Vibration energy absorption in the whole-body system of a tractor operator

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▌ Abstract

Many people are exposed to whole-body vibration (WBV) in their occupational lives, especially drivers of vehicles such as tractor and trucks. The main categories of effects from WBV are perception degraded comfort interference with activities-impaired health and occurrence of motion sickness. Absorbed power is defined as the power dissipated in a mechanical system as a result of an applied force. The vibration-induced injuries or disorders in a substructure of the human system are primarily associated with the vibration power absorption distributed in that substructure. The vibration power absorbed by the exposed body is a measure that combines both the vibration hazard and the biodynamic response of the body. The article presents measurement method for determining vibration power dissipated in the human whole body system called Vibration Energy Absorption (VEA). The vibration power is calculated from the real part of the force-velocity cross-spectrum. The absorbed power in the frequency domain can be obtained from the cross-spectrum of the force and velocity. In the context of the vibration energy transferred to a seated human body, the real component reflects the energy dissipated in the biological structure per unit of time, whereas the imaginary component reflects the energy stored/released by the system. The seated human is modeled as a series/parallel 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 has been determined as a function of the agricultural combination operating speed $1.39 - 4.16$ ms^{-1}.

▌ Key words

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

INTRODUCTION

Vehicle vibration has direct impact on human riding comfort, driver fatigue and safety.

Humans are most sensitive to whole body vibration under low-frequency excitation in the seated posture. Biodynamics of seated human subjects has been a topic of interest over the years, and a number of mathematical models have been established. The concept of absorbed energy was discussed in the mid-1960's by a group of scientists (Lee, Pradko), who presented results from investigations which indicated that the subjective experience of vibration is related to the amount of vibration energy absorbed by the body. Lidström showed that the prevalence of vibration-induced injuries is related to the amount of absorbed energy [1].

Biodynamic responses of the human body in sitting conditions have been widely measured under whole-body vibration. Vibration power absorption into the whole-body vibration system is one of the most important biodynamic measures that can be used to quantify the vibration exposure for assessing its potential effects. Although the exact relationship between the amount of absorbed power and the cell or tissue damage remains unknown, the vibration power absorption can be simply regarded as a physical measure of vibration-induced mechanical stimulus that acts directly on the cells and tissues

Knowledge of how vibration is transmitted to and through the human body can provide an important input to our understanding of human response to whole-body vibration.

Vibration-induced injuries or disorders in a substructure of the human system are primarily associated with the vibration power absorption distributed in that substructure. The measures are most often expressed in terms of force-motion relations at the driving-point, namely, mechanical impedance, apparent mass and absorbed power. The measured biodynamic responses have been used to identify critical frequency ranges associated with resonances of different body segments. A simple model that captures the essential dynamics of a seated human exposed to whole body vibration is the 4-DOF dynamic model of the human body developed by Wan and Schimmels, or by Boileau and Rakheja. After introduction of the excitation, the response in particular segments of the model can be analyzed. As an example, the operator's response has been determined for the agricultural combination tractor-soil cultivator. The biodynamic response has been determined as a function of the agricultural combination operating speed (5–15 km/h).

Biomechanical modeling. A number of biodynamic models have been proposed in the literature to estimate the magnitude of forces transmitted to particular subsystems within the body, to establish potential damage mechanisms, and to assess the tolerance to vibration under exposure to intense vibration levels. The human body in a sitting posture can be modeled as a mechanical system that is composed of several rigid bodies interconnected by springs and dampers [2].

In 1981, the International Organization for Standardization (ISO) published a parallel 2-DOF model for both sitting and standing positions. In 1995, Wan and Schimmels developed a series/parallel 4-DOF human dynamic model designed to match the response of seated humans exposed to vertical vibration. In this model, the seated human body was

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400

Annals of Agricultural and Environmental Medicine 2014, Vol 21, No 2

Jan Szczepaniak, Wojciech Tanaś, Jacek Kromulski. Vibration energy absorption in the whole-body system of a tractor operator

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 [3]. The Boileau and Rakheja 4-DOF human-body model consists of four mass segments interconnected by four sets of springs and dampers with a total mass of 55.2 kg.

The model parameters were obtained by comparing simulation results with the results of experimental tests on human subjects. The topology of the 4-DOF models are illustrated in Figure 1, and the biomechanical parameters of the model are listed in Tables 1 and 2.
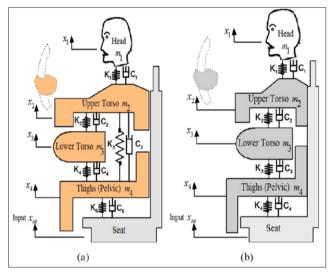

Figure 1. Biomechanical models: (a) Wan and Schimmels 4-DOF model; (b) Boileau and Rakheja 4-DOF model [4]

Table 1. Parameter values of the Wan and Schimmels 4-DOF model

Biomechanical parameters		
Mass (kg)	Damping (kg/s)	Stiffness (N/m)
head $m_1 = 4.17$	$c_1 = 250$	$k_1 = 134400$
lower torso $m_2 = 15$	$c_2 = 200$	$k_2 = 10000$
upper torso $m_3 = 5.5$	$c_3 = 909.1$	$k_3 = 192000$
pelvis $m_4 = 36$	$c_4 = 330$	$k_4 = 20000$
	$c_5 = 2475$	$k_5 = 49340$

Table 2. Parameter values of the Boileau and Rakheja 4-DOF model

Biomechanical parameters		
Mass (kg)	Damping (kg/s)	Stiffness (N/m)
head $m_1 = 5.31$	$c_1 = 400$	$k_1 = 310000$
lower torso $m_2 = 28.49$	$c_2 = 4750$	$k_2 = 183000$
upper torso $m_3 = 8.62$	$c_3 = 4585$	$k_3 = 162800$
pelvis $m_4 = 12.78$	$c_4 = 2064$	$k_4 = 90000$

Estimation of biodynamic response characteristics. There are two methods to solve system equations of motion; time domain and frequency domain. The system equations of motion for the model can be expressed in matrix form as follows:

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=\{f\} \tag{1}$$

where, $[M]$, $[C]$ and $[K]$ are mass, damping, and stiffness matrices, respectively; $\{f\}$ is the force vector due to external excitation. For Wan and Schimmels model: $\{f\}=\{0,0,0,c_5\dot{x}_{se}+k_5x_{se}\}$.

By taking the Fourier transformation of equation (1), the following matrix form of equation can be obtained:

$$\{X(j\omega)\}=[[K]-\omega^2[M]-j\omega[C]]^{-1}\{F(j\omega)\} \tag{2}$$

where, $\{X(j\omega)\}$ and $\{F(j\omega)\}$ are the complex Fourier transformation vectors of $\{x\}$ and $\{f\}$, respectively, and ω is the excitation frequency.

Vector $X(j\omega) = \{X_1(j\omega), X_2(j\omega), X_3(j\omega), \ldots, X_n(j\omega)\}$ contains complex displacement responses of n mass segments as a function of ω. $F(j\omega)$ consists of complex excitation forces on the mass segments as a function of ω as well, and for the Wan Schimmels model is $F(j\omega) = \{(0,0,0,(k_5 + j\omega c_5)X_{se}(\omega)\}$ where $X_{se}(\omega)$ is the amplitude of input displacement excitation [3, 5].

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. In this study, the velocity was obtained by integrating the measured acceleration time history.

The instantaneous power P_{Tr} transmitted to the structure is conventionally defined as:

$$P_{Tr} = F(t) \cdot v(t) = P_{Abs}(t) + P_{El}(t) \tag{3}$$

$P_{Abs}(t)$ 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 structure during each period of excitation and averages 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.

$$\langle P_{Abs} \rangle = \langle P_{Tr} \rangle = \langle F(t) \cdot v(t) \rangle \tag{4}$$

The power transmitted to the body can be calculated in the frequency domain from the cross-spectrum between the force and the velocity [6,7]. The real part of the transmitted power represents the power absorbed by the body [8, 9]:

$$P_{abs} = \mathrm{Re}\{G_{vF}(f)\} \tag{5}$$

where P_{abs} is the absorbed power, $\mathrm{Re}\{G_{vF}(f)\}$ is the real part of the cross-spectrum between the velocity and the force. The absorbed power spectrum, P_{abs}, has units of $\mathrm{Nms^{-1}Hz^{-1}}$.

The imaginary part of the transmitted power represents the power that enters and leaves the body (i.e., there is energy exchange between the body and the vibrating surface during each cycle of motion).

The biological system with finite damping consumes the vibratory energy by means of relative motions between the tissues, muscles and skeletal systems, which is transformed into heat. It has been speculated that this dissipative component could be related to musculoskeletal disorders, while the restoring part relates to vibration comfort and perception [10].

The total power absorbed at each input interface was obtained by integrating the absorbed power spectra over the frequency range.

Annals of Agricultural and Environmental Medicine 2014, Vol 21, No 2   401

Jan Szczepaniak, Wojciech Tanaś, Jacek Kromulski. Vibration energy absorption in the whole-body system of a tractor operator

Vibration power absorption of agricultural combination operator. The data used for identification of the power absorbed by the body was collected from a series of typical scenarios for operational driving conditions. The agricultural combination tractor-soil cultivator operates at different operating speeds (1.39; 2.08; 2.78; 3.47; 4.16 ms^{-1}) [11].

Figure 2. Agricultural combination tractor-soil cultivator during field work

In order to study the energy content of the vibration transmitted to the whole body and to different body segments, a four-degree of freedom linear biodynamic models is selected to represent the body. The local absorbed powers and the total power absorption under different excitations (various working speeds) are calculated.

According to ISO2631 [12], the weighted value of acceleration a_w can be used to evaluate the human riding comfort of a man-agricultural combination system (ISO 2631–1,1997). The vector sum of weighted values of acceleration can be obtained thus:

$$(a_w)_{wek} = \sqrt{[1,4(a_w)_x]^2 + [1,4(a_w)_y]^2 + [(a_w)_z]^2} \qquad (6)$$

Table 3. Vector-sum (root-sum-of-squares) vibration magnitude, the r.m.s. acceleration and vibration energy absorbed by the body during work with the aggregate at various working speeds

No	Agricultural combination	Weighted value of	Vector sum of weighted values of	Absorbed power by the body (pelvis) in vertical direction [W]	
	speed [ms^{-1}]	acceleration in vertical direction $(a_w)_z$	acceleration in direction 'x', 'y' 'z' $(a_w)_{wek}$	Wan and Schimmels 4-DOF model	Boileau and Rakheja 4-DOF model
1	1.39	0.3000	0.9131	13.58	9.42
2	2.08	0.4287	1.1020	32.40	23.43
3	2.78	0.5871	1.3114	68.57	51.36
4	3.47	1.0082	1.7583	85.52	64.89
5	4.16	1.1409	1.8409	97.75	87.98

Figures 3 and 4 show the spectrum of absorbed power measured at the pelvis during work with the aggregate at various working speeds
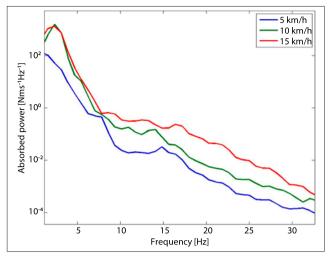

Figure 3. Wan and Schimmels 4-DOF model. Absorbed power measured at the pelvis during work with the aggregate at various working speed
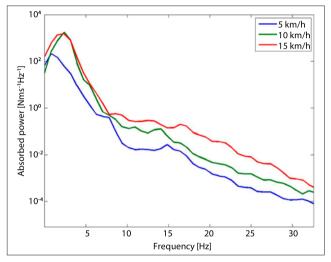

Figure 4. Boileau and Rakheja 4-DOF model. Absorbed power measured at the pelvis during work with the aggregate at various working speeds

CONCLUSIONS

The concept of absorbed power as a measure for evaluation of WBV exposure opens a new area for research. A useful way to compare this concept with other measures of vibration exposure in relation to health effects would be to conduct epidemiological studies on different categories of professional drivers.

Knowledge of the 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.

In the presenteds paper, the vibration energy absorption characteristics of a seated human exposed to vertical whole-body vibration are investigated under different agricultural combination speeds (1.39 – 4.16 ms^{-1}).

During the field test of the agricultural unit, it was found that the whole body vibration was about 3 times higher in the vertical direction when working at a speed of 4.16 ms^{-1} than at the speed of 1.39 ms^{-1}. The vibration energy absorbed by the operator's body was also increased by increasing the driving speed of the agricultural combination.

402

Annals of Agricultural and Environmental Medicine 2014, Vol 21, No 2

Jan Szczepaniak, Wojciech Tanaś, Jacek Kromulski. Vibration energy absorption in the whole-body system of a tractor operator

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