# Assessment of the Effectiveness of Anti-Vibration Gloves. A Comparison of the Conventional and Energy Method. Introduction – Part One

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## Abstract

The article is an introduction to the assessment of the effectiveness of anti-vibration gloves. The assessment was conducted for a specific glove. The impact of the glove was taken into account in a model of the biodynamic system consisting of the human operator, the anti-vibration glove and the hand-held power tool. The synthetic model was created by integrating the physical model of the human body and the glove model specified in the International Standard ISO 10068:2012 with a model of an electric angle grinder. The first part of the study describes an alternative model of the glove, developed on the basis of experimental data. The article also presents a description of dynamic and energy models for analyzing dynamic structures of the biomechanical system. Results obtained at this stage are used to analyse and interpret the observed phenomena and to compare methods of assessing the effectiveness of anti-vibration gloves, which are discussed in detail in the second part.

***Key words:*** biomechanical system, local vibrations, energy method of assessment

## 1. Introduction

Studies involving discrete models of the human body were already conducted in the 1970s. Major contributions in this field were made by Griffin [6], Meltzer [7] and Reynolds [8]. Nowadays this problem is being studied by other researchers [3–5].

It is worth noting that most of those analyses have focused mainly on the response generated by the model, which should always be similar to the result produced by the real system. While this is no doubt a major criterion in modelling, it is also necessary to consider the internal structure of the model, which will be fully compatible with the real system not only when it generate a specific response but also when its internal structure is sufficiently well defined.

The present article is an introduction to a comparative assessment of the impact of vibrations on the human operator using an anti-vibration glove. Two methods of assessment were applied: the conventional and the energy method. For this purpose, the physical model of the human body and the model of the glove specified in the ISO 10068:2012 standard were used. In addition, the assessment was based on experimental data for a specific anti-vibration glove, which satisfied safety requirements for this kind of personal protective equipment according to industrial standards [10, 11].

## 2. Results of laboratory measurements

The necessary laboratory measurements were conducted in the Laboratory of Dynamics and Ergonomics of the Human-Technical Object-Environment Metasystem at Poznan University of Technology using the Brüel & Kjær integrating vibration meter, type 2513. The meter was set to read RMS values of vibration accelerations, which were averaged during each reading with a 1 second time constant. The linear weighting was selected, which means that no filters were used and the measurement frequency range was between 10 and 10,000 Hz. The experimental setting was designed to represent the case of an operator using an angle grinder with a 125 mm disc and a rotation speed of 11,000 rpm.

Accelerations of vibrations in the human body separately in three directions, i.e. along the „*x*”, „*y*” and „*z*” axis, were measured. However, in the article we only present results of vibrations along the dominant direction, i.e. the „*z*” axis. It is worth noting that it is often the most important direction analysed in tests of various tools. The purpose of measurements was to obtain input data along the specified direction of movement for subsequent numerical simulations. The test was designed to recreate the following three conditions:

a) when the tool is used without the glove – RMS values of vibration accelerations at the handle were measured, which are equivalent to RMS values of vibration accelerations experienced by the operator, i.e. at the contact surface between the palm and the handle,
b) when the operator uses an anti-vibration glove – RMS values of vibration accelerations at the handle were measured, which have changed as a result of being gripped through the anti-vibration layer of the glove,
c) when the operator uses an anti-vibration glove – RMS values of vibration accelerations at the contact surface between the operator's hand and the anti-vibration layer of the glove were measured.

Measurements for each condition were expressed as 2 numbers identifying particulars measurement series: the mean (the measure of central tendency) and standard deviation (the measure of dispersion). The precision of measurements burdened with random errors was determined using confidence intervals with Student's *t*-distribution. The confidence interval was set at 95% ($\alpha = 0.05$), with 9 degrees of freedom ($k = 9$, given 10 measurements for each condition). The critical value of the test statistic $t_{(\alpha;k)}$ for such criteria was obtained from statistical tables. Table 1 shows results for the three conditions.

Table 1. (RMS) values of vibration accelerations – laboratory measurements

| **Measurement condition** | **Value** | **Unit** |
|---|---|---|
| at the handle (without the glove) | 101.00 ± 2.82 | $m/s^2$ |
| at the handle (with the glove) | 117.00 ± 6.79 | |
| at the palm of the hand (with the glove) | 26.55 ± 0.83 | |

It should be noted that the classic approach focusing on the vibration amplitude revealed a negative effect of the anti-vibration glove on RMS values of vibration accelerations on the handle. It turns out that the fact of holding the grinder through the anti-vibration layer of the glove actually increases the amplitude of vibrations measured at the handle. Moreover, RMS values of vibrations at the handle without the glove are more consistent, i.e. less dispersed. This is confirmed by values of standard deviations shown in Table 1.

In addition, vibration acceleration signals generated by the grinder along the „*z*” axis were recorded using an oscilloscope. The experimental data to model signals of vibration accelerations for simulation purposes was used. The progressive mechanical wear of the disc, which was mainly due to its quality, caused a static imbalance. The grinding disc wore out unevenly, producing more complex patterns of oscilloscope signals. The basic section of acceleration signals consisted of six sines of varying amplitude and frequency. Figure 1 shows the signal of vibration accelerations used for purposes of simulation, which was modelled on the basis of signals recorded by the oscilloscope. Consistency of the modelled signal with the experimental data was confirmed by equal RMS values.

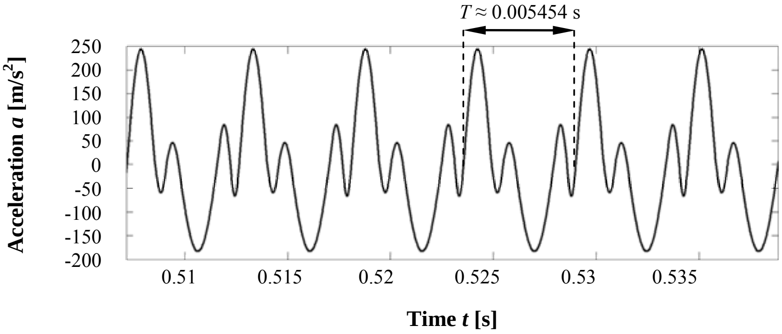
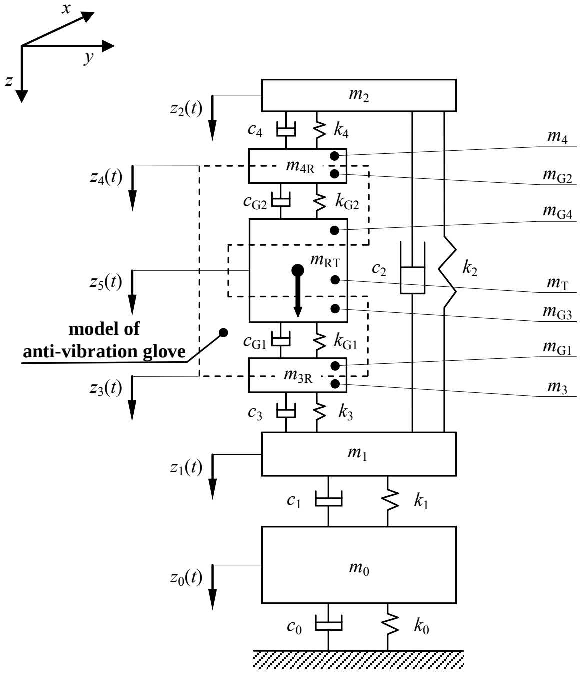


Fig. 1. The signal curve of vibration accelerations at the handle modelled on the basis of recorded data, with the basic section indicated.

The next stage of the study involved developing a model of the H – G – T system, consisting of the human operator (H), the anti-vibration glove (G) and the hand-held power tool (T). Figure 2 shows the combined biomechanical system, which consists of the physical model of the human body and the dynamic structure of the glove model presented in the ISO 10068:2012 standard [9]. These discrete models contain points of reduction, which are interconnected by damping and elastic elements. Values of the dynamic parameters for the model of the human body, i.e. $m_i$, $k_i$ and $c_i$ were taken from the ISO 10068:2012 standard [9].



Points of reduction: $m_{RT} = m_{G3} + m_{G4} + m_T$;
$m_{3R} = m_3 + m_{G1}$; $m_{4R} = m_4 + m_{G2}$.

Fig. 2. Physical model of the biodynamic H – G – T system created by combing the physical model of the human body and the glove model described in ISO 10068:2012 [9] with the tool model

Original values provided for the glove model were adapted to match the results of measurements obtained for the anti-vibration glove tested in the laboratory. The dynamic parameters for the glove, i.e. $m_{Gi}$, $k_{Gi}$ and $c_{Gi}$ are presented in Table 2.

Table 2. Values of dynamic parameters for the anti-vibration glove along the „*z*” axis

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| $m_{G1}$ | 0.0540 | kg |
| $m_{G2}$ | 0.0140 | |
| $m_{G3}$ | 0.0018 | |
| $m_{G4}$ | 0.0013 | |
| $k_{G1}$ | 10.60 | N/m |
| $k_{G2}$ | 19.64 | |
| $c_{G1}$ | 36.5 | Ns/m |
| $c_{G2}$ | 36.0 | |

The third element of the H – G – T model – the model of the percussive tool – was represented by one concentrated mass $m_T$. Data for analysis came from measurements involving an angle grinder operated at the maximum speed of 11,000 rpm, i.e. at an operational frequency of 183.(3) Hz, with period $T \approx 0.005454$ – Fig. 1.

## 3. Theoretical results

The first step in the theoretical part was to derive mathematical models of the dynamic structures using Lagrange equations of the second kind given by:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial E}{\partial \dot{q}_j}\right) - \frac{\partial E}{\partial q_j} = Q_j + Q_{j\mathrm{P}} + Q_{j\mathrm{R}} \qquad j = 1,2,\dots,s \tag{1}$$

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

The mathematical model of the H – G – T system (Fig. 2) contains the following 6 generalized coordinates:

$j = 1$, $q_0 = z_0(t)$ – 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 masses $m_3$ and $m_{\mathrm{G1}}$,
$j = 5$, $q_4 = z_4(t)$ – displacement of masses $m_4$ and $m_{\mathrm{G2}}$,
$j = 6$, $q_5 = z_5(t)$ – displacement of masses $m_{\mathrm{G3}}$, $m_{\mathrm{G4}}$ and $m_{\mathrm{T}}$.

The generalized coordinates were then used to derive differential equations of forces for the H – G – T model, which is given by:

$$\begin{aligned}
&j = 1, && m_0\ddot{z}_0 + (c_0 + c_1)\dot{z}_0 + (k_0 + k_1)z_0 - c_1\dot{z}_1 - k_1 z_1 = 0 \\
&j = 2, && m_1\ddot{z}_1 + (c_1 + c_2 + c_3)\dot{z}_1 + (k_1 + k_2 + k_3)z_1 - c_1\dot{z}_0 - k_1 z_0 - c_2\dot{z}_2 - k_2 z_2 \\
& && \quad - c_3\dot{z}_3 - k_3 z_3 = 0 \\
&j = 3, && m_2\ddot{z}_2 + (c_2 + c_4)\dot{z}_2 + (k_2 + k_4)z_2 - c_2\dot{z}_1 - k_2 z_1 - c_4\dot{z}_4 - k_4 z_4 = 0 \\
&j = 4, && (m_3 + m_{\mathrm{G1}})\ddot{z}_3 + (c_3 + c_{\mathrm{G1}})\dot{z}_3 + (k_3 + k_{\mathrm{G1}})z_3 - c_3\dot{z}_1 - k_3 z_1 - c_{\mathrm{G1}}\dot{z}_5 - k_{\mathrm{G1}} z_5 = 0 \\
&j = 5, && (m_4 + m_{\mathrm{G2}})\ddot{z}_4 + (c_4 + c_{\mathrm{G2}})\dot{z}_4 + (k_4 + k_{\mathrm{G2}})z_4 - c_4\dot{z}_2 - k_4 z_2 - c_{\mathrm{G2}}\dot{z}_5 - k_{\mathrm{G2}} z_5 = 0 \\
&j = 6, && (m_{\mathrm{G3}} + m_{\mathrm{G4}} + m_{\mathrm{T}})\ddot{z}_5 + (c_{\mathrm{G1}} + c_{\mathrm{G2}})\dot{z}_5 + (k_{\mathrm{G1}} + k_{\mathrm{G2}})z_5 - c_{\mathrm{G1}}\dot{z}_3 - k_{\mathrm{G1}} z_3 \\
& && \quad - c_{\mathrm{G2}}\dot{z}_4 - k_{\mathrm{G2}} z_4 = F(t)
\end{aligned} \tag{2}$$

For the second condition, when the operator is working without the anti-vibration glove, i.e. for the model of the system consisting of the human operator and the tool (H – T), the generalized coordinates are 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 masses $m_3$, $m_4$ and $m_T$.

The number of generalized coordinates is smaller since the model of the anti-vibration glove (enclosed by dotted line in Fig. 2) is not included. As a result, masses $m_3$ and $m_4$ are in direct contact with mass $m_T$, which is a substitute for the tool. The exclusion of the glove model eliminates two points of reduction from model (2), i.e. $j = 4$ and $j = 5$. Consequently, the mathematical model of the biomechanical system with 4 degrees of freedom can be expressed as:

$$
\begin{aligned}
&j = 1, && m_0\ddot{z}_0 + (\mathrm{c}_0 + \mathrm{c}_1)\dot{\mathrm{z}}_0 + (k_0 + k_1)z_0 - c_1\dot{z}_1 - k_1 z_1 = 0 \\
&j = 2, && m_1\ddot{z}_1 + (c_1 + c_2 + c_3)\dot{z}_1 + (k_1 + k_2 + k_3)z_1 - c_1\dot{z}_0 - k_1 z_0 - c_2\dot{z}_2 - k_2 z_2 \\
& && - c_3\dot{z}_3 - k_3 z_3 = 0 \\
&j = 3, && m_2\ddot{z}_2 + (c_2 + c_4)\dot{z}_2 + (k_2 + k_4)z_2 - c_2\dot{z}_1 - k_2 z_1 - c_4\dot{z}_3 - k_4 z_3 = 0 \\
&j = 4, && (m_3 + m_4 + m_T)\ddot{z}_3 + (c_3 + c_4)\dot{z}_3 + (k_3 + k_4)z_3 - c_4\dot{z}_2 - k_4 z_2 \\
& && -c_3\dot{z}_1 - k_3 z_1 = F(t)
\end{aligned}
\tag{3}
$$

The next step involved assessing the effect of vibrations on the human body in terms of energy, which consists in determining three components of energy inputs, associated with three kinds of structural forces: inertial, dissipative and elastic. This was achieved by applying the First Principle of Power Distribution in a Mechanical System [1, 2]. The components of energy were calculated using numerical simulations, i.e. by determining energy inputs flowing through the dynamic structure of the H – G – T system. Specific energy inputs absorbed by the human body were calculated as integrals of the absolute values of structural forces. In this way, it is possible to define and compare the flow of energy through the human body under both conditions, i.e. when using the tool with and without the glove. Values of component energy inputs in the dynamic structure of the human body, defined as a sum of energy inputs due to specific types of forces at all point of reduction, were defined as follows:

- the energy component due to inertial forces for the human operator working without the glove:

$$E_{\text{H-INE},t} = \int_0^t \left|m_0\ddot{z}_0\dot{z}_0\right|\mathrm{d}t + \int_0^t \left|m_1\ddot{z}_1\dot{z}_1\right|\mathrm{d}t + \int_0^t \left|m_2\ddot{z}_2\dot{z}_2\right|\mathrm{d}t + \int_0^t \left|(m_3 + m_4)\ddot{z}_3\dot{z}_3\right|\mathrm{d}t \tag{4}$$

- the energy component due to dissipative forces for the human operator working without the glove:

$$E_{\text{H-DIS},t} = \int_0^t \left|(c_0 + c_1)\dot{z}_0^2\right|\mathrm{d}t + \int_0^t \left|(c_1 + c_2 + c_3)\dot{z}_1^2\right|\mathrm{d}t + \int_0^t \left|(c_2 + c_4)\dot{z}_2^2\right|\mathrm{d}t + \int_0^t \left|(c_3 + c_4)\dot{z}_3^2\right|\mathrm{d}t \tag{5}$$

- the energy component due to elastic forces for the human operator working without the glove:

$$
\begin{aligned}
E_{\text{H-ELA},t} &= \int_0^t \left|(k_0 + k_1) z_0 \dot{z}_0\right| \mathrm{d}t + \int_0^t \left|(k_1 + k_2 + k_3) z_1 \dot{z}_1\right| \mathrm{d}t + \int_0^t \left|(k_2 + k_4) z_2 \dot{z}_2\right| \mathrm{d}t \\
&+ \int_0^t \left|(k_3 + k_4) z_3 \dot{z}_3\right| \mathrm{d}t
\end{aligned}
\tag{6}
$$

For the condition with the anti-vibration glove, energy components are given as follows:

- the energy component due to inertial forces for the human operator working with the glove:

$$
E_{\text{H+G-INE},t} = \int_0^t \left|m_0 \ddot{z}_0 \dot{z}_0\right| \mathrm{d}t + \int_0^t \left|m_1 \ddot{z}_1 \dot{z}_1\right| \mathrm{d}t + \int_0^t \left|m_2 \ddot{z}_2 \dot{z}_2\right| \mathrm{d}t + \int_0^t \left|m_3 \ddot{z}_3 \dot{z}_3\right| \mathrm{d}t + \int_0^t \left|m_4 \ddot{z}_4 \dot{z}_4\right| \mathrm{d}t
\tag{7}
$$

- the energy component due to dissipative forces for the human operator working with the glove:

$$
\begin{aligned}
E_{\text{H+G-DIS},t} &= \int_0^t \left|(c_0 + c_1) \dot{z}_0^2\right| \mathrm{d}t + \int_0^t \left|(c_1 + c_2 + c_3) \dot{z}_1^2\right| \mathrm{d}t + \int_0^t \left|(c_2 + c_4) \dot{z}_2^2\right| \mathrm{d}t \\
&+ \int_0^t \left|c_3 \dot{z}_3^2\right| \mathrm{d}t + \int_0^t \left|c_4 \dot{z}_4^2\right| \mathrm{d}t
\end{aligned}
\tag{8}
$$

- the energy component due to elastic forces for the human operator working with the glove:

$$
\begin{aligned}
E_{\text{H+G-ELA},t} &= \int_0^t \left|(k_0 + k_1) z_0 \dot{z}_0\right| \mathrm{d}t + \int_0^t \left|(k_1 + k_2 + k_3) z_1 \dot{z}_1\right| \mathrm{d}t + \int_0^t \left|(k_2 + k_4) z_2 \dot{z}_2\right| \mathrm{d}t \\
&+ \int_0^t \left|k_3 z_3 \dot{z}_3\right| \mathrm{d}t + \int_0^t \left|k_4 z_4 \dot{z}_4\right| \mathrm{d}t
\end{aligned}
\tag{9}
$$

Simulations were implemented in MATLAB/simulink R2009a, using the ode113 (Adams) solver, with integration steps ranging from a minimum of 0.00001 to a maximum of 0.0001 second, and a tolerance of 0.001. Simulations were performed for two periods, i.e. $t_1 = 5$ and $t_2 = 30$ seconds. In order to exclude the impact of unsteady motion during startup on the value of the final energy input used for comparative analysis, it was calculated as a difference between energy input values aftertime $t_2$ and $t_1$. Results obtained for the two methods are analysed, interpreted and compared in the second part of the article.

## 4. Summary

The main outcome of the work undertaken in this part of the study is the formulation of a discrete model of the anti-vibration glove, which was used in experimental tests. In addition, the vibration acceleration signal generated by the motion of the working grinder and affecting the operator was modelled – Fig.1.

Performance results obtained during tests demonstrated that the application of the anti-vibration glove increased vibrations of the grinder, as indicated by higher RMS values of vibration accelerations measured at the handle – Table 1.

The first part of the study was only the starting point for the second part, in which we compare results obtained by applying the two method mentioned above. Results of comparative analysis are presented in the second part: "*Assessment of the effectiveness of anti-vibration gloves. A comparison of the conventional and energy-based method. Analysis and interpretation of results – part two.*"

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## References

1. M. W. Dobry, *Optymalizacja przepływu energii w systemie Człowiek – Narzędzie – Podłoże (CNP)*, Politechnika Poznańska, Poznań 1998.
2. M. W. Dobry, *Podstawy diagnostyki energetycznej systemów mechanicznych i biomechanicznych*, Wydawnictwo Naukowe Instytutu Technologii Eksploatacji – PIB, Radom 2012.
3. R. G. Dong, J. H. Dong, J. Z. Wu, S. Rakheja, *Modeling of biodynamic responses distributed at the fingers and the palm of the human hand–arm system*, Journal of Biomechanics, **40** ( 2007 ) 2335 – 2340.
4. R. G. Dong, S. Rakheja, T. W. McDowell, D. E. Welcome, J. Z. Wu, *Estimation of the biodynamic responses distributed at fingers and palm based on the total response of the hand-arm system*, International Journal of Industrial Ergonomics, **40** ( 2010 ) 425 – 436.
5. R. G. Dong, D. E. Welcome, T. W. McDowell, J. Z. Wu, *Modeling of the biodynamic responses distributed at the fingers and palm of the hand in three orthogonal directions*, Journal of Sound and Vibration, **332** ( 2013 ) 1125 – 1140.
6. M. J. Griffin, *Handbook of Human Vibration*, Academic Press, London 1990.
7. G. Meltzer, *A Vibration Model for the Human Hand-Arm-System*, Studies in Environmental Science, **13** ( 1981 ) 210 – 221.
8. D. D. Reynolds, *Hand-arm vibration: A review of three years' research*, in: Proceedings of the 3rd International Hand-Arm Vibration Conference, Ohio, USA, ( 1977 ) 99 – 129.
9. ISO 10068:2012, *Mechanical vibration and shock - Mechanical impedance of the human hand-arm system at the driving point.*
10. PN-EN ISO 10819:2000, *Drgania i wstrząsy mechaniczne. Drgania oddziałujące na organizm człowieka przez kończyny górne. Metoda pomiaru i oceny współczynnika przenoszenia drgań przez rękawice na dłoń operatora.*
11. PN-EN ISO 10819:2013-12, *Drgania i wstrząsy mechaniczne. Drgania oddziałujące na organizm człowieka przez kończyny górne. Pomiar i ocena współczynnika przenoszenia drgań przez rękawice na dłoń operatora.*