Power Distribution in Anti-Vibration Gloves

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Abstract

The article analyses power distribution in an anti-vibration glove. The glove of interest was modelled in a biodynamic model of the Human – Glove – Tool system. The model was a combination of the human model and the glove model specified in the ISO 10068:2012 standard and the model of the vibration tool. To determine the power distribution in the glove, its energy model was developed. The power distribution in the model was determined using numerical simulation in order to show how power was distributed in the dynamic structure of the anti-vibration glove. Three kinds of powers were distinguished, which are related to forces of inertia, dissipation and elasticity. It turned out that out of the three kinds of powers identified in the anti-vibration glove, only one is dominant: namely the power of dissipation.

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

1. Introduction

The first important stage of modelling consists in a systematic analysis of the real object. One should remember that the researcher's awareness, knowledge and needs affect the degree to which he or she simplifies the reality. This implies that the process of modelling depends, above all, on the degree of simplification which is applied to the real object. What is more, a model always replaces the object of study and only resembles it with respect to certain characteristics selected by the researcher [8].

A model can be similar to the real object in terms of structure. This means that the model represents features of the internal structure which it shares with the real object. Another kind of similarity is functional compatibility. Unfortunately, this kind of model does not lend itself to a precise assessment of its structure [8]. These facts are especially important when one wants to select a model to determine the impact of vibrations on the human body.

Nowadays the human response to vibration can be analysed using of a range of discrete human models that are available in the literature [6, 7, 10, 11]. These models differ from one another with respect to the number of degrees of freedom, the number of components making up the dynamic structure and the way they are connected. In other words, all of these models have different structures and differ in the way they transmit, dissipate and store vibration energy. In this study the analysis of the impact of vibration on the human body is based on the human model from the ISO 10068:2012 standard [11], which was used as part of the bigger biodynamic model of the Human – Glove – Tool system (H – G – T).

The approach presented in this article is completely different from those adopted to analyse anti-vibration gloves so far. Until recently studies of anti-vibration gloves were limited to computing coefficients to measure the effectiveness of vibroisolation [5]. This approach only involved comparing system responses and determining factor changes between them as a result of applying the anti-vibration glove. What is more, exact requirements for anti-vibration gloves are specified in the relevant standards [4, 9, 12].

This article, in contrast, describes an analysis of the flow of energy through the glove, which was treated as an energy transformation system. A similar approach, though applied to machines, was adopted by Cempel, who described it in his works [1, 4]. This article, however, describes the idea of analysing the flow of vibroacoustic energy related to dynamic properties of the system under consideration, which can be used to analyse mechanical and biomechanical systems. The theory developed by Dobry makes it possible to switch from the dynamic analysis implemented in the domain of amplitudes of kinematic quantities to the energy analysis implemented in the power domain [2, 3].

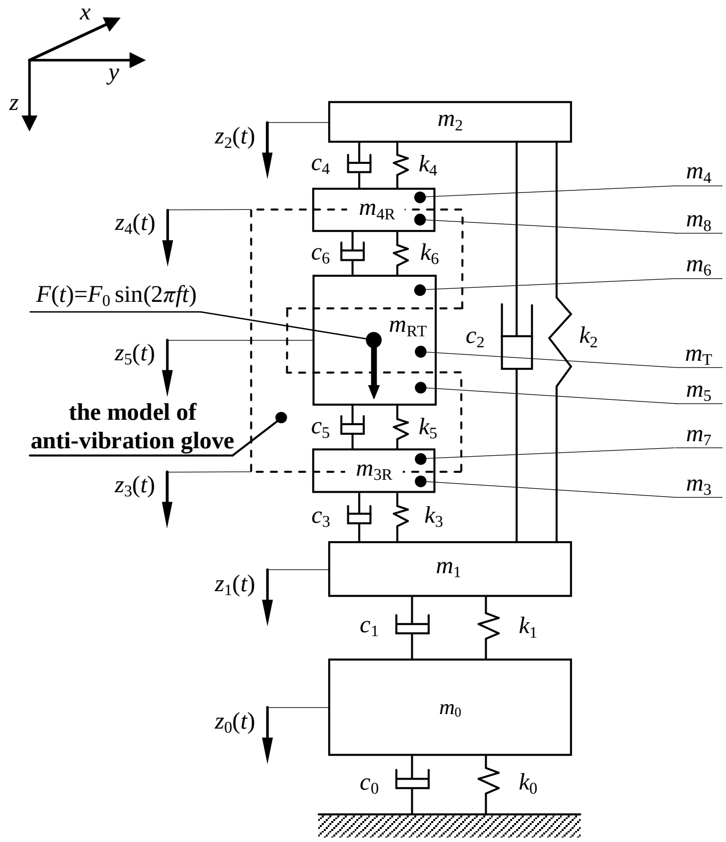
The power distribution in the anti-vibration glove was determined using the energy method. The aim of the analysis was to check whether the discrete model of the anti-vibration glove adopted from the ISO 10068:2012 standard [11] has an appropriate structure. The energy method consists in identifying three kinds of powers related to forces of inertia, dissipation and elasticity. The theoretically determined power distribution in the dynamic structure of the glove will make it possible to identify what happens to the energy of vibration only in the glove as a subsystem of the entire biomechanical H – G – T system.

2. The structure of the energy model

Figure 1 shows the combined H – G – T biodynamic model. The analysis is based on the human and glove models from the ISO 10068:2012 standard [11] The models selected are discrete models containing points of reduction connected through damping and elastic elements. The values of dynamic parameters for both models, that is m_i, k_i and c_i (Fig. 1) specified in the ISO 10068:2012 standard [11].

The human model from the said standard was used to determine values of vibrations along three directions, i.e. along the “*x*”, “*y*” and “*z*” axes. This article describes a simplified case limited to one dominant direction of vibrations, i.e. along the “*z*” axis, which is the most significant one in tests of many tools.

The H – G – T model must also include a model of the vibration tool. In this case, the tool was limited to one concentrated mass m_T and a sinusoidally varying driving force $F(t)$ acting on the H – G – T system. Hence, the model is assumed to represent a hypothetical situation of an operator using a grinder with an unevenly worn-out grinding disc. Additionally, the dashed line denotes the subsystem analysed by the energy method (Fig. 1), that is the anti-vibration glove.



where:

m_0, m_1, m_2, m_3, m_4, k_0, k_1, k_2, k_3, k_4, c_0, c_1, c_2, c_3, c_4 – dynamic parameters in the human physical model

$\boldsymbol{m_5, m_6, m_7, m_8}$, $\boldsymbol{k_5, k_6, c_5, c_6}$ – **dynamic parameters in the glove model**

m_T – tool mass

Points of reduction: $m_{RT} = m_5 + m_6 + m_T$;

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

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

In the first step, a mathematical model of the dynamic structure was derived, using Lagrange equations of the second kind given by:

$$\frac{d}{dt}\left(\frac{\partial E}{\partial \dot{q}_j}\right) - \frac{\partial E}{\partial q_j} = Q_j + Q_{jP} + Q_{jD} \qquad j = 1, 2, \ldots, s \tag{1}$$

where: E – kinetic energy of the system, q_j – generalized coordinates,
$\dot{q}_j$ – generalized velocities, Q_j – active external forces, Q_{jP} – potential forces,
Q_{jD} – forces of dissipation, s – the number of degrees of freedom.

The mathematical model was fed with generalized coordinates. For the model of the H – G – T system (Fig. 1), the generalized coordinates were as follows:

$j = 1$, $q_0 = z_0(t)$ – displacement of mass m_0,
$j = 2$, $q_1 = z_1(t)$ – displacement of mass m_1,
$j = 3$, $q_2 = z_2(t)$ – displacement of mass m_2,
$j = 4$, $q_3 = z_3(t)$ – displacement of mass m_{3R},
$j = 5$, $q_4 = z_4(t)$ – displacement of mass m_{4R},
$j = 6$, $q_5 = z_5(t)$ – displacement of mass m_{RT}.

After adopting the generalized coordinates, it was possible to derive differential equations of motion for the H – G – T model. The mathematical model in matrix form is given by:

$$\mathbf{M}\ddot{\mathbf{q}}(t) + \mathbf{C}\dot{\mathbf{q}}(t) + \mathbf{K}\mathbf{q}(t) = \mathbf{F}(t) \tag{2}$$

where:

– matrix of displacements: – matrix of masses: – matrix of forces:

$$\mathbf{q}(t) = \begin{bmatrix} z_0(t) \\ z_1(t) \\ z_2(t) \\ z_3(t) \\ z_4(t) \\ z_5(t) \end{bmatrix} \qquad \mathbf{M} = \begin{bmatrix} m_0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_{3R} & 0 & 0 \\ 0 & 0 & 0 & 0 & m_{4R} & 0 \\ 0 & 0 & 0 & 0 & 0 & m_{RT} \end{bmatrix} \qquad \mathbf{F}(t) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ F(t) \end{bmatrix}$$

– matrix of damping:

$$\mathbf{C} = \begin{bmatrix} (c_0 + c_1) & -c_1 & 0 & 0 & 0 & 0 \\ -c_1 & (c_1 + c_2 + c_3) & -c_2 & -c_3 & 0 & 0 \\ 0 & -c_2 & (c_2 + c_4) & 0 & -c_4 & 0 \\ 0 & -c_3 & 0 & (c_3 + c_5) & 0 & -c_5 \\ 0 & 0 & -c_4 & 0 & (c_4 + c_6) & -c_6 \\ 0 & 0 & 0 & -c_5 & -c_6 & (c_5 + c_6) \end{bmatrix}$$

– matrix of stiffness:

$$\mathbf{K} = \begin{bmatrix} (k_0 + k_1) & -k_1 & 0 & 0 & 0 & 0 \\ -k_1 & (k_1 + k_2 + k_3) & -k_2 & -k_3 & 0 & 0 \\ 0 & -k_2 & (k_2 + k_4) & 0 & -k_4 & 0 \\ 0 & -k_3 & 0 & (k_3 + k_5) & 0 & -k_5 \\ 0 & 0 & -k_4 & 0 & (k_4 + k_6) & -k_6 \\ 0 & 0 & 0 & -k_5 & -k_6 & (k_5 + k_6) \end{bmatrix}$$

The next step in modelling the H – G – T system involved creating the energy model. The model was formulated by applying the First Principle of Power Distribution in a Mechanical System [2, 3]. The principle enables the switch from the dynamic model to the energy model implemented in the power domain. The model was derived using differential equations of motions (2). The energy model of the H – G – T system (Fig. 1), consists of equations of power given by:

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

The energy model of the H – G – T system was derived using a program implemented in the MATLAB/simulink environment in order to compute curves of powers of inertia, dissipation and elasticity. The energy method makes it possible to analyse each subsystem separately, while taking into account the impact of the other subsystems. For this reason, when analysing the energy model for the whole dynamic structure of the H – G – T system, one should only consider the part of power which is transferred to the anti-vibration glove. In the computations it was necessary to include only those dynamic parameters, which were used to model the glove – the fragment of the model marked off in Fig. 1. RMS values of powers, calculated as sums of powers at all points of reduction in the glove model, were defined as follows:

– the power of inertia expressed in [W]:

$$P_{\mathrm{G-INE}} = \sqrt{\frac{1}{t}\int_0^t [(m_5 + m_6)\ddot{z}_5\dot{z}_5]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t [m_7\ddot{z}_3\dot{z}_3]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t [m_8\ddot{z}_4\dot{z}_4]^2 \mathrm{d}t} \tag{4}$$

– the power of dissipation expressed in [W]:

$$P_{\mathrm{G-DIS}} = \sqrt{\frac{1}{t}\int_0^t \left[c_5 \dot{z}_3^2\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[c_6 \dot{z}_4^2\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[(c_5 + c_6)\dot{z}_5^2\right]^2 \mathrm{d}t} \tag{5}$$

– the power of elasticity expressed in [W]:

$$P_{\mathrm{G-ELA}} = \sqrt{\frac{1}{t}\int_0^t \left[k_5 z_3 \dot{z}_3\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[k_6 z_4 \dot{z}_4\right]^2 \mathrm{d}t} + \sqrt{\frac{1}{t}\int_0^t \left[(k_5 + k_6) z_5 \dot{z}_5\right]^2 \mathrm{d}t} \tag{6}$$

3. The results of the energy method

In the study 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 $m_{\mathrm{T}} = 6$ kg.

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 presents the resulting structural power distribution in the anti-vibration glove. The percentage share of each kind of power was determined by relating it to the total power in the glove. The relationship is expressed by the following formula:

$$S_{\mathrm{Z}} = \frac{P_{\mathrm{Z}}}{P_{\mathrm{G-INE}} + P_{\mathrm{G-DIS}} + P_{\mathrm{G-ELA}}} \cdot 100\% \tag{7}$$

where:

P_{Z} – RMS value of the power of inertia, dissipation or elasticity determined at all points of reduction in the anti-vibration glove.

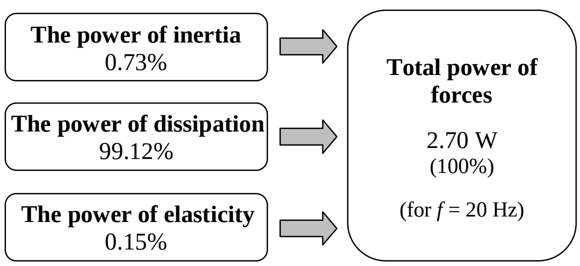


Figure 2. Structural power distribution in the anti-vibration glove for frequency of the driving force $f = 20$ Hz

The results reveal the power distribution in the dynamic structure of the subsystem under consideration. The results presented in Figure 2 indicate that the dominant role of the power of dissipation forces. The percentage share of the power of dissipation for the frequency of the driving force *f* = 20 Hz exceeded 99% of total power.

This means that the dynamic structure of the glove experiences energy loss (dissipation), with kinetic energy being converted to heat. This implies that the amount of energy transferred to the human body is limited. In other words, the energy method has successfully demonstrated a positive influence of the anti-vibration glove in the H – G – T system. Moreover, the dynamic structure of the glove was correctly modelled, which is confirmed by the results that are consistent with expectations. The study suggests that an anti-vibration glove should be made using materials characterized by high energy dissipation. This implies that the glove should be capable of dissipating large amounts of energy.

4. Summary

The study has resulted in determining the structural power distribution in the anti-vibration glove for the operating frequency *f* = 20 Hz. The results indicate the dominant role of only one kind of power. It turns out that the power of dissipation accounts for over 99% of total power in the glove.

More importantly, the analysis correctly confirmed the anti-vibration properties of the glove. The model structure ensures energy dissipation, which is responsible for decreasing the vibration energy transferred to the human body. This property should be taken into consideration in choosing materials for the manufacturing of anti-vibration gloves.

Further studies will be devoted to specifying the power distribution in the human physical model. Knowing power distributions in these two subsystems will make it possible to assess the level of dynamic load they are exposed to. Another goal will be to calculate the ratio change in the distribution of the three kinds of powers in the dynamic structure of the human and glove model.

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