Differences in Power Distribution in the Subsystems of the Human – Anti-Vibration Glove – Tool System

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Abstract

The article continues the analysis presented in the article „Power distribution in anti-vibration gloves" [6], which described the approach adopted to construct an energy model of the Human – Glove – Tool system (H – G – T). The outcome of the analysis was the power distribution calculated only for the anti-vibration glove. This article continues the energy analysis for another subsystem of the H – G – T system – the human physical model. The energy method was also used to calculate the power distribution in its dynamic structure in order to account for interactions between the elements of the H – G – T system. The results obtained in the study indicate that the power distribution in the human physical model and in the glove model is completely different.

Keywords: biomechanical system, hand-arm vibrations, power distribution, energy method

1. Introduction

Every physical model corresponds to the real system in terms of key features selected by the researcher, which are relevant for a given research problem. At the beginning of the modelling process one always starts with a number of simplifying assumptions, which, however, should not lead to approximations that distort the modelling goal. Ideally, one should only introduce simplifications that result in a simple model and facilitate the process of drawing conclusions while providing an accurate representation of the real system [1].

In this case, the problem becomes particularly interesting when one studies the discrete models used for analysing the impact of vibrations on the human body [7, 8, 10, 11]. The models differ from one another in terms of structure, because they are made up of a different number of mass, damping and elastic elements. This is a significant difference, because there is a relationship between an object's structure and its function. It should be emphasized that it is a cause and effect relationship. Hence, only models displaying structural similarity can guarantee the most reliable information about the real system [9]. It follows, then, that one should not create models with arbitrary structures that represent the real system's response only approximately.

The problem in question is important when one wants to determine the strain exerted on the dynamic structure of the model. The reason why this is a significant consideration is because this value should properly reflect the strain exerted on the real system. In this case, we use the response generated by the system, of course, but we also take into account the model's structure and the value of its dynamic parameters.

In the case analysed in the study it is assumed that the model is an energy transformation system. A similar approach, though applied to machines, was adopted by Cempel [2, 5], who described it in his works. In this article the approach is combined with the energy method implemented according to the theory developed by Dobry [3, 4].

The aim of the analysis was to determine the degree of difference between the load exerted on the dynamic structures of the human physical model and glove model. This assessment was based on three kinds of powers identified theoretically and related to the forces of inertia, dissipation and elasticity. This made it possible to determine which of the two subsystems of the H – G – T system was exposed to a higher dynamic load.

2. The human energy model

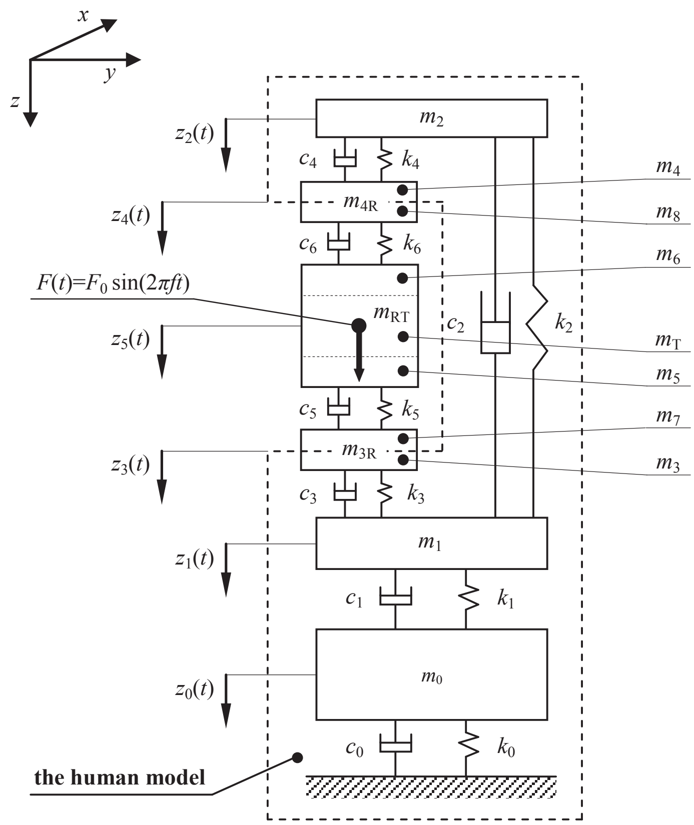
The dynamic load of the human physical model, which is a component of the H – G – T system, was calculated using the energy method. The H – G – T system was composed of the human physical model and the glove model specified in the ISO 10068:2012 standard [11].

Using the energy model of the H – G – T system, it is possible to identify the power distribution in the dynamic structure of the human physical model. A detailed description of the process of constructing the energy model and the application of the First Principle of Power Distribution in a Mechanical System [3, 4] is presented in another article [6]. The energy model of the H – G – T system (Fig. 1) represented by equations of power, is given by [6]:

$$
\begin{aligned}
&j=1, && m_0\ddot{z}_0\dot{z}_0+(c_0+c_1)\dot{z}_0^2+(k_0+k_1)z_0\dot{z}_0-c_1\dot{z}_1\dot{z}_0-k_1z_1\dot{z}_0=0\\
&j=2, && m_1\ddot{z}_1\dot{z}_1+(c_1+c_2+c_3)\dot{z}_1^2+(k_1+k_2+k_3)z_1\dot{z}_1-c_1\dot{z}_0\dot{z}_1-k_1z_0\dot{z}_1-\\
& && -c_2\dot{z}_2\dot{z}_1-k_2z_2\dot{z}_1-c_3\dot{z}_3\dot{z}_1-k_3z_3\dot{z}_1=0\\
&j=3, && m_2\ddot{z}_2\dot{z}_2+(c_2+c_4)\dot{z}_2^2+(k_2+k_4)z_2\dot{z}_2-c_2\dot{z}_1\dot{z}_2-k_2z_1\dot{z}_2-c_4\dot{z}_4\dot{z}_2-k_4z_4\dot{z}_2=0\\
&j=4, && m_{3R}\ddot{z}_3\dot{z}_3+(c_3+c_5)\dot{z}_3^2+(k_3+k_5)z_3\dot{z}_3-c_3\dot{z}_1\dot{z}_3-k_3z_1\dot{z}_3-c_5\dot{z}_5\dot{z}_3-k_5z_5\dot{z}_3=0\\
&j=5, && m_{4R}\ddot{z}_4\dot{z}_4+(c_4+c_6)\dot{z}_4^2+(k_4+k_6)z_4\dot{z}_4-c_4\dot{z}_2\dot{z}_4-k_4z_2\dot{z}_4-c_6\dot{z}_5\dot{z}_4-k_6z_5\dot{z}_4=0\\
&j=6, && m_{RT}\ddot{z}_5\dot{z}_5+(c_5+c_6)\dot{z}_5^2+(k_5+k_6)z_5\dot{z}_5-c_5\dot{z}_3\dot{z}_5-k_5z_3\dot{z}_5-\\
& && -c_6\dot{z}_4\dot{z}_5-k_6z_4\dot{z}_5=F(t)\dot{z}_5
\end{aligned}
\tag{1}
$$

The energy method makes it possible to determine the dynamic load for each of the subsystems of the H – G – T system, taking into account the influence of the other subsystems. This article focuses on only one subsystem, i.e. the human body, which was analysed by means of the energy method.

For this purpose, one should isolate from the energy model for the whole dynamic structure of the H – G – T system the power introduced into the human physical model. Consequently, in the following calculations it is necessary to take into account only those dynamic parameters that were used to model the behaviour of the human body (the part marked off in Figure 1). The dynamic parameters for the human physical model and the glove model, i.e. m_i, k_i, c_i are specified in the ISO 10068:2012 standard [11].



where:

$\boldsymbol{m_0, m_1, m_2, m_3, m_4}$
$\boldsymbol{k_0, k_1, k_2, k_3, k_4}$
$\boldsymbol{c_0, c_1, c_2, c_3, c_4}$ } **dynamic parametersof the human model**

m_5, m_6, m_7, m_8
k_5, k_6, c_5, c_6 } dynamic parametersof the glove model

m_T – tool mass

Reduction points: $m_{RT} = m_5 + m_6 + m_T$;

$m_{3R} = m_3 + m_7$; $m_{4R} = m_4 + m_8$.

Figure 1. The physical model of the biomechanical H – G – T system, obtained by combining the physical models from the ISO 10068:2012 standard [11] with the tool model

RMS values of power, calculated as a sum of powers at all points of reduction for the human model are defined as follows:
– the power of inertia expressed in [W]:

$$P_{\mathrm{H-INE}} = \sqrt{\frac{1}{t}\int_0^t \left[m_0\ddot{z}_0\dot{z}_0\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[m_1\ddot{z}_1\dot{z}_1\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[m_2\ddot{z}_2\dot{z}_2\right]^2 \mathrm{d}t} + \\ + \sqrt{\frac{1}{t}\int_0^t \left[m_3\ddot{z}_3\dot{z}_3\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[m_4\ddot{z}_4\dot{z}_4\right]^2 \mathrm{d}t} \tag{2}$$

– the power of dissipation expressed in [W]:

$$P_{\mathrm{H-DIS}} = \sqrt{\frac{1}{t}\int_0^t \left[(c_0+c_1)\dot{z}_0^2\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[(c_1+c_2+c_3)\dot{z}_1^2\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[(c_2+c_4)\dot{z}_2^2\right]^2 \mathrm{d}t} + \\ + \sqrt{\frac{1}{t}\int_0^t \left[c_3\dot{z}_3^2\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[c_4\dot{z}_4^2\right]^2 \mathrm{d}t} \tag{3}$$

– the power of elasticity expressed in [W]:

$$P_{\mathrm{H-ELA}} = \sqrt{\frac{1}{t}\int_0^t \left[(k_0+k_1)z_0\dot{z}_0\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[(k_1+k_2+k_3)z_1\dot{z}_1\right]^2 \mathrm{d}t} + \\ + \sqrt{\frac{1}{t}\int_0^t \left[(k_2+k_4)z_2\dot{z}_2\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[k_3z_3\dot{z}_3\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[k_4z_4\dot{z}_4\right]^2 \mathrm{d}t} \tag{4}$$

3. The results of the energy method

In the case under consideration the energy model was solved for the same conditions as in the previous article [6]. The biodynamic model of the H – G – T system was exposed to a sinusoidally varying driving force $F(t)$ with an amplitude of 115 N. The analysis was conducted assuming the value of frequency f = 20 Hz and tool mass m_T = 6 kg. As a result, it was possible to compare power distributions for the human model and the glove model.

The energy model was solved using numerical simulation for time t = 100 seconds. Integration was carried out using algorithm ode113 (Adams) with a tolerance of 0.0001. Simulations were implemented in the MATLAB/simulink environment with integration time steps ranging from a maximum value of 0.0001 to a minimum of 0.00001 second.

Figure 2 shows the structural power distribution for the human physical model and the glove model. The results for the glove model come from the previous article [6]. In the case of the human physical model and the glove model the percentage share of each type of power was calculated by relating the each type of power to the total power, equal to the sum of power generated in the two subsystems. The relationship can be expressed by the following formula:

$$S_{\mathrm{Z}} = \frac{P_{\mathrm{Z}i}}{P_{\mathrm{H-INE}} + P_{\mathrm{H-DIS}} + P_{\mathrm{H-ELA}} + P_{\mathrm{G-INE}} + P_{\mathrm{G-DIS}} + P_{\mathrm{G-ELA}}} \cdot 100\% \tag{5}$$

where:

- $P_{\mathrm{Z}i}$ – RMS value of the power of inertia, dissipation or elasticity determined at all points of reduction for the given model,
- $P_{\mathrm{G-Z}i}$ – RMS value of the power of inertia, dissipation or elasticity determined at all points of reduction for the glove model [6],
- $P_{\mathrm{H-Z}i}$ – RMS value of the power of inertia, dissipation or elasticity determined at all points of reduction for the human model (2) ÷ (4).

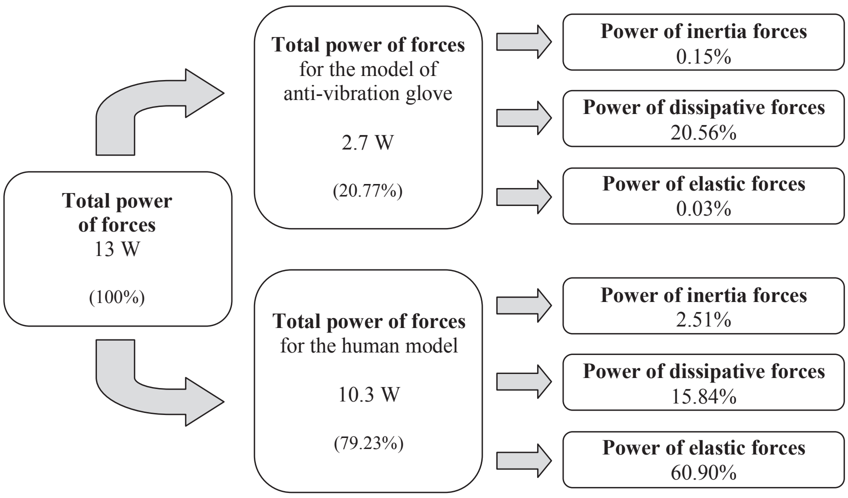


Figure 2. The structural power distribution of forces for the human model and the glove model [6] for the operating frequency of the tool $f = 20$ Hz

The results shown in Figure 2 indicate that the total power determined for the human model and the glove model for the operating frequency of the tool $f = 20$ Hz is equal to 13 W. The resulting value can be further decomposed into two total powers of forces introduced into both subsystems, i.e. for the human model and the glove model. The energy method demonstrated that the strain exerted on the dynamic structures in the analysis was different. It is worth noting that the total power for the human model is over 3.81 times larger than that calculated for the glove model.

More importantly, the results indicate that the power distribution computed for both models is completely different. This is reflected by the percentage share of each kind of power in each subsystem. For the glove model, the powers are ordered as follows: the power of dissipative forces – 20.56%, the power of inertial forces – 0.15% and the power of elastic forces – 0.03%. In the case of the human physical model the order is completely different. The contributions of the three kinds of power are ordered as follows: the power of elastic forces – 60.90%, the power of dissipative forces – 15.84% and the power of inertial forces – 2.51%.

It is worth noting that only one kind of force is comparable in quantitative terms. Quantitative comparison of powers between the models is presented in Figure 3.

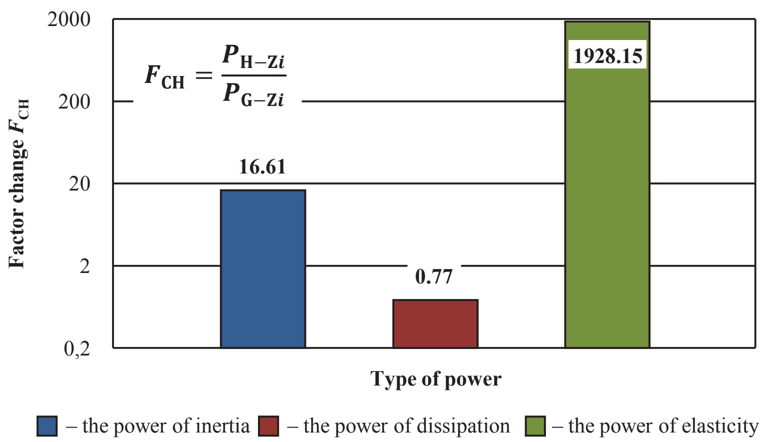


Figure 3. Quantitative comparison of three kinds of powers between the human model and the glove model for the operating frequency of the tool $f = 20$ Hz

The results shown in Figure 3 indicate that the only kind of power that is quantitatively comparable is the power of dissipation. More importantly, it is the only kind of power that is greater for the glove model than for the human model. The comparison results are quite different the powers of inertia and dissipation: in this case the factor change is equal to 16.61 for the power of inertia and 1928.15 for the power of elasticity. The values of the two kinds of forces computed for the dynamic structure of the tool are exactly as many times smaller than the results obtained for the structural human model.

4. Summary

The study has resulted in computing the power distribution for the human model, which is part of the biodynamic H – G – T system. More importantly, the results provide the basis for a comparative assessment of this subsystem with the values obtained for the anti-vibration glove. In this way it was possible to demonstrate that out of the two subsystems of the H – G – T system, it is the human operator who is exposed to more dynamic load. The results indicate the human dynamic structure receives 3.81 times more load than the glove.

Moreover, the analysis conducted in the study reveals that the disparate character of the load exerted on the two subsystems of the H – G – T system. The dynamic structure of the anti-vibration glove experiences a loss (dissipation) of energy, or its conversion into heat. In the human physical model, the dominant power component is related to the forces of elasticity. This is important because the computed power of forces can be related to specific changes in the human body [4]. The power of elastic forces should be linked to elastic elements in the human body. It should be emphasized that the elements of the human biological structure exposed to the greatest amount of dynamic stress are tendons, joints and muscles. When people are exposed to vibrations, it is these body parts that are adversely affected first and show pathological changes.

In the following stages of research the analysis will be extended to include other selected operating frequencies of the tool. As a result, curves of factor changes will be computed to enable a quantitative comparison of the powers of inertia, dissipation and elasticity between the different models. On this basis it will be possible to assess changes in the structural power distribution of forces in the subsystems of the H – G – T system in terms of the operational frequencies used in power hand-held tools.

Acknowledgments

The study was partly financed by the Ministry of Science and Higher Education as a project entitled: *Energy informational considerations of vibroacoustics, diagnostics and biomechanics of systems*.

Study code: 02/21/DSPB/3465

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