THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI
FASCICLE IX. METALLURGY AND MATERIALS SCIENCE
N°. 1 - 2025, ISSN 2668-4748; e-ISSN 2668-4756
Article DOI: https://doi.org/10.35219/mms.2025.1.01

SOME ASPECTS REGARDING THE ACTION OF VIBRATIONS ON THE HUMAN KNEE JOINT

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ABSTRACT

Machines that use vibrations in the work process are found in various activities, on construction sites or within the premises of some constructions. Their operators are affected over time by mechanical oscillations. Entering the body through the hand-arm assembly, through the legs, or while sitting, the vibrations affect the human body, usually in a negative way. The positive effects are currently being studied in order to be able to improve various human joint conditions or to improve physical condition, but exposure must be done in a controlled environment and under well-established conditions defined by specialists.

Over time, various studies have been carried out and solutions have been sought to reduce the effects of vibrations on the human body. The difficulty of performing in vivo experiments on people has led to the use of increasingly complex theoretical models to study the problem. By comparing the results obtained from modeling with experimental results collected through measurements under different conditions on the construction site or in the laboratory, useful information was obtained, which can be used to improve the working conditions of workers.

The search for a theoretical model as efficient as possible, and for methods as fast as possible to obtain information about the vibrations that affect the human body, is ongoing, the human body being very complex and difficult to model.

This article investigates the effect of mechanical oscillations on the knee joint of rotary hammer operators, comparing results obtained through laboratory measurements with those obtained from modeling.

KEYWORDS: mechanical oscillations, rotary impact machine, knee joint

1. Introduction

A wide variety of rotary hammer machines are used both on open-air organized construction sites and within the premises of new constructions or those that are being rehabilitated. Their excessive use can produce vibrations with harmful effects on the bodies of their operators.

Oscillatory movements enter the human body through the hand-arm system, while sitting, or through the legs.

Each individual responds differently to the influence of vibrations. Among the relevant factors tare: age, tolerance to oscillations, state of health, etc.

Research conducted over time has shown that the internal organs of the human body have their own natural oscillation frequencies, and the effect of vibrations on the human body can be amplified due to resonance [1].

The lower limb, like the internal organs, can be affected by vibrations generated by the equipment used by humans. One of its joints, the human knee, is a complex joint that connects the thigh to the calf. It is a pivoting joint with the ability to bear weight [2]. Exposure to vibration affects this joint over time. Depending on the duration of exposure and the frequency of oscillations, there may also be some positive effects.

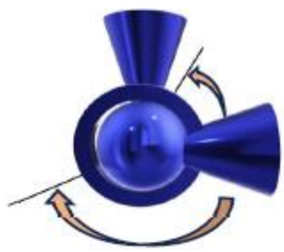

Fig. 1. *The knee joint* [2, 5]

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Studies conducted over time have mainly focused on the negative effects of vibrations and how to protect operators.

In papers [3] and [4], a 3D model with 12 degrees of freedom for the human knee was proposed for studying movement and analysing the forces acting on it [2].

Human gait and the effects of body weight on it were the subjects of research conducted by Anne E. Martin and James P. Schmiedeler in 2014 and by Stefan Seiterle, Tyler Susko, Panagiotis K. Artemiadis, Robert Riener, and Hermano Igo Krebs in 2015 [2].

A 2016 study on human fall risk by Anne E. Martin, Dario J. Villarreal and Robert D. Gregg led to the development of a kinematic model of the human knee that can be integrated into a complex gait model [2, 6].

Akio Yamamoto, Shun Sasagawa, Naoko Oba and Kimitaka Nakazawa (2015), as well as Hyunggwi Song, Heewon Park, and Sukyung Park (2016), presented pendulum-type models of the lower limb in their published works, designed to investigate human gait [2, 7, 8].

An article published in 2018 by Raj Desai, Anirban Guha, and P. Seshu, researchers at the Indian Institute of Technology Bombay, Department of Mechanical Engineering, presents a biomechanical model of a seated individual with 20 degrees of freedom. The model was created to study the effects of low-frequency vibrations on the human body during the operation of heavy machinery and various vehicles [2, 9].

Raynaud's syndrome, a condition resulting from exposure to vibrations in the upper and lower limbs, affects the vascular and neurological systems. This condition manifests as numbness, tingling, and whitening of the toes or fingers. The problem was studied by Goggins, Tarabini, et al. in 2019, who sought to identify the resonance frequencies of different areas of the human foot in a natural position. The same topic was also researched by D. Chadefaux et al. in 2020, whose results may lead to the development of new materials and improvements in equipment designed to attenuate vibrations transmitted through the feet [2, 10].

Vibrations can have beneficial effects on the knee joint and the human body under certain well-defined conditions. Studies conducted in recent years have followed this line of research, particularly in the medical field.

In order to reduce the negative effects of vibrations (typically through damping or isolation) it is first necessary to determine the levels of certain vibration characteristics.

The authors propose to measure, as accurately as possible, the level of vibrations acting on the operator’s knee joint while using a rotary hammer.

Fig. 2. *Rotary impact machine used to perforate various materials* [13]

2. Theoretical model

Reviewing the models presented in the literature, the authors considered it appropriate to study the effect of vibrations on the knee joint using a physical double pendulum model (Figure 3), in which the lower leg and foot are modeled as an articulated bar connected to a bar representing the thigh. Two disturbing forces, F_1 and F_2, were assumed to act on the double pendulum.

To dampen vibrations and limit displacement, two pairs of elastic springs were placed at the centres of gravity of the bars [2].

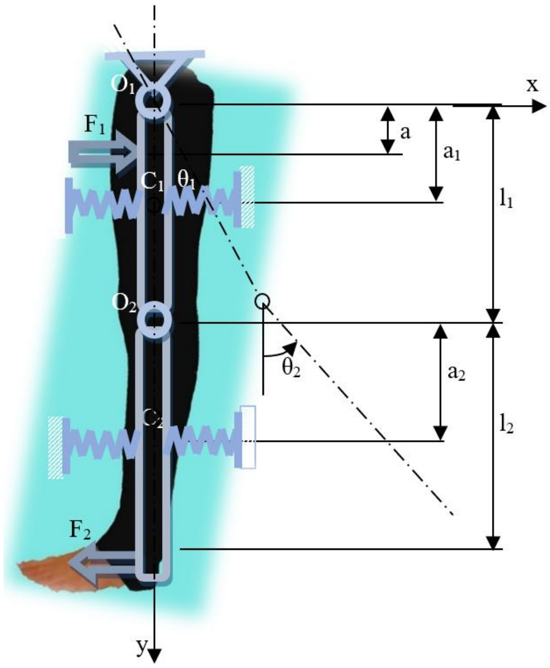

Fig. 3. *Theoretical calculation model* [2]

In order to achieve the proposed goal -namely, the determination of the pulsations of the considered

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system and the application of real values in the study - Lagrange's equations of the second kind were used.

The differential equations of the mechanical system in Figure 3, in matrix form, are presented in equation (1). It should be noted that the notations used are identical to those commonly found in the specialized literature.

After performing the calculations, we obtained the equation of the natural pulsations, given in equation (2).

In order to solve the equation of the natural pulsations, we started from the following anthropometric data presented in Table 1.

The estimated values for the position of the centre of gravity for the thigh (a_1) is 21.65 cm, and for the calf and foot (a_2) is 23.81 cm. The hip and knee joints were denoted by O_1 and O_2; C_1 – the centre of gravity of the thigh; C_2 – the centre of gravity of the calf and foot.

Using dedicated vibration sensors, measurements were made on a single person operating a rotary hammer (the source of vibration). Data collection was performed by attaching the accelerometer, alternately, to the drill and to the knee of the person operating the tool. Tests were performed while the drill was running idle and then when it was being used to perform various operations.

The measurements were made with professional vibration sensors, typically used in demanding static situations scenarios.

The operator's anthropometric data were identical to those used in the calculation aimed at determining the intrinsic pulsations (see Table 1, Chapter 2).

$$\begin{bmatrix} \frac{m_1 l_1^2}{3} + m_2 l_1^2 & m_2 l_1 a_2 \\ m_2 l_1 a_2 & \frac{m_2 l_2^2}{12} + m_2 a_2^2 \end{bmatrix} \begin{Bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{Bmatrix} + \begin{bmatrix} m_1 g a_1 + m_2 g l_1 + 2k_1 a_1^2 + 2k_2 l_1^2 & 2k_2 l_1 a_2 \\ 2k_2 l_1 a_2 & m_2 g a_2 + 2k_2 a_2^2 \end{bmatrix} \begin{Bmatrix} \theta_1 \\ \theta_2 \end{Bmatrix} = \begin{Bmatrix} F_{01} a \\ F_{02} l_2 \end{Bmatrix} sin\omega t \tag{1}$$

$$\left[(m_1 g a_1 + m_2 g l_1 + 2k_1 a_1^2 + 2k_2 l_1^2) - \left(\frac{m_1 l_1^2}{3} + m_2 l_1^2\right) \cdot p^2\right] \cdot \left[(m_2 g a_2 + 2k_2 a_2^2) - \left(\frac{m_2 l_2^2}{12} + m_2 a_2^2\right) \cdot p^2\right] - (2k_2 l_1 a_2 - m_2 l_1 a_2 p^2)^2 = 0 \tag{2}$$

Table 1. *Anthropometric dimensions of the operator* [2]

Total mass [kg]	Thigh mass [kg]	Calf mass [kg]	Foot mass [kg]	Calf and foot mass [kg]	Thigh height, l1 [m]	Calf height [m]	Foot height [m]	Calf and foot height, l2 [m]	Total height [m]	Leg length, l_p [m]
104	10.5	5.61	1.97	11.05	0.5	0.47	0.08	0.55	1.71	0.26

The estimates were made starting from the total mass of the individual and from the dimensions of the lower limb segments, according to [4].

After substituting the values presented above, the pulsation equation is obtained in the form:

$$(244.127 - 3.638 \cdot p^2) \cdot (55.431 - 0.863 \cdot p^2) - (66.302 - 1.271 \cdot p^2)^2 = 0$$

The values of the system's natural pulsations, obtained by solving the equation using Wolfram Alpha software, satisfying the specified conditions (positive values, see [4]), are: $p_1 = 7{,}74089\ s^{-1}$ and $p_2 = 10{,}0018\ s^{-1}$.

3. Experimental determinations

Within the Research Institute for Construction Equipment and Technologies - ICECON S.A., the necessary measurements for the experimental part of the study were performed.

The 4506-B-003 Brüel & Kjaer sensor was used for most tests. To improve sensitivity in data collection from the knee joint area, the HVA-4447 sensor was used.

Fig. 4. *Sensors used for measurements* [2]

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Fig. 5. *The operator during the tests* [2]
(images taken from a personal archive)

Measurements were performed in a controlled environment, with the 4506-B-003 Brüel & Kjaer sensor mounted on the knee. Acceleration values and the Fast Fourier Transform response to the signal received from it are presented in Tables 2 and 3, and in Figures 6 and 7.

Table 2. *Acceleration signal measured over time with 4506-B 003 Brüel&Kjaer* [2]

axis x		axis y		axis z	
Time - Acceleration_0		Time - Acceleration_1		Time - Acceleration_2	
0	1.96864	0	1.53548	0	0.952996
0.0002	1.99453	0.0002	1.5684	0.0002	0.843923
0.0004	1.94018	0.0004	1.55931	0.0004	0.891622
0.0006	1.93933	0.0006	1.51778	0.0006	0.989659
0.0008	2.01936	0.0008	1.54625	0.0008	0.873572

Table 3. *Frequency spectrum analysis for data collected by the sensor 4506-B 003 Brüel&Kjaer* [2]

axis x Frequency - Acceleration_0 (FFT - (RMS))		axis y Frequency - Acceleration_1 (FFT - (RMS))		axis z Frequency - Acceleration_2 (FFT - (RMS))	
28.3088	0.000375	28.3088	0.0037335	28.3088	0.0019797
28.3824	0.001598	28.3824	0.0034778	28.3824	0.0020299
28.4559	0.0014465	28.4559	0.003396	28.4559	0.0007455
28.5294	0.0011605	28.5294	0.0035702	28.5294	0.0018432
28.6029	0.0005488	28.6029	0.0037101	28.6029	0.0016722

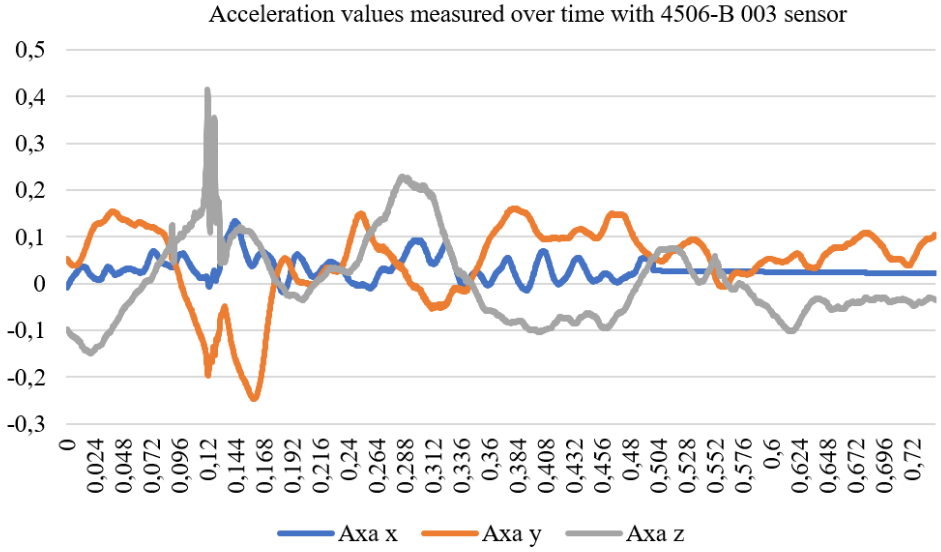

Fig. 6. *Results obtained when measuring acceleration with the Brüel&Kjaer 4506-B 003 sensor located on the operator's knee*

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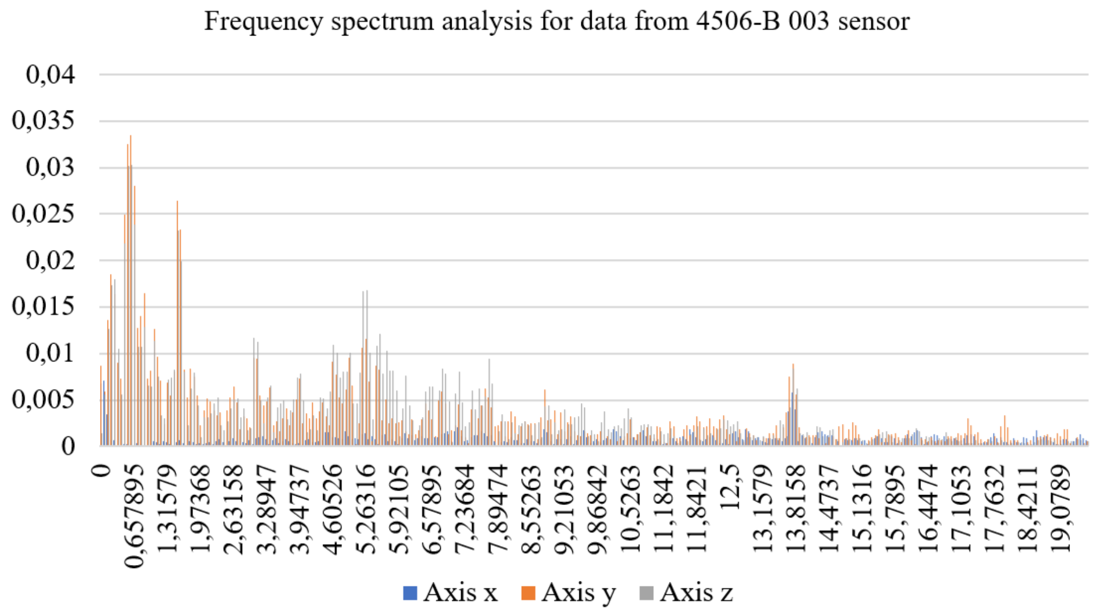

Fig. 7. *Frequency spectrum analysis for data obtained with Brüel&Kjaer 4506-B 003 sensor*

Table 4. *Acceleration signal measured over time with HVA 4447 sensor* [2]

axis x		axis y		axis z	
Time - Acceleration_0		Time - Acceleration_1		Time - Acceleration_2	
0	-0.0081065	0	0.0530285	0	-0.0993299
0.0002	-0.00726	0.0002	0.0528431	0.0002	-0.0981359
0.0004	-0.0061183	0.0004	0.0513116	0.0004	-0.0997383
0.0006	-0.0050573	0.0006	5.07E-02	0.0006	-0.0986921
0.0008	-0.0039561	0.0008	0.0508645	0.0008	-0.100873

Table 5. *Frequency spectrum analysis for data collected by the sensor HVA 4447* [2]

axis x		axis y		axis z	
Frequency - Acceleration_0 (FFT - (RMS))		Frequency - Acceleration_1 (FFT - (RMS))		Frequency - Acceleration_2 (FFT - (RMS))	
28.1579	0.0003477	28.1579	0.0005003	28.1579	0.00157591
28.2237	0.0005421	28.2237	3.33E-04	28.2237	0.000648375
28.2895	0.000567	28.2895	0.0006668	28.2895	0.00149551
28.3553	0.0002332	28.3553	0.00072	28.3553	0.00193745
28.4211	1.20E-04	28.4211	4.32E-04	28.4211	0.000947946

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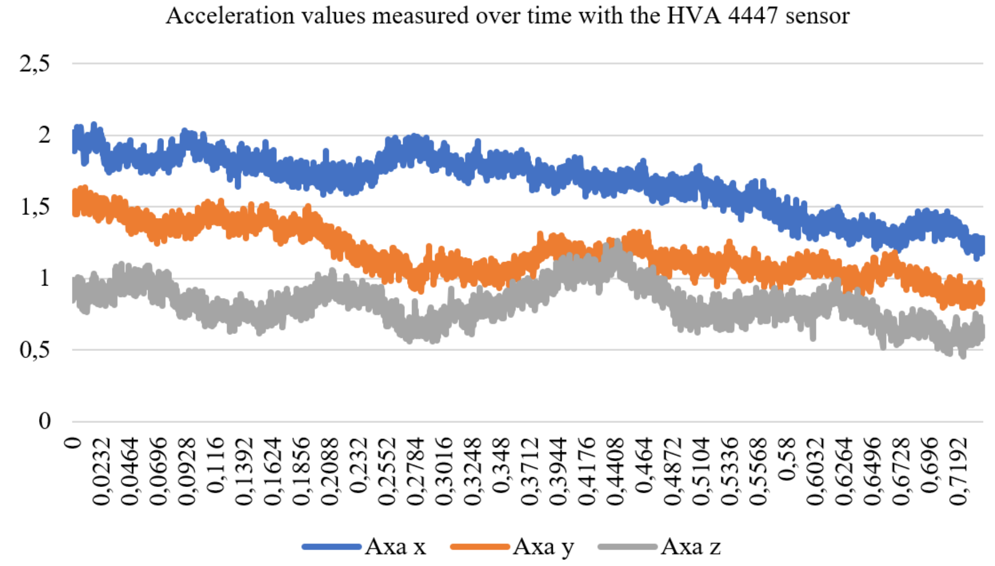

Fig. 8. *Results obtained when measuring acceleration with the HVA 4447 sensor located on the operator's knee*

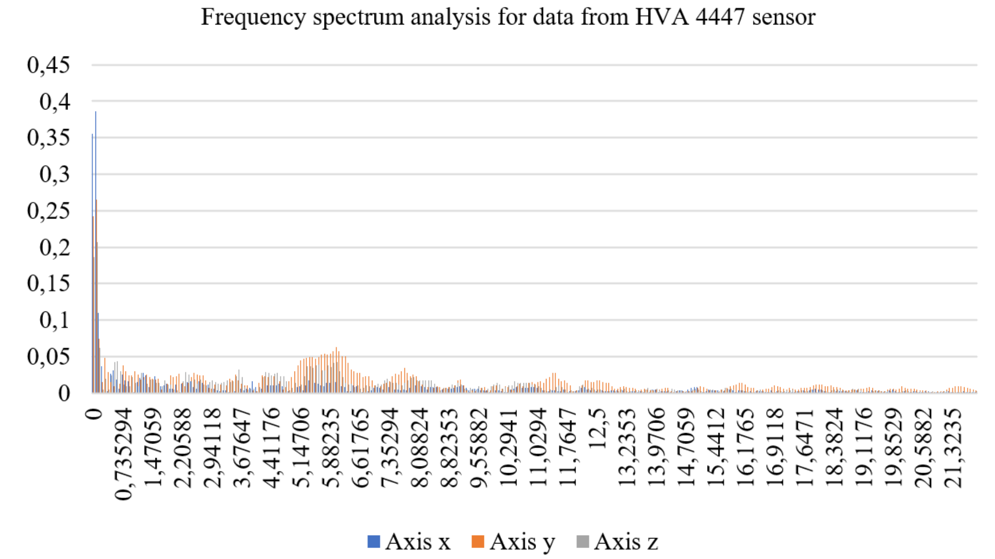

Fig. 9. *Frequency spectrum analysis for data obtained with HVA 4447 sensor*

Considering that a sensor with higher sensitivity (below 10 Hz) was needed, the HVA 4447 accelerometer was used for a new set of measurements. The values obtained for accelerations with this type of sensor and the Fast Fourier transform response to the signal are presented in Tables 4 and 5 and in Figures 8 and 9.

4. Validation of the theoretical model

The determinations made with the two types of sensors, on the drill and on the operator, validated the theoretical model to a good extent, the errors being in the range of 2% - 3%.

With the Brüel&Kjaer 4506-B 003 sensor, an average acceleration of 23.61 m/s^2 was obtained at idle.

The average acceleration values, measured with the HVA 4447 sensor, were 9.24 m/s^2 (idle running); 5.22 m/s^2 (in wood); and 5.64 m/s^2 (in concrete).

5. Conclusions

In several previous studies, the authors attempted to perform the same determinations, but on

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the human elbow joint. It was found with certainty that the effect of vibration phenomena on the elbow is more significant than on the knee.

Vibrations generated by rotary hammers can affect knee health, especially for operators who are frequently and long-term exposed to this type of vibration. It is important for both employers and workers to adopt preventive measures to protect joints and reduce the risk of illness.

Reducing the negative effects of vibrations in the knee area can be achieved by using appropriate protective equipment (footwear, knee protectors), regular breaks for workers and proper operator training to use the machine tool efficiently and with minimal health risks.

We believe that in one of the following articles it is imperative to review the most widespread actions taken to combat and prevent the negative effects of vibrations.

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