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# Dynamic loads acting on the farm tractor operator at work in the field with the increased operating speed

*Abstract: The article presents the results of dynamic load analysis of the tractor with agregate for pre sawing tillage that were made while working in the field with nominal and increased operating speed. The results of research on actual vibration level on tractor driver's seat cooperating with the agricultural aggregate, equipped with innovative spring teeth, have been presented. The amount of absorbed power by the tractor's operator, based on physical model (7 degrees of freedom) have been calculated, as a function of operating speed of tractor and agricultural aggregate.*

Keywords: *vibration, dynamic loads, tractor, agriculture, increased operating speed*

## Obciążenia dynamiczne oddziaływujące na operatora zestawu ciągnik rolniczy - agregat podczas pracy na polu ze zwiększoną prędkością roboczą

*Streszczenie: W artykule przestawiono wyniki badań układu ciągnik - agregat do upraw przedsiewnych, wykonane podczas pracy na polu z nominalną i ze zwiększoną prędkością roboczą. Przedstawiono wyniki badań dotyczące rzeczywistego poziomu drgań siedziska operatora ciągnika rolniczego współpracującego z agregatem uprawowym przedsiewnym, wyposażonym w innowacyjne zęby sprężyste. Wyznaczono wielkość energii zaabsorbowanej przez operatora, w oparciu o model fizyczny (7 stopni swobody), w funkcji prędkości ruchu zestawu ciągnik rolniczy - agregat.*

Słowa kluczowe: *drgania, obciążenia dynamiczne,ciągnik rolniczy, rolnictwo, zwiększona prędkość robocza*

## 1. Introduction

Tractor drivers are exposed to whole-body vibration (WBV) in their work especially while working on the field with an aggregate. The main categories of side effects from WBV are perception degraded comfort interference with activities impaired health and occurrence of motion sickness. The vibration-induced injuries or disorders in a substructure of human system are primarily associated with the vibration power absorption distributed in that substructure. Absorbed power is defined as the power dissipated in a mechanical system as a result of an applied force [6]. The vibration power absorbed by the exposed body is a measure that combines both the vibration hazard and the biodynamic response of the body.

There is a tendency in the agriculture to increase the operation speed on the field in order to increase the efficiency of work, however with the increase of operation speed the level of vibration increases as well. The level of vibration on operator's seat depends on many factors like vibration originating from combustion engine and agricultural aggregate as well as irregularity of field surface and dumping system of seat and tractor etc. Therefore it is necessary to know, be able to calculate and predict the behavior of human body in that complex working conditions.

The seated human is modeled as a series/parallel 7-DOF dynamic models. After introduction of the excitation data (obtained from the real experimental measurements on the field) we can analyze the response in particular segments of the human physical model. Based on that data, the vibration power dissipated in operator's body can be determined as a function of the operating speed 1.39 - 4.16 $ms^{-1}$ of tractor with aggregate.

## 2. Biomechanical model

Different biodynamical models of human body have been proposed in the literature to estimate the magnitude of forces transmitted to particular subsystems within the human body [1-6]. The human body in a sitting posture is modeled as a mechanical system consist of several rigid bodies interconnected by springs and dampers [2]. The main difference between the human body 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. 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 study for the calculation a Patil and Palanichamy 7-DOF model have been used [3]. The structure of Patil and Palanichamy the 7-DOF model is illustrated in Fig. 1

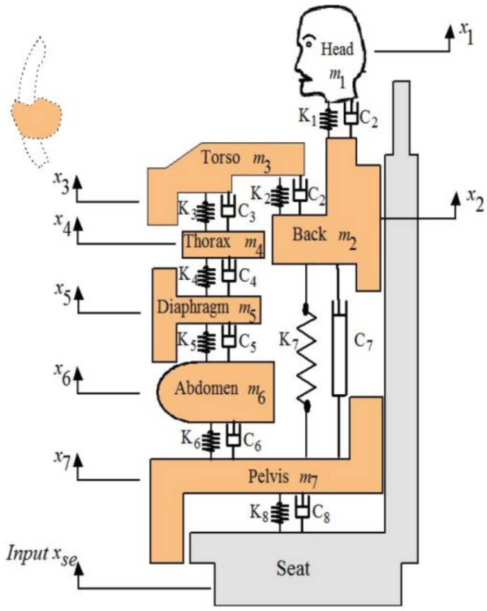


Fig. 1 Schematic diagram of human body model [3,8]

The model parameters were obtained by comparing simulation results with the results of experimental tests on human subjects [3]. Biomechanical parameters of the model which were taken into account during calculations are listed in Table 1.

Table 1. Parameter values of the Patil and Palanichamy 7-DOF model

| Biomechanical parameters | | |
|---|---|---|
| Mass (kg) | Damping (kg/s) | Stiffness (N/m) |
| $m_1$ = 5.55 | $c_1$ = 3651 | $k_1$ = 53640 |
| $m_2$ = 6.94 | $c_2$ = 3651 | $k_2$ = 53640 |
| $m_3$ = 33.33 | $c_3$ = 298 | $k_3$ = 8941 |
| $m_4$ = 1.389 | $c_4$ = 298 | $k_4$ = 8941 |
| $m_5$ = 0.4629 | $c_5$ = 298 | $k_5$ = 8941 |
| $m_6$ = 6.02 | $c_6$ = 298 | $k_6$ = 8941 |
| $m_7$ = 27.7 | $c_7$ = 3651 | $k_7$ = 53640 |
| | $c_8$ = 378 | $k_8$ = 25500 |

## 3. 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:

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

where: $[M]$, $[C]$ and $[K]$ are mass, damping, and stiffness matrices, respectively; $\{f\}$ is the force vector due to external excitation. For Patil and Palanichamy model the force vector is given as:

$$\{f\}=\{0,0,0,0,0,0,c_8\dot{x}_{seat}+k_8x_{seat}\}.$$

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

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

Where, {X(jω)} and {F(jω))} are the complex Fourier transformation vectors of {x} and {f}, respectively. ω is the excitation frequency.

Vector $X(j\omega)=\{X_1(j\omega),X_2(j\omega),X_3(j\omega),\dots,X_n(j\omega)\}$ 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 Patil and Palanichamy model is given as: $F(j\omega)=\{(0,0,0,(k_8+j\omega c_8)X_{seat}(\omega)\}$ where $X_{seat}(\omega)$ 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:

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

$P_{Abs}(t)$ 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 $<P_{Abs}>$ equals the transmitted power, $<P_{Tr}>$ i.e.

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

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]:

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

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 [9].

## 4. Vibration power absorption of agricultural tractor with aggregate for pre sawing tillage

The data used for identification power absorbed by the body was collected from a series experiments on the field in a typical operational condition driving scenario - fig.2. Agricultural combination tractor – aggregate for pre sawing tillage (cultivator) have been worked at a different operating speed 1.39 ÷ 4,16 $ms^{-1}$.

Fig.2. Agricultural tractor with aggregate for pre sawing tillage during field tests [4]

According to ISO2631 [10], the weighted value of acceleration $a_w$ can be used to evaluate human riding comfort of man- agricultural combination system (ISO 2631-1,1997).
Vector sum of weighted values of acceleration can be obtained:

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

During the tractro's operation a vibration level on driver seat have been measured. Examples of an one- third and octave spectrum of the acceleration of vibration in the tractro's cabin on operator's seat have been presented in Fig. 3 to 5.

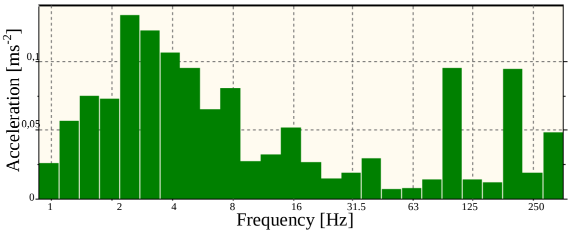


Fig. 3. The example of 1/3 octave spectrum of the accelerations of vibrations in operator's seat of the aggregate (direction "z", speed v = 1.39 m/s)

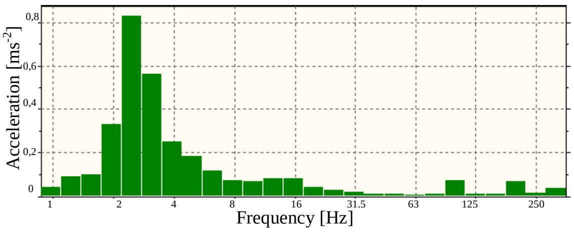


Fig. 4. The example of 1/3 octave spectrum of the accelerations of vibrations in operator's seat of the aggregate (direction "z", speed v = 2.78 m/s)

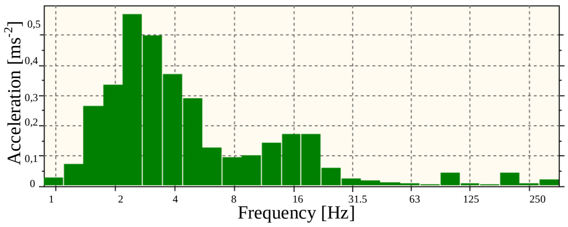


Fig. 5. The example of 1/3 octave spectrum of the accelerations of vibrations in operator's seat of the aggregate (direction "z", speed v = 4.16 m/s)

Patil and Palanichamy 7-DOF model absorbed power measured at the pelvis during the work of the aggregate with various working speed have been presented in Fig.6.

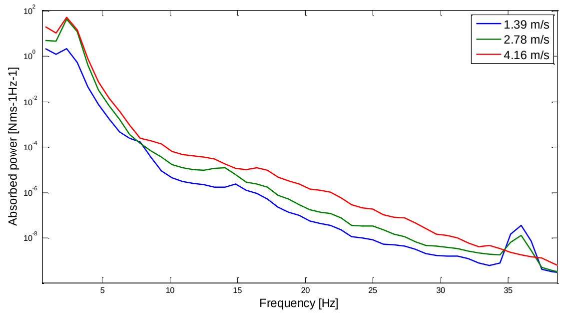


Fig. 6. Patil and Palanichamy 7-DOF model absorbed power measured at the pelvic during the work of the aggregate with various working speed

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

Table 2. The vector-sum (root-sum-of-squares) vibration magnitude, the r.m.s. acceleration and the vibration energy absorbed by the body during the work of the aggregate with 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" $(a_w)_{wek}$ | Absorbed power by the body (pelvic) in vertical direction [W] Patil and Palanichamy 7-DOF model |
|---|---|---|---|---|
| 1 | 1.39 | 0.3000 | 0.9131 | 4.0 |
| 2 | 2.08 | 0.4287 | 1.1020 | 25.9 |
| 3 | 2.78 | 0.5871 | 1.3114 | 39.4 |
| 4 | 3.47 | 1.0082 | 1.7583 | 52.4 |
| 5 | 4.16 | 1.1409 | 1.8409 | 59.9 |

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## 5. 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.

Structural model of human operator allows to determine the dynamic characteristics of the model and to study the energy flow between the elements of the model based on the real exciting forces from experimental research in field condition.

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

The energy absorbed by the operator can as can become in the future an indicator of vibration level acceptable in the place of human work.

## Nomenclature / *Skróty i oznaczenia*

DOF Degrees Of Freedom / *stopnie swobody*

WBV Whole - Body vibration / *drgania całego ciała*

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