CONSIDERATIONS REGARDING THE EFFECTS OF SHOCKS AND VIBRATIONS ON OPERATORS OF SELF-PROPELLED AGRICULTURAL EQUIPMENT
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CONSIDERATIII PRIVIND EFECTELE ŞOCURILOR ŞI VIBRAŢIILOR ASUPRA OPERATORILOR UTILAJELOR AGRICOLE AUTOPROPULSATE

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ABSTRACT

Vibrations are part of the category of dynamic phenomena and are manifested in some environments as a consequence of an external excitation in the form of oscillations. These oscillations have negative effects on the environment in which they manifest. In the particular case where the environment is represented by the human body, the negative effects are felt at the level of its health, and the consequences are sometimes irreversible. In this context, it is necessary to study and know the effects that vibrations have on the human body. The main purpose of researches carried out in this field is to establish the limit up to which man can work in environments that generate vibrations, without the vibrations affecting his state of health.

REZUMAT

Vibraţiile fac parte din categoria fenomenelor dinamice și se manifestă în unele medii ca și consecință a unei excitaţii exterioare sub forma unor oscilaţii. Aceste oscilații au efecte negative asupra mediului în care se manifestă. În cazul particular în care mediul este reprezentat de corpul uman, efectele negative se resimt la nivelul sănătății acestuia, iar consecinţe sunt uneori ireversibile. În acest context, se impune necesitatea studierii şi cunoaşterii efectelor pe care le au vibraţiile asupra corpului uman. Scopul principal al cercetărilor realizate în acest domeniu este stabilirea limitei până la care omul poate lucra în medii generatoare de vibraţii, fără ca vibrațiile să îi afecteze starea de sănătate.

INTRODUCTION

Vibrations are dynamic phenomena that occur in elastic or quasi-elastic environment, after a local excitation; they behave as elastic oscillations as the excitation propagates throughout the environment (*Broch J.T., 1984*). The excitation, propagation, and radiation of an elastic wave can be studied if the environment has at least one geometric dimension big enough that the initial excitation can be regarded as local.

Vibrations are classified according to their direction, frequency, magnitude, and duration (*van Heuvelen et al., 2021*). The factors that influence the definition of the vibratory phenomenon allow for a broad classification of oscillations and elastic waves. Thus, depending on the dynamics of the phenomena, vibrations with low variation frequencies, such as those seen in mechanical structures, building structures, and seismic waves, exist alongside vibrations with high variation frequencies.

The physical nature of the environment determines how the oscillations propagate: in a solid environment, both transverse and longitudinal waves can propagate, whereas only longitudinal waves can propagate in a fluid environment (*Buzdugan Gh., 1982*).

In agriculture, the interaction between the tires of agricultural machines and the ground produces shocks and vibrations whose emission levels are significantly influenced by both the unevenness of the land and the nature of the agricultural work (*Pochi et al., 2022*), as well as by the constructive characteristics of the agricultural machine (*Nguyen and Inaba, 2011*; *Stojic et al., 2017*).

Vibrations are transmitted to the operator's body through various points of contact between him and the agricultural machine: steering wheel, seat, levers, pedals and especially the floor of the machine (*Biriș et al., 2022*).

Among the hazards to which operators of self-propelled agricultural machinery are subjected, the physical element arising from mechanical vibrations stands out (*Lima et al., 2023*). Researchers around the world have conducted extensive studies on the long-term exposure of agricultural machinery operators to shocks and vibrations (occupational exposure), which has negative consequences from the perspective of human health risks and from a socio-economic perspective (*Litchfield M.H., 1999*).

Many tractors emit vibrations above the exposure action value recommended by the Directive 2002/44/CE (by 0.5 m/s^2). Low frequency vibrations in the 1–10 Hz range are considered to have substantial adverse effects on human health (*Liang and Chiang, 2008*). Even vibrations with a frequency lower than 2 Hz can affect human health, to some extent or for short periods of time, because they cause motion sickness, felt by the operator of the agricultural machine as a discomfort that affects his working capacity (*Cutini et al., 2017*). The critical frequencies emitted by the moving tractor are usually in the range of 1–7 Hz, which are similar to the natural frequencies of different parts of the human body (*Kumar et al., 2001*).

Because of these critical frequencies, tractor operators are mainly at risk of developing musculoskeletal problems (*Punnett and Wegman, 2004*), the most affected being the lumbar region of the spine (*Prakash et al., 2013; Essien et al., 2018*). These spinal problems worsen when the operator works in difficult conditions (uncomfortable positions, non-ergonomic seats, repeated manual handling of weights, etc.) (*EU-OSHA, 2005*). The prolonged exposure of operators to vibrations in the 2–20 Hz range has been demonstrated to induce spinal degenerative diseases (*Okunribido et al., 2006*).

Some hand-held agricultural equipment creates high levels of vibrations, which are conveyed to the operators' arms, putting them at risk of developing hand and arm vibration syndrome, which affects the upper limb systems (musculoskeletal, neurological, and vascular) (*Bovenzi M., 1998*).

In addition to concerns for increasing the functional performance of agricultural machines, the designers and manufacturers of agricultural machines constantly make substantial efforts to limit the exposure of agricultural operators to vibrations (*Singh et al., 2022; Vlăduţ et al., 2013; Sorică et al., 2017)*. They are constantly looking for solutions to improve the comfort of the tractor operator, by designing and implementing ergonomic solutions such as active seats, front suspensions or cab suspension systems (*Cutini et al., 2017; Cârdei et al., 2023; Vlăduţ et al., 2014*).

These efforts are supported by standards and norms that regulate / establish certain limits regarding the exposure of the whole body to mechanical vibrations and repeated shocks (*SR EN ISO 13090-1*, *2002*; *ISO 5008*, *2002*; *SR EN ISO 10819:2013/A1, 2019*; *SR EN ISO 10819:2013/A2, 2023*; *ISO 2631-1, 2001*; *ISO 2631-5, 2018*).

MATERIALS AND METHODS

- **Vibration of the entire body**

The human body is a psychical and biological "system" of extraordinary complexity. It has a lot of linear and non-linear "elements" when seen as a mechanical system, and its mechanical qualities vary greatly from person to person.

From a biological standpoint, the situation is complicated, especially when psychical impacts are included. When considering the human response to vibrations and shocks, it is vital to consider both mechanical and psychical impacts (*Broch J.T., 1984*).

Because human body experiments are complex and time-consuming, the majority of available data has come from animal experiments. Of course, it is not always practical to compare the results of animal tests with the reactions predicted from humans, but such investigations frequently yield significant information.

At low vibration frequencies and levels, the human body, considered as a mechanical system, can be roughly approximated by a linear system of grouped parameters, as shown in Figure 1. The "thorax-abdomen" system appears to be one of the most essential parts of this system in terms of the impacts of vibrations and shocks.

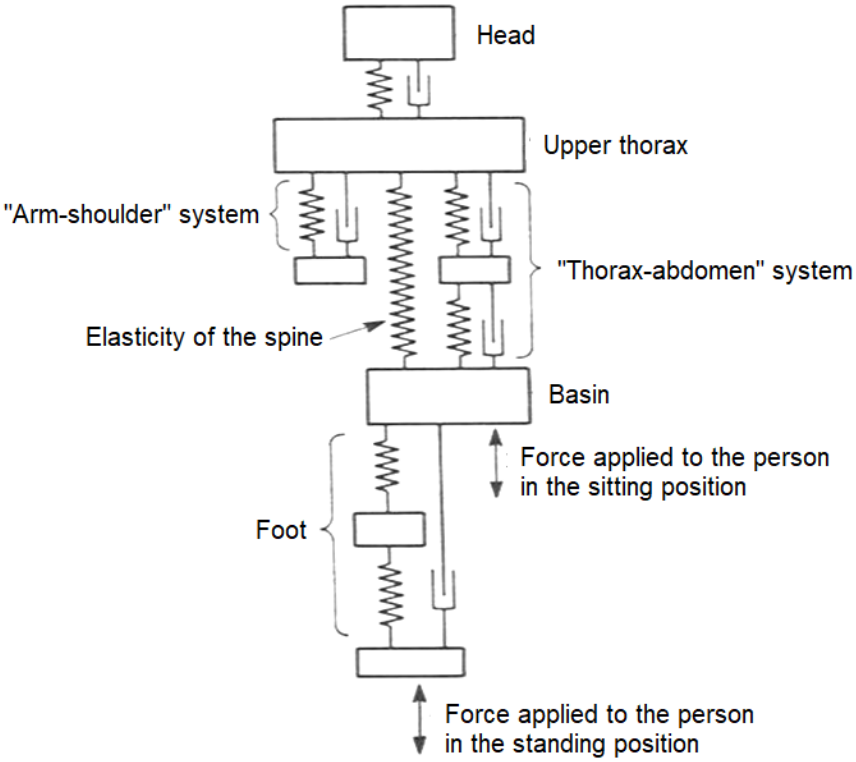

Fig. 1 – A simplified mechanical system which depicts the human body standing upright on a vertical vibrating platform

This is due to a specific resonance effect arising in the 3–6 Hz band (Figures 2 and 3), making effective vibration isolation when sitting or standing extremely challenging. Furthermore, the "head-neck-shoulder" system causes the resonance effect, which occurs between 20 and 30 Hz (Figure 3). The disturbances are also equivocal between 60–90 Hz, implying an eyeball resonance; between 100–200 Hz, a low resonance effect was discovered in the jaw-skull system.

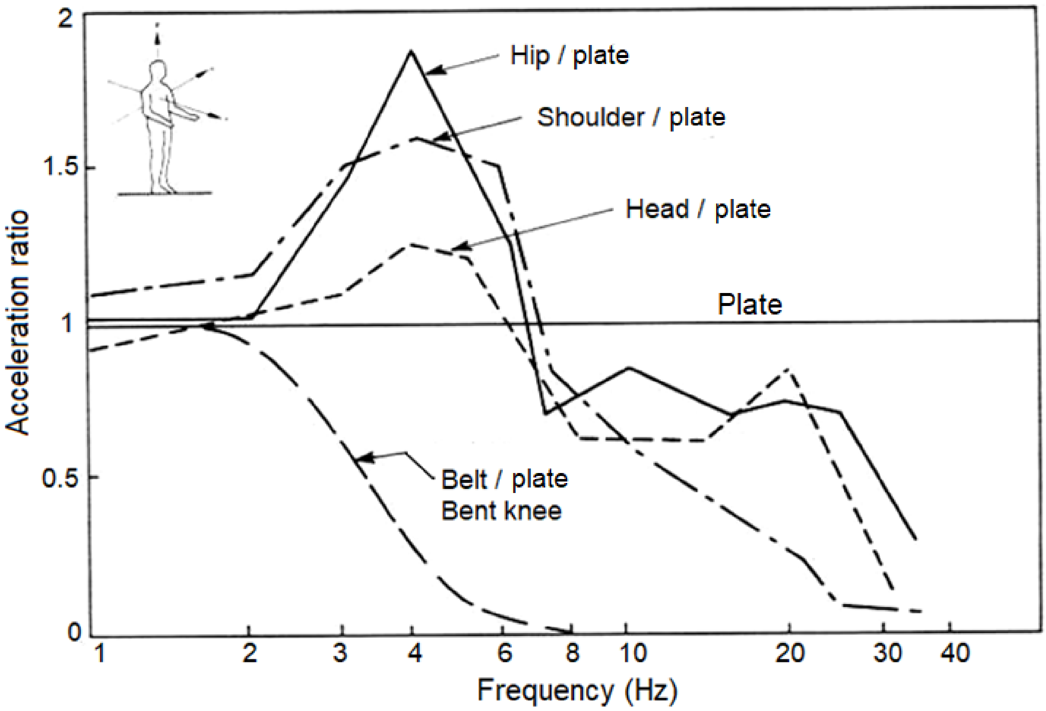

Fig. 2 – Transmission of vertical vibrations from the plate (platform) to different parts of the human body in the standing position, as a function of frequency

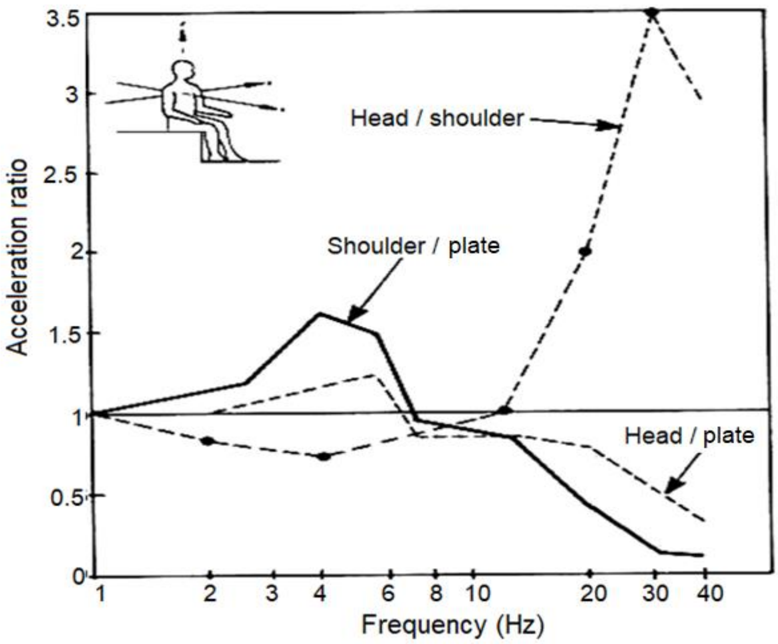

Fig. 3 – **Vertical vibration transmission from the plate (platform) into different parts of the body while in the seated position, as a function of frequency**

Above 100 Hz, the characteristics of the simple established models are similar to those given in Figure 1; however, they are not very useful. Continuous structural analysis methods, which can grow highly sophisticated, must be used. Such studies revealed the fundamental mode of vibration for the skull itself, which looks to be in the range of 300–400 Hz, with resonances for high modes about 600–900 Hz. Both signal (wave) theories must be utilized at calm high frequencies, in the form of the cut signal and the compression signal (sound signal).

The most important aspect of shock and vibration is tracking the peak of the low frequency string. Thus, some very interesting measurements were made, focused on the attenuation of vibrations along the human body (von Bekesy). Figure 4 depicts the data obtained at 50 Hz, as well as the attenuation from feet to head, which is on the order of 30 dB. Hand-to-head attenuation is approximately 40 dB.

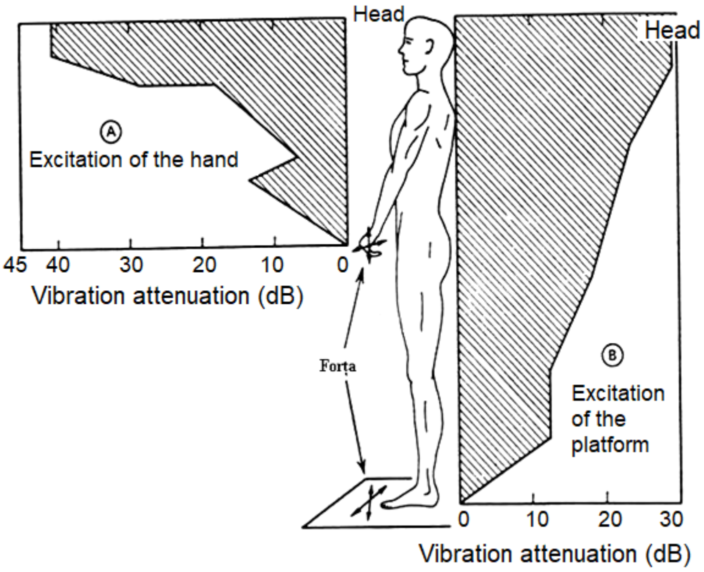

Fig. 4 – **Vibration attenuation at 50 Hz across the human body**

The attenuation is measured in decibels, beneath the value of the excitation point, when the hand (A) and platform (B) are excited on a subject that maintains the "standing" position. Recent research has focused on the perceived psychological impacts, discomfort, and pain. The majority of researches have focused on automotive drivers and airplane pilots, whose abilities to complete complicated tasks under adverse environmental conditions, such as vibration, are critical.

The available data is mainly used for subjects who are standing or seated. The ISO 2631-1:2001 and ISO 2631-5:2018 standards conveniently combine these data for a set of vibration curves for lateral and vertical vibrations spanning a frequency range of 1–80 Hz. These curves are depicted in Figure 5 (vertical accelerations – az) and Figure 6 (longitudinal accelerations – ax and transverse accelerations – ay), and are applied to vibrations conveyed to a person's torso when sitting or standing on the stated system's axis.

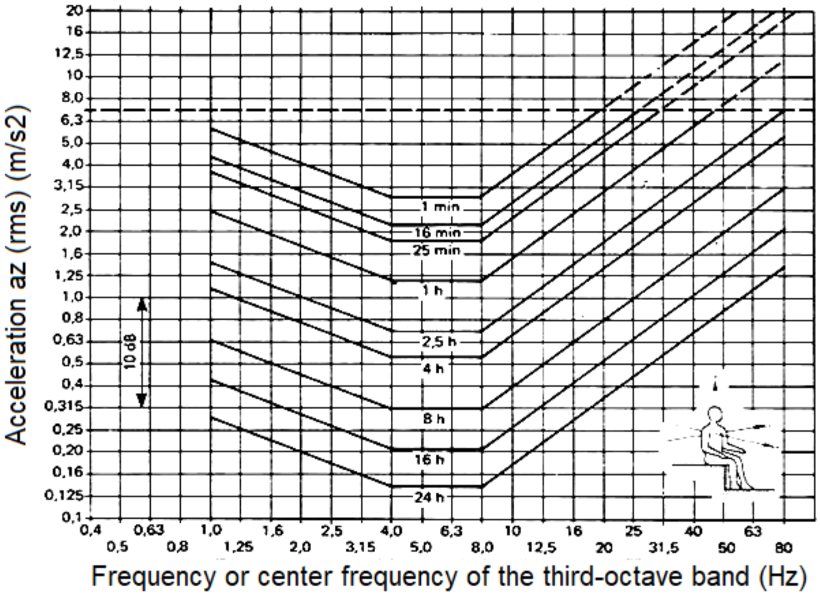

Fig. 5 – **The limit of vertical vibration exposure curves**

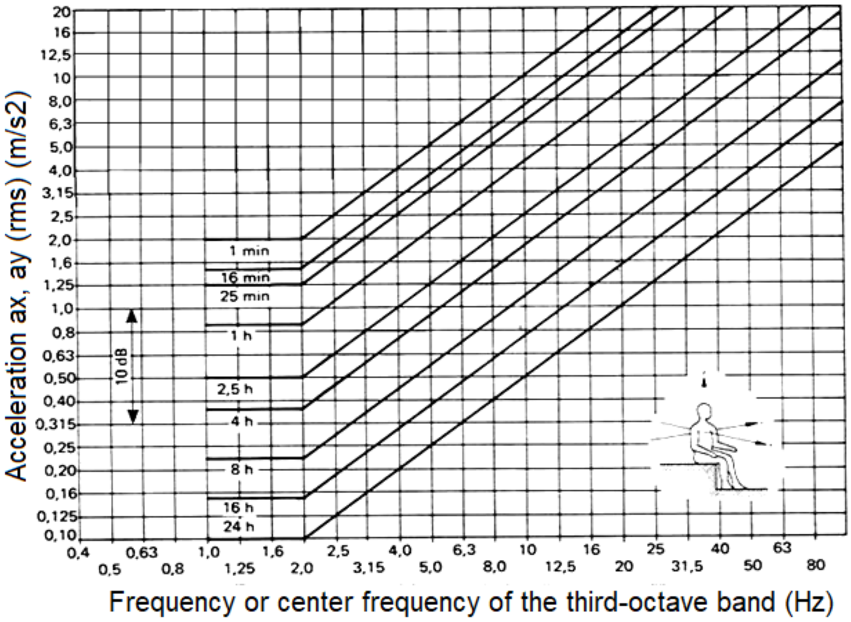

Fig. 6 – **The limit of exposure curves to longitudinal and transverse vibrations**

The upper part of the plate exposure limit is taken to be 2 times higher than the "fatigue reduction limit" shown in Figure 5, although the "reduced comfort limit" should be about a third of the specified levels. These criteria are provided as suggested guidelines or guideline curves, which is analogous to the quantitative classification of limits.

In Figure 7, the tolerance of the human subject to the acceleration pulsation of a single shock is indicated. The subjective reaction is expressed as a function of the maximum displacements of the original pulse over time. The number indicates the following reactions from the surfaces between the lines: I_a – the perception threshold; I_b – easy perceptions; I_c – strong, irritating perceptions; II_a – very uncomfortable perceptions, long exposures may pose a risk; II_b – extremely uncomfortable, very dangerous perceptions.

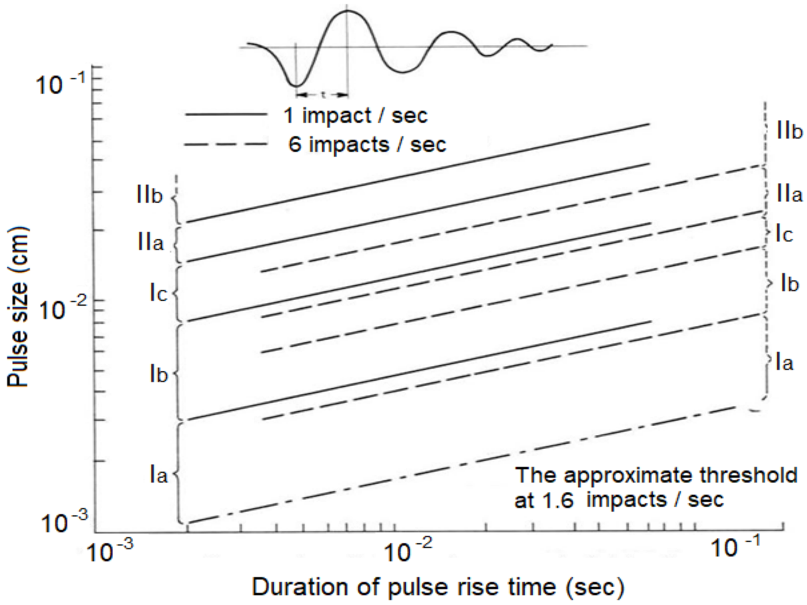

Fig. 7 – **Tolerance of the human subject, standing or lying down, to representative pulsations of repeated vertical impacts**

- **Arm vibration**

Arm vibration is the second big problem regarding the surface involved in the transmission to the human body. As a result, the challenges it poses differ from those raised by whole body vibration. Taking into account the vibration transmitted to the body while standing or sitting, the transmission of general problems such as: harmful movements, discomfort, reduced work efficiency, and so on, the vibration applied to the arm can also produce local physical damage if the level and exposure time are high enough.

When used for typical industrial durations, the vibration levels in many regularly used power tools are high enough to cause harm. ISO 5349-84 tries to collect common information about the appropriate form and to enable verdicts about the risk of harm from vibration exposure assessed in practice to be formed.

Figure 8 depicts suggested direction levels spanning the frequency range of 8 Hz to 1 kHz. Although exposure (presentation) curves for third-octave frequencies and octave bands are shown, when applied to the discrete spectrum frequency commonly encountered in hand rotation with tools, third-octaves are more stringent than octave bands.

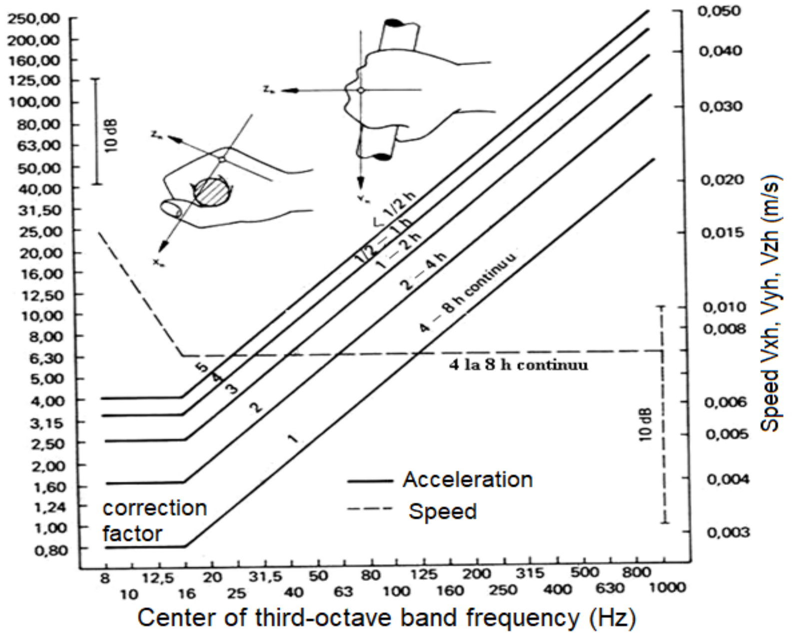

Fig. 9 – **The exposure guidelines for vibration transmitted to the hand**

RESULTS

- **Vertical vibrations' impact on the human body**

Most of the physical characteristics of the human body were obtained by analysing the experimental results, considering the human body as a passive and linear mechanical system. Of course, this is a valid hypothesis only in the case of very small amplitudes, and the presented results cannot be used in the study of mechanical tissue injuries. In reality, even well below the amplitudes required to produce injury, the response is nonlinear. This can be seen from the analysis of the experimental results, where the variation of the stiffness and resistance of the soft tissues is shown, depending on the elastic deformation.

The behaviour of bones is similar to that of solid bodies; in contrast, soft elastic tissues (muscles, tendons, connective tissues, etc.) behave similar to elastomers in terms of longitudinal modulus values and the S-shape of the stress-strain specific curve. These properties were investigated and connected with the quasi-static, pressure-volume connections of organs having internal cavities (such as the arteries, heart, and urinary bladder), taking linear behaviours into account while analysing dynamic responses. As a result, soft tissue can be represented phenomenologically as a viscoelastic environment; plastic deformations should be considered only if injuries occur.

Figure 9 depicts the mechanical impedance variation of a man standing or sitting on a platform that vibrates vertically. The body behaves as a unitary mass at frequencies less than about 2 Hz. The first resonance occurs between 4–6 Hz for the seated man, and the resonance peaks between 5–12 Hz for the standing human. The total energy transmitted to the person undergoing tests can be calculated using the numerical values of the impedance and the phase angle.

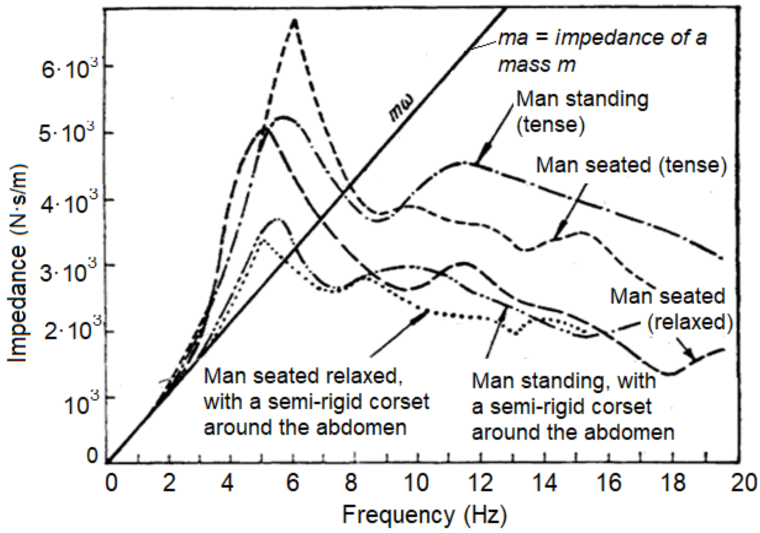

Fig. 9 – **The mechanical impedance variation of a man standing or sitting on a vertically vibrating platform**

The amplitudes of body motions caused by vibrations are smaller than the amplitudes of the vibrating plate at frequencies greater than 10 Hz and decrease continuously with increasing frequency. Figure 10 depicts the attenuation of vibrations transmitted from the vibrating plate to the skull. This attenuation is around 40 dB at 100 Hz.

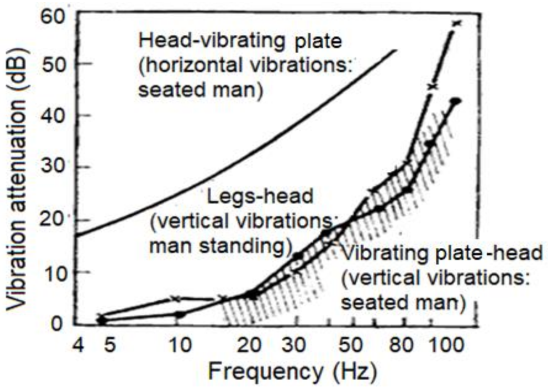

Fig. 10 – **Attenuation of vibrations transmitted from the vibrating plate to the head**

The effects of longitudinal vibrations on the human body

The thorax-abdomen system is one of the most significant subsystems of the body that is activated both in the sitting and seated (lying) positions. Because of the high flexibility of the diaphragm and the volume of air behind it, in the lungs, and in the chest cavity, the organs in the abdomen have enormous mobility. The abdominal mass vibrates inside and outside the thoracic cavity as a result of the trunk's longitudinal and transverse vibrations; therefore, vibrations occur in directions other than the longitudinal direction of excitation.

When the forces of inertia are directed towards the hips during the period of cycle, the abdominal wall is forced outwards and the abdomen appears dilated. Simultaneously, the deformation of the diaphragm towards the lower part of the body causes a decrease in the thoracic perimeter. In the second part of the cycle, the abdominal wall is forced inward, while the diaphragm is directed upward, and the chest circumference increases. The periodic movement of the abdominal organs has a strong resonance at frequencies of 3–3.5 Hz (Figure 11).

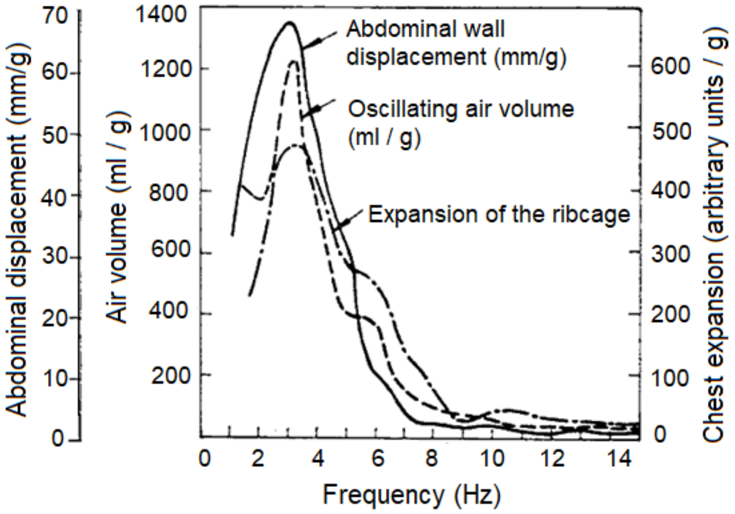

Fig. 11 – **The resonance domain for the abdominal organs**

In the mouth-thoracic cavity system, the oscillations of the abdominal mass are connected with the oscillations of the air. The measurement of the impedance of the latter system (by applying air at the level of the mouth with oscillating pressure) reveals that the abdominal wall and the front section of the chest cavity react to this pressure. Between 7–8 Hz, the impedance is low and the phase angle is zero.

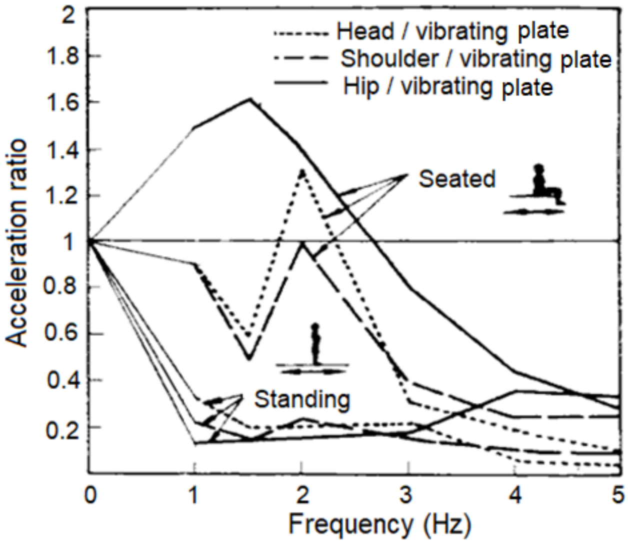

Fig. 12 – **Electrical circuit equivalent to the abdomen-chest-mouth system**

The abdominal wall responds best between 5–8 Hz, whereas the front region of the chest responds best between 7–11 Hz. The abdominal system's vibration, as a result of exposure to vibrations of a man standing or sitting, is easily determined from the modulation of the speed of an air current coming out of the mouth (Figure 11). Therefore, at high vibration amplitudes, speech can be modulated with the vibration frequency of the abdominal system. An electrical circuit equivalent to the abdomen-chest-mouth system is given in Figure 12.

- **The effects of transverse vibrations on the human body**

The human body's reaction to transverse vibrations - for example to horizontal vibrations, when it is in the normal, vertical position - is different from that corresponding to vertical vibrations. In this case, the forces act in a direction creating a right angle with the line of action of gravity's force. Because of this, the distribution of body mass along this line is of particular importance. Thus, the response to transverse vibrations of a seated and a standing body differs greatly, unlike the case of vertical vibrations, which correspond to the usual loading situation for the skeleton and spine, which usually take vertical loads.

Figure 13 contains experimental data regarding the transmission of vibrations at different levels along the body. In the case of a man standing, the amplitudes of the movements of the hip, shoulder and head are, at the frequency of 1 Hz, approximately 20–30% of the amplitude of the vibrating plate and decrease with increasing frequency.

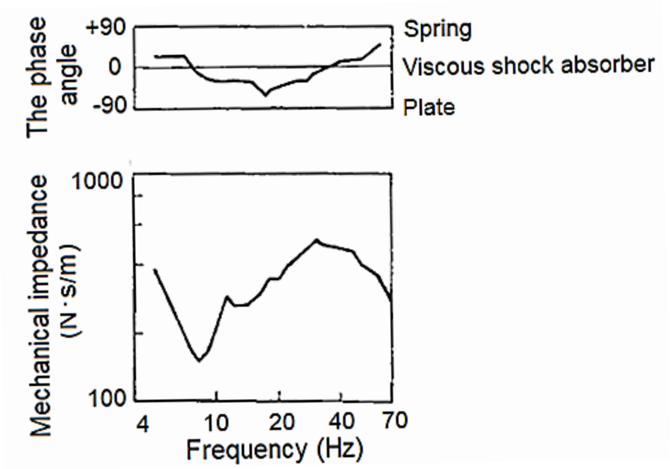

Fig. 13 – Transmission of vibrations at different levels along the body

At 2 and 3 Hz, the relative maximum values of the shoulder and head oscillation amplitudes occur. In the case of the man in the sitting position, an amplification of the oscillations of the hip at 1.5 Hz and of the head at 2 Hz is observed. All critical resonance frequencies are found between 1 and 3 Hz. The form of transverse body vibrations can be approximated to that of standing waves by comparing the body to a bar excited by transverse (bending) waves. As the excitation frequency increases, nodal points in the body move closer to the feet, because the phase shifts between the body elements and the vibrating plate increases continually with frequency. At the first frequency of resonance (1.5 Hz), the head of the seated person is 180° out of phase with the vibrating plate; between 2–3 Hz the phase shift is 360° (*Broch J.T., 1984*).

Apart from the transverse movements described in Figure 13 and analysed above, there are also longitudinal movements of the head, excited by the transverse vibrations.

Because of the architecture of the top vertebrae and the position of the head's centre of gravity, the human performs a forward-backward swaying movement of the head. At frequencies above 5 Hz, for a man either sitting or standing, the head movement occurs mainly in the vertical direction (with about 10–30% of the amplitude of the horizontal movement of the vibrating plate).

Vibrations emitted from hands

In connection with the studies on the use of vibrating hand tools, measurements were made regarding the transmission of vibrations from the hand to the arms and body.

Figure 14 depicts the mechanical impedance measured at the handle of a hand tool under representative working conditions. In the range of frequencies below 5 Hz, the impedance shows a maximum probably determined by the natural frequencies between 1–3 Hz, of the human body subjected to transverse vibrations. A second strong maximum arises between 30–40 Hz, where the hand's effective mass (about 1 kg) is found in resonance due to the elasticity (estimated at 2 x 10^{-5} m/N) of the soft tissues in the palm bridge.

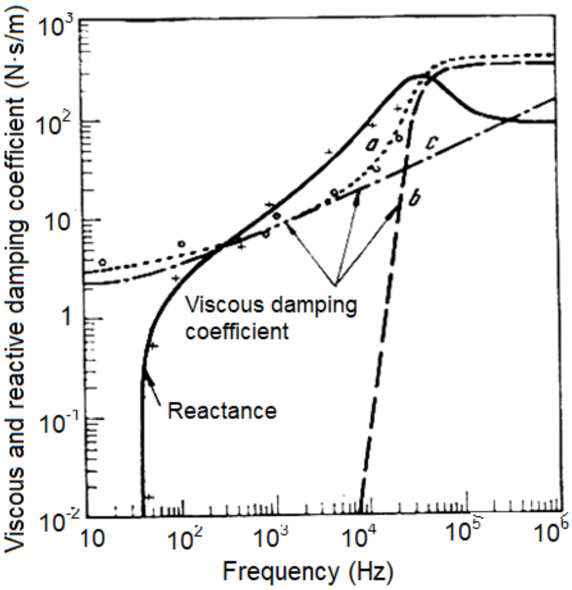

Fig. 14 – Mechanical impedance measured at the handle of a hand tool under representative working conditions

In the case of a manual tool that works at frequencies between 40–50 Hz, the amplitude of the vibration diminishes from the palm to the back of the hand by 35–65%. Other damping occurs at the elbow and shoulder joints.

- **Environment frequency domain**

In the frequency range above 100 Hz, simple models with concentrated parameters become less and less satisfactory for describing tissue vibration. At higher frequencies, the tissue must be viewed as a continuous environment through which vibrations travel.

Vibrations of the skull

The spectrum of skull vibrations is similar to that of a spherical elastic shell. According to the discovered nodal lines, the fundamental resonance frequency is between 300–400 Hz, and the resonances for higher modes of vibration occur at frequencies between 600–900 Hz.

The experimentally obtained ratio between the frequencies corresponding to the vibration modes is 1.7, while the theoretical ratio for the sphere is 1.5. The value of the elastic constant of the bones of the head, calculated according to the values obtained at the resonance) was considered the modulus of elasticity $E = 1.4 \cdot 10^9$ N/m^2) corresponds quite well with the results of statistical tests, on samples from dry skulls, but it is somewhat lower than the one calculated from the data obtained during the static tests performed on the femur. The mechanical impedances of some small surfaces of the skull above the mastoid were measured, as well as the skin impedance in the auditory canal, the results being used in the studies on ear protection means.

A simple mass-spring system with a resonance frequency of 100–200 Hz in respect to the skull can describe the vibration of the lower jaw in reference to the skull.

Soft tissue impedance in the human body. Measurements were made of the impedance of the soft tissues of the human body on small surfaces (between 1–17 cm^2), with the help of vibrating pistons, whose frequency was between 10–20,000 Hz. At low frequencies, the impedance has the character of a high-value elastic reactance. As the frequency increases, the elastic reactance decreases, it cancels out at the mass resonance frequency if the frequency increases further (Figure 15).

These results cannot be explained based on a simple model with concentrated parameters, but require modelling based on a system with distributed parameters, including a viscoelastic environment. Because of the environment's high viscosity, several simplifying theoretical hypotheses, such as the hypothesis of an uniform, isotropic, and infinite environment, or the hypothesis that the vibrating element is a sphere and a cylindrical piston, can be used. The results obtained based on these simplifications are consistent with the measured characteristics. Thus, absolute values can be assigned to the tangential viscosity and transverse modulus of soft tissue.

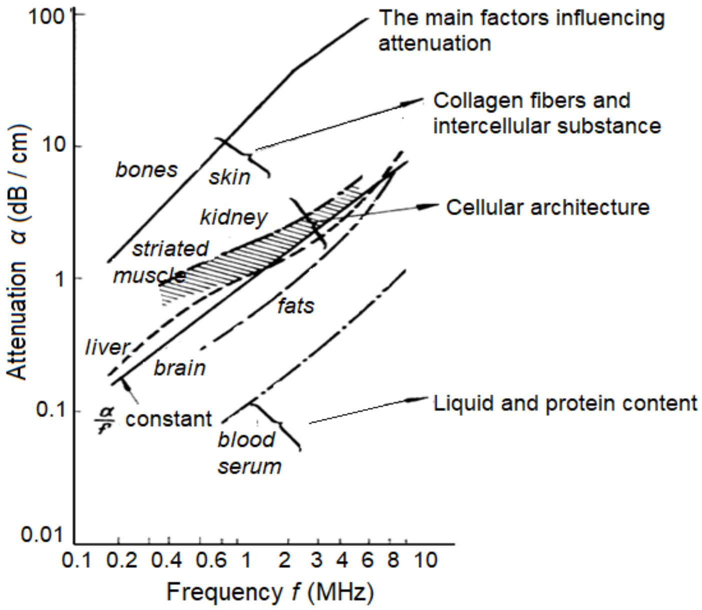

Fig. 15 – **The impedance of the soft tissues of the human body**

Both theory and measurements reveal that, in the audio frequency range, the majority of vibration energy spreads through tissue as transverse waves rather than longitudinal waves. At 200 Hz, the speed of transverse waves is around 20 m/s and grows roughly with the square root of the frequency. For comparison, the constant speed of sound (longitudinal waves) is about 1500 m/s. Surface waves, which have been observed optically, carry some of the energy along the body's surface. Their propagation speed is of a comparable order as that of transverse waves.

- **Effects of shocks and vibrations**

Movements and mechanical stresses caused by mechanical actions on the human body can have numerous impacts, including:

1. Movement can directly interfere with physical activity;
2. Mechanical damage or injury may occur;
3. Side effects (including subjective phenomena) might occur, causing changes in the body via biological receptors and transmission systems.

As for the thermal and chemical effects, they are usually negligible.

Mechanical influence

Of course, the methods of application and the effects of the forces on the body are different. Certain types of movements, speeds and accelerations (if they are high enough) can greatly disturb sensory and neuromuscular activities, such as: reading the indications of some devices, fine-tuning controls or body position, etc. Also, verbal communications can be made considerably more difficult.

Very little data is known regarding the size and type of movement that influences a certain type of activity. When there are such data, they are expressed only from the point of view of the human's ability to tolerate them, without disturbing the activity he submits. For example, the disturbance of visual acuity (Figure 16) that occurs due to body vibrations does not depend only on the frequency, but is approximately proportional to the amplitude of the vibration.

The disturbance can be limited by changing the frequency, by reducing the amplitude, or its influence can be reduced by reducing the requirements imposed to perform a certain operation. If they are of short duration and not repeated at very short intervals, most operations that man can perform are not directly influenced by the mechanical movement resulting from random shocks.

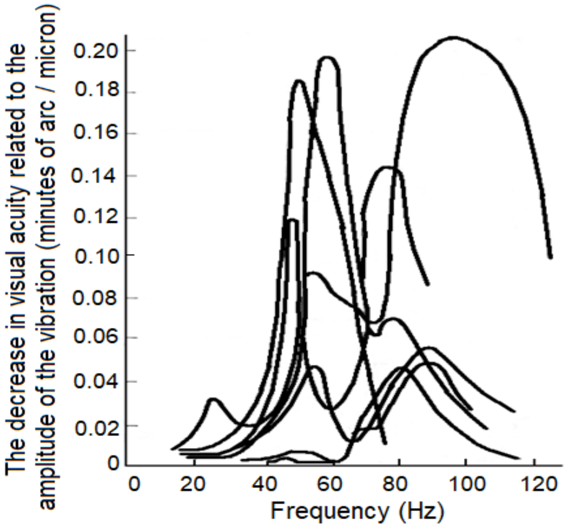

Fig. 16 – Disturbance of visual acuity due to body vibrations

In general, following the shock, the modification of the human working capacity occurs due to biological responses or mechanical injuries.

CONCLUSIONS

Given that prolonged vibrations and shocks are a problem for operators of self-propelled agricultural machinery working on uneven agricultural land, the imposition of time limits for uninterrupted work has become a priority, namely the identification of constructive solutions to reduce or minimize the harmful influence that they have an effect on the human body, as follows:

- at the European and international level (then taken over at the national level), standards have appeared that establish the general working conditions and limits for operators of agricultural machinery: SR EN ISO 13090-1: 2002; ISO 5008: 2002; SR EN ISO 10819:2013/A1: 2019; SR EN ISO 10819:2013/A2: 2023; ISO 2631-1: 2001; ISO 2631-5: 2018;
- constructive solutions were sought and identified to reduce vibrations at the main active parts of agricultural machines (especially the moving parts) that produce the greatest vibrations;
- new suspension systems and ergonomic seats have been developed that absorb the vast majority of vibrations so that the amplitude of those that reach the operator is minimal or reduced to zero, thus being able to work without health problems even 24 hours without interruption.

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