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INVESTIGATION OF THE INFLUENCE OF SIMULTANEOUS VIBROACOUSTIC EXPOSURES ON THE OPERATOR

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A new method of combined assessment of the influence of vibrations (hand-arm and whole-body) and noise hazards simultaneously acting on employees is presented in the paper. The method has been developed on the basis of tests performed in selected means of road transportation. The investigations have shown that separate estimation of individual factors leads to unreasonable omission of a certain part of energy influencing the employee. The suggested assessment method is based on the grounds of adding all kinds of the vibroacoustic energy. The application of this method allows one to take into consideration vibrations and noise occurring simultaneously, and due to this, the significant difference between results of the hazard assessment at workplaces in comparison to results obtained by previously used standardised methods is revealed.

Key words: mechanical vibrations, noise, assessment method

1. Introduction

Noise and mechanical vibrations are troublesome and hazardous factors of the everyday life. Approximately 33% of inhabitants of Poland is under the influence of noise and vibrations in their workplaces, at home and even when resting. Noise and vibration hazards take a lead among all occupational hazards in the work environment. Investigations concerning noise and vibration hazards have been carried on for many years in Poland. However, there was no research on the simultaneous influence of noise and mechanical vibrations (hand-arm and whole-body).

The paper presents a method of simultaneous assessment of hand-arm and whole-body vibration hazards as well as noise hazard. The proposed method is based on appropriate additions of vibration and noise doses. Practical verifications were performed on the example of workplaces of drivers.

Presently, any assessment of vibration and noise hazards of workers is being done on the basis of methods included in current standards. Methods of measuring and assessing given there assume a separate treatment of hand-arm and whole-body vibrations and noise. The basic parameters used for the assessment of such hazards are:

- Daily exposure to hand-arm vibration: $A(8)$,
- Daily exposure to whole-body vibrations: $A(8) = \max\{A_x(8), A_y(8), A_z(8)\}$,
- Level of daily noise exposures $L_{EX,8h}$.

Exposures to hand-arm and whole-body vibrations are determined on the basis of measured corrected accelerations of vibrations, while noise exposure levels on the basis of measured acoustic pressure.

Taking into account the exposure only to one vibroacoustic factor, in the situation when all those hazards occur, means disregarding the part of energy (vibration or noise dose), which can additionally cause unfavourable health effects in the worker's organism. Regardless of differences in influencing the human organism by hand-arm and whole-body vibrations and by noises, the estimation of combined exposures to those factors is possible due to appropriate summing of the vibroacoustic energy.

Undertaking this problem was additionally prompted by the European Union Directives considering the minimum requirements in health protection and safety of employees endangered by physical factors (vibration and noise).

2. Assessment of the simultaneous exposure

The operator during his work is very often endangered by simultaneous influence of hand-arm and whole-body vibrations and noise, i.e. by vibroacoustic factors. Each of these effects is a source of partial energy. Thus, the total vibroacoustic energy transferred into the human organism is the sum of the corresponding partial energies

$$E_{WA} = \sum_{j=1}^{k} E_j \tag{2.1}$$

where E_j is the partial energy. Equation (2.1) was used for development of the method of combined assessment of hazards caused by local and general vibrations and noise. It is assumed that the vibroacoustic energy influencing the worker E_{WA} is proportional to the total dose D of vibration and noise

$$E_{WA} \sim D \tag{2.2}$$

The total dose D is a function of individual partial doses of vibrations and noise determined according to standards [13]

$$D = F(D_O, D_M, D_H) \tag{2.3}$$

where

D_O – dose of whole-body vibration

D_M – dose of hand-arm vibration

D_H – noise dose.

The partial doses D_O, D_M, D_H depend on the frequency f and on the exposure time.

These parameters are determined by the following expressions

$$D_O = \sum_{i=1}^{n} a_{O_i}^2 t_{O_i} \tag{2.4}$$

where a_{O_i} is determined from $a_{O_i} = \sqrt{(1.4a_{wOx_i})^2 + (1.4a_{wOy_i})^2 + a_{wOz_i}^2}$ and t_{O_i} is the action time of partial vibration accelerations a_{wOx_i}, a_{wOy_i}, a_{wOz_i}, s

$$D_M = \sum_{i=1}^{n} a_{M_i}^2 t_{M_i} \tag{2.5}$$

where $a_{M_i} = \sqrt{a_{wMx_i}^2 + a_{wMy_i}^2 + a_{wMz_i}^2}$ and t_{M_i} is the action time of partial vibration accelerations a_{wMx_i}, a_{wMy_i}, a_{wMz_i}, s.

The noise exposure is a value characterising the noise dose [13]

$$E_A = 1.15 \cdot 10^{-5} \cdot 10^{0.1L_{EX,8h}} \tag{2.6}$$

where $L_{EX,8h}$ denotes the level of daily noise exposure.

The general dependence used in the proposed method of the assessment of vibration and noise acting simultaneously is in the form of a sum of doses corrected by appropriate coefficients A, B, C

$$D = AD_O + BD_M + CD_H \tag{2.7}$$

Due to the lack of permissible values for the combined assessment of vibroacoustic factors, it has been additionally assumed that taking into account the weighting filters W_h, W_d, W_k, A as well as permissible values given in current regulations will be possible in the proposed method.

The permissible values for individual factors are introduced into Equation (2.6) in form of coefficients A, B, C. They are presented below together with values of the corresponding coefficients

$$
\begin{aligned}
&A(8)_{O,per} = 0.8\,\frac{\mathrm{m}}{\mathrm{s}^2} && A = \frac{1}{D_{O,per}} = \frac{1}{A(8)^2_{O,per}T_0} = \frac{1}{0.8^2 \cdot 28800} \\
&A(8)_{M,per} = 2.8\,\frac{\mathrm{m}}{\mathrm{s}^2} && B = \frac{1}{D_{M,per}} = \frac{1}{A(8)^2 T_0} = \frac{1}{2.8^2 \cdot 28800} \\
&E_{A,per} = 3.64 \cdot 10^3\ \mathrm{Pa^2 s} && C = \frac{1}{D_{H,per}} = \frac{1}{E_{A,per}} = \frac{1}{3.64 \cdot 10^3}
\end{aligned}
$$

The corrected, by means of the presented above coefficients, doses of vibrations and noise can be presented as multiplication factors of the permissible values of these doses

$$
K_{D_O} = \frac{D_O}{D_{O,per}} \qquad K_{D_M} = \frac{D_M}{D_{M,per}} \qquad K_{D_H} = \frac{D_H}{D_{H,per}}
$$

Equation (2.6) will be then

$$
K = K_{D_O} + K_{D_M} + K_{D_H} \tag{2.8}
$$

where K_D was assumed as the assessment index of the total hazard of vibrations and noise acting simultaneously.

On the basis of previous works concerning the indices of the vibration transfer and computer simulations, three alternative relationships were prepared for the combined method of assessment of vibrations and noise acting simultaneously: (2.9) and (2.10)

$$
K_I = \sqrt{K^2_{D_M} + K^2_{D_O} + K^2_{D_H}} \qquad\qquad K_{II} = \Big(\sum_{i=1}^{n} K_i^{\frac{n+3}{4}}\Big)^{\frac{4}{n+3}} \tag{2.9}
$$

where n is the number of assessed factors, Ki – multiplication factor of the permissible dose determined for the factor i (e.g. $K_{D_O} = K_1$, $K_{D_M} = K_2$, $K_{D_H} = K_3$).

In the case of Equation $(2.9)_2$, the factor n takes on a value between 1 and 3, depending on the number of vibroacoustic factors acting simultaneously (e.g. $n = 3$ when hand-arm and whole-body, vibrations and noise are assessed; $n = 2$ when e.g. only hand-arm vibration and noise are assessed).

The results of several investigations indicate that reactions of the human organism to mechanical vibration and noise are not of the linear character. Therefore, for the description of the combined assessment, another dependence which represents this phenomenon more accurately than the linear function has been chosen

$$K_{III} = \log(10^{K^2_{D_M}} + 10^{K^2_{D_O}} + 10^{K^2_{D_H}}) \tag{2.10}$$

The values of indices of the assessment of the combined hazard of vibrations and noise K, K_I, K_{II}, K_{III} as functions of elements K_{D_O}, K_{D_M}, K_{D_H} are presented in Fig. 1.

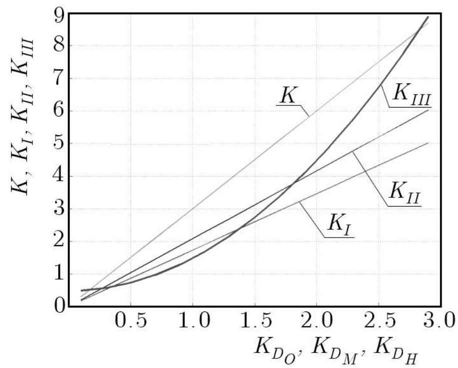

Fig. 1. Indices K, K_I, K_{II}, K_{III} as functions of elements K_{D_O}, K_{D_M}, K_{D_H} value

Equation (2.10) can be applied for total ranges of individual partial elements K_{D_O}, K_{D_M}, K_{D_H} however, due to properties of the assumed mathematical function, a physical interpretation is only possible when at least two elements (out of: K_{D_O}, K_{D_M}, K_{D_H}) exceed 0.3.

The index K_{III} is always above zero ($K_{III} > 0$). Since it is assumed that the criterion value is 1; a value of K_{III} lower than one means that the combined hazard is permissible, while above 1 means that the hazard is not acceptable (the combined hazard is considered small when each multiplication factor K_{D_O}, K_{D_M}, K_{D_H} is smaller than 0.3). The index K_{III} below 1 means additionally that none of the factors (hand-arm, whole-body vibrations, noise) exceed the permissible value when considered separately (in relation to the standard assessment method). However, $K_{III} > 1$ does not necessary mean that the permissible value for a single factor is exceeded, but might indicate high simultaneous intensity of several factors and the exceeding of the criterion value.

If we have a situation in which all three factors are 90% of the individually established permissible value ($K_{D_O} = 0.9$; $K_{D_M} = 0.9$; $K_{D_H} = 0.9$), the assessment performed on the basis of the standardised method will not indicate a hazard. The assessment will be the same as in the case of a hazard caused by one factor only, e.g. hand-arm vibration ($K_{D_O} = 0$; $K_{D_M} = 0.9$; $K_{D_H} = 0$). Underestimation of the occupational risk is clearly visible in such a situation.

This effect has been eliminated in the proposed combined method since the exceeding of the criterion value 1.0 will be assessed and $K_{III} = 1.287$.

The assumed criterion 1 does not mean increased requirements applied in the standardised methods. It can be similarly interpreted and classified for the estimation of the occupational risk

$$K_{III} \in \begin{cases} \langle 0, 0.5 \rangle & - \quad \text{small risk} \\ \langle 0.5, 1.0 \rangle & - \quad \text{medium risk} \\ \langle 0, +\infty) & - \quad \text{high risk} \end{cases}$$

3. Experimental studies

The proposed energetic method was verified experimentally. Due to generally occurring vibration and noise hazards at workplaces of drivers, several vehicles representing various means of road transportation were chosen for the tests.

The aim of the site tests was to recognise and compare vibroacoustic conditions in various vehicles most often met on Polish roads.

In order to provide similar measuring conditions, the routes were selected in such a way as to have similar road conditions in relation to length, surface quality, usual driving speed as well as the proportion between city traffic and outside travelling (this proportion was set 25%-75%). Measurements were performed at similar weather conditions.

All tested trucks and lorries were loaded during the measurements, while buses, minibuses and coaches carried passengers.

The site tests of hand-arm and whole-body vibration as well as noise occurring jointly in the same time were performed by simultaneous recording of vibration acceleration and acoustic pressure signals. A digital measuring recorder and accelerometers, microphone and appropriate pre-amplifiers were used (Fig. 2).

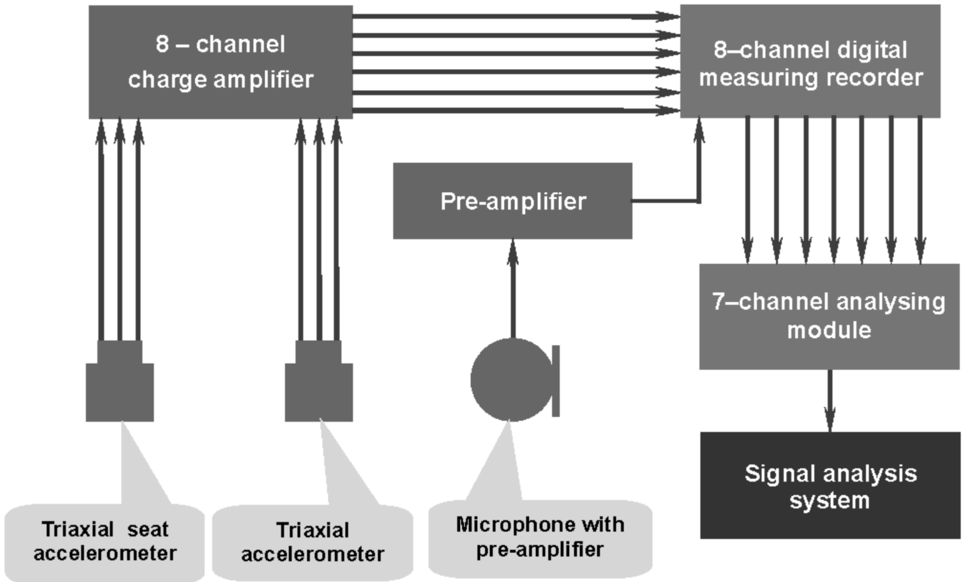

Fig. 2. Diagram of measuring set-up

4. Analysis of the obtained results

The recorded signals of vibration acceleration and the acoustic pressure level were analysed and a set of frequency characteristics was prepared for each vehicle: vibration spectra on the steering wheel in the X, Y, Z directions; vibration spectra on the seat as well as the spectrum of the acoustic pressure. The results of vibration and noise analysis are presented on an example of a TIR-type truck (Fig. 3).

On the grounds of the determined spectra, the daily exposures to hand-arm vibration $A(8)$ (Fig. 4.), whole-body vibration $A(8)$ (Fig. 5) as well as exposure levels to noise $L_{EX,8h}$ (Fig. 6) were determined.

The following notations are introduced in Figs. 4, 5 and 6:

A	–	Passenger car	H	–	Dump truck
B	–	Van	I	–	Motor coach 1
C	–	Microbus	J	–	Motor coach 2
D	–	Bus	K	–	TIR 1 truck
E	–	Small delivery truck	L	–	TIR 2 truck
F	–	Delivery truck	M	–	TIR 3 truck
G	–	Trunk lorry			

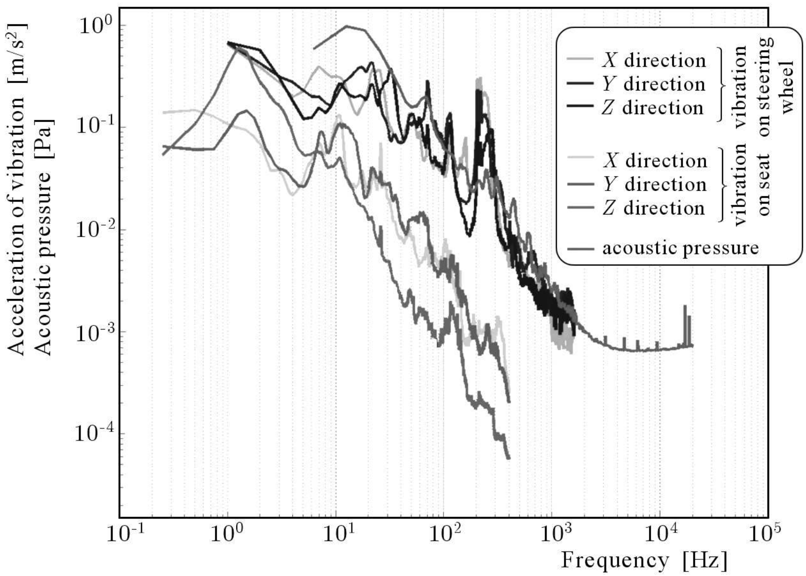

Fig. 3. Vibration and noise spectra recorded for TIR 1 truck in motion

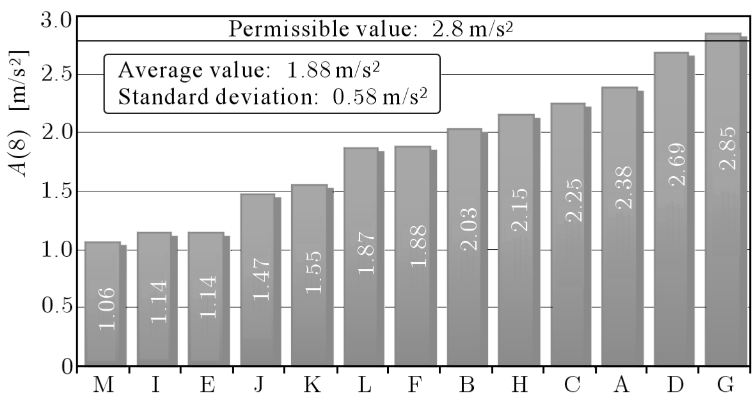

Fig. 4. Daily exposures to hand-arm vibration $A(8)$

On the basis of the determined exposure values (Figs. 4-6,) the assessment of vibration and noise hazards at the workplaces was performed (according to the binding regulations). The multiplication factors of permissible values k (Table 1) were determined by referring the calculated vibration and noise exposures to the following Maximum Permissible Intensities (MPI):

$A(8)_{per} = 2.8\,\mathrm{m/s^2}$ – for hand-arm vibration
$A(8)_{per} = 0.8\,\mathrm{m/s^2}$ – for whole-body vibration
$L_{EX,8h,per} = 85\,\mathrm{dB}$ – for noise

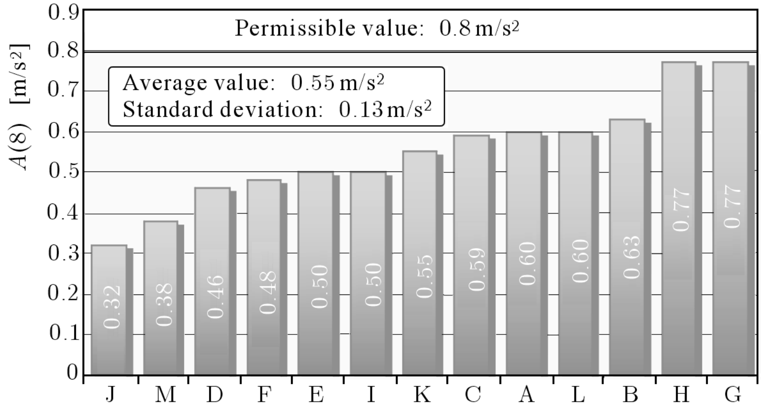

Fig. 5. Daily exposures to whole-body vibration $A(8)$

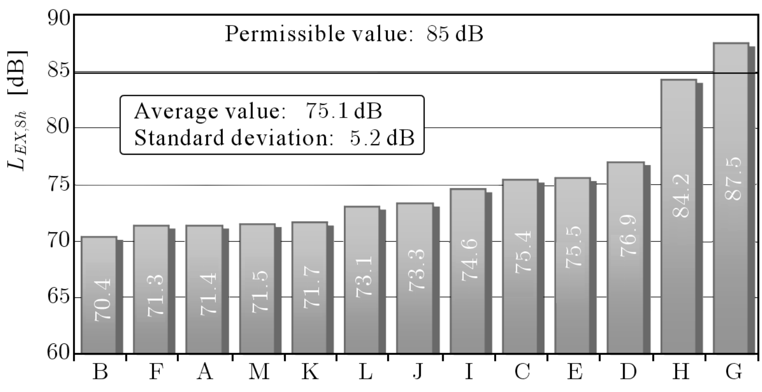

Fig. 6. Daily noise exposures $L_{EX,8h}$

The exceeding of the MPI value was found in one case only – for the trunk lorry (daily exposure to hand-arm vibration of $2.85\,\mathrm{m/s^2}$ exceeded the permissible value of $2.8\,\mathrm{m/s^2}$, and the daily noise exposure being 87.5 dB exceeded the permissible value of 85 dB).

On the basis of the recorded signals of vibration acceleration and acoustic pressure levels and in accordance with the binding standards, further assessment of the combined exposure was performed by the proposed new method. Values of the index K_{III} were calculated. Due to the same criterion value being 1, the values of the proposed combined hazard index K_{III} cpuld be directly compared with the determined k values (multiplication factors of permissible values) according to PN-EN and the determined MPI. The same three-stage scale could also be applied to the occupational risk assessment.

Table 1. Selected parameters of vibration and noise estimated according to the standard methods

		Hand-arm vibration		Whole-body vibration		Noise	
		Daily exposure $A(8)$ [m/s^2]	Multiplication factor of exceeding permissible value k	Daily exposur $A(8)$ [m/s^2]	Multiplication factor of exceeding permissible value k	Daily exposure level $L_{EX,8h}$ [dB]	Multiplication factor of exceeding permissible value k
Means of transportation	Passenger car	2.38	0.85	0.60	0.75	71.4	0.044
	Van	2.03	0.73	0.63	0.79	70.4	0.035
	Microbus	2.25	0.8	0.59	0.74	75.4	0.110
	Bus	2.69	0.96	0.46	0.57	76.9	0.155
	Small delivery truck	1.14	0.41	0.50	0.62	75.5	0.112
	Delivery truck	1.88	0.67	0.48	0.60	71.3	0.043
	Trunk lorry	2.85	1.02	0.77	0.97	87.5	1.778
	Dump truck	1.48	0.77	0.77	0.97	84.2	0.832
	Motor coach 1	1.14	0.41	0.50	0.62	74.6	0.091
	Motor coach 2	1.47	0.53	0.32	0.40	73.3	0.068
	TIR 1 truck	1.55	0.55	0.55	0.69	71.7	0.047
	TIR 2 truck	1.87	0.67	0.60	0.75	73.1	0.065
	TIR 3 truck	1.06	0.38	0.38	0.47	71.5	0.045

The calculated values of indices K_{III} and k_{max} (being for a given vehicle the highest multiplication factor of the permissible value calculated separately for an individual vibroacoustic signal) as well as hazards determined by both methods – are presented in Table 2. The relative differences between K_{III} and k_{max} values allow one to compare quantitatively the results obtained by both methods.

According to the expectations, in all the examined cases the assessment performed by the combined method shows an apparent hazard increase as compared to the hazard determined by the standardised method.

Out of 13 workplaces assessed by the standardised method, only at one place the hazard exceeded the MPI value (trunk lorry: 1.78 – large hazard); at 11 places the hazard was medium and at one place the hazard was small.

Table 2. Vibrations and noise hazard assessment determined by the combined method as well as by the standardised method – at the driver's workplace of various means of road transportation

		K_{III}	Hazard determined by the combined assessment method	k_{max}	Hazard determined according to PN-EN	Relatve difference between K_{III} and k_{max} [%]
Means of transportation	Passenger car	1.35	large	0.85	medium	37.0
	Van	1.19	large	0.79	medium	33.6
	Microbus	1.19	large	0.8	medium	32.8
	Bus	1.12	large	0.96	medium	14.3
	Small delivery truck	0.83	medium	0.62	medium	25.3
	Delivery truck	0.90	medium	0.67	medium	25.6
	Trunk lorry	3.17	large	1.78	large	43.8
	Dump truck	1.53	large	0.97	medium	36.6
	Motor coach 1	0.78	medium	0.62	medium	20.5
	Motor coach 2	0.68	medium	0.53	medium	22.1
	TIR 1 truck	1.00	medium	0.69	medium	31.0
	TIR 2 truck	1.13	large	0.75	medium	33.6
	TIR 3 truck	0.71	medium	0.47	small	33.8

When the same places were assessed by the combined method, at 7 places the hazard was found to be large, and in 6 a medium one. The hazard estimated by the combined method in one case changed from small to medium and in 6 cases from medium to large as compared with the standardised method of assessment. In the remaining 6 cases, the hazard estimated by both methods was classified the same, however the relative differences between K_{III} and k_{max} were between 20.5% (for motor coach 1) and 43.8% (for the trunk lorry). For all 13 tested workplaces those differences were within the range between 14.3% (for the bus) and 43.8% (for the trunk lorry).

5. Conclusions

On the basis of multiple tests performed at the Central Institute of Labour Protection, the authors proposed an energetic technical assessment method of hazard endangering employees who are simultaneously influenced by hand-arm and whole-body vibrations and noise. The method is based on summation of the so called „doses" which are determined by measurements. The sum of doses determined by measurements is corrected by appropriate coefficients A, B, C, which are developed by taking into consideration the permissible values given in the standards (separately for each factor). The coefficients A, B, C proposed in Eq. (2.7) can also be determined by means of the Singular Value Decomposition (SVD), which will be the next step of the presented research. To reach this aim, a matrix of partial doses and objects of tests will be developed (the so called observation matrix). This matrix will be decomposed by the SVD technique into three specific matrices, in which the same information on relationships between partial doses, as in the observation matrix, will be included, however, obtained by means of orthonormal vectors. Thus, it will be possible to reduce the developed simulation model by applying an appropriate approximation order. Expectedly, the newly formed matrices will enable one to obtain identical numbers for all tested objects and for each individual index. Those numbers treated as the correcting indices will be used for the global assessment of vibroacoustic hazard.

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This paper is dedicated to Professor Józef Nizioł on His 70th Birthday.

Badania wpływu jednoczesnych ekspozycji wibroakustycznych na operatora

Streszczenie

W artykule przedstawiono nową metodę oceny łącznej drgań (miejscowych i ogólnych) i hałasu działających równocześnie na pracowników. Opracowano ją na podstawie wyników badań przeprowadzonych w wybranych środkach transportu drogowego. Badania wykazały, że niezależna ocena działających poszczególnych czynników wiąże się z nieuzasadnionym pomijaniem w ocenie części energii wibroakustycznej docierającej do pracownika. Proponowana metoda oceny opiera się na zasadzie sumowania energii wibroakustycznej. Zastosowanie opisanej metody pozwala na uwzględnienie jednoczesnego działania drgań i hałasu; powoduje to istotne różnice wyników oceny narażenia czynnikami wibroakustycznymi na stanowisku pracy w stosunku do wyników uzyskanych dotychczasowymi metodami znormalizowanymi.

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