DOI: 10.2478/rjti-2025-0004

ROMANIAN JOURNAL
OF TRANSPORT INFRASTRUCTURE

A FEW CONSIDERATIONS ABOUT THE ACTION OF VIBRATION ON THE HUMAN ELBOW JOINT

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Abstract:

Vibrations produced by modern equipment and machines used at work or in various other situations affect the human body over time. Studies have shown that the organs of our body have a certain resonance frequency. Once this value is reached, the effects of mechanical oscillations on the body are amplified. Since the main gateway for vibrations is the hand-arm assembly, the joints in this area are the first to be affected.

Over time, people have wanted to understand the functioning of their body and the effects of the environment on the body. To simplify the study, attempts have been made to model the human body and its component elements. Thus, theoretical models have been created that imitate the functioning of areas of the human body and that have been subjected to possible situations in everyday life (exposure to vibrations, shocks, travel in rugged areas, overloads, etc.).

The human elbow joint is a pivot joint that connects the arm with the forearm. It is exposed to vibrations that enter the body through the hand due to the manipulation of various machine tools or other vibrating equipment. Due to prolonged exposure to oscillatory phenomena, this joint can function poorly, affecting the circulatory and nervous systems.

This article presents theoretical models and experimental determinations with the help of which the effects of vibrations on the human elbow joint were studied.

Key words: vibrations, elbow, drill, model, experiment

1. INTRODUCTION

Some machinery and equipment used in production activities or on road or building construction sites use mechanical oscillations in the work process. These technical solutions are effective in terms of productivity and reducing the effort required by machine operators. However, over time, workers are affected by the vibrations generated by the tools they use.

People who work in a vibrating environment may have problems with the muscular and skeletal system, both of the hand and arm, neck and back. The mode of transmission of vibration from the machine to the operator is through the hand-arm-forearm system, through the legs (the individual is in a vertical position) or through the buttocks and back (the individual is in a sitting position). In the last two cases, the vibration affects the entire body. [1]

Looking for solutions to protect human operators from the negative effects of mechanical oscillations, various studies and researches have been carried out that follow the body's behavior under the action of vibrations.

Because it is difficult to perform some types of experiments on humans in real time, researchers have sought theoretical models useful in different situations of interest with which to obtain results close to reality.

Beginning in 1953-1954, the first simple biomechanical models for the hand-arm-forearm system were made. More complex models were developed in 1964 by Takahiro Miwa, in 1972 by D. Reynolds and W. Soedel, in 1974 by Suggs and Mishoe. [1] [2] The models they made were composed of masses suspended on rigid springs.

In the years 1996 and 1997, two biomechanical models made by Walter Murel and a group of collaborators are presented, in which the bones of the upper limb are modeled in the form of rigid cylinders. [1] [2]

A four-degree-of-freedom nonlinear model composed of four masses and four pairs of springs and dampers is made in 1998 by Liu, Shi, and Li. They created the model by having access to a series of tensile tests. [1] [2]

In 1996, continuing previous research on the influence of vibrations on the human body, Cherian together with Rakheja and Bhat created a five-degree-of-freedom model for the hand-arm system. [1] [2]

Researchers from Guleph University in Canada (Hussein Abdullah, Cole Tarry, Rahul Datta, Gauri Mittal and Mohamed Abderrahim) published an article in 2007 presenting a dynamic biomechanical model used in the evaluation and monitoring of upper limb therapy, in which the elbow joint had two degrees of freedom. [1] [2]

In his doctoral thesis defended in 2013, A. Picu presented a nonlinear model with three degrees of freedom of the hand-arm system under the action of vibrations, assimilated to a triple pendulum with masses moving in a vertical plane having kinematic restrictions at the free end. [1] [2] [3]

R. Panaitescu-Liess, in 2013, in his doctoral thesis, presented an 8-degree-of-freedom model of the hand-forearm-arm system and calculated its pulsations and natural frequencies using the Matlab program, neglecting damping. [1] [2]

Marco Tarabini, Bortolino Saggin, Diego Scaccabarozzi, Giovanni Moschioni studied the resistance of the hand-arm system under the action of random vibrations (2013). [1] [5]

A group of researchers from the University of Coimbra, Portugal (L.M. Roseiro, M.A. Neto, A.M. Amaro, C.J. Alcobia and M.F. Paulino) studied the behavior of the hand-arm system and the human body under the influence of vibrations resulting from sports activities such as motocross and cycling (2016). [1] [6]

In 2016, Munsur Rahmana, Akin Cil and Antonis P. Stylianou published a study on the elbow joint in which they aimed to create a model that would allow monitoring the behavior of the cartilages of the humerus, ulna and radius during repeated flexion-extension movements. [1] [7]

The transmission mode of vibrations in the human body starting from the hand to the arm, shoulder, back, neck and head was studied by Xueyan S. Xu, Ren G. Dong, Daniel E. Welcome, Christopher Warren, Thomas W. McDowell, John Z. Wu and presented in a paper published in 2017. [1] [8]

In 2021, a study was published by Sooraj Sabu, K.S.R.Varun Teja, Sreejith Mohan, Nivish George, S.P. Sivapirakasam (Department of Mechanical Engineering, National Institute of Technology, Tiruchirappalli, Tamil Nadu, India), in which a biomechanical model of the bent hand-arm system was developed. The purpose of this model was to be able to predict vibration transmissibility when different vibration-damping gloves are used by portable power tool operators. [1] [9]

Zunming Wang, Yi Qiu, Xu Zheng, Zhiyong Hao and Chi Liu presented in a paper published in 2022 a hybrid hand-arm model created to simulate the vibration transmitted from the steering wheel of a forklift to the hand and arm with different gripping forces. The results showed that the developed model that takes into account the grip force and hand-handle contact conditions is able to predict the vibration transmission of the hand-arm system of vehicle drivers. [1] [10]

Following the studies carried out by researchers over time, it was found that vibrations cause damage to the internal organs, the muscular and bone system or psychological effects such as discomfort, fatigue or fear.

This article examines the effect of vibration on the human elbow joint when an operator uses a rotary hammer. This is a common occurrence on road and highway construction sites (Figure 1).

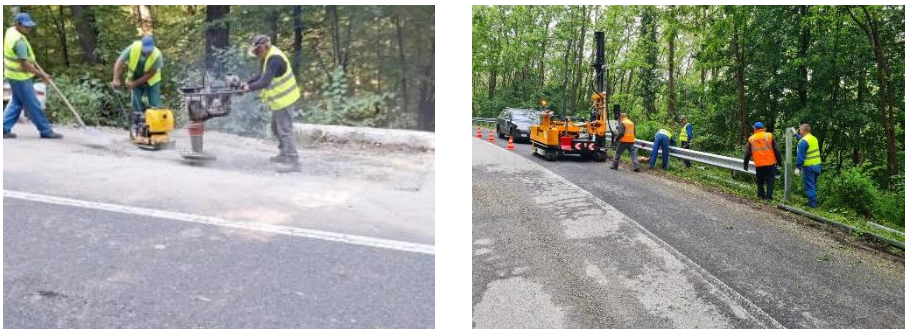

Figure 1. Workers with vibratory equipment on road construction sites [20]

2. THEORETICAL STUDY. CALCULATION MODEL

Pursuing the study of the effect of vibrations on the human elbow from a theoretical and experimental point of view, the author of the article, after reviewing the specialized literature, used a theoretical model with two degrees of freedom of the hand-arm-forearm system. The hand-arm assembly and the forearm were modeled from two cylindrical bodies of mass m_1 and m_2, with radius r_1 and r_2 and length l_1 and l_2. The cylindrical bodies are articulated by a torsion bar of negligible mass, Figure 2. The system is acted upon by the disturbing force F, produced by a rotary hammer. This force is opposed by the resisting moment M from the operator's shoulder. [1] [4]

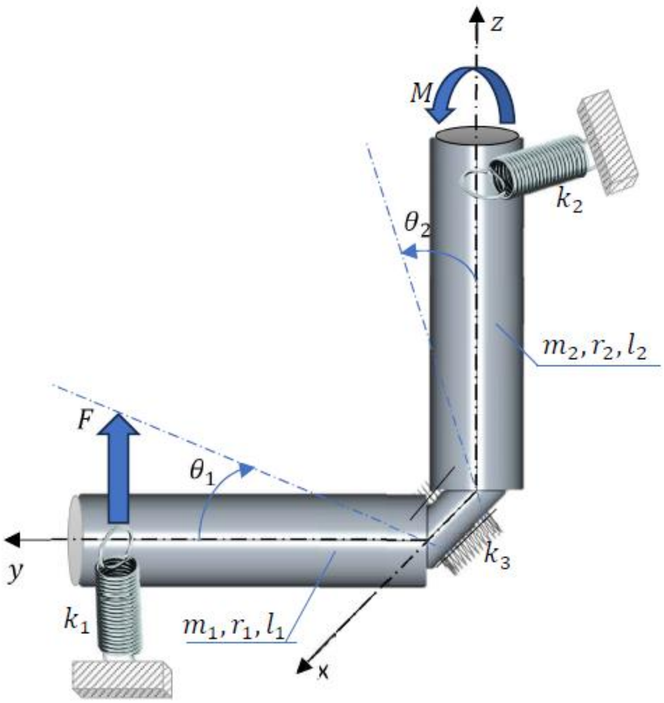

Figure 2 Theoretical model used to study the effects of vibrations on the elbow joint [1]

The differential equations of motion (1) of the model proposed in Figure 2 were determined starting from the Lagrange equations of the second kind. [1]

$$\begin{cases} m_1 \cdot \left[3r_1^2 + l_1^2 + \left(\frac{l_1}{2}\right)^2\right] \cdot \ddot{\theta}_1 + (k_1 \cdot l_1^2 + k_3) \cdot \theta_1 + k_3 \cdot \theta_2 = F \cdot l_1 \cdot sin\omega t \\ m_2 \cdot \left[3r_2^2 + l_2^2 + \left(\frac{l_2}{2}\right)^2\right] \cdot \ddot{\theta}_2 + k_3 \cdot \theta_1 + \left(-\frac{m_2 \cdot g \cdot l_2}{2} + k_2 \cdot l_2^2 + k_3\right) \cdot \theta_2 = M \cdot sin\omega t \end{cases} \quad (1)$$

Note: I specify the fact that the notations used are identical to the consecrated ones, used in the specialized literature.

The system (1) written in a matrix form is:

$$[M]\begin{Bmatrix}\ddot{\theta}_1 \\ \ddot{\theta}_2\end{Bmatrix} + [K]\begin{Bmatrix}\theta_1 \\ \theta_2\end{Bmatrix} = \{H\}sin\omega t \quad (2)$$

To solve it, the assumption is made that the solutions are of the form $x = a_1 sin(pt + \beta)$, $\theta = a_2 sin(pt + \beta)$, which replaced in (2) lead to [1]:

$$[K]\begin{Bmatrix}a_1 \\ a_2\end{Bmatrix} - p^2[M]\begin{Bmatrix}a_1 \\ a_2\end{Bmatrix} = \{0\} \quad (3)$$

WolframAlpha software was used to solve equation (3) and four possible values of pulsation were obtained. The positive values, practically the natural pulsations of the system under consideration, are used in the following for the proposed study. [1]

$$p_{1,2} = \sqrt{\frac{(k_{11} \cdot m_{22} + m_{11} \cdot k_{22} - 2 \cdot k_{12} \cdot m_{12})}{2 \cdot (m_{11} \cdot m_{22} - m_{12}{}^2)} \pm \frac{\sqrt{(k_{11} \cdot m_{22} - m_{11} . k_{22} + 2 \cdot k_{12} \cdot m_{12})^2 - 4 \cdot (k_{11} \cdot k_{22} - k_{12}{}^2) \cdot (m_{11} \cdot m_{22} - m_{12}{}^2)}}{2 \cdot (m_{11} \cdot m_{22} - m_{12}{}^2)}} \quad (4)$$

The anthropometric values used in the theoretical research and in the experimental part correspond to a 43-year-old worker, total mass 104 kg, forearm length 24 cm, arm length 32 cm. The forearm was likened to a cylinder of radius 14 cm and the arm to a cylinder of radius 18 cm. The forearm mass was calculated to be 1.87 kg and the arm mass to be 2.8 kg. The way to calculate the masses and stiffnesses for the upper limb are presented in [1].

For the forearm, the stiffness coefficient is 48.78 kN/m, and for the arm, the coefficient is 73.04 kN/m. The damping coefficient for the arm is 228.07 Ns/m and for the forearm 152.32 Ns/m. The stiffness coefficient k3 has the value of 10.55 kN/m and was determined as the arithmetic mean of some experimental values presented in the literature and in [2]. [1]

The differential equations with the known data were entered into the WolframAlpha program and the natural pulsations of the considered model were determined [1]:

$p_1 = 2{,}56604\ s^{-1}$
$p_2 = 8{,}33947\ s^{-1}$

3. EXPERIMENTAL STUDY. DETERMINATION OF SOME CHARACTERISTIC VIBRATION QUANTITIES

This chapter presents the experimental results obtained through measurements performed with professional sensors in the laboratory and with Arduino sensors outside it. The experiments performed aimed to obtain sets of values for vibration accelerations measured at the human elbow. The measurements were performed on a 43-year-old, right-handed worker, whose anthropometric data were presented in chapter 2. The source of vibrations was a rotary hammer. [1]

The first measurements were carried out in the laboratory of the Research Institute for Construction Equipment and Technologies – ICECON S.A., with the professional vibration sensor (Brüel&Kjaer type 4506-B accelerometer) fixed in turn on a drill and on the operator’s elbow (figure 3). The data were collected when the tool was running idle and during its use to drill materials made of concrete and wood. [1]

The information obtained from the sensors was processed using the LABVIEW program. [1] The experimental results obtained were presented in tables (see Tables 1 and 2), and the graphical representations obtained are the subject of Figures 4 and 5.

Figure 3. Sensor attached to the drill and the operator's elbow [1]
(images from the author's personal archive)

Table 1 Vibration acceleration measured on the elbow with the Brüel&Kjaer type 4506-B accelerometer [1]

Time-Acceleration [s]	x-axis [m/s^2]	y-axis [m/s^2]	z-axis [m/s^2]
0.4248	1.40683	0.935894	0.920813
0.425	1.47544	0.915416	1.03094
0.4252	1.5415	1.00056	1.02126
0.4254	1.5343	0.934267	0.963788
0.4256	1.53794	1.02132	1.01529
0.4258	1.47852	0.996381	0.97502
0.426	1.46178	0.993713	0.990834
0.4262	1.46096	0.963684	0.919981
0.4264	1.48435	1.04246	1.00908
0.4266	1.46952	1.04425	0.970091
0.4268	1.48781	1.01994	0.898603
0.427	1.46852	1.02999	0.952022

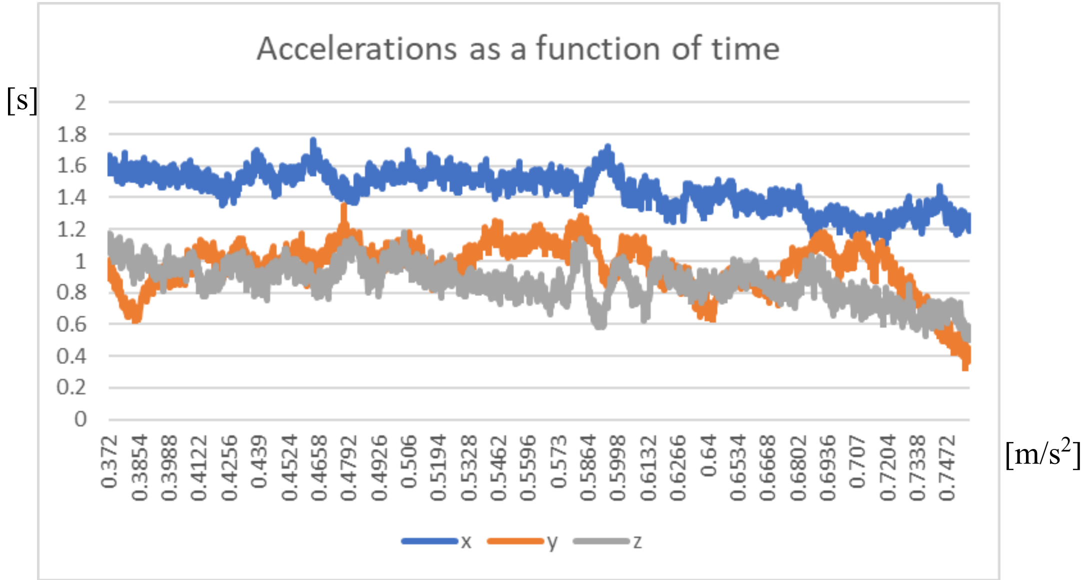

Figure 4. Vibration values recorded with the Brüel&Kjaer type 4506-B sensor

Table 2 Fast Fourier Transform Analysis of previously obtained results [1]

Frequency [Hz]	Amplitude x-axis (FFT - (RMS)) [mm]	Amplitude y-axis (FFT - (RMS)) [mm]	Amplitude z-axis (FFT - (RMS)) [mm]
7.03947	0.00541843	0.0152775	0.00845776
7.10526	0.00380436	0.013974	0.00227259
7.17105	0.00331514	0.0387201	0.00668112
7.23684	0.00276978	0.0462481	0.00988134
7.30263	0.0032487	0.0299106	0.0110239
7.36842	0.00380313	0.0521001	0.0153841
7.43421	0.00309157	0.0714761	0.0145443
7.5	0.00462849	0.0568717	0.00855858
7.56579	0.00497697	0.0802465	0.0135695
7.63158	0.00123053	0.100017	0.0221246
7.69737	0.00194267	0.0852627	0.0216228

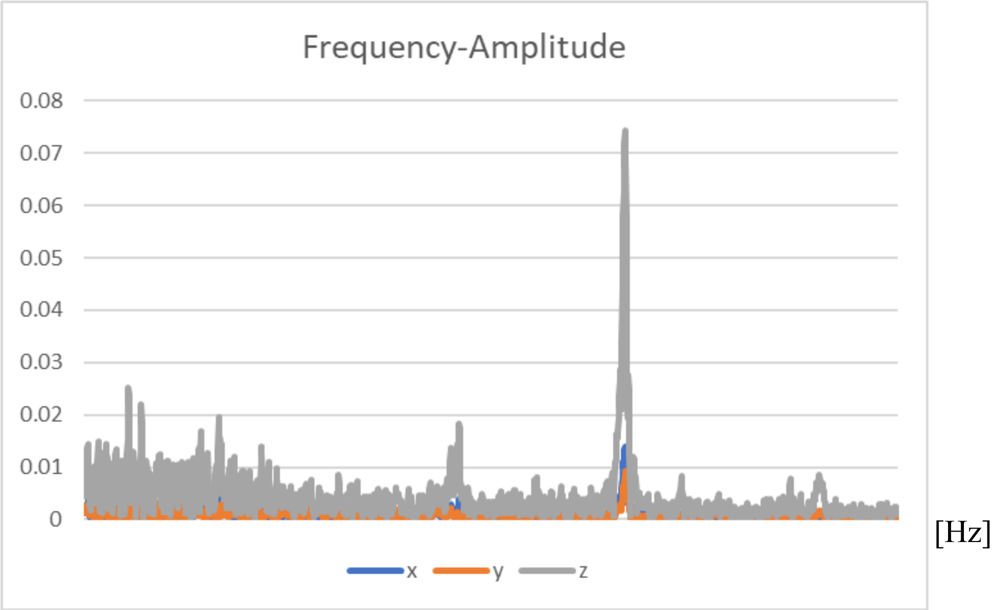

Figure 5. Fast Fourier Transform Analysis

Analyzing the graph in Figure 5, it is found, as expected, that the highest values for the vibration amplitude are recorded on the z-axis, the peak being around 0.075 mm.

A second set of measurements was performed with an Arduino-compatible ADXL345 accelerometer. The test subject, the same one from the ICECON laboratory, operated the drill by repeating the movements in the laboratory. The difference was in the data collection method. Two ADXL345 accelerometers were used, simultaneously fixed on the operator's elbow and on the drill. The information from the sensors was collected via Arduino Uno R3 boards and transmitted to a laptop. Data processing was done with Microsoft Excel. [1] The information is presented in tables (Table 3) and graphs (Figure 6).

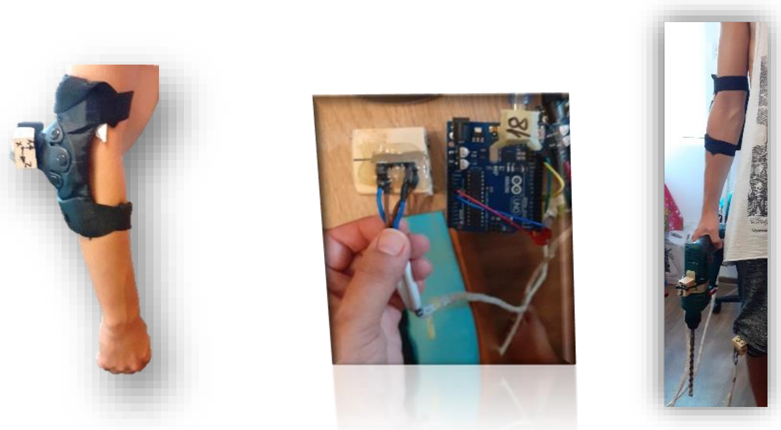

Figure 6. Arduino experiment – sensor arrangement [1]

(images from the author's personal archive)

Table 3 Acceleration measured on the three axes, 90° angle, with the ADXL345 sensor, [m/s²] [1]

20:27:39.961 -> Xa= 3.78 Ya= -1.28 Za= 6.16	20:27:45.225 -> Xa= 5.06 Ya= -0.09 Za= 4.97
20:27:40.162 -> Xa= 3.78 Ya= -1.28 Za= 6.19	20:27:45.426 -> Xa= 1.34 Ya= -4.25 Za= 7.22
20:27:40.324 -> Xa= 3.84 Ya= -1.28 Za= 6.16	20:27:45.627 -> Xa= 4.31 Ya= -2.47 Za= 6.69
20:27:40.563 -> Xa= 3.81 Ya= -1.37 Za= 6.16	20:27:45.828 -> Xa= 4.66 Ya= 2.16 Za= 5.22
20:27:40.764 -> Xa= 3.88 Ya= -1.19 Za= 6.13	20:27:46.029 -> Xa= 1.25 Ya= -1.69 Za= 6.78
20:27:40.965 -> Xa= 4.47 Ya= -0.56 Za= 6.34	20:27:46.218 -> Xa= 5.22 Ya= -3.00 Za= 6.41
20:27:41.127 -> Xa= 1.69 Ya= -4.47 Za= 7.81	20:27:46.431 -> Xa= 5.63 Ya= -1.75 Za= 5.09
20:27:41.366 -> Xa= 1.47 Ya= 0.91 Za= 7.22	20:27:46.631 -> Xa= 1.37 Ya= 0.88 Za= 7.13

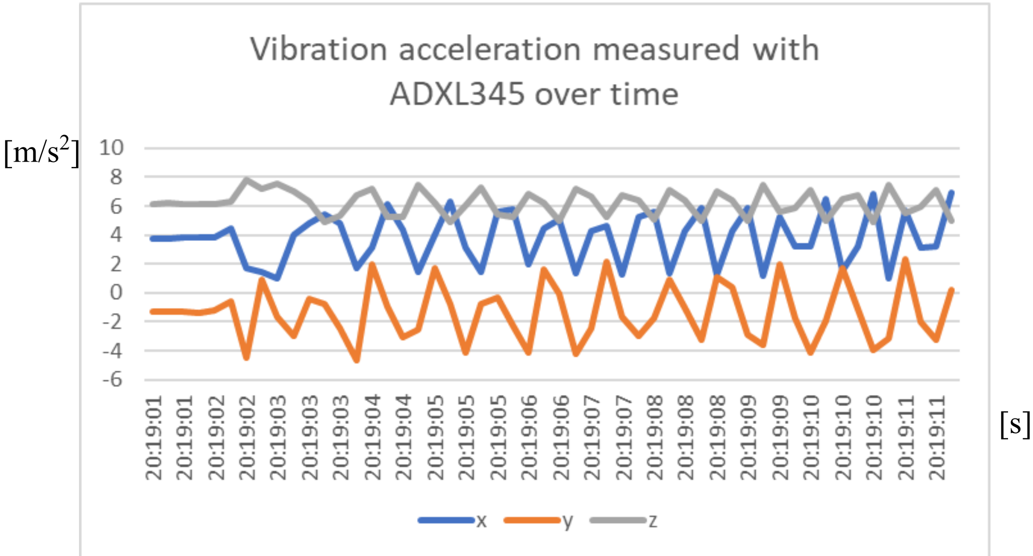

Figure 7. Received data from ADXL345 sensor

4. CONCLUSIONS

Following the experiments performed, we found that the results obtained from measurements with professional and non-professional sensors were close to the values calculated based on the theoretical model. The two types of accelerometers used had close average values on the x and y axes. The calculated errors were around 2.16%.

Thus, it can be considered that we can obtain credible results either using the theoretical model or by making in situ measurements using accelerometers. It is important that, following the results obtained, the appropriate protective measures are applied. If the operator is exposed to high values of vibrations generated by the rotary hammer machine, protective measures such as gloves, frequent breaks, etc. are required to reduce their harmful effect on the elbow.

The author of the article aims to continue the study of the negative effects of vibration phenomena on the elbow joint and to identify possible effective protective measures.

REFERENCES

[1] STĂNESCU (DOGARU), M.G. *Biomechanical modeling of human body joints under the action of mechanical vibrations*, PhD Thesis, Bucharest, **2022**

[2] PANAITESCU-LIESS, R. *Biomechanical modeling of the human body under the action of vibrations*, PhD Thesis, Bucharest, **2013**

[3] PICU, A.A., *Nonlinear biomechanical modeling of human body dynamics under the action of transmitted vibrations*, PhD Thesis, **2010**

[4] DOGARU, M.G., LEGENDI, A., PAVEL, CR., PANAITESCU-LIESS, R. *Vibrations of the forearm-arm system modeled as a biomechanical model with two degrees of freedom*, Article, Journal Sinteze de Mecanică Teoretică și Aplicată, vol. IX, **2018**, nr. 2, Publishing house MatrixRom, Bucharest, ISSN 2068-6331

[5] MARCO TARABINI, BORTOLINO SAGGIN, DIEGO SCACCABAROZZI, GIOVANNI MOSCHIONI, *Hand-arm mechanical impedance in presence of unknown vibration direction,* International Journal of Industrial Ergonomics 43, **2013,** 52e61, www.elsevier.com/locate/ergon

[6] ROSEIRO L.M., NETO M.A., AMARO A.M., ALCOBIA C.J., PAULINO M.F., *Hand-arm and whole-body vibrations induced in cross motorcycle and bicycle drivers,*

International Journal of Industrial Ergonomics 56, **2016**, 150e160, www.elsevier.com/locate/ergon

[7] MUNSUR RAHMAN, AKIN CIL, ANTONIS P. STYLIANOU, *Prediction of elbow joint contact mechanics in the multibody framework,* Medical Engineering and Physics 38, **2016**, 257–266, www.elsevier.com/locate/medengphy

[8] XUEYAN S. XU, REN G. DONG, DANIEL E. WELCOME, CHRISTOPHER WARREN, THOMAS W. MCDOWELL, JOHN Z. WU, *Vibrations transmitted from human hands to upper arm, shoulder,back, neck, and head.* International Journal of Industrial Ergonomics 62, **2017**, 1e12, www.elsevier.com/locate/ergon

[9] SOORAJ SABU, K.S.R. VARUNTEJA, SREEJITH MOHAN, NIVISH GEORGE, S.P. SIVAPIRAKASAM, *A biomechanical model to predict hand-arm vibration when using different vibration damping gloves*, Materials Today: Proceedings, Volume 56, Part 6, **2022**, Pages 3527-3533, Elsevier, https://doi.org/10.1016/j.matpr.2021.11.239

[10] ZUNMING WANG, YI QIU, XU ZHENG, ZHIYONG HAO, CHI LIU, *Biomechanical models of the hand-arm system to predict the hand gripping forces and transmitted vibration*, International Journal of Industrial Ergonomics, Volume 88, March **2022**, 103258, https://doi.org/10.1016/j.ergon.2021.103258

[11] PANAITESCU-LIESS R., LEGENDI A., PAVEL C. *Analysis of a mechanical system's dynamic properties by vibrations measurements* - 34rd National Conference on Mechanics of Solids, 16-18 September 2010, Reșița (Annals of the University "EFTIMIE MURGU" Resiţa, anul XVII, nr. 1, **2010**, ISSN 1453 – 7397, p. 39-44

[12] TOADER D., DOGARU M., URSACHE R., BAUŞIC F. *Partial experimental contributions on the validation of biomechanical models of the human body subjected to the action of mechanical vibrations,* Article. Journal of Modeling in Civil and Environmental Engineering, vol. 16, nr. 4/**2021**, pag. 25-33, ISSN: 2784-1391

[13] STĂNESCU, M.G., *Biomechanical models proposed for the study of elbow and knee joints under the action of vibrations.* Research Report no. 2, Bucharest, **2015**

[14] PANAITESCU-LIESS, R., *Experimental research on the influence of vibration on elbow mobility*, Scientific Bulletin of the Technical University of Civil Engineering Bucharest, **2013**, p. 55

[15] PANAITESCU-LIESS, R. *A Comparative study about the Influence of Vibration on Elbow Joint Mobility*, Annals of the University "Eftimie Murgu" Reşiţa, Anul XXI, nr. 1, **2014**, ISSN 1453 – 7397, p. 307-310

[16] PAVEL, C., CONSTANTINESCU, A. *Mechanical vibrations*, Publishing house Matrix Rom, Bucharest, **2009**, ISBN 978-973-755-468-0

[17] MAGHEȚI, I., SAVU, M., *Mechanical vibrations. Theory and practice*, ISBN 973-648-389-4, Publishing house BREN, Bucharest, **2004**

[18] DIACONU, CR., PAVEL, CR., BAUȘIC, F., STOICESCU, D., *Mechanical vibrations. Homework.* U.T.C.B., Bucharest, **1998**

[19] BRATU, P., *Mechanical vibrations. Theory and technical applications*, ISBN 973-98409-5-7, Publishing house Impuls, Bucharest, **1998**

[20] https://mesageruldesibiu.ro/tag/drumuri-si-poduri/

[21] https://www.bksv.com/en/products/transducers/vibration/accelerometers/4506-B-003

[22] www.robofan.ro – Arduino for the beginners

[23] https://www.hse.gov.uk/vibration/wbv/calculator.htm

[24] https://doi.org/10.1016/j.matpr.2021.11.239

[25] https://doi.org/10.1016/j.ymssp.2021.108513

[26] https://doi.org/10.1016/j.ergon.2021.103258