758. Prognostics of vibration induced risk to operators of agricultural machinery

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Abstract. Frequent use of vibrating hand-held tools and operation of machinery can result in various chronic diseases. Operators of machinery are often afflicted with peripheral and systematic disorders. The statistical data collected over several decades clearly indicate the lack of operator's safety from exposure to vibrations. The causes and impacts of vibration effects on humans are reviewed in annual reports by health and safety experts in many countries. One of the most common occupational diseases that has been frequently reported is the musculoskeletal disorder due to extended exposure to mechanical vibrations. The influence of vibrations during time period τ can be described by vibro-energy load $a_\tau^2 \cdot \tau$. If this load value over a specified time period does not exceed the permissible level $a^2 \cdot T_0$, it will not induce negative effects on human health. This approach was used in the present study for the prediction of hands and whole body vibration effects on operators of various vibration inducing machinery. Agricultural operators were selected as test subjects, since agricultural tractors and other mobile machinery emit high levels of vibration. Vibration data were obtained from statistical reports developed in the time period from 1988 to 2008. It was found that majority of agricultural machinery does not guarantee proper vibration safety. Thus organizational prevention methods should be developed and implemented. Reduction of vibrations by various technical methods and/or reduction of vibration exposure could be costly, but they are needed in order to provide effective solutions in reducing vibration risk to operators.

Keywords: vibration load, vibration risk, whole-body vibration, hand-arm vibration.

Introduction

Disregard of vibration safety is one of the most common causes of occupational diseases at present. The extensive list of occupational diseases and statistical data show large numbers of vibration caused diseases. A rapidly increasing number of musculoskeletal diseases and their effects on human health are widely reviewed in various scientific papers [1, 2]. Vibration risk is especially noticed by operators of self-propelled machinery and hand-held tools, where vibro-energy interaction is a continuous process. Reports of European Foundation for the Improvement of Living and Working Conditions show that 24 % of all EU-27 workers report exposure to vibrations more than a quarter of their work time. About 63 % of workers in the construction sector and ~44 % in manufacturing and mining industries are exposed to whole-body vibrations (WBV) and/or hand-arm vibrations (HAV), while one in three workers in agriculture report that they are mainly exposed to WBV. Statistical data of occupational diseases in Lithuania during the time period 2005 to 2009 also indicate inadequacy of vibration safety (Fig. 1).

Influence of vibration in balanced circumstances can be described as follows:

$$E_m = E_k + E_p + E_\eta, \tag{1}$$

where E_m is the average vibro-energy flow of the machine; E_k is the kinetic energy; E_p is the potential energy; $E_\eta = \eta v^2$ is the dissipated energy, where dissipation coefficient η describes the absorption properties of the system oscillating at a speed v.

The average energy flow $E_h = - E_p$ and the energy dissipated over the human body from the perspective of "Man – Machine" system fault can be described as [3, 4]:

$$E_\eta = \eta T \int_0^T v^2 dt, \tag{2}$$

where T is the absorption duration (interval) of cumulative energy.

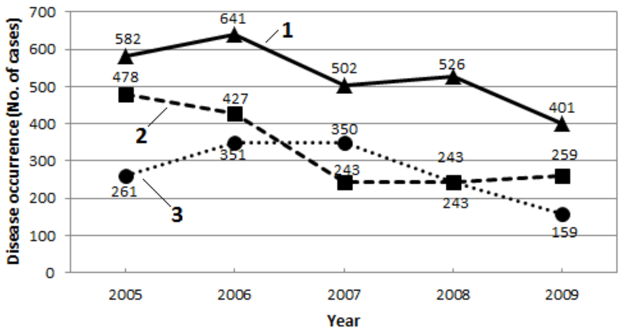

Fig. 1. Occupational diseases in Lithuania during the 2005–2009 time period: 1 – diseases of connective tissue and musculoskeletal system, 2 – ear diseases, 3 – diseases of nervous system

Parameter E_η describes human response to vibration and it has a close relationship to vibration dose. Vibration dose expressed in terms of the speed parameter can be written as $D_a=\omega_0^2 \cdot D$, and by the amplitude of vibration acceleration a can be written as (ω_o – characteristic frequency of human body parts):

$$D_a = \int_0^T a^2 dt = \left(\frac{\eta}{T}\right) E_\eta = \left(\frac{2T}{m}\right) E_k. \tag{3}$$

Parameter D_a refers to the quantity of energy dose received by the operator during the time period T, which acts on its mass unit m. Vibration dose can be also used for objective risk prediction (its acceptance or inadmissibility) on workers that mainly depend on environmental and individual properties (Fig. 2).

Effects of vibration on humans are strongly influenced by the factors shown in the above figure. Individual properties of the operator could significantly increase or decrease vibration risk. However, one of the most prevailing factors is the exposure duration. Approximately 50 % of occupational diseases caused by vibration were diagnosed for operators with long-term exposure. This was proved by Matvejev [3], where he calculated the probability of expected vibrational syndromes when working with hand-held equipment. Compound effects of vibrations were noticed on humans if they are simultaneously exposed to intense noise or low temperature. Ilgakojis et al. [5] found that operators are more sensitive to vibration from 1.5 to 3.5 times, if the exposure continues for more than 10 years together with effects of noise of 95 to 100 dBA and low temperatures. This clearly indicates that the degree of risk depends not only on the characteristics of a machine and its radiated energy, but also on other environmental and individual properties.

When the values or tendencies of parameters shown in equation (1) are known, it becomes possible to apply any preventative solutions for the reduction of vibration risk to workers. This leads to an improvement of occupational safety in workplaces [5, 6].

The aim of this investigation was to analyze the vibrational energy interchange between the machine and the operator from the perspective of human health. This was achieved by considering functional parameters of agricultural machinery.

Conditions and causes		
Physical load	***Conditions of psychology***	***Exposure***
Amplitude	*Active and (or) passive protection*	*Daily*
Harmony (disharmony)	*Body position*	*Yearly*
Oscillation directivity	*Degree of skills*	*Pauses*
Impact directivity		
Additional loads (noise, cold weather conditions)		

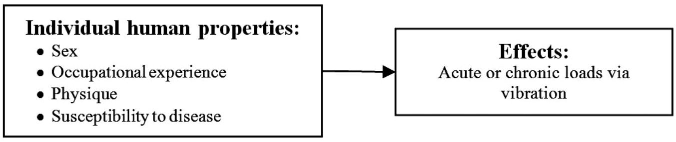

Fig. 2. Factors influencing vibrational risk on human health [3]

Methodology

Under the balanced conditions of vibro-energy exchange between the machine and the operator (analogous to expressions (2) and (3)), the average quantity of kinetic energy $\overline{E}_k$ is proportional to vibration dose $D_a=\omega_0^2 \cdot D$ and is calculated as follows:

$$D_a = \int_0^T a^2 dt = \left(\frac{2T}{m}\right) E_k = \omega_0^2 D, \tag{4}$$

where ω_0 is the specific frequency of human body parts or mechanical system.

The integral part $a_\tau^2 \cdot \tau$ for discrete time intervals $\tau = T_i$ describes human response to vibration, i.e. vibro-energy load. This integral parameter is also important for estimating vibration risk R. Conforming to Matvejev [3], whole body and hand-arm vibration risk can be calculated by using the equations:

$$R_{HAV} = 0.025 a_{HAV} p^{1/2} \left(\tau / T_0\right)^{1/2}, \tag{5a}$$

$$R_{WBV} = 0.2 a_{WBV} p^{1/2} \left(\tau / T_0\right)^{1/2}, \tag{5b}$$

where R_{HAV}, R_{WBV} are the hand-arm and whole-body vibration risk, respectively, over the time period τ; p – probability of vibration risk over the time period τ; T_o – duration of vibration exposure (day, week, year); $a_{hw\tau}$, $a_{w\tau}$ – weighted acceleration of hand-arm and/or whole-body vibration over the time period τ.

In calculating the overall vibration dose received by the operator, attention must be directed to synergic hand-arm and whole-body vibration effects. The overall effect of these two members can be expressed as their arithmetic sum:

$$\frac{a_{hw\tau}^2 \tau}{a_{hw,rib}^2 T_0} + \frac{a_{w\tau}^2 \tau}{a_{w,rib}^2 T_0} \leq 1.0, \tag{6}$$

where T_o is the duration of standard work shift (8 hours).

By using the method of fault tree analysis described in [7] for the assessment of mechanical vibrations and by the expressions of (5a), (5b) and (6) dependencies, we can assess the risk of vibration on human health. This can be implemented by using the statistical data over the time period τ:

$$\tau^* = \frac{p}{R^*}, \tag{7}$$

where R^* is the individual marginal risk marker.

By using the quantitative value of risk, we can express:

$$R = pU, \tag{8}$$

where U is the degree of damage.

Approximate levels of vibration risk were defined by Matvejev [3]. It was determined that only a small risk is reached when the value of $R_{lim} < 0.02$, menace level is $0.02 < R_{lim} < 1.0$ and considerable risk is when $R_{lim} > 0.2$. It should be noted that the above indicated values of R_{lim} can be used when vibration is the only detrimental factor in the working environment. If the operator is under the influence of intensive noise, cold environment or high humidity, the effect of vibration on risk can increase by several magnitudes (i.e. 100 dBA noise level during time period $\tau = 10$ years, increases risk by a factor of 1.5 [2]). Then, the vibration dose received by the operator can be described as follows:

$$D = D_m + \sum_{i=1}^{n} \Delta D_i, \tag{9}$$

where: D_m is the measured or calculated vibration dose; ΔD_i is the level of risk effects on vibration, defined by determining the excess of vibration dose in comparison to permissible level.

This leads to increased sensitivity to vibration effects. It was found by Jankauskas [8] that a period of 33 to 35 years of working in a vibratory environment is enough for the appearance of symptoms of vibration induced disease. It is also known that impulse-type and low-frequency sound ($f < 50$ Hz) is also a contributing factor to the detrimental effect of vibrations. The condition of energy interaction between the operator and the machinery usually causes critical situations (both hand and whole body vibrations appear), especially if the mechanical impedance of human body coincides with the amplitude and frequency of vibration [6]. These conditions must be taken into account when the value of p is being determined. This also requires analysis of statistical data, i.e. proper interpretation of this data guarantees increased reliability of the results. Analysis of statistical data of agricultural machinery in Lithuania during the 1988 to 2008 time period was not sufficient to perform a full analysis because some of the machinery was not accounted in statistical reports. For this reason, we analyzed additional data from the reports of agricultural inventory and from import/export tendencies.

Results and discussion

The lack of vibration safety is evident in technological processes, where mobile agricultural machinery or hand-held equipment is operated [3, 5, 6]. Causalities of vibration risk on human health were analyzed in this study. The obtained final results to vibration exposure were indicative to be the symptoms of vibration disease. Daily vibration acceleration (a_{WBV} and a_{HAV}) was taken at time factor $\tau = T_0$.

As regulated by the legal requirements, permissible levels of vibration per $T_o = 8$ h time period are $a_h < 5$ m/s^2 for HAV and $a \leq 1.1$ m/s^2 for whole-body exposure. In determining these conditions over the time period of 1988-1998, the structural changes in the machinery's stock were taken into consideration. The results from the Lithuanian registry of "tractors, propelled and agricultural machinery and their trailers" indicate the domination of machinery made in CIS countries. This machinery is known as having insufficient vibration safety. It was clearly evident that the vibro-acoustic climate in the cabins of these tractors is more intense when compared to modern machinery [6]. Vibration measurements were performed on several new tractors (see Table 1). The results show tangible differences in vibration levels between the machinery made in EU countries and those made in eastern countries. For this comparison, we have tested tractors of the same pulling class, similar construction and similar engine power. Bruel&Kjaer vibration analyzer type 4447 with tri-axial accelerometer (type B&K 4524-B-001

Delta Tron) and seat accelerometer (type B&K 4515-B-002) were used. Hand-arm vibration measurements were carried out according to ISO 5349-2:2001, while whole-body measurements were obtained under the requirements of ISO 2631-1:1997.

Table 1. WBV and HAV acceleration values at operator workplace under various conditions

	WBV RMS values (m/s^2)				HAV RMS values (m/s^2)			
	X	*Y*	*Z*	*A*(8)	*X*	*Y*	*Z*	*A*(8)
Made in CIS *on asphalt paving at:*								
10 km/h	3,851	2,725	4,723	5,392	1,936	0,756	1,754	2,720
15 km/h	4,176	4,015	7,564	7,564	1,481	1,041	1,279	2,217
On gravel paving at:								
10 km/h	3,813	2,815	4,558	5,339	1,532	1,352	1,906	2,795
15 km/h	6,358	3,934	7,290	8,901	1,202	0,920	1,097	1,870
Free-running (1800 rpm)	0,759	0,483	1,292	1,292	1,741	0,280	1,690	2,443
Made in EU *on asphalt paving at:*								
10 km/h	1,607	2,233	2,339	3,126	0,274	0,379	0,359	0,590
15 km/h	2,894	2,908	5,208	5,208	0,343	0,484	0,557	0,814
On gravel paving at:								
10 km/h	2,284	2,673	4,233	4,233	0,357	0,575	0,597	0,902
15 km/h	2,732	3,379	5,002	5,002	0,390	0,500	0,679	0,930
Free-running (1800 rpm)	0,366	0,624	0,341	0,873	0,272	0,393	0,278	0,553

During the time period of 1999-2008, functional changes in the stock of machinery influenced the overall situation, i.e. more modern machinery was registered. However, this change did not significantly affect the overall situation – CIS made machinery is still more common and in general vibration loads are higher (calculated by equation (6)) than those permissible (Fig. 3). It should be taken into consideration that vibration levels in obsolete tractors are constantly increasing, which also depends on tractor's operation duration cumulative hours.

Data in Table 1 clearly indicates vibrations of different intensity. The most intense vibrations are in the direction of *Z* axis (5 to 9 dB) either at a loaded mode or at free-running conditions. The predicted difference between L_{HAV} and L_{WBV} is much larger (20-23 dB and 16-20 dB over *Z* and *X* axis, respectively) for the case of hand-arm vibration. In addition, the risk to the operator is much more significant when the operator is under the influence of whole-body vibration. If the energy excess, compared to the maximum allowable is 5 to 6 dB higher for hand-arm vibration and 8 to 10 dB higher for whole-body vibration, risk is attributed to menace, but it is still acceptable. In accordance to equations (5a) and (5b), the R_{HAV} and R_{WBV} ratio level $L_R = 10 \lg (R_{WBV}/R_{HAV}) = 10 \lg (0.025 \cdot 5/0.2 \cdot 1.1) = 2.5$ dB and $\Delta L_{WBV} - \Delta L_{HAV} =$ 3…4 dB. Similar tendencies were observed during the later time period (1999 to 2008).

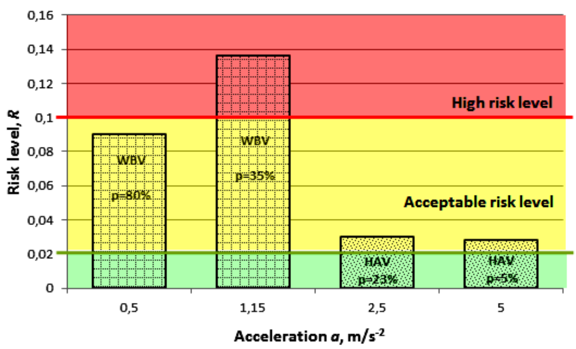

Fig. 3. Vibration induced risk of agricultural machinery and its risk to operators' health

Analyzing the levels of hand-arm and whole- body vibrations in agricultural tractors, it was found that operation of standard duration, i.e., 8 hours per day can be insecure. It was determined that 80 % of all tractors reach the value of 114 dB (or 0.50 m/s^2), and approximately 35 % of all tractors exceed the maximum permissible vibration level of 1.15 m/s^2 (or 122 dB). About 23 % of all agricultural tractors are exceeding the preventative vibration level on the steering wheel (0.5 m/s^2). The WBV daily exposure (1.15 m/s^2) was exceeded at about 25 % of lorries and trucks, while HAV values higher than 5.0 m/s^2 were found at 2.5 % of all working places. Values of daily vibration exposure and their interpretation as a risk factor P, enabled to calculate and predict the level of risk and to decide about its acceptance [7]. By using expressions (5a) and (5b), the probability of vibration impact was calculated considering the allowable value of daily vibration acceleration $a_{HAV} = a_h$ and $a_{WBV} = a_{rib}$, when $R_{HAV} = R_{rib} = 0.017 = R_{WBV}$. Employing the value of vibration risk, the probability of vibration risk can be calculated for HAV and WBV cases, respectively: $p_{HAV} = (0.017/(0.025\cdot5))^2 = 1.8\cdot10^{-2}$ and $p_{WBV} = (0.017/(0.02\cdot1.1))^2 = 6\cdot10^{-2}$.

The probability values calculated are good indicators for the prediction of vibration risk on operators. If the vibration acceleration is greater than the value allowed or when ΔL_{HAV} and ΔL_{WBV} are high enough, it is possible to predict the level of risk (R) as a function of acceleration increment ΔL and to compare to the reference level (Fig. 4). Values of R_{HAV} and R_{WBV} depend on the severity of vibration acceleration ΔL. Values of ΔL less than 2-3 dB have no significant influence on vibrational risk (R). Inadmissibility of vibration risk is significantly affected when the value of ΔL increases by more than 5-6 dB. The level of risk in this case exceeds the acceptable risk level (R = 0.2), but it is below the maximum permissible value (R = 1). High levels of vibrations were found in the cabs of CIS made tractors, where ΔL > 5-6 dB higher than for those tractors made in EU countries. Considering the mix of tractors that are registered in Lithuania, it can be stated that only insignificant improvement in overall vibration safety can be achieved. This is also because old tractors offer poor vibro-acoustic comfort and their numbers are still dominant. Better tendencies are observed in modern machinery, where together with technological advantages and better working conditions, vibration safety is of a higher level.

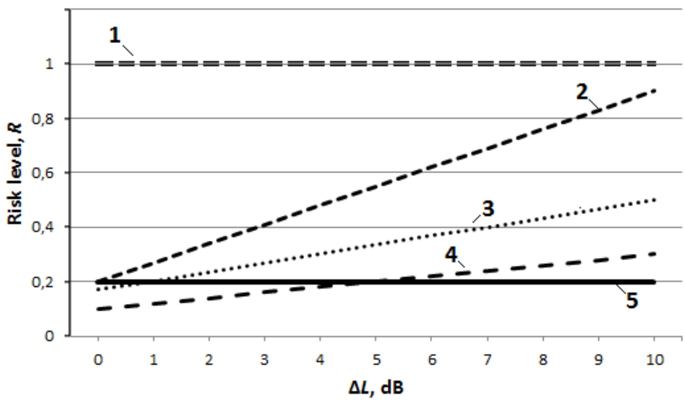

Fig. 4. Dependence of vibration risk (R) and intensity (a_{HAV}, a_{WBV}) as a function of permissible (reference) levels: 1 – level of unacceptable high risk; 2 – $R_{WBV} = 0.22\cdot10^{0.05L}a_{WBV}$, $p_{1\%}$; 3 – vibration impact on human health when probability value is acceptable; 4 – $R_{HAV} = 0{,}017\cdot10^{0.05L}a_{HAV}$, $p_{1\%}$; 5 – level of potentially harmful vibration effect

Calculated value of R_{WBV} indicates better vibration safety, i.e. vibration risk is up to 1.5-2 times higher in CIS made tractors. Considering the obtained results, it can be stated that organizational means should be applied to keep operators safe and healthy.

Conclusions

Adopting a vibro-energy interchange of vibration ($a_x^2\tau_x$) and permissible ($a_{rib}^2T_0$) loads with regard to $(a_x^2\tau_x)/(a_{rib}^2T_0)$, qualitative method of predicting vibrational effect on human health was developed. Allowable hand-arm and whole-body vibration by the means of evoked risk equivalency, the probability of negative vibration effect increases by a factor of 3. This indicates that the expectancy of negative whole-body vibration occurs up to three times more frequently. Excess in vibration intensity ΔL < 2-3 dB from daily vibration exposure is satisfactory, while an increase ΔL > 5-6 dB is considered as an unacceptable vibration risk. Only a quarter of all tractors operated in Lithuania satisfy acceptable risk to human health, if the duration of work shift is at least 8 hours.

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