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THE VIBRATION ENERGY ABSORPTION OF TRACTOR OPERATOR EXPOSED TO VERTICAL WHOLE-BODY VIBRATION UNDER WORK OF THE AGGREGATE TRACTOR-ROUND BALER

Summary

Humans are most sensitive to whole body vibration (WBV) within the frequency range of 1 to 20 Hz. Whole-body vibration can cause fatigue, stomach problems, headache. After daily exposure over a number of years, whole-body vibration can affect the entire body and result in a number of health disorders. Workers driving tractors or other vehicles are especially at risk of being exposed to WBV. On the basis of the guidance provided in ISO 2631-1 to relate vibration exposure with the risks of health effects are established based on absorbed power. The 4-DOF dynamic model developed by Wan and Schimmels is recommended for the study of biodynamic responses of seated human subjects under vertical whole body vibration. This model of the human body is used to estimate the absorbed power distributed in head, upper torso, lower torso and thighs. The vibration energy (power) absorption of seated human that is exposed to vertical whole-body vibration are investigated under work of the aggregate tractor-round baler.
***Key words**: tractor operator, round baler, whole body vibration; human body model, power; absorption*

ABSORPCJA ENERGII DRGAŃ O ODDZIAŁYWANIU OGÓLNYM PRZEZ OPERATORA AGREGATU CIĄGNIK-PRASA ZWIJAJĄCA

Streszczenie

Ludzie są najbardziej wrażliwi na drgania o działaniu ogólnym w zakresie częstotliwości od 1 do 20 Hz. Drgania o działaniu ogólnym mogą powodować zmęczenie, problemy żołądkowe, ból głowy. Po codziennej, wieloletniej, ekspozycji na drgania o oddziaływaniu ogólnym może zostać powstać szereg zaburzeń zdrowotnych. Pracownicy prowadzący ciągniki lub inne pojazdy są szczególnie narażeni na kontakt z drganiami o oddziaływaniu ogólnym. Na podstawie wytycznych zawartych w normie ISO 2631-1 istnieje powiązanie narażenia na wibracje z ryzykiem skutków zdrowotnych na podstawie pochłoniętej mocy drgań. Model biodynamiczny o czterech stopniach swobody 4-DOF opracowany przez Wana i Schimmelsa jest zalecany do badania reakcji siedzącego kierowcy na pionowe drgania o oddziaływaniu ogólnym. Model ten pozwala wyznaczyć pochłoniętą moc drgań w poszczególnych elementach ciała człowieka: głowa, górną część tułowia, dolną część tułowia oraz uda. Model ten zastosowano do badania absorpcji mocy drgań przez operatora agregatu ciągnik-prasa zwijająca.
***Słowa kluczowe**: operator ciągnika, prasa zwijająca, drgania o oddziaływaniu ogólnym, model ciała kierowcy, rozkład mocy drgań*

1. Introduction

Whole body vibration (WBV) is an important physical risk factor that appears in the farmers' work environment. The vibration occurs on the seats of agricultural vehicles during the performance of specified field and transportation work tasks.

Employers should make adjustments in the light of technical progress and scientific knowledge regarding risks related to exposure to vibration, with a view to improving the safety and health protection of workers [1].

On the basis of the guidance provided in ISO 2631-1 [5] to relate vibration exposure with the risks of health effects are established based on absorbed power.

The concept of power absorbed by the human body when exposed to seat-transmitted vibration was first proposed in the mid-1960s by Pradko et al. [12], in order to evaluate the health, safety and comfort of occupants of military vehicles. Mansfield et. al [10] concluded that absorbed power correlates well to subjective discomfort.

Xie [15] claimed that the evaluation of health risk is based on the total absorbed power in the body. However, where a particular body segment may be experiencing excessive vibrations causing local fatigue and health consequences, investigations on the local fatigue and health risk should be based on the local absorbed powers.

2. Biomechanical model

Various biodynamic models have been developed on the basis of diverse field measurements to describe the biodynamic responses of human body. Depending on different modeling techniques, these models can be grouped as lumped-parameter models, finite element (FE) models and multibody models. Lumped-parameter models consider the human body in a sitting posture as several concentrated masses interconnected by springs and dampers. The main difference between the lumped-parameter models refers to the number of degrees of freedom (DOF).

One of the first model was presented in 1981 by the International Organization for Standardization (ISO). It was a parallel 2-DOF model for both sitting and standing positions of a driver body.

In ISO 5982 standard a 3-DOF model was presented [4]. The structure of the 3-DOF ISO 5982 model is illustrated in Fig. 1.

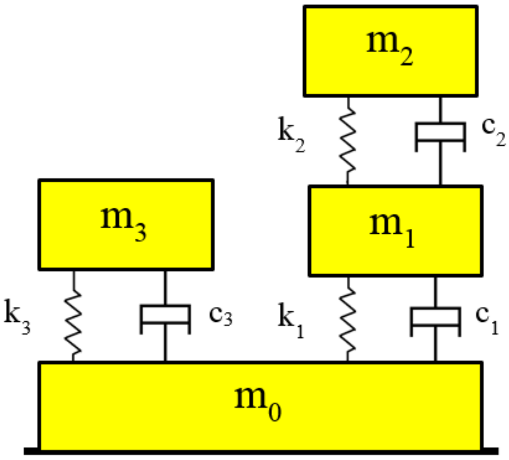


Fig. 1. Three-degree-of-freedom, lumped-parameter biodynamic model of the seated human body vertical vibration [4]

Rys. 1. Model biodynamiczny o trzech stopniach swobody i parametrach skupionych opisujący drgania pionowe siedzącego człowieka [4]

The model parameters listed in Table 1 would most likely apply to a subject with total body mass of 75 kg, while assuming that 73% of the mass is resting on the seat.

The sum of the masses, however, should correspond to the body mass supported by the seat.

Some other human body biodynamic models have also been developed by Muskian and Nash, Patil and Palanichamy, Qassem and Othman, Boileau and Rakheja, Qiu and Griffin [8] and Harsha [3].

From simulations of lumped-parameter models listed in study on biodynamic models of seated human subjects exposed to vertical vibration [8], the four-DOF model developed by Wan and Schimmels (1995) match experimental data most closely. Accordingly, this model is recommended for the study of biodynamic responses of seated human subjects exposed to vertical whole body vibration [8].

In this study, for the calculation a 4-DOF model developed by Wan and Schimmels have been used as well. We chose this model, taking into account the accuracy of fitting results for the different models available in the literature.

In 4-DOF Wan and Schimmels model, the seated human body was constructed with four separate mass segments interconnected by five sets of springs and dampers, with a total human mass of 60.67 kg. The four masses represent the following body segments: head and neck, upper torso, lower torso and thighs and pelvis. The arms and legs are combined with the upper torso and thigh, respectively.

The structure of the 4-DOF models are illustrated in Fig. 2, and the biomechanical parameters of the model are listed in Table 2.

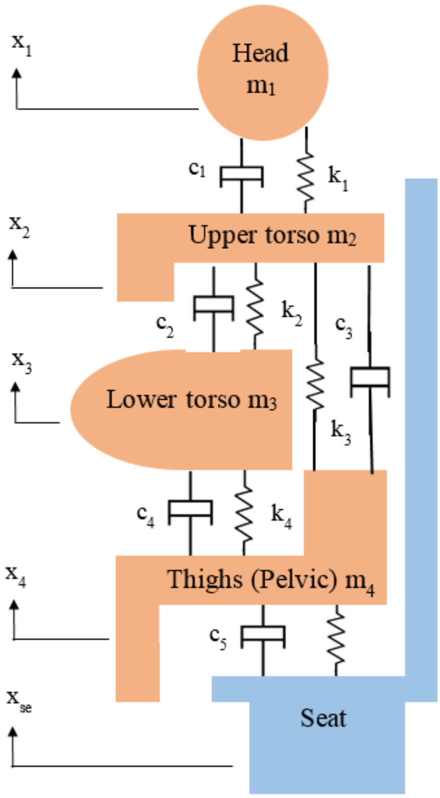


Fig. 2. Wan and Schimmels 4-DOF biomechanical model of human body [8, 16]

Rys. 2. Biomechaniczny 4-DOF model ciała człowieka wg Wana i Schimmelsa [8, 16]

Table. 1. Values for the parameters of the model (body mass of 75 kg) [4]

Tab. 1. Wartości parametrów modelu (masa ciała 75 kg) [4]

Parameter	Mass [kg]				Stiffness [N m^{-1}]			Damping coefficient [N s m^{-1}]		
value	m_0	m_1	m_2	m_3	k_1	k_2	k_3	c_1	c_2	c_3
	2	6	2	45	9990	34400	36200	387	234	1390

Table 2. Parameter values of the Wan and Schimmels 4-DOF model [8, 16]

Tab. 2. Wartości parametrów modelu o 4-DOF wg Wana i Schimmelsa [8, 16]

Biomechanical parameters		
Mass [kg]	Damping [N s m^{-1}]	Stiffness [N m^{-1}]
head m_1 = 4.17	c_1 = 250	k_1 = 134400
lower torso m_2 = 15	c_2 = 200	k_2 = 10000
upper torso m_3 = 5.5	c_3 = 909.1	k_3 = 192000
pelvic m_4 = 36	c_4 = 330	k_4 = 20000
	c_5 = 2475	k_5 = 49340

The equations of motion of the 4-DOF model developed by Wan and Schimmels of the seated human are formulated as follows:

$$m_1\ddot{x}_1 + c_1(\dot{x}_1 - \dot{x}_2) + k_1(x_1 - x_2) = 0$$
$$m_2\ddot{x}_2 + c_1(\dot{x}_2 - \dot{x}_1) + c_2(\dot{x}_3 - \dot{x}_2) + c_3(\dot{x}_2 - \dot{x}_4) + k_1(x_2 - x_1) + k_2(x_2 - x_3) + k_3(x_2 - x_4) = 0$$
$$m_3\ddot{x}_3 + c_2(\dot{x}_3 - \dot{x}_2) + c_4(\dot{x}_3 - \dot{x}_4) + k_2(x_3 - x_2) + k_4(x_3 - x_4) = 0$$
$$m_4\ddot{x}_4 + c_3(\dot{x}_4 - \dot{x}_2) + c_4(\dot{x}_4 - \dot{x}_3) + c_5\dot{x}_4 + k_3(x_4 - x_2) + k_3(x_4 - x_2) + k_5x_4 = c_5\dot{x}_{se} + k_5x_{se} \quad (1)$$

Significance of variables are represented in Fig. 2 and Table 2.
The above differential equations can be expressed in matrix form:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{f\} \quad (2)$$

where $[M]$, $[C]$ and $[K]$ are mass, damping and stiffness matrices with a size of 4 × 4, respectively; $\{\ddot{\boldsymbol{x}}\}$, $\{\dot{\boldsymbol{x}}\}$ and $\{\boldsymbol{x}\}$ are acceleration, velocity and displacement vectors, respectively, with a size of 4 × 1; $\{f\}$ is an 4 × 1 excitation force vector. All the above matrices and vectors can be expressed as follows:

$$M = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix}; K = \begin{bmatrix} k_1 & -k_1 & 0 & 0 \\ -k_1 & k_1 + k_2 + k_3 & -k_2 & -k_3 \\ 0 & -k_2 & k_2 + k_4 & -k_4 \\ 0 & -k_3 & -k_4 & k_3 + k_4 + k_5 \end{bmatrix}$$
$$C = \begin{bmatrix} c_1 & -c_1 & 0 & 0 \\ -c_1 & c_1 + c_2 + c_3 & -c_2 & -c_3 \\ 0 & -c_2 & c_2 + c_4 & -c_4 \\ 0 & -c_3 & -c_4 & c_3 + c_4 + c_5 \end{bmatrix} \quad (3)$$

$$\{\ddot{x}\} = \begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \ddot{x}_3 \\ \ddot{x}_4 \end{Bmatrix}; \{\dot{x}\} = \begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{Bmatrix}; \ \{x\} = \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{Bmatrix}; \{f\} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ c_5\dot{x}_{se} + k_5x_{se} \end{Bmatrix} \quad (4)$$

3. Theory for vibration energy absorption measurement

By analogy with the kinetic and potential energy functions, Rayleigh's dissipation function R is defined by Woodhouse [17]:

$$R = \frac{1}{2}\{\dot{x}\}^H[C]\{\dot{x}\} \quad (5)$$

and it is equal to half the rate of energy dissipation [2, 17].

After multiplication the equation (1) by $\{\dot{x}\}^H$, equation of energy flow in the structure can be determined [6]:

$$\{\dot{x}\}^H[M]\{\ddot{x}\} + \{\dot{x}\}^H[C]\{\dot{x}\} + \{\dot{x}\}^H[K]\{x\} = \{\dot{x}\}^H\{f\} \quad (6)$$

The expression (6) describes the distribution of power in a mechanical system.
In terms of the component energy, the basic system elements can be divided into two groups: energy-storage elements (i.e. masses and springs) and energy dissipation elements (i.e. dampers). The absorbed power is the power dissipated in the dampers; the elastic power is the power stored and released in the springs.

The right side of the equation is instantaneous power input delivered to the system under the influence of an external force. The quantity $\{\dot{x}\}^H[M]\{\ddot{x}\} + \{\dot{x}\}^H[K]\{x\}$ is the instantaneous rate of energy intake by the inertia and elastic elements. The quantity $\{\dot{x}\}^H[C]\{\dot{x}\}$ represents the instantaneous rate of energy dissipation by the viscous damper.

$$\{\dot{x}\}^H[C]\{\dot{x}\}=\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{Bmatrix}^H\begin{bmatrix}c_1 & -c_1 & 0 & 0\\ -c_1 & c_1+c_2+c_3 & -c_2 & -c_3\\ 0 & -c_2 & c_2+c_4 & -c_4\\ 0 & -c_3 & -c_4 & c_3+c_4+c_5\end{bmatrix}\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{Bmatrix}=$$

$$=\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{Bmatrix}^H\begin{bmatrix}c_1 & -c_1 & 0 & 0\\ -c_1 & c_1 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{Bmatrix}+\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{Bmatrix}^H\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & c_2 & -c_2 & 0\\ 0 & -c_2 & c_2 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{Bmatrix}+\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{Bmatrix}^H\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & c_3 & 0 & -c_3\\ 0 & 0 & 0 & 0\\ 0 & -c_3 & 0 & c_3\end{bmatrix}\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{Bmatrix}+$$

$$+\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{Bmatrix}^H\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & c_4 & -c_4\\ 0 & 0 & -c_4 & c_4\end{bmatrix}\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{Bmatrix}+\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{Bmatrix}^H\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & c_5\end{bmatrix}\begin{Bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{Bmatrix} \quad (7)$$

According to equation (7), the total rate of energy dissipated in the system may be broken down as a sum of energy dissipated on individual damping elements of the system.

The instantaneous absorbed powers for different body segments are computed from [9, 11]:

$$P_{Abs,i}(t)=c_i(\dot{x}_i-\dot{x}_{i+1})^2 \quad (8)$$

The total instantaneous absorbed power is given by:

$$P_{Tot}(t)=\sum_{i=1}^{4}c_i(\dot{x}_i-\dot{x}_{i+1})^2\,. \quad (9)$$

The vibration energy absorbed by different body segments and total absorbed power was calculated using the equation (8)-(9).

Absorbed power is used to study ride comfort and is correlates with subjective response.

Physically, the absorbed power relates to dissipation of energy attributed to relative motions of the visco-elastic tissues, muscles and skeletal system, which under prolonged exposures could lead to physical damages in the musculo-skeletal system [13].

It is thus reasonable to hypothesize that the power absorption is associated with the vibration-induced discomfort and some health effects.

4. Identification of the vibration energy absorbed by the body during the work of the aggregate tractor-round baler

In order to study the energy content of the vibration transmitted to the whole body and to different body segments, the Wan and Schimmels 4 DOF biodynamic model is chosen to represent the body.

The energy models of the human driver have been implemented in the MATLAB environment to determine values of the power of inertia, loss and elasticity.

The local absorbed power and the total absorbed power under different excitations are derived.

The total rate of energy dissipated in the system and dissipated on individual damping elements of the system was calculated using the equation (8-9).

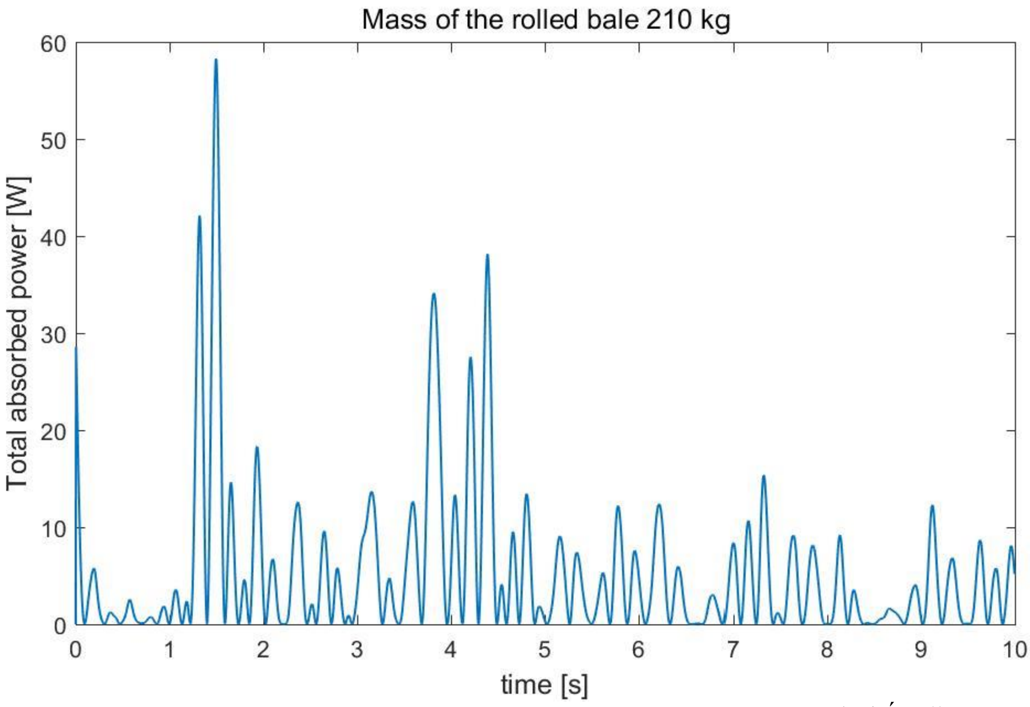
The data used for identification absorbed power and whole body vibration value was collected from a series experiments on the field, in a typical operational condition driving scenario (Fig. 3). During the bale rolling, the amount of material in the bale chamber was determined. The vibrations transmitted to the driver's seat depended on the process of forming the bale.

Source: own study / *Źródło: opracowanie własne*

Fig. 3. Tractor-round baler set during field tests

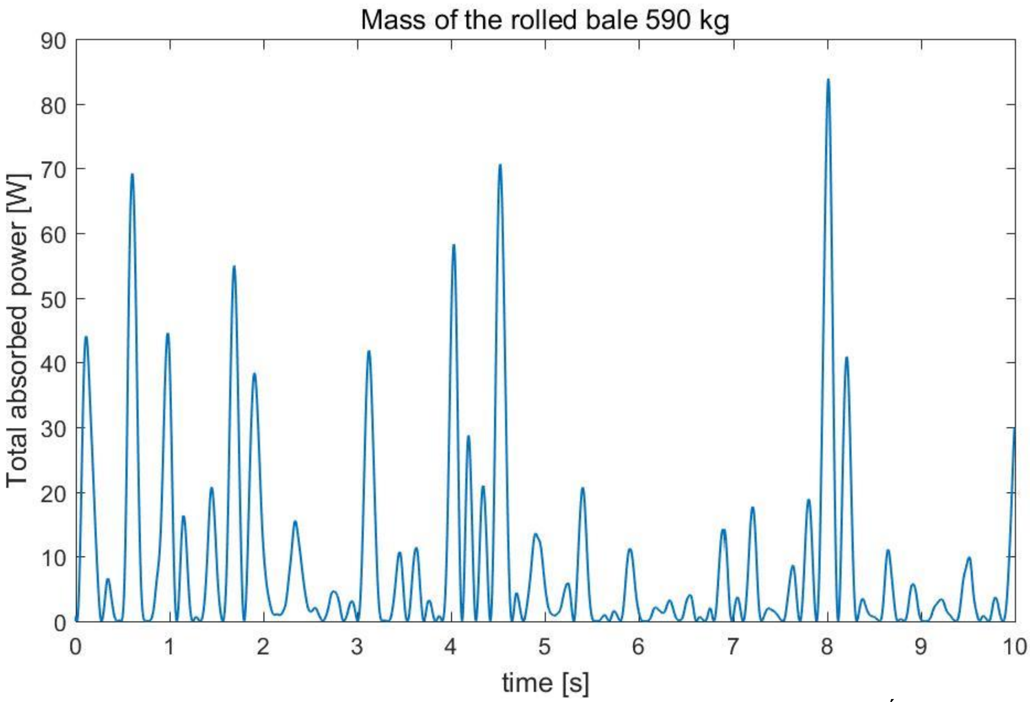
Rys. 3. Agregat ciągnik prasa zwijająca podczas badań polowych

Figs 4-6 present the values of the total absorbed power (energy) of vibrations by the aggregate operator body for three different states of filling the working chamber with crushed material.



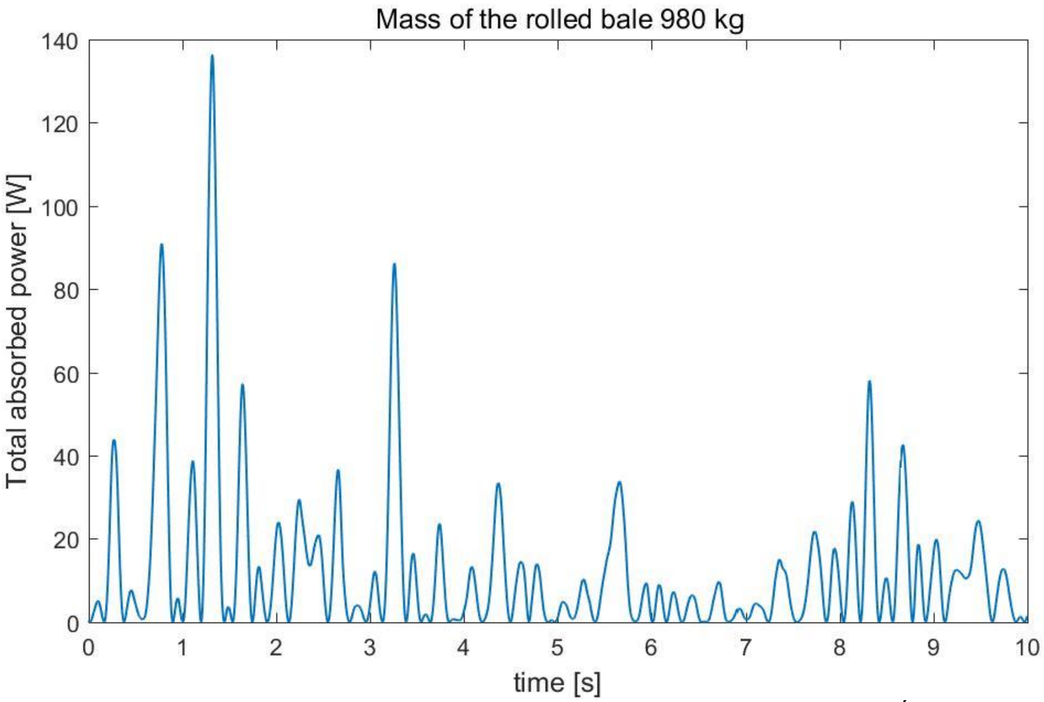
Source: own study / *Źródło: opracowanie własne*

Fig. 4. Total absorbed power in human body during the bale rolling, average mass of the rolled bale 210 kg
Rys. 4. Całkowita pochłaniana moc w ciele człowieka podczas zwijania beli, średnia masa zwijanej beli 210 kg



Source: own study / *Źródło: opracowanie własne*

Fig. 5. Total absorbed power in human body during the bale rolling, average mass of the rolled bale 590 kg
Rys. 5. Całkowita pochłaniana moc w ciele człowieka podczas zwijania beli, średnia masa zwijanej beli 590 kg



Source: own study / *Źródło: opracowanie własne*

Fig. 6. Total absorbed power in human body during the bale rolling, average mass of the rolled bale 980 kg
Rys. 6. Całkowita pochłaniana moc w ciele człowieka podczas zwijania beli, średnia masa zwijanej beli 980 kg

The table 3 presents the average and maximum vibration energy (power) stored and released in the springs and absorbed energy dissipated in the dampers absorbed by the body during the work of the aggregate during the bale rolling.

Table. 3. The vibration power absorbed by the body during the work of the aggregate during the bale rolling
Tab. 3. Moc drgań pochłonięta przez ciało podczas pracy agregatu podczas walcowania beli

No	Mass of the rolled bale	The elastic power stored and released in the springs [W]		The absorbed power dissipated in the dampers [W]	
		average	maximum	average	maximum
1.	210	8,93	60,96	9,47	58,29
2.	590	26,60	127,53	16,99	83,88
3.	980	29,80	182,87	22,08	136.39

Source: own study / *Źródło: opracowanie własne*

The vibration energy absorbed by the operators body is increased by increasing the mass of the rolled bale. The greatest value of the total absorbed power during the work of the aggregate are in the final bale rolling phase. During the final stage of bale rolling, the values the elastic power are 3 times higher and values dissipated power are 2,5 times higher than at the beginning of bale rolling The vibration energy absorbed by the operators body is small compared to the results obtained for other machines [7].

Xie [15] studied the response of Boileau and Rakheja 4 DOF human model to forced vibration which originates from a urban bus traveling over an obstacle. In this case the maximum amplitude total absorbed power was 36 W.

5. Conclusions

The evaluation of health risk is based on the total absorbed power in the body. The four-degrees-of-freedom the Wan and Schimmels model of the human body is used to estimate the absorbed power distributed in head, upper torso, lower torso and thighs.

The vibration energy absorption of seated human exposed to vertical whole-body vibration are investigated during work of the aggregate tractor-round baller.

The vibration energy absorbed by the operators body is increased by increasing the mass of the rolled bale. The greatest value of the total absorbed power during the work of the aggregate are in the final bale rolling phase.

6. References

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