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HUMAN COMFORT AND MOTION UNDER SIMULATED VIBRATION EXPOSURE OF MOBILE MACHINERY

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Abstract

In order to develop more user-friendly mobile machinery, more information on the connection between the human comfort experience, human-seat interaction, and measurable quantities, like the motion of the operator's seat, are needed. In this paper we describe a study on the mechanical response and the subjective comfort feeling of a human exposed to high level vibration. Experimental tests were accomplished in a laboratory motion platform, which simulated the vibration excitation that an operator experiences in a heavy mobile work machine. The test excitations were based on field measurements and included such activities as cultivation, moving in forest and on gravel road. Vibration responses of 23 test subjects were measured using four tri-axial accelerometers. The test subjects were equipped with heart rate monitor and they evaluated the vibration exposure based on a five scale comfort criteria and described their subjective experience. R.M.S-values, based on the ISO 2631-1 standard, were calculated from the acceleration data from the floor, seat and head of the test subjects. The human comfort is a sum of many different variables, and the analysis of the test data is complicated due to individual differences. In this paper we introduce the findings concerning the relationship between the measurable quantities and the comfort feeling based on the experimental tests

INTRODUCTION

Human operator undergoes vigorous vibration in a heavy mobile work machine and off-road vehicles. Whole body vibration can be very harmful and injurious for the operator. The directive 2002/44/EC [1] has given great goal and challenge for controlling whole body vibration levels of mobile machine operators. On the other hand, subjective comfort feeling should be taken into account, too. The healthy vibration levels according standards and subjective comfort feelings of the operator do not necessarily correlate. Comfortable body vibration might be more injurious than uncomfortable and vice versa. Anyway, comfort of mobile machines and heavy vehicles is an important competitive advantage and both comfort and health issues should be both taken into account and linked to smart control of vibration dampers of mobile machine's chassis, cabin and seat. Often, conventional passive vibration damping systems are not capable of reducing injurious whole-body vibration levels enough on wide frequency band. New active or semi-active dampers are needed.

The goal of our research project has been to develop novel methods and devices for vibration damping and measuring and to create models in order to simulate vibration of human-machine system. One important goal has been to find out subjective feelings depending on vibration type. In this paper we introduce the findings concerning correlation between human body vibration, average heart rate, anthropometry, body mass index and the subjective comfort feeling.

Whole body vibration comfort by ISO 2631-1 and European directive

The calculations of the vibration values and whole body vibration measurements are based on the ISO 2631-1 (1997) standard [3]. The standard is the main guide for conducting whole body vibration measurements and the directive is based on it [1]. The standard divides the effect of vibration to human into four categories: 1) health, 2) comfort 3) perception and 4) motion sickness. The health is defined only for a seated person, requiring measurements of three translational axes from the seat surface. The comfort evaluation needs 12-axis measurements, which contain seat surface (6-axis), backrest (3-axis) and feet (3-axis). The combined vector sum of all these values are needed to perform standardized comfort evaluation. However, there are no commercial equipments available for evaluating comfort of vibration exposure [5]. The perception is measured and analyzed like health; expect that there are no multiplying factors for horizontal directions. The motion sickness on the other hand is limited to frequencies below 0,5 Hz, which separates it from comfort and perception analysis.

There is no other ISO standard for evaluation of comfort of vibration exposure. Comfort studies that are based on the ISO 2631-1 standard have been rare. There are only few publications that have concentrated on the 12-axis measurements and analysis [4],[5]. The concentration in the whole body vibration research has been health, but the comfort is important also as the frequency weightings for health analyses are based on the subjective responses of the persons [2].

The Directive 2002/44/EC [1] on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) (PAD), requires those responsible for workplaces to introduce measures to protect workers from the risks arising from vibration. Member states have to implement PAD by July 2005. Two limit values are used: 1) daily exposure limit value and 2) daily action value. The daily exposure limit value (1.15 m/s2) can never be exceeded in the standard 8-hour working day. The daily action value (0.5 m/s2) sets a limit to when the employer has to start a program to reduce the vibration levels. PAD lists basic measures that the employer should take when the vibration levels are too high. Only the highest value of the three directions (x, y and z) is used to assess the vibration exposure.

METHODS

23 test subjects were measured on a motion platform. Heart rate and R.M.S of testees were measured and subjective feelings were assessed and recorded after vibration excitations.

ISO 2631-1 standard

Acceleration affecting the test subject was measured with accelerometer mounted under the cushion of the seat. The whole body vibration analysis were based on ISO 2631-1 standard [3], which gives the equation to calculate the Root-Mean-Square (R.M.S) acceleration

$$a_w(T) = \left(\frac{1}{T} \int_o^T a_w{}^2(t) dt \right)^{\frac{1}{2}} , \qquad (1)$$

where $a_w(t)$ is the frequency weighted acceleration and T the duration of measurement. The acceleration data was first frequency weighted, which is also described in ISO 2631-1

Measurements

Experimental tests were accomplished in a laboratory motion platform (Figure 1), which simulated the vibration excitation that operator undergoes in heavy mobile machine. The test excitations were based on field measurements and included such activities as cultivation, moving in forest and on gravel road. Vibration response of test subjects was measured by four tri-axial accelerometers. The test subjects were equipped with heart rate monitor. Heart rate measurements were made with heart monitoring devices Suunto T6 and Polar S810i. Pressure distribution applied on the seat cushion under the seated person was measured with pressure sensitive foil having multiple sensing points on matrix-like measuring grid (Emfit - Electromechanical Film). This was mainly used in developing simulation model of human-machine system. The measurements were recorded by two video cameras. Result of the video pattern recognition analysis was the 3D motion data of the different marker points on the body, which was then synchronized with the other measurement data for further analysis. Pimex-PC (Picture Mixed Exposure) mixes acceleration data and video which helps to find out afterwards what happened in certain situation e.g. when acceleration or discomfort values were high. R.M.S-

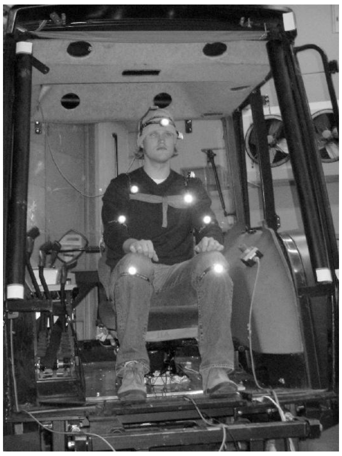

Figure 1 - Test person seated in cabin of motion platform

values, based on the ISO 2631-1 standard, were calculated from the acceleration data from the vibrating base, cabin's floor, seat and head of the test subjects. The motion platform consisted of a hydraulic driven base, which can be programmed to give any desired vibration pattern, a tractor cabin which is mounted on top of the base (passive damping) and a data acquisition system for measuring and saving the data.

Comfort analysis methods

A subjective comfort assessment form was used to gather data from motion platform tests. In the inquiry form test subject's name, sex, age, height, mass, rest heart rate and maximum heart rate (if known) were registered. Also, subjective estimation of their own condition in scale of physical activeness: low, fair, high and top. Activeness level was divided as follow: "low" if training is not regular, "fair" if training is regular, "high" if person trains effectively at least three times a week and "top" if effective training is almost daily. After every test excitation a test subject assessed possible pain and discomfort. A body map with numbered body areas was used to asses pain or discomfort in certain part of body. The subjective comfort was described with the *RPE* value in the scale from 1 to 5, 5 being the most uncomfortable level. Every testee was subjected to so called reference excitation and the comfort level given to describe this particular excitation, $RPE_{ref,}$ divided by the maximum *RPE* value, $RPE_{max,}$ was named the sensitivity factor, *s*,

$$s = \frac{RPE_{ref}}{RPE_{\max}} . \tag{2}$$

To put the given *RPE* values of different test subjects to the same scale they were multiplied by the sensitivity factor

$$RPE_{scaled} = s \cdot RPE . \tag{3}$$

The values of RPE_{scaled} vary between 0..5. The body mass indexes were calculated for comfort analysis with general equation.

$$BMI = \frac{m}{l^2} , \tag{4}$$

Where *m* is the mass of the test subject in kilograms and *l* is the height of the test subject in meters. The test subjects assessed also the comfort level of vibration so that they imagined working eight hours in suchlike trembling environment. This assessment was five level form: not discomfort, slightly discomfort, tolerable discomfort, discomfort and very discomfort. After all ten excitations testees gave verbal statement of different vibration types and if there was any special feeling.

RESULTS AND ANALYSIS

Subjects in this study were 23 students of technology with variable experiences of operating mobile work machines. Their ages varied from 19 to 30 years. Testees' particulars were collected with inquiries and their measurements are shown in Table 1.

Table 1 - Testees' particulars

Testee	Age	Hight	Weight	Sex	Testee	Age	Hight	Weight	Sex
1	23	176	74	m	13	20	180	81	m
2	25	186	83	m	14	28	174	60	m
3	22	170	60	m	15	22	186	86	m
4	23	192	88	m	16	20	159	54	f
5	26	174	80	m	17	21	164	62	f
6	19	186	72	m	18	21	160	57	f
7	22	178	76	m	19	22	183	86	m
8	20	170	60	m	20	26	183	90	m
9	23	171	81	f	21	24	168	70	f
10	24	175	68	f	22	30	175	80	m
11	23	177	76	m	23	30	176	70	f
12	20	190	82	m					

Comfort Rating vs. Frequency weighted acceleration (R.M.S value)

In Figure 2 there is graphical comparison of uncomfortable values as a function of R.M.S. Dispersion is high and there was found no correlation in any cases with these parameters.

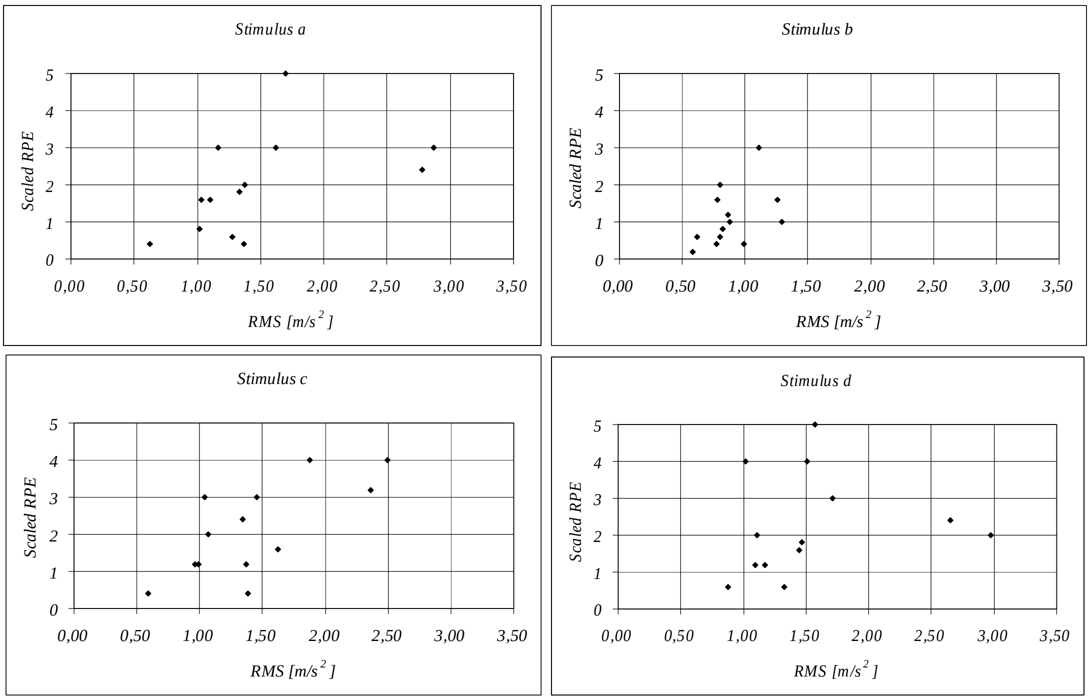

Figure 2 - Comparison of uncomfortable values as a function of R.M.S.

Comfort Rating vs. Average Heart Rate

In Figure 3 there is graphical comparison of the scaled uncomfortable values, RPE_{scaled}, and the average heart (*BPM*) rate during each excitation period. The dispersion is high and there is found no clear correlation in any excitation case with these parameters.

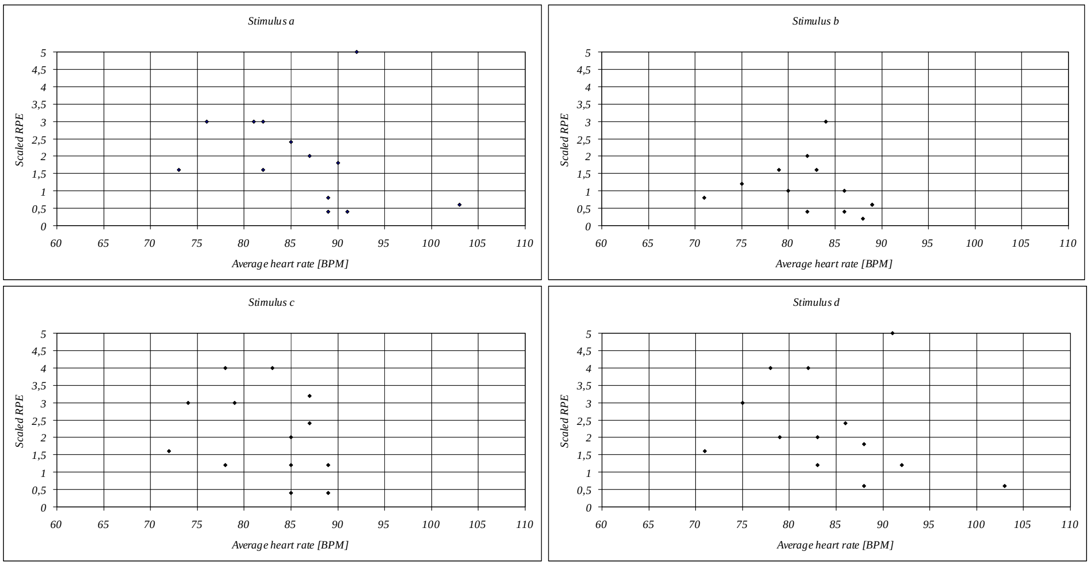

Figure 3 - Comparison of uncomfortable values as a function of heart rate.

Comfort Rating vs. Body Mass Index

Subjective comfort feeling varied a lot with testees and dispersion is considerable, see Figure 4. Here is observed the two reference excitation cases and absolute *RPE* values of the 23 test subjects

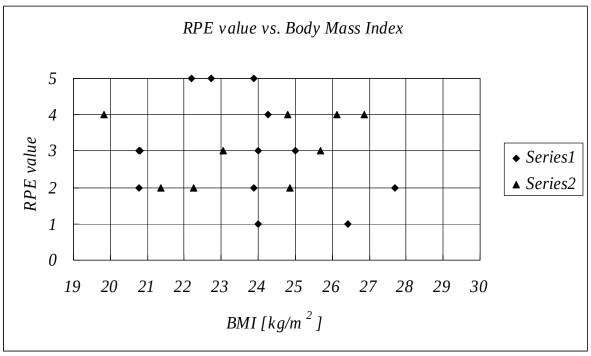

Figure 4 - Uncomfortable values and body mass indexes of testees in case of test drive with two reference stimulus (series 1 and 2).

The median of the body mass indexes (*BMI*) is *23.7* and generally persons, who have *BMI* over *25*, are considered overweight. In this study we found, that testees with *BMI* under *23.7* estimated their uncomfortable in average *3.2*. On the other hand persons whose body mass index was over *25* gave on an average value *2.8*. These results are shown in Table 2. So in this case it is possible to see the trend that feeling of discomfort increases when body mass index decreases. But the number of the testees was small, so this tendency needs to be verified with larger population.

Table 2 - Body mass indexes of the testees versus average uncomfortable on the left and differences between minimum and maximum heart rate on the right

Testee	RPE	BMI	Testee	RPE	BMI	Testee	Max-Min	Testee	Max-Min
14	4	19,8	7	1	24,0	14	9	7	15
3	2	20,8	2	3	24,0	3	45	2	23
8	3	20,8	11	4	24,3	8	17	11	6
6	3	20,8	21	4	24,8	6	23	21	33
16	2	21,4	15	2	24,9	16		15	18
10	5	22,2	13	3	25,0	10	15	13	10
18	2	22,3	19	3	25,7	18		19	5
12	5	22,7	22	4	26,1	12	18	22	6
17	3	23,1	5	1	26,4	17	23	5	14
4	2	23,9	20	4	26,9	4	27	20	8
1	5	23,9	9	2	27,7	1	32	9	8
Average RPE						**Average max-min**			
3,2	BMI < 23,7					21	BMI < 23,7		
3,0	23,7 < BMI < 25					9	23,7 < BMI < 25		
2,8	BMI ≥ 25					8	BMI ≥ 25		

Also heart rate maximum and minimum variability seems to have correlation with that trend. In Table 2, there are shown differences between testees' minimum and maximum heart rate measured during one minute stimulated period. The average heart rate difference is *21* for testees with *BMI* under *23.7*, whereas the difference is only *8* for those whose *BMI* is over *25*.

SUMMARY

Objective of this study has been to find out correlation between health and subjective feelings depending on vibration type in order to develop more user-friendly machinery. Significant amount of data was gathered from the 23 test subjects. In this paper the focus is on the evaluation of the human body movement, heart rate and subjective comfort. The purpose was to find out if there is correlation between them. The evaluation of comfort based on the translational vibration levels from the seat gave inconsistent results, as expected. The measurement method for health cannot be used for comfort analysis. However the motion of the body (e.g. head) and the comfort assessments gave more consistent results.

Comparison of uncomfortable values as a function of heart rate and R.M.S and comparison of the scaled uncomfortable values and the average heart rate showed also that dispersion is high and there was found no correlation in any cases with these parameters. When comparing uncomfortable values and body mass indexes (BMI) we found, that testees with body mass index under 23.7 estimated their uncomfortable in average 3.2. On the other hand persons whose BMI was over 25 gave an average value 2.8. The median of the body mass indexes is 23.7 and generally persons, who have BMI over *25*, are considered overweight. So in this case it is possible to see the trend that feeling of discomfort increases when body mass index decreases. But the number of the testees was small, so this tendency needs to be verified with larger population. Also heart rate maximum and minimum variability seems to have correlation with that trend. Could it be so, that persons with high body mass index have more internal damping in their body, which cause less uncomfortable feelings or are they perhaps just more jovial. More research is needed to find out which are the factors of comfort feeling and how they can be measured.

These results could be a good base for further studies of correlation between comfort and physiological phenomena and measurements in case of mobile work machines which are sold and used globally. An interesting subject for further studies would be long term monitoring in real mobile work machine and with larger sample and more specified inquiry. With that kind of measurements it could be possible to find factors which can be taken in to the count when designing or modeling comfort and that way more effective mobile work machines for global users.

REFERENCES

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