Absorbed power distribution in the whole-body system of a tractor operator

Jacek Kromulski[1], Tadeusz Pawłowski[1], Jan Szczepaniak[1], Wojciech Tanaś[2], Andrzej Wojtyła[3], Mariusz Szymanek[2], Jacek Tanaś[4], Waldemar Izdebski[5]

[1] Industrial Institute of Agricultural Engineering, Poznań, Poland
[2] University of Life Sciences, Lublin, Poland
[3] Department of Health Sciences, University of Medical Sciences, Poznań, Poland
[4] University of Technology, Lublin, Poland
[5] Warsaw University of Technology, Poland

Abstract

Introduction and objective. Many people are exposed to vibration (WBV) in their occupational lives. The biodynamic responses of the human body in sitting conditions have been widely measured under whole-body vibration (WBV). The measures are most often expressed in terms of force-motion relations at the driving-point, namely, mechanical impedance, apparent mass and absorbed power, and flow of vibration through the body, such as seat-to-head and body segments vibration transmissibility. The absorbed power is a measure of the energy absorbed by the subject due to the external forces applied to the system.

Materials and methods. The body behaves like a vibrating physical system with distributed energy-storage elements (masses, springs) and energy-dissipation elements (dampers). The total quantity of power can be divided into 2 components – one real and one imaginary. The real component reflects the energy-absorbing part of the system, due to the transformation of friction into heat within the tissues. The imaginary component reflects the energy-storing part of the system which does not consume any vibration energy.

Results. The seated human is modeled as a series 4-DOF dynamic models. After introduction of the excitation, the response in particular segments of the model can be analyzed. As an example, the vibration power dissipated in an operator's body segments has been determined as a function of the agricultural combination operating speed 1.4 – 2.75 ms^{-1}.

Conclusions. The concept of absorbed power as a measurement for evaluation of WBV exposure opens a new area for research. The important character of absorbed power is that it has physical significance and therefore can be measured as well as computed analytically.

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 damage in the musculoskeletal system. A structural model of the human operator allows determination of the dynamic characteristics of the model, and study of the energy flow between the elements of the model.

Key words

vibration, whole body, human body model, power, absorption

INTRODUCTION

The human body is a very sophisticated dynamic system. Plenty of mathematical models have been developed to describe the biodynamic responses of human beings [1]. According to 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 as several concentrated masses (rigid bodies) interconnected by springs and dampers. This type of model is simple to analyze and easy to validate with experiments [2]. The main difference between the lumped-parameter human body models refers to the number of degrees of freedom (DOF).

OBJECTIVES

The subjective experience of vibration is related to the amount of vibration energy absorbed by the body. The body behaves like a vibrating physical system with distributed energy-storage elements (masses, springs) and energy-dissipation elements (dampers). The prevalence of vibration-induced injuries within different occupational groups is related to the amount of absorbed energy. The important characteristic of absorbed power is that it has physical significance, and therefore can be measured as well as computed analytically. Power is a scalar quantity and can be summed-up in complex multi-degree of freedom systems to determine the human response. A structural model of a human operator allows determination of the dynamic characteristics of the model, and study of the energy flow between the elements of the model.

374

Annals of Agricultural and Environmental Medicine 2016, Vol 23, No 2

Jacek Kromulski, Tadeusz Pawłowski, Jan Szczepaniak, Wojciech Tanaś, Andrzej Wojtyła, Mariusz Szymanek, Jacek Tanaś, Waldemar Izdebski. Absorbed power distribution…

MATERIALS AND METHODS

Biomechanical modeling. In 1981, one of the first models, a parallel 2-DOF model for both sitting and standing position, was presented by the International Organization for Standardization (ISO 5982) [3]. In 1995, Wan and Schimmels developed a series/parallel 4-DOF human dynamic. Muksian and Nash proposed 6- and 2-DOF models, respectively, to study the biodynamic responses of seated human bodies. Patil and Palanichamy suggested a 7-DOF model by adding another set of springs and dampers into Muskian's 6-DOF model [4, 5, 6, 7].

In the presented study, a series 4-DOF models have been used, in which the seated human body was constructed with 4 separate mass segments interconnected by 4 sets of springs and dampers, with a total human mass of 76 kg. The masses represent the following body segments: head and neck (m_1), upper torso (m_2), lower torso (m_3), and thighs and pelvis (m_4). The arms and legs are combined with the upper torso and thigh, respectively. The stiffness and damping properties of thighs and pelvis are (k_4) and (c_4), the lower torso (k_3) and (c_3), upper torso (k_2) and (c_2), and head (k_1) and (c_1).

Physical parameters of the biodynamic model were calculated on the basis of the power spectral densities (PSD) quotients of mechanical vibration acceleration measured at the points of freedom of the system.

The schematic of the model is shown in Figure 1, and biomechanical parameters of the model listed in Table 1.

Table 1. Parameter values of the identified 4-DOF

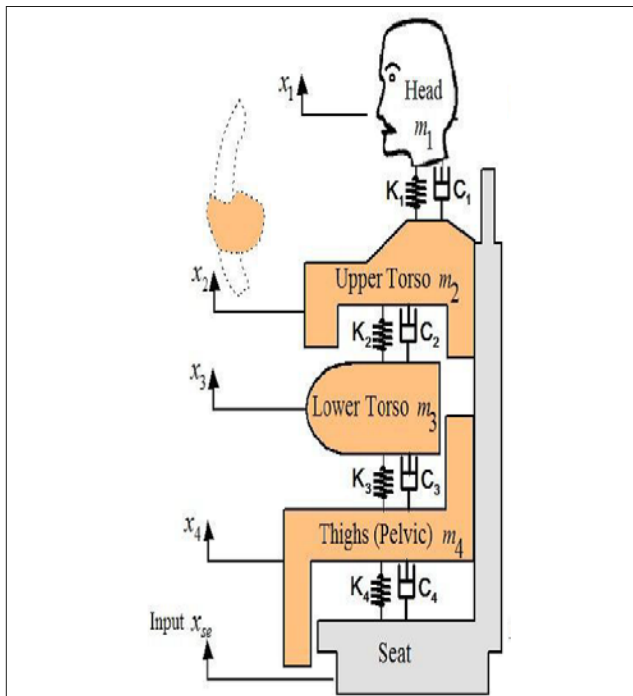| Biomechanical parameters		
Mass (kg)	Damping (kgs^{-1})	Stiffness (Nm^{-1})
head m_1 = 5,5	c_1 = 94.8	k_1 = 5909
upper torso m_2 = 40,3	c_2 = 232,4	k_2 = 309570
lower torso m_3 = 12,2	c_3 = 1920	k_3 = 17219
pelvis m_4 = 18	c_4 = 500	k_4 = 21667

Figure 1. Schematic diagram of 4-DOF seated human model [4, 5]

Estimation of biodynamic response characteristics. The equations of motion for the analyzed 4-DOF model is determined by applying Newton's Second Law to a free body diagram of each mass. The result is an equation of motion for each degree of freedom (1):

$$m_1\ddot{x}_1 + c_1\dot{x}_1 - c_1\dot{x}_2 + k_1x_1 - k_1x_2 = 0$$
$$m_2\ddot{x}_2 + \dot{x}_2(c_1 + c_2) + x_2(k_1 + k_2) - c_1\dot{x}_1 - c_2\dot{x}_3 - k_1x_1 - k_2x_3 = 0 \quad (1)$$
$$m_3\ddot{x}_3 + \dot{x}_3(c_2 + c_3) + x_3(k_2 + k_3) - c_2\dot{x}_2 - c_3\dot{x}_4 - k_2x_2 - k_3x_4 = 0$$
$$m_4\ddot{x}_4 + \dot{x}_4(c_3 + c_4) + x_4(k_3 + k_4) + k_3x_3 - c_3\dot{x}_3 = c_4\dot{x}_{se} + k_4x_{se}$$

written in matrix form as (2):

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

where $[M]$, $[C]$ and $[K]$ denote the mass, damping and stiffness matrices,

$$M = \begin{bmatrix} m_1 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 \\ 0 & 0 & m_3 & 0 \\ 0 & 0 & 0 & m_4 \end{bmatrix}; K = \begin{bmatrix} k_1 & -k_1 & 0 & 0 \\ -k_1 & k_1 + k_2 & -k_2 & 0 \\ 0 & -k_2 & k_2 + k_3 & -k_3 \\ 0 & 0 & -k_3 & k_3 + k_4 \end{bmatrix}$$

$$\quad (3)$$

$$C = \begin{bmatrix} c_1 & -c_1 & 0 & 0 \\ -c_1 & c_1 + c_2 & -c_2 & 0 \\ 0 & -c_2 & c_2 + c_3 & -c_3 \\ 0 & 0 & -c_3 & c_3 + c_4 \end{bmatrix}$$

$\{f\}$, $\{\dot{x}\}$, $\{\ddot{x}\}$ and $\{x\}$ are the force, displacement, velocity and acceleration vectors, respectively. For the presented 4-DOF model the force vector is given as [4,8]:

$$\{f\} = \{0,0,0,c_4\dot{x}_{se} + k_4x_{se}\} \quad (4)$$

This set of equations represents the dynamic characteristics of the system in terms of mass, stiffness, and damping. Each matrix is square and symmetric with size equal to the number of degrees of freedom of the system.

Identification of vibration energy absorbed in the biodynamical model. The measurement of absorbed power can be performed either in the time or in the frequency domain:
- in the time domain, it requires the simultaneous measurement of force and velocity at any given instant of time;
- in the frequency domain, absorbed power is calculated as the real part of the complex cross-spectrum of force and velocity.

The instantaneous power (P_{Tr}) transmitted to the human body during vibration can be calculated from the product of the force (F) and velocity (v) measured at the interface between the body and the vibrating surface [9, 10, 11].

$$P_{Tr} = F(t)v(t) = P_{Abs}(t) + P_{El}(t) \quad (5)$$

$P_{Abs}(t)$ is the absorbed part of the power, accounting for the energy necessary for keeping pace with the energy dissipated through structural damping The elastic power $P_{El}(t)$ is continuously delivered to and removed from the body

Annals of Agricultural and Environmental Medicine 2016, Vol 23, No 2

375

Jacek Kromulski, Tadeusz Pawłowski, Jan Szczepaniak, Wojciech Tanaś, Andrzej Wojtyła, Mariusz Szymanek, Jacek Tanaś, Waldemar Izdebski. Absorbed power distribution…

during each period of excitation, and averages to zero for each sinusoidal cycle of motion. Thus, the time-averaged absorbed power $\langle P_{Abs} \rangle$ equals the transmitted power $\langle P_{Tr} \rangle$, i.e.,

$$\langle P_{Abs} \rangle = \langle P_{Tr} \rangle = \langle F(t)v(t) \rangle \qquad (6)$$

The power transmitted to the body can be calculated in the frequency domain from the cross-spectrum between the force and the velocity. The real part of the transmitted power represents the power absorbed by the body [12, 13, 14]:

$$P_{Abs} = \mathrm{Re}(G_{vF}(f)) \qquad (7)$$

where Re is real part and G_{vF} is the cross-spectrum of velocity and force signals, and f is the frequency. Acceleration signals (a) are generally used instead of velocity (v) for practical measurements. By inserting the relationship v=a/jω, and using , total active power injected through a point junction by a point force is obtained as:

$$P_{Abs} = \frac{1}{\omega}\mathrm{Im}(G_{Fa}) \qquad (8)$$

where G_{Fa} is the cross-spectrum of force and acceleration signals, Im is the imaginary part, and ω=2πf is the angular frequency. By adding the value of ω, it is possible to obtain an input power equation in terms of frequency (f):

$$P_{Abs} = \frac{0.159}{f}\mathrm{Im}(G_{Fa}) \qquad (9)$$

RESULTS

In order to study the energy content of the vibration transmitted to the whole body and to different body segments, a 4-DOF linear biodynamic model was chosen to represent the body. The local absorbed power and total power absorption under different excitations (different operating speed) are obtained.

Identification of vibration energy absorbed by the body during the work of the aggregate at various working speeds. The data used for identification of absorbed power was collected from a series experiments in the field, in a typical operational condition driving scenario (Fig. 2). An agricultural combination tractor-mower were operated at a different operating speed 1.4 ÷ 2.75 ms^{-1}.

Whole body vibration (WBV) exposures were calculated per ISO 2631–1 (1997) [15]. According to ISO 2631–1, the weighted value of acceleration (a_w) can be used to evaluate human riding comfort.

Table 2. Vector-sum (root-sum-of-squares) vibration magnitude, the r.m.s. acceleration in operator's seat during work of the aggregate at various working speeds

No.	Agricultural combination speed [ms^{-1}]	weighted value of acceleration in vertical direction ($a_w)_z$	Vector sum of weighted values of acceleration in direction 'x', 'y' 'z' ($a_w)_{wek}$
1	1.40	0.60	1.53
2	2.15	0.74	1.79
3	2.75	1.18	2.79

Figure 2. Tractor-mower set during field tests. Instantaneous absorbed powers for different body segments were computed from [11, 16]

$$P_{Abs,i}(t) = c_i(\dot{x}_i - \dot{x}_{i+1})^2 \qquad (10)$$

total instantaneous absorbed power is given by:

$$P_{Tot}(t) = \sum_{i=1}^{4} c_i(\dot{x}_i - \dot{x}_{i+1})^2 \qquad (11)$$

The vibration energy absorbed by different body segments and total absorbed power was calculated using the equation (12)-(13).

Table 3. Vibration energy absorbed by the body during work of the aggregate at various working speeds

No.	Absorbed power in body segments [W]	Tractor mower set speed [ms^{-1}]		
		1.40 ms^{-1}	2.15 ms^{-1}	2.75 ms^{-1}
1	Absorbed power in damper C_4 associated with the thighs and pelvis in contact with the seat	1.20	2.04	6.67
2	Absorbed power in damper C_3 associated with the lower torso in contact with thighs and pelvis	2.90	3.78	10.31
3	Absorbed power in damper C_2 associated with the upper torso in contact with the lower torso.	19.78	24.69	57.93
4	Absorbed power in damper C_1 associated with the head	3.03	3.73	5.70
5	**Total absorbed power**	**26.91**	**34.24**	**80.61**

DISCUSSION

Very little energy is absorbed in damper 1 associated with the head. while most of the absorbed power occurs in damper 2, associated with the upper torso in contact with the lower torso.

The maximum amplitude the total absorbed power during the work of the aggregate with working speeds 2.75 ms^{-1} was 423 W. Total absorbed power most often reached value of about 100 W. Xie [11] studied the response of a 4-DOF human model to forced vibration originating from a vehicle (urban bus) traveling over an obstacle. In this case, the maximum amplitude total absorbed power was 36 W.
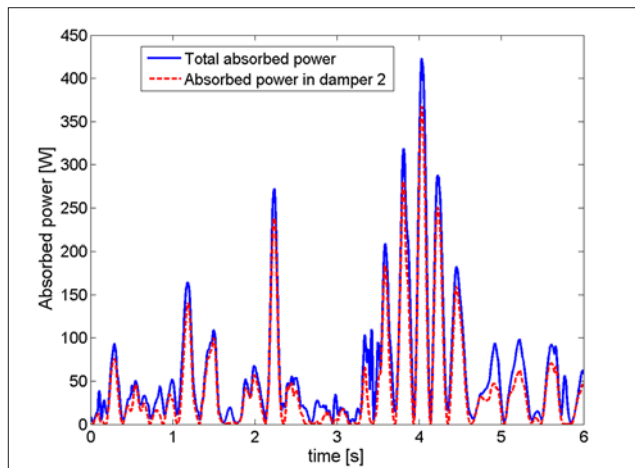
376　Annals of Agricultural and Environmental Medicine 2016, Vol 23, No 2

Jacek Kromulski, Tadeusz Pawłowski, Jan Szczepaniak, Wojciech Tanaś, Andrzej Wojtyła, Mariusz Szymanek, Jacek Tanaś, Waldemar Izdebski. Absorbed power distribution…

Figure 3. Total absorbed power and absorbed power in damper associated with the upper torso in contact with the lower torso during work of the aggregate with working speeds 2.75 ms^{-1}
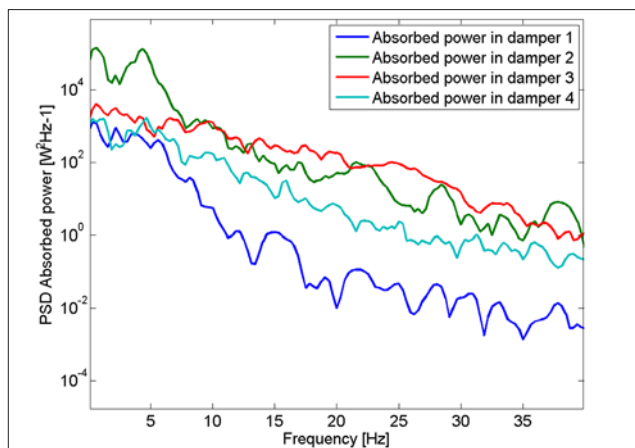

Figure 4. 4-DOF biodynamic model. Power spectral density (PSD) of absorbed power in various dampers during work of the aggregate with working speeds 2.75 ms^{-1}

As can be seen from the spectra, the biggest power absorption occurred in the low-frequency band. In the frequency range 0.1 – 7.8 Hz, most of the absorbed power occurred in the damper associated with the upper torso in contact with the lower torso. In the frequency range 10.0 – 35.5 Hz, most of the absorbed power occurred in the damper associated with the lower torso in contact with thighs and pelvis.

CONCLUSIONS

The concept of absorbed power as a measurement for evaluation of WBV exposure opens a new area for research. The important characteristic of absorbed power is that it has physical significance, and therefore can be measured as well as computed analytically. Power is a scalar quantity and can be summed-up in complex multi-degree of freedom systems to determine human response. A structural model of the human operator allows determination of the dynamic characteristics of the model, and study of the energy flow between the elements of the model, based on the real exciting forces from experimental research in field condition.

The vibration energy absorbed by the operators body is increased by increasing the driving speed of the agricultural combination.

In the analyzed 4-DOF biodynamic model, very little energy was absorbed in the damper associated with the head, while most of the absorbed power (more than 70%) occurred in damper associated with the upper torso in contact with the lower torso.

In the future, the energy absorbed by the operator can become an indicator of the vibration level acceptable in this place of human work. A useful way to compare this concept with other measurements of vibration exposure in relation to health effects, would be to conduct epidemiological studies on different categories of professional drivers.

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