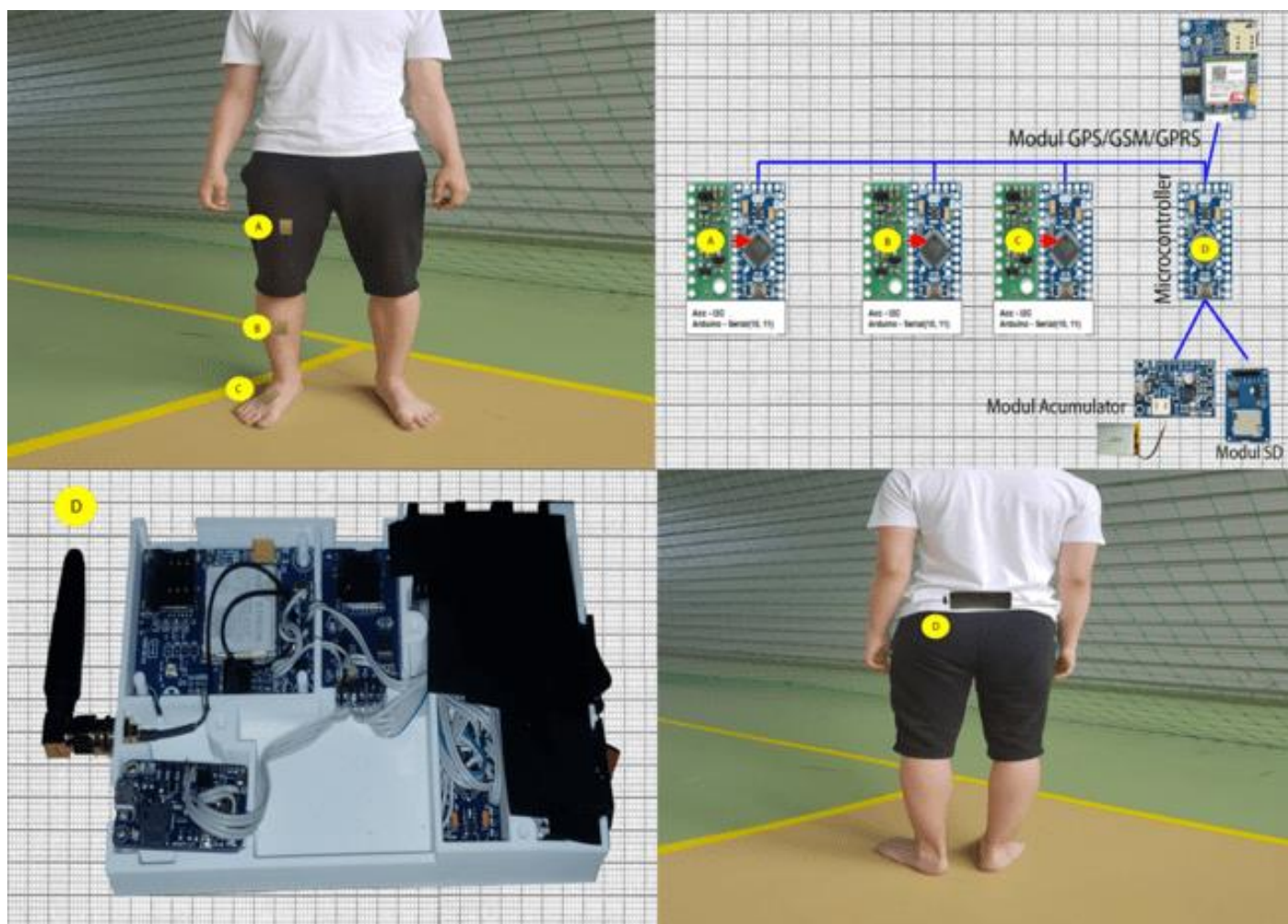


Fig. 4.1. Data acquisition system

4.1. Partial experimental determinations

Two sets of determinations were carried out viz:

1 – determinations without the use of equipment that works with vibrations;

2 – determinations with the use of two equipments:

a) compactor plate;

b) percussion drill.

4.2. Acquisition of ladder descent data

The system was mounted on the subject [fig. 4.2.] and the collection of recorded data [fig. 4.3., 4.4., 4.5.] when he descends a ladder.



Fig. 4.2. Mounted system for collection scale down data

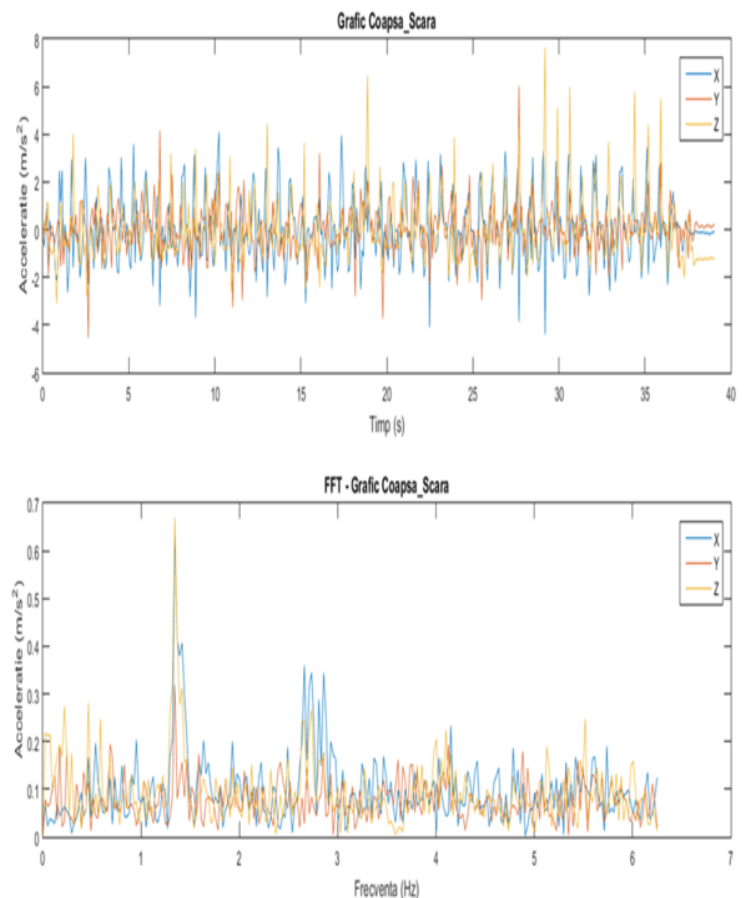


Fig. 4.3. Thigh Scale Charts

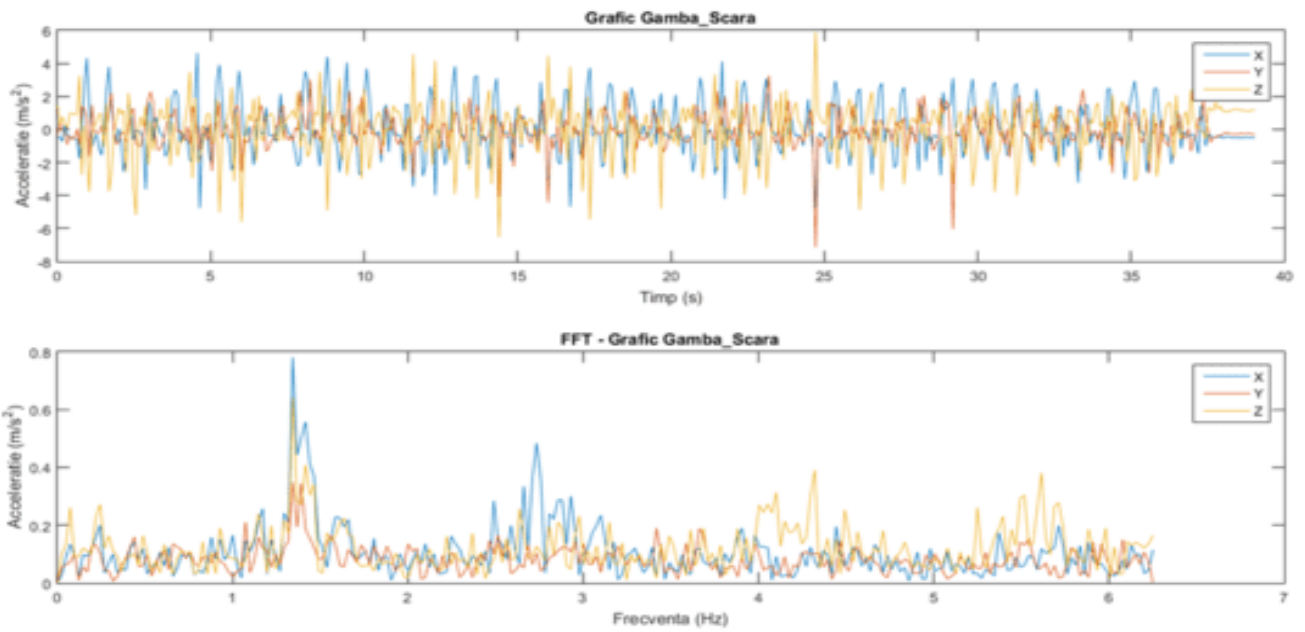


Fig. 4.4. Calf Scale Graphics

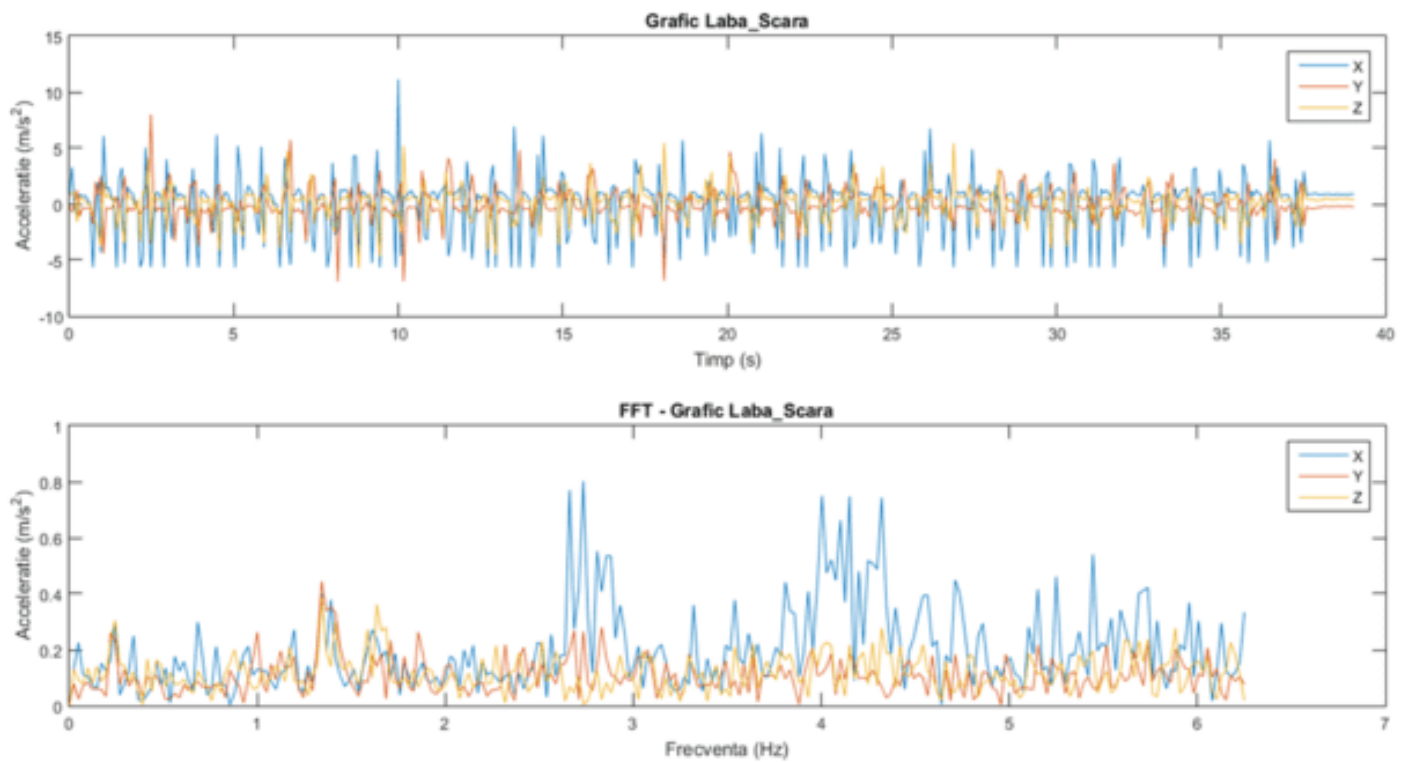


Fig. 4.5. Scale Paw Graphics

4.3. Acquisition of straight terrain displacement data

The system was mounted on the subject [fig. 4.6.] and the collection of recorded data [fig. 4.7., 4.8., 4.9.] when it moves on straight ground.



Fig. 4.6. Mounted system for straight terrain data collection

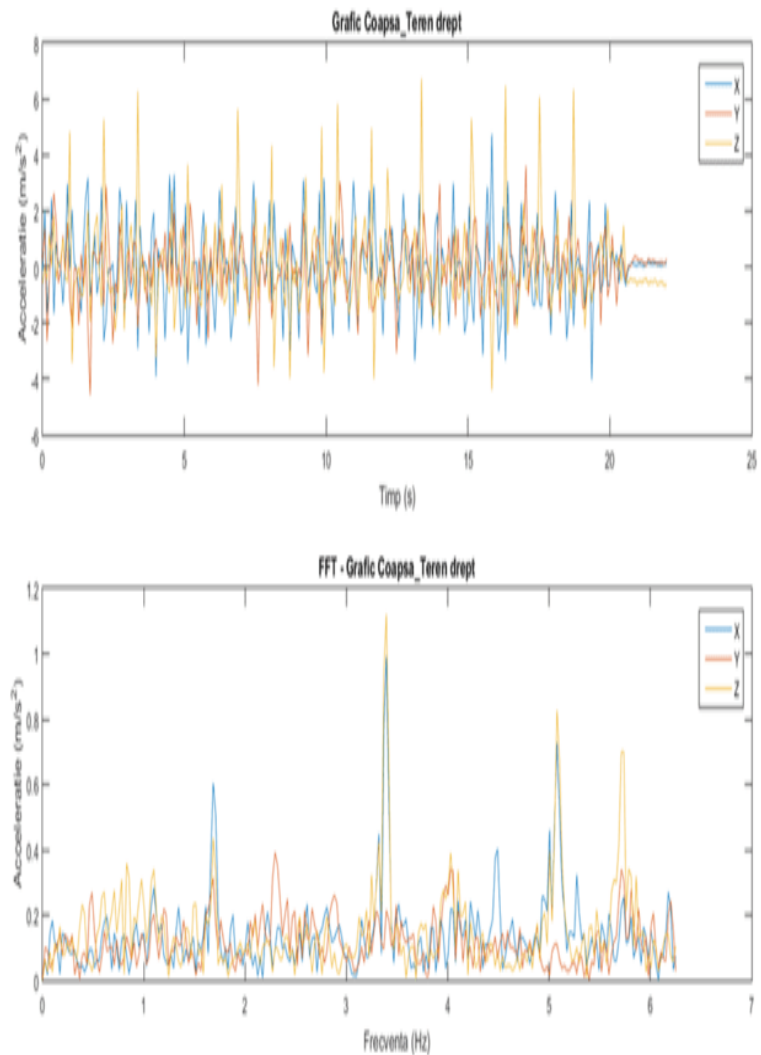


Fig. 4.7. Thigh Charts Straight Ground

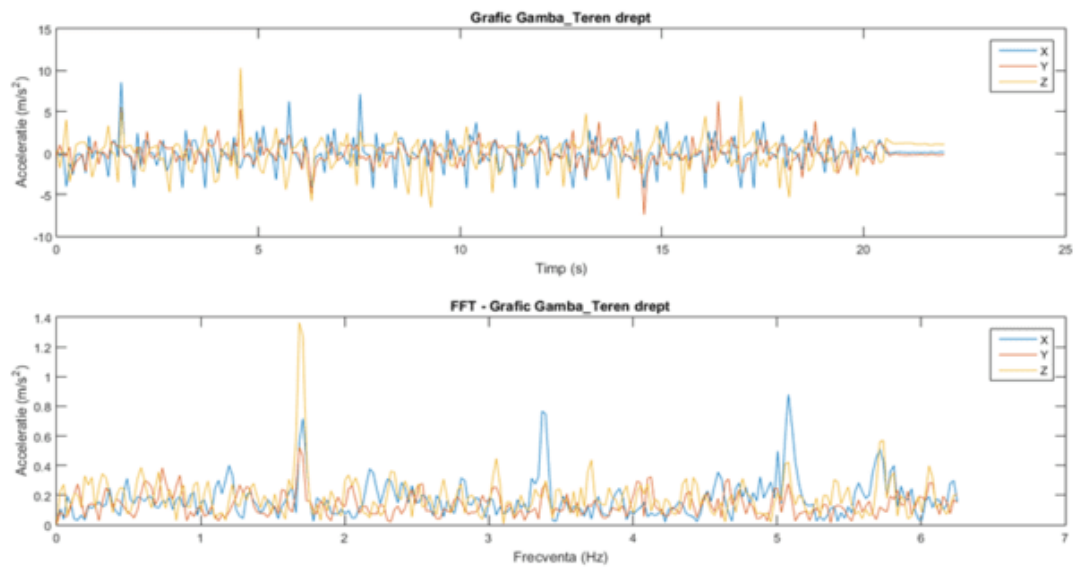


Fig.4.8. Calf Graphics Straight Pitch

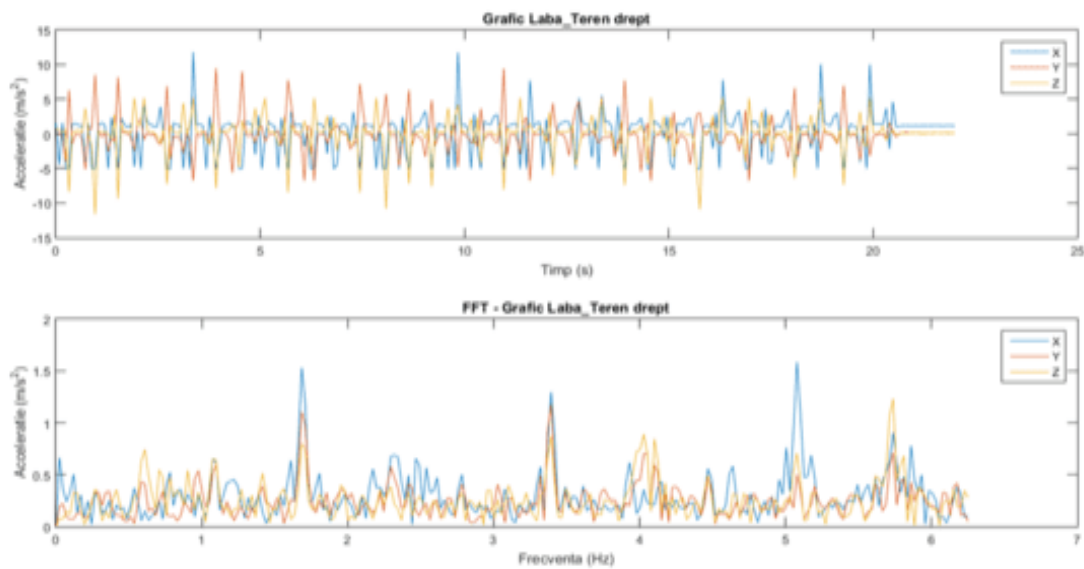


Fig.4.9. Right Land Paw Graphics

4.4 Percussion drill data acquisition

The system was mounted on the subject [fig. 4.10., 4.11., 4.12.] and the collection of recorded data [fig. 4.13., 4.14., 4.15.] when he uses a percussion drill in the following situations:

- accelerometer mounted on the handle of the equipment with/without FFT;
- arm left and right hand with/without FFT;
- forearm left and right hand with/without FFT.

Technical features percussive drill:

- model: Bosch GBH 2-26 DFR;
- engine power: 800W;
- drill diameter: 6mm;
- speed: 1300RPM;
- drill length: 10cm.



Fig. 4.10. Mounted system for data collection drill with percussion - front view



Fig. 4.11. Percussion drill mounted data collection system - side view



Fig. 4.12. Mounted Percussion Drill Data Collection System - Rear View

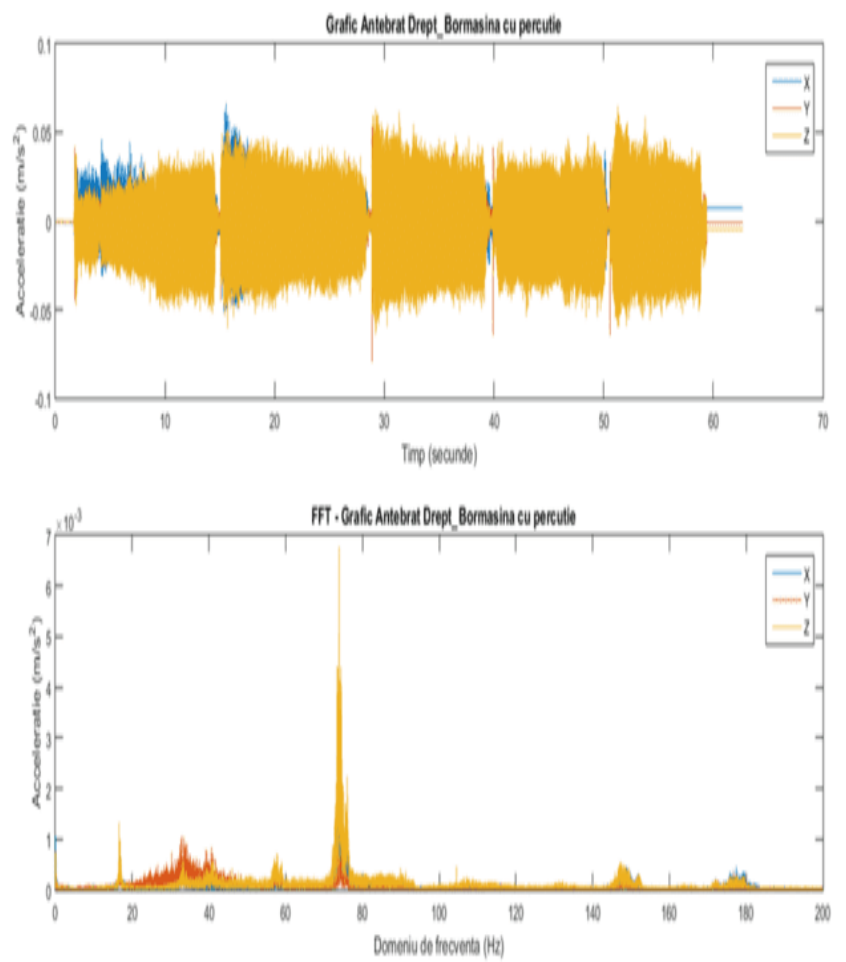


Fig. 4.13. Straight Forearm Percussion Drill Chart

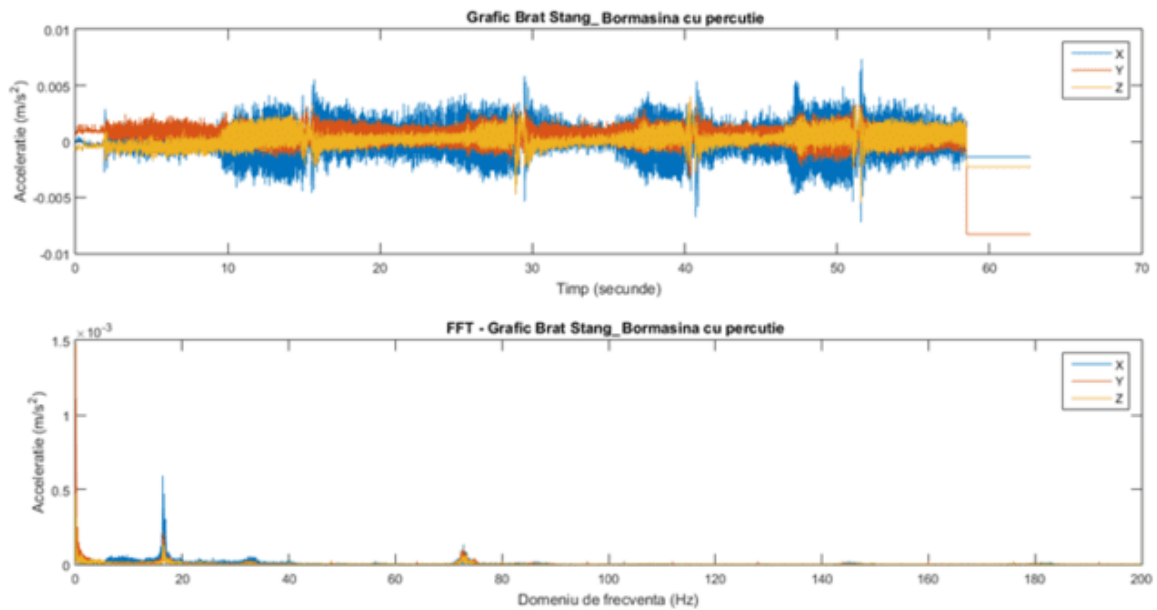


Fig. 4.14. Percussion drill left arm graphic

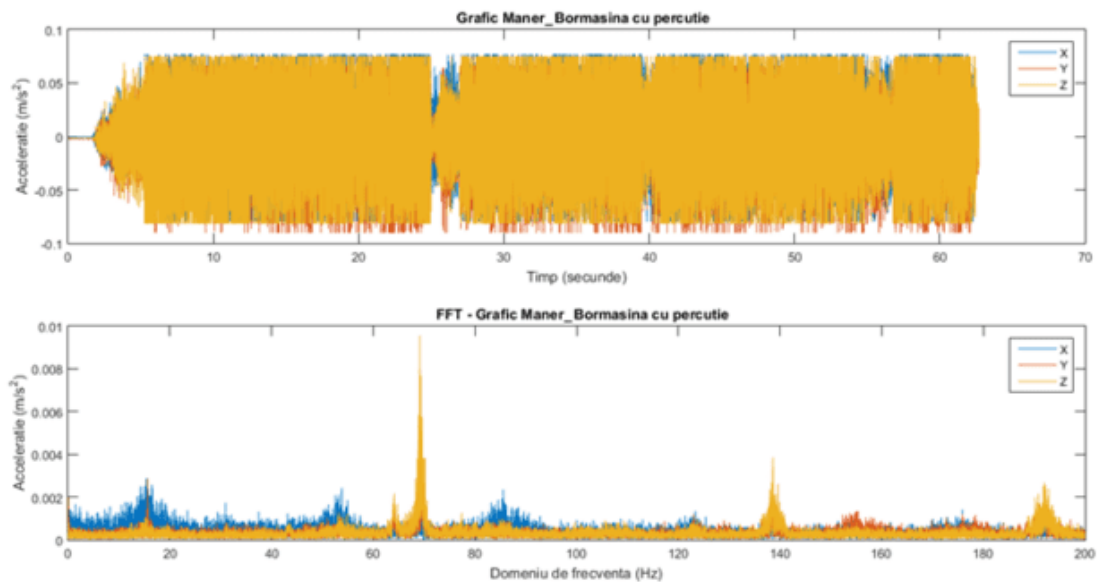


Fig. 4.15. Percussion drill handle graphic

4.5. Acquisition of vibrating plate data

The system was mounted on the subject [fig. 4.16., 4.17.] and the collection of recorded data [fig. 4.18., 4.19., 4.20., 4.21.] when he handles a vibrating plate in the following situations:

- accelerometer mounted on the handle of the equipment with/without FFT;
- arm left and right hand with/without FFT;
- forearm left and right hand with/without FFT.

Technical characteristics vibrating plate:

- model: Wacker Neuson VP1340AW;
- engine power: 3900RPM;
- speed: 3600 RPM.



Fig. 4.16. Mounted system for plate data collection vibrators - front view



Fig. 4.17. Mounted vibrating plate data collection system - side view

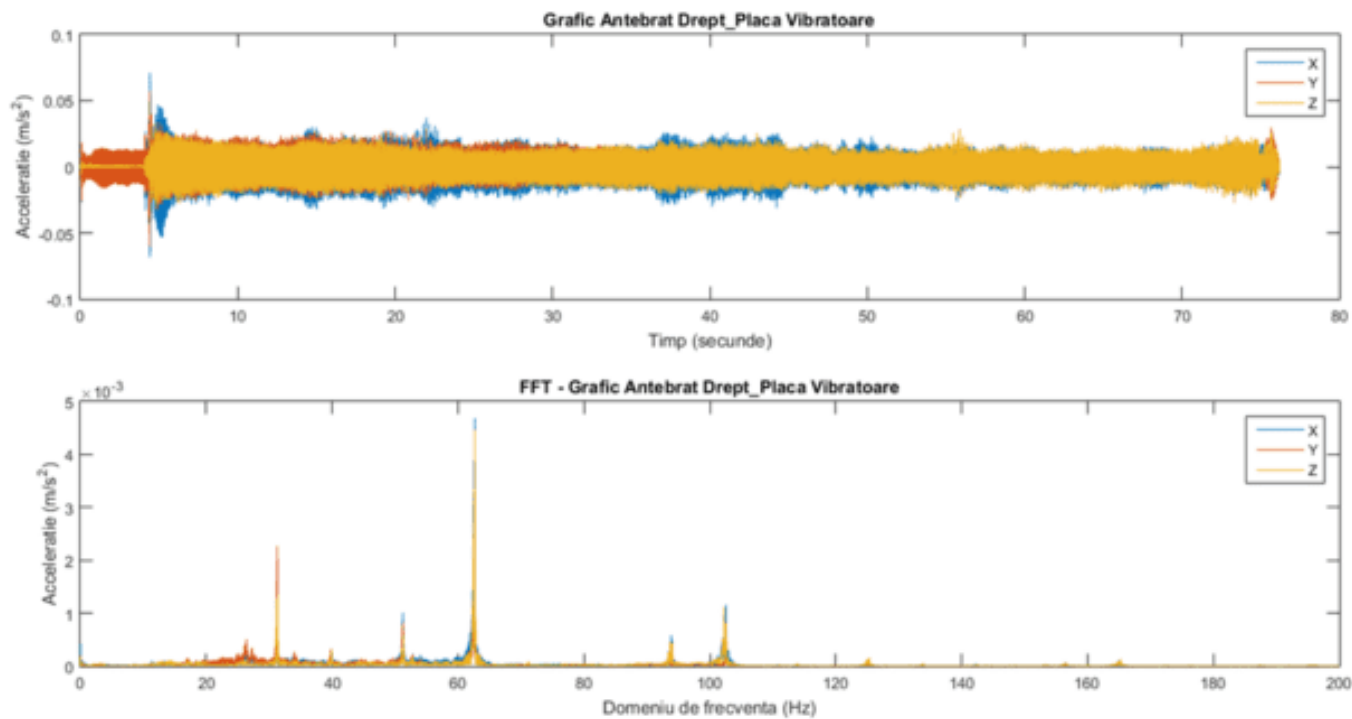


Fig. 4.18. Forearm Straight Vibrating Plate Graphic

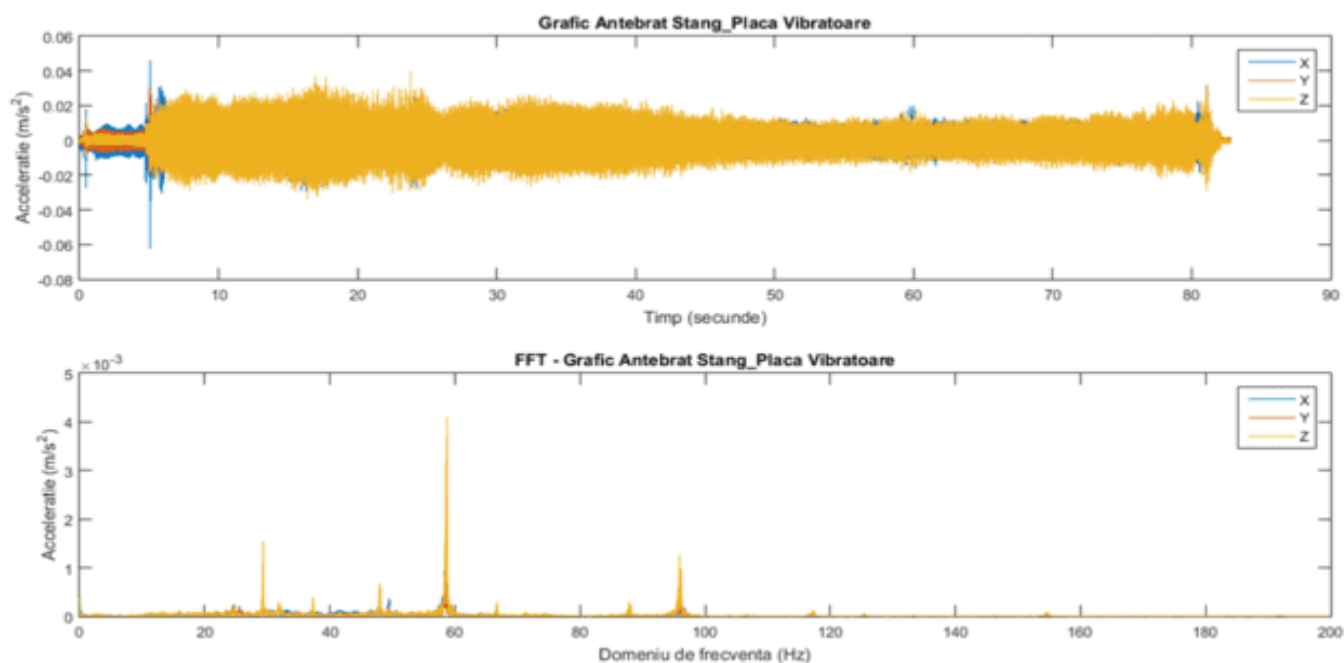


Fig. 4.19. Graphic left forearm vibrating plate

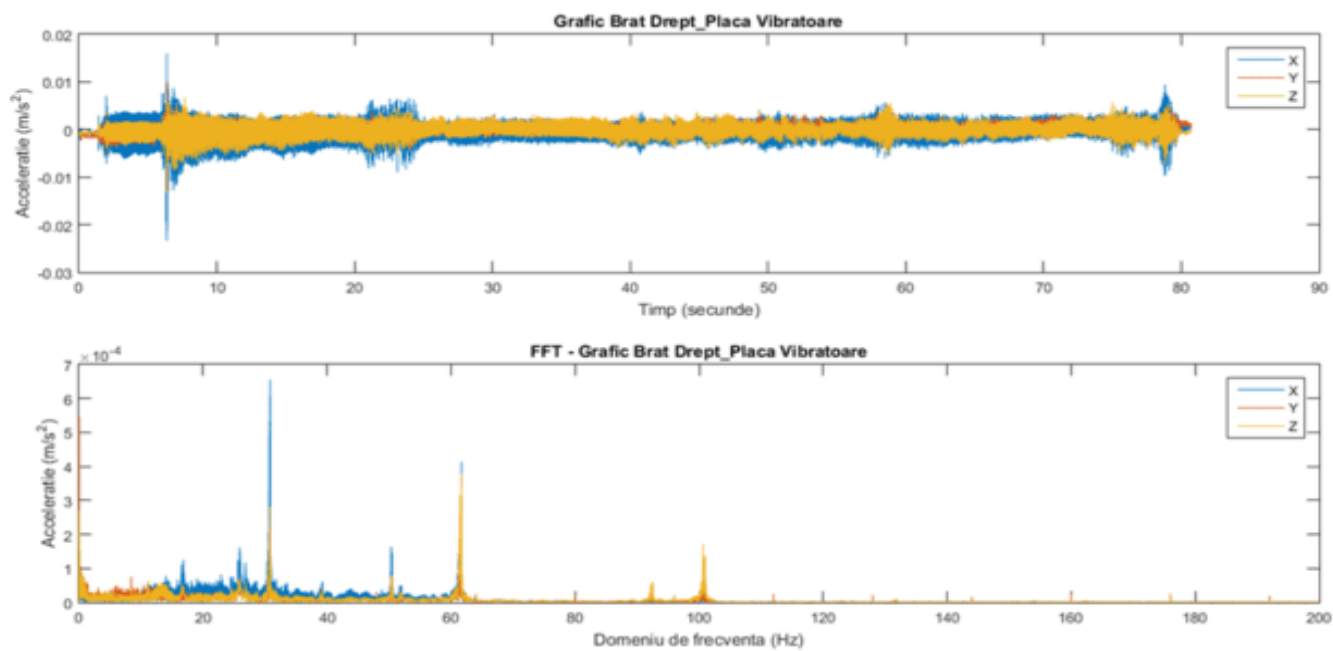


Fig. 4.20. Vibrating plate straight arm graph

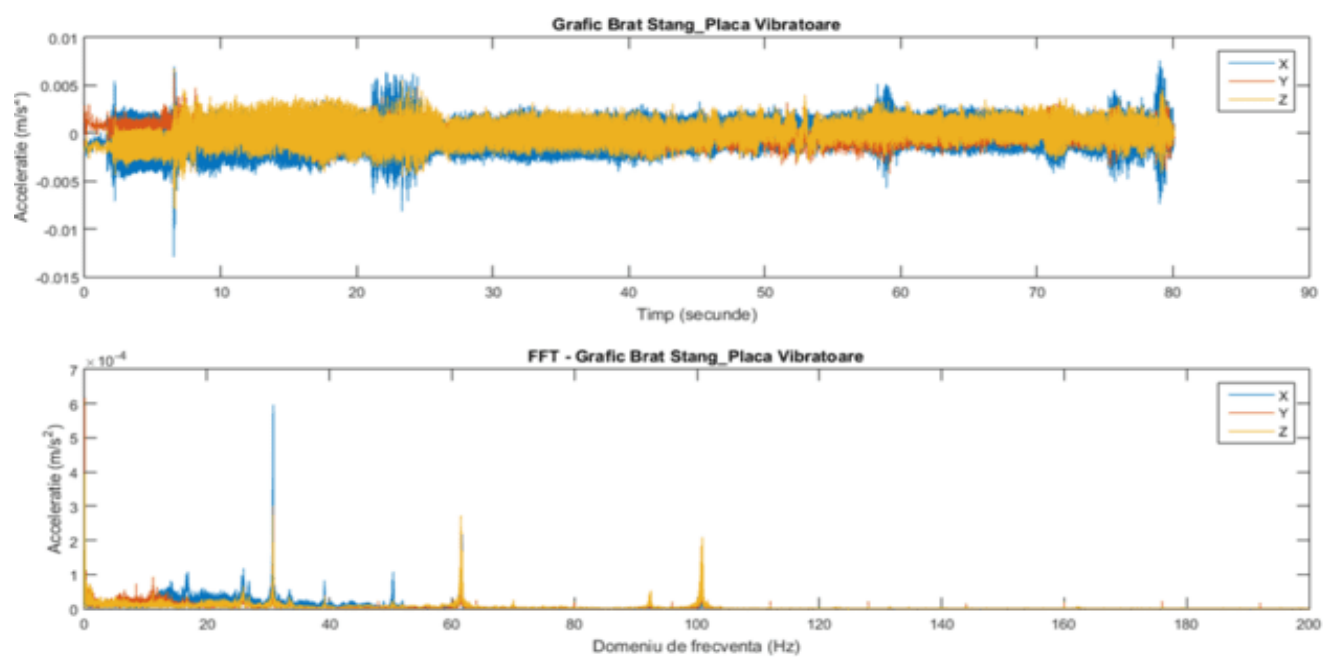


Fig. 4.21. Vibrating plate left arm graphic

The images below [fig. 4.22., 4.23.] presents the way in which the data acquisition system is located on the subject.



Fig. 4.22. Mounted data acquisition system for data collection percussive drill - side view



Fig. 4.23. Mounted data acquisition system for percussive drill data collection - rear view

5. Conclusions

From the analysis of the graphs without the use of vibrations, the frequencies of 1.53 Hz, 2.74 Hz, 4.23 Hz and 4.37 Hz were obtained for descending the stairs and the frequencies of 1.51 Hz, 3.24 Hz and 5, 23 Hz when walking on a straight road for a 15-year-old male subject with a height of 175cm and a weight of 65kg. Some frequencies correspond to the studies done on young subjects in [1] and shown in the following graphs as well as those in [19].

[1] AN ATTEMPT TO ESTIMATE NATURAL FREQUENCIES OF PARTS OF THE CHILD'S BODY-DARIUSZ WIĘCKOWSKI;

<http://www.bq.utp.edu.pl/artarchiwum20motoryzacji2012wieckowski>

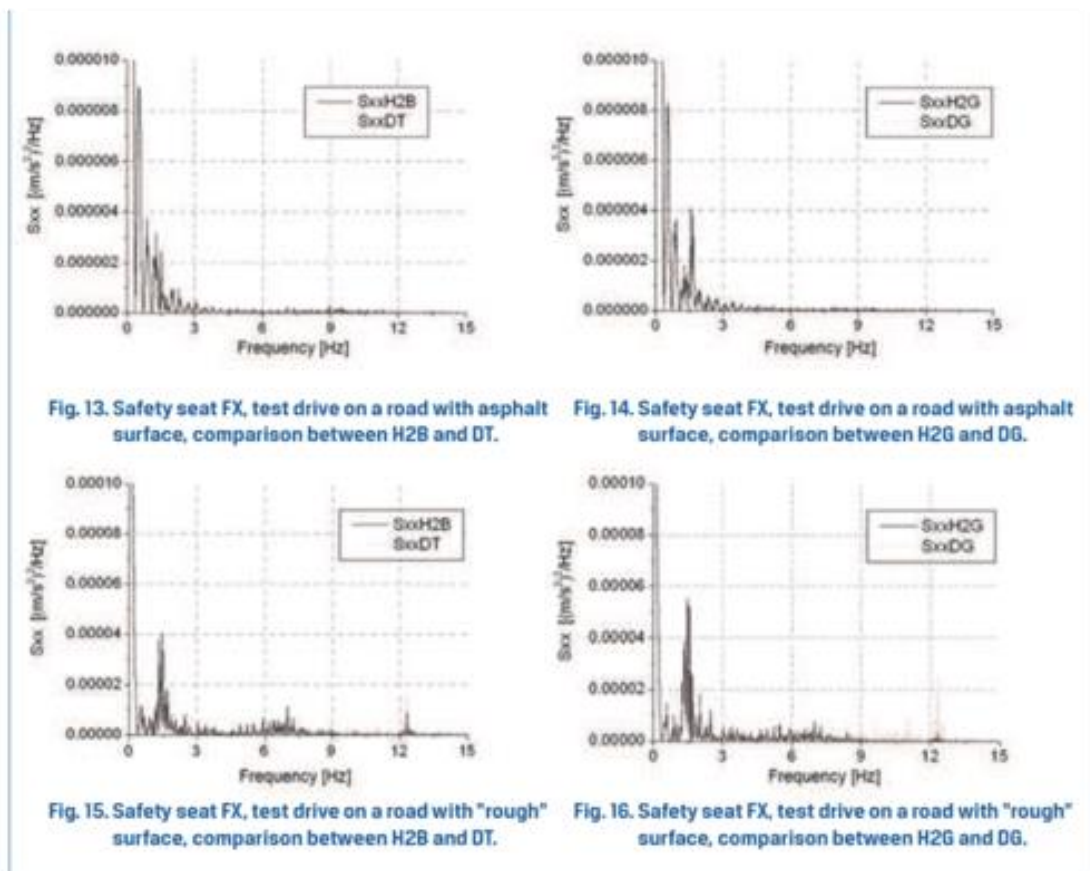


Fig. 5.1. An attempt to estimate natural frequencies of parts of the child's body

[19]Discussion of human resonant frequency

By James M. W. Brownjohn¹, Xiahua Zheng²

The experimental obtaining of some frequencies in the presented cases (acquisition of stair descent data, acquisition of straight terrain displacement data) are close to those obtained by researchers James M. W. Brownjohn and Xiahua Zheng with the help of the montage in the adjacent figure.

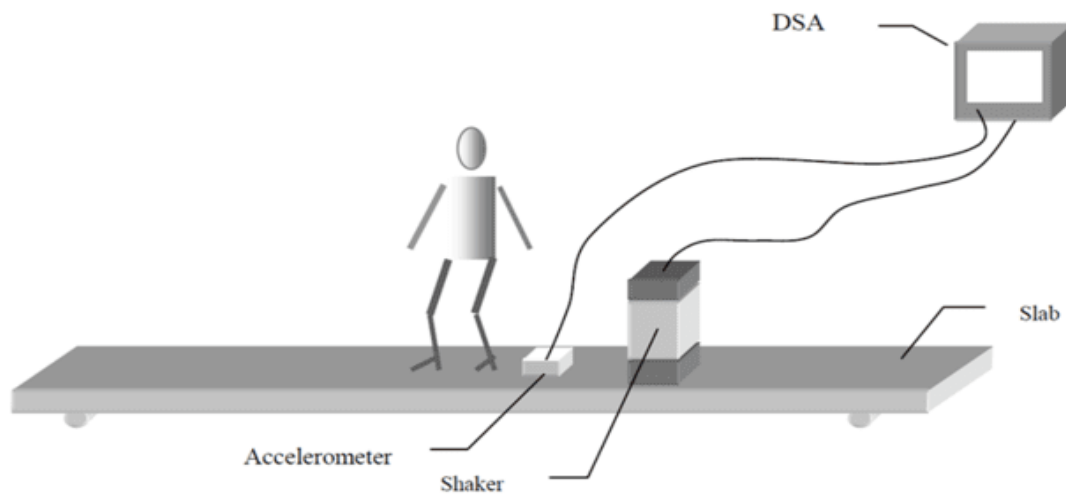


Table 1 Human resonant frequency

Slab Modal Mass	Human Weight	Human Posture	Frequency (unoccupied)	Frequency (occupied)	Human Frequency
331kg	76kg	stand	7.03	7.62	4.78
331kg	76kg	sit	7.03	7.54	4.54
331kg	76kg	stand stiff	7.03	8.14	5.90
331kg	47kg	stand	7.05	7.42	4.73
331kg	47kg	sit	7.05	7.23	3.67
331kg	70kg	stand	6.80	7.30	4.53
331kg	70kg	sit	6.80	7.20	4.19
230kg	70kg	stand	9.00	9.23	3.44
230kg	76kg	stand	9.00	9.28	3.62

Fig. 5.2. Discussion of human resonant frequency

From the analysis of the graphs when using the percussion drill, a frequency of 70Hz was obtained for all measurement points, a frequency that is found in the studies carried out in [2].

[2]STUDIUL EXPERIMENTAL AL ACȚIUNII VIBRAȚIILOR MAȘINILOR-UNELTE PORTABILE ASUPRA SISTEMULUI UMAN MÂNĂ-BRAT Anamaria BIRIS. Claudiu Alin GLIGOR. Mariana ARGHIR

A XIII-a Conferință Națională multidisciplinară – cu participare internațională,
"Profesorul Dorin PAVEL – fondatorul hidroenergeticii românești",
SEBEȘ, 2013

A rotary impact drill, model STERN Austria, was used for the measurements, with the following characteristics: motor power – 710W; maximum diameter of the drill – 13mm; speed – 0-2400RPM.

It should also be specified that the machine tool is used at maximum speed with a drill of $\Phi = 8\text{mm}$ and a length of 120mm for concrete. The measurements were made in the case of drilling a concrete slab with dimensions 200x600x150mm.

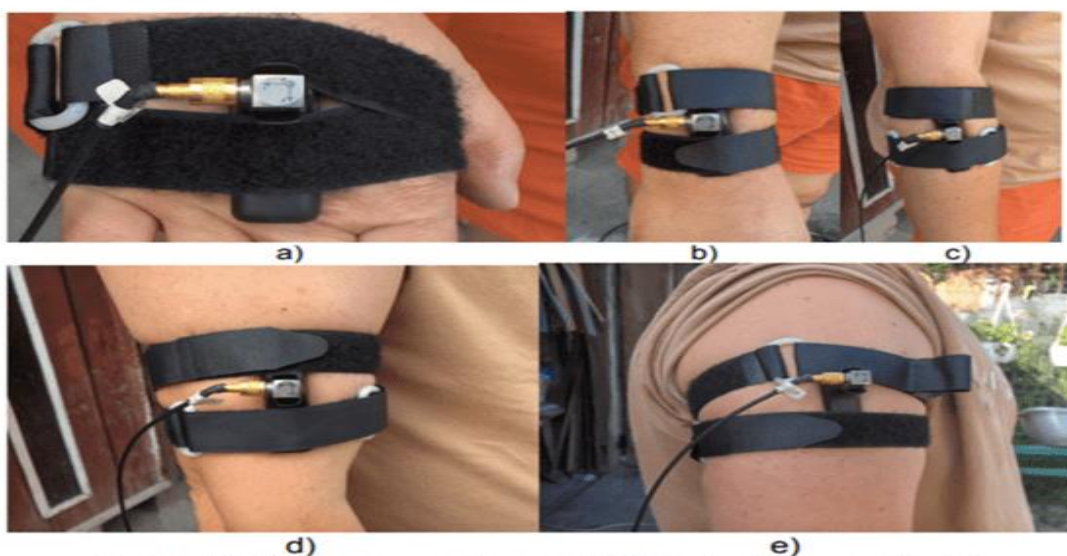


Fig. 5.3. Positioning of the accelerometer on the operator's arm: a) on the hand, b) after the wrist, c) before the elbow, d) after the elbow, e) on the upper part of the arm

On the X-axis: the RMS acceleration measured has significant values, frequencies of 50, 70, 150, 250, 350, 450, 550 and 650Hz, this being attenuated by the hand, remaining a single maximum at 130Hz, after the wrist it translates to 136Hz and by here it undergoes attenuation, disappearing entirely after the elbow.

In future research, the studies will be refined using other equipment that produces vibrations during work and the calibration of the experimental setup will be optimized to obtain results as close as possible to those in the specialized literature.

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