Health Risk Evaluation of Whole-body Vibration by ISO 2631-5 and ISO 2631-1 for Operators of Agricultural Tractors and Recreational Vehicles

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Abstract: This paper presents experimental research evaluation of the vibration exposure for the health risk prediction during vehicle operation. The vibration measurements were carried out on a recreational vehicle and two types of agricultural tractors. The vibration levels were measured for different surfaces and vehicle speed conditions. Based on the analysis of the results in the small agricultural tractor operated in the workplace (frameworks), S_{ed} exceeded 0.80 MPa by ISO2631-5:2004, and Av exceeded 0.89 m/s^2 by ISO2631-1:1997. That means that operators driving small agricultural tractors more than 8 h a day have a high probability of adverse health effects. However, the exposure value for the recreational vehicle had $S_{ed} < 0.5$ MPa by ISO2631-5:2004 and Av < 0.5 m/s^2 by ISO2631-1:1997 on highways and local roads. That means Recreational Vehicle operators driving more than 8 h a day, have a low probability of adverse health effects. Also, for the recreational vehicle, vibration was taken at different speeds (40–60 km/h, 80 km/h, 100–120 km/h). However, the speed change did not appear to affect the vibration dose variation while driving a vehicle on the highway and road. Finally, the health effect index of ISO2631-5:2004 are almost the same as assessment of health effect by ISO2631-1:1997.

Key words: Vibration exposure, Health risk, Vibration level, ISO 2631-1, ISO 2631-5

Introduction

As industries develop, many workers are exposed to whole-body vibration in their places of work every day. Most exposure to whole-body vibration occurs in seated postures while driving. Moreover, whole-body vibration is usually transmitted through the human body when the human body is in contact with vibrating surfaces i.e. a driv-

ing seat, a seat back-rest or floor in vehicles. In general, if the human body is continuously exposed to whole-body vibration, it is possible that human body will have adverse effects from the whole body vibration.

It is believed that exposure to whole body vibration is a health risk factor for low back pain[1]. Also, it is widely recognized that tractor operators are exposed to high levels of whole-body vibration during typical farm operations[1]. Therefore, it is necessary to evaluate the health effect from exposure time and vibration dose during vehicle operation. The most popular standards for measurement and evaluation of human response to whole-body vibration are ISO

2631-1 (1997) and ISO2631-5 (2004). For the assessment of the effects of vibration on health, it is proposed to use the frequency-weighted r.m.s. of ISO 2631-1 based on translational motion of the each axis on the seat surface if the crest factor is less than 9[2]. ISO 2631-1 also suggests that if the crest factor is less than 9, the weighted RMS is normally sufficient for evaluation of vibration. On the other hand, ISO 2631-5 (2004) provides the additional guidance on assessment of vibration containing multiple shocks. ISO 2631-5 (2004) focused on the lumbar response in humans exposed to whole-body vibration. Although the assessment point on humans differ depending on the ISO standard indices, it is necessary to compare effects of vibration on health by the current standard (ISO2631-1) with that by the multiple shocks standard (ISO2631-5).

The purpose of this study is to measure the vibration in two different agricultural tractors and recreational vehicles in order to evaluate the vibration transmitted to a human body through the seat. Measurements were recorded for different road surfaces and vehicle speeds. The vibration dose is evaluated for the health effect based on ISO2631-5:2004 and ISO2631-1:1997.

Theory

In ISO2631-5:2004 recommendations, the vibration effects to the human body are evaluated by compression stress in the lumbar spine. The frequency-weighted spinal stress is calculated. The detailed procedure for calculating the daily equivalent static stress is shown in the following sections[3, 7].

Spinal response in horizontal direction
    (x-axis, y-axis)
    In the x- and y-axes, the spinal response is approximately linear and is represented by a single-degree-of-freedom (SDOF) lumped-parameter model. The lumbar response, a_{lk} in m/s^2, is calculated from Eq.(1).

$$a_{lk}(t) = 2\varsigma\omega_n(v_{sk} - v_{lk}) + \omega_n^2(s_{sk} - s_{lk}) \tag{1}$$

Where, $\varsigma = 0.22$: critical damping ratio, $\omega_n = 13.35s^{-1}$: natural frequency.
$k = x$ or y, s_{sk}, s_{lk}: the displacement time histories in the seat and in the spine.

Spinal response in vertical directions
    (z-axis)
    In the z-direction, the spinal response is non-linear and can be represented by a recurrent neural network model.

Lumbar spine z-axis acceleration, a_{lz} in m/s^2 is predicted by using the following equations.

$$a_{lz} = \sum_{i=1}^{7} W_j u_j(t) + W_8 \tag{2}$$

$$u_j(t) = \tanh\left[\sum_{i=1}^{4} w_{ji} a_{lz}(t-i) + \sum_{i=5}^{12} w_{ji} a_{sz}(t-i+4) + w_{j13}\right] \tag{3}$$

Where, u_j, w_j are shown in tables in the draft of ISO2631-5 and these parameters are applicable when data is sampled at 160 Hz.

Calculation of acceleration dose
    The acceleration dose D_k [m/s^2] is defined as

$$D_k = \left[\sum_i A_{ik}^6\right]^{1/6} \tag{4}$$

Where, k= x, y or z, A_{ik} is the ith peak of the response acceleration $a_{ik}(t)$.
    The peaks are picked up in both the positive and negative directions for x-, y-directions. Otherwise, for z-direction, only positive peaks shall be counted.
    The average daily acceleration dose is D_{kd} [m/s^2]
    Equation (4) can be used when the total daily exposure is represented from a single measurement period. When the daily vibration exposure consists of two or more periods of different magnitudes the average daily acceleration dose can be calculated as follows:

$$D_{kd} = \left[\sum_{j=1}^{n} D_{kj}^6 \frac{t_{dj}}{t_{mj}}\right]^{1/6} \tag{5}$$

Where, t_{dj}: the duration of the daily exposure to condition j, t_{mj}: the period over which D_{kj} has been measured.

The daily equivalent static compression dose Blob#58
    S_{ed} is defined as

$$S_{ed} = \left[\sum_{k-x,y,z} (m_k D_{kd})^6\right]^{1/6} \tag{6}$$

Where, D_{kd} is the average daily acceleration dose and the recommended values in ISO2631-5:2004 of m_k are $m_x = 0.015$[MPa/(m/s^2)], $m_y = 0.035$[MPa/(m/s^2)], $m_z = 0.032$[MPa/(m/s^2)].
    In the situation that a person receives vibration 240 d per year during 40 working-years, 8 h per day, $S_{ed} = 0.5$ and $S_{ed} = 0.8$ MPa are criteria for judging the effect of vibration dose ($S_{ed} < 0.5$ MPa: low probability of an adverse health effect, $S_{ed} > 0.8$ MPa: high probability of an adverse health effect).

The obtained values are evaluated by using frequency-weighted R.M.S (Root Mean Square) accelerations in accordance with ISO2631-1:1997[4, 7].

The weighted r.m.s method [m/s^2]

The evaluation of vibration is calculated using the weighted r.m.s. acceleration defined by equation (7) from ISO 2631-1, as shown below

$$a_w r.m.s = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{1/2} \qquad (7)$$

Where, $a_w r.m.s$: the root-mean-square (r.m.s), $a_w(t)$: the frequency-weighted acceleration at time t. T: the measurement duration

For evaluation of the effects of vibration on health, according to ISO 2631-1, and the magnitude of vibration is evaluated by RMS, MTVV and VDV. Moreover, ISO 2631-1 suggests that if the crest factor is less than 9, the weighted RMS is normally sufficient for evaluation of vibration. Therefore, this study did not consider the MTVV and the VDV. The reason is that measurement shock or transient vibration did not occur and CF did not exceed 9 in the experiment. If someone were exposed to whole body vibration for 8 h per day, this provides the health guidance caution zones presented in ISO 2631-1. (Av < 0.5 m/s^2: health effects have not been clearly documented, 0.5 m/s^2 < Av <0.8 m/s^2: caution with respect to potential health risk indicated, Av > 0.8 m/s^2: health risk is likely.).

Methods

In order to evaluate the vibration level by both standards, Experiments were carried out for three different conditions[5, 6].

Three condition
Type of vehicle

The vibration level was measured for the different types of vehicles such as agricultural tractors [(Small size: CX 1805, Large size: USPRO), YAMAHA Corporation, Japan] and RV [(Recreational Vehicle (Exterior, TOYOTA Corporation, Japan)]. It is necessary to investigate how the vibration level differs when we estimate the vibration using ISO2631-1 or ISO2631-5 during the evaluation of the effects of vibration on health viewpoints.

Vehicle speed and type of road surface

In general, the vehicle vibration sources are the engine, road surface and suspension, etc[7]. It may be reasonable to assume that when drivers are exposed to vibration, vibration is one of the potential contributors to development of low back pain or back disorders. Therefore, the experiments were carried out in 3 categories; different road surfaces (workplace and road), and different speeds.

In the case of agricultural tractors, the vibration level is measured from operation of agricultural tractors (small; 5 km/h, large; 3.2 km/h) on farmland. Second, the vibration level was also measured on an asphalt road surface during normal speed (small; 21.6 km/h, large; 20 km/h) and above the normal speed (small; 54 km/h, large; 30.5 km/h). In of RV case, the vibration level was measured on the highway or a national road. In order to investigate the change of vibration level by change of speed, the measurements were carried out at 80 km/h, 100–120 km/h on the highway and 40–60 km/h on a national road. Moreover, in the case of 80 km/h on the high way, the vibration level was measured two times. Condition 1 was measured at a sampling frequency of 160 Hz as recommended in ISO2631-5:2004, while condition 2 was measured at an additional sampling frequency of 3 kHz shown in Table 3. It is necessary to evaluate how the vibration level differs when comparing 160 Hz with 3 kHz (including the high frequency parts).

The conditions are given in Table 1. There were 10 different data sets.

The schematic representation of experimental setup is shown in Fig. 1.

The measuring devices are given in Table 2 and shown in Fig. 2.

Two healthy male subjects participated in the experiment. Before the experiment, the purpose of this study was explained to all subjects. We allowed that the subjects adjust to the seat location to obtain a natural driving position. Measurement equipment used in the experiment was a three-axis piezo-electric accelerometer (B&K 4322), a charge amplifier (B&K 2692), and data recorder. A three-axis piezo-electric accelerometer (B&K 4322) mounted on the seat surface. Also, the sampling frequency is 160 Hz, and both agricultural tractors are measured for 6 min in the workplace and on the road. RV is measured for 10 min on highways and 16 min on local roads. All data was processed using MATLAB software (Mathworks, Version 6.1.0.450). The vibration dose is evaluated by ISO2631-5:2004 and ISO2631-1:1997.

Results

(1) Acceleration values were obtained on different sur-

Table 1. Measuring conditions for data acquisition

Condition No.	Vehicle	Surface	Speed [km/h]	Sampling frequency [Hz]
1	Small agricultural tractor	Workplace	5	160
2	Small agricultural tractor	Road	54	160
3	Small agricultural tractor	Road	21.6	160
4	Large agricultural tractor	Workplace	3.2	160
5	Large agricultural tractor	Road	30.5	160
6	Large agricultural tractor	Road	20	160
7	RV vehicle	Highway	80	160
8	RV vehicle	Highway	80	3 kHZ
9	RV vehicle	Highway	100–120	160
10	RV vehicle	Road	40–60	160

Table 2. Measuring devices and sampling conditions

	Acceleration sensor	Type 4321 (Bruel & Kjaer)
	Condition amplifier	Type 5974 (Bruel & Kjaer)
	Data recorder	NR-2000 (KEYENCE)
Normal	Sampling Frequency	160 Hz
Condition	Sampling Duration	6, 10, 16 min

Fig. 1. Schematic representation of experimental setup.

faces (farmland, road) by agricultural tractor size (small, large) and the evaluation was done by ISO 2631-5:2004 and ISO 2631-1:1997.

Table 3 indicates the vibration level from both agricultural tractors.

It is evident (Table 3) that the threshold value for the index (S_{ed} >0.5 MPa, Av >0.5 m/s^2) was exceeded with both agricultural tractors in the workplace. If the driver operates the agricultural tractor in the workplace for a long time, the vibration level (Table 5) in both ISO health hazard assessment indexes indicates a probability of an adverse health effect. The small agricultural tractor (S_{ed}:0.80 MPa, Av:0.89 m/s^2) created a higher vibration than the large agricultural tractor (S_{ed}:0.68 MPa, Av:0.72 m/s^2) did in the workplace. Although the reason is not clear, the small agricultural tractor is easily affected by change of road surface (workplace). Moreover, we evaluated the vibration level by change of speed in the both agricultural tractors. The small agricultural tractor produced similar results from ISO2631-5:2004 and ISO2631-1:1997 (condition 2; 0.69 MPa and 0.34 m/s^2 and condition 3 ; 0.67 MPa and 0.35 m/s^2), while the large agricultural tractor produced different results from ISO2631-5:2004 and ISO2631-1:1997 (condition 5 ; 0.89 MPa and 0.68 m/s^2 and condition 6 ; 0.55 MPa and 0.38 m/s^2). It seems that the large agricultural tractor is affected by change of speed more than that of the small agricultural tractor.
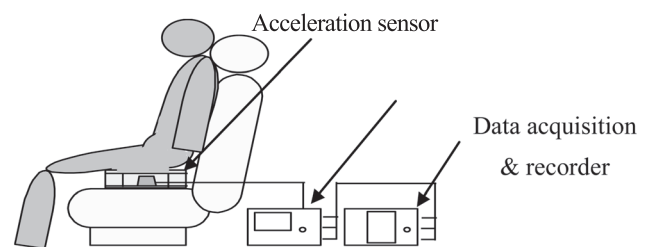
(2) Acceleration values were obtained at different speeds (40, 80, 100 km/h) and different locations (highway, road) for the RV and the evaluation was done by ISO 2631-5:2004 and ISO 2631-1:1997.

The results are given in Table 4 which shows the measured data in a recreational vehicle. All results indicate that the index S_{ed} < 0.5 was not exceeded on the highway and the road. This means there is a low probability of an adverse health effect.

The measurements under the different conditions are shown in Table 4. Condition 1 was measured at a sampling frequency of 160 Hz as recommended in ISO2631-5:2004. Condition 2 was measured at a sampling frequency of 3 kHz. It is necessary to evaluate how the vibration level differs when the comparing 160 Hz with 3 kHz (including the high frequency parts). However, from the evaluation of the effects of vibration on health, both results are in the same zone when using ISO2631-5:2004 and ISO2631-1:1997 (condition 1 ; 0.20MPa and 0.43 m/s^2 and condition 2 ; 0.24 MPa and 0.45 m/s^2).

In order to investigate the change of vibration level by change of speed in the vehicle, the measurements were carried out at 80 km/h and 100–120 km/h on the highway and at 40–60 km/h on a national road. When the vibration level for "80 km/h" and the vibration level for
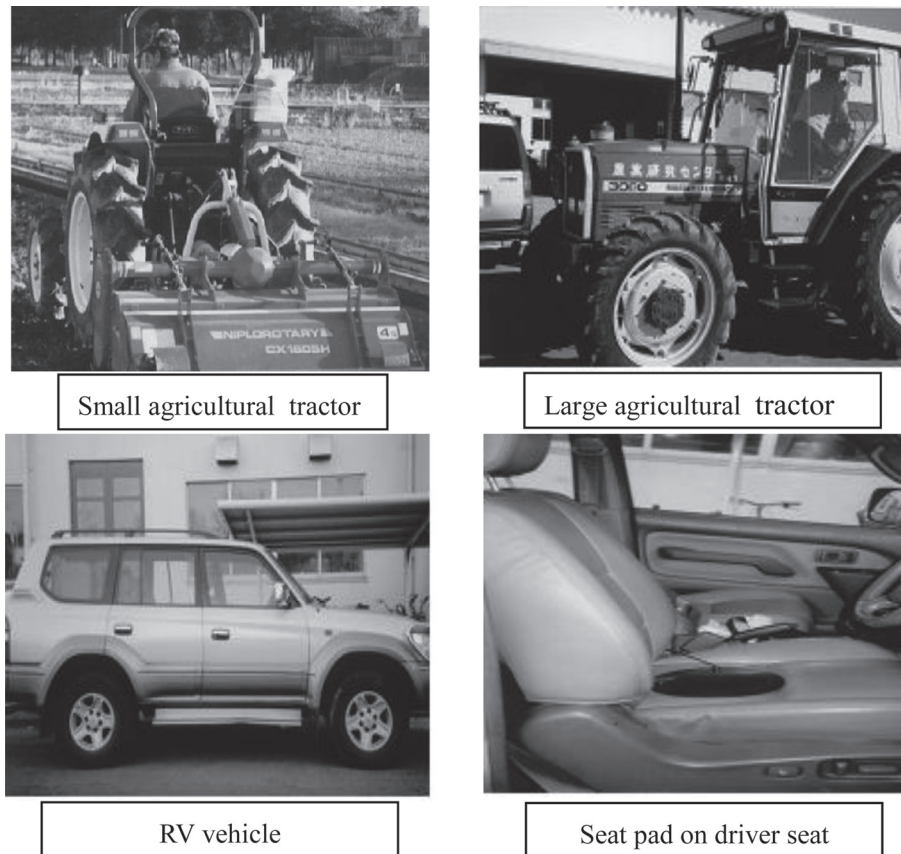
Small agricultural tractor

Large agricultural tractor

RV vehicle

Seat pad on driver seat

Fig. 2.   Measuring object (vehicle) and location of seat pad sensor.

Table 3.   Vibration dose in agricultural tractors by ISO2631-5 and ISO2631-1

Condition No.	Vehicle	Surface	Speed [km/h]	ISO2631-5 S_{ed} (MPa)	ISO2631-1 Av (m/s^2)
1	Small agricultural tractor	Workplace	5	0.80	0.89
2	Small agricultural tractor	Road	54	0.34	0.69
3	Small agricultural tractor	Road	21.6	0.35	0.67
4	Large agricultural tractor	Workplace	3.2	0.68	0.72
5	Large agricultural tractor	Road	30.5	0.68	0.89
6	Large agricultural tractor	Road	20	0.38	0.55

Table 4.   Vibration dose in RV vehicle by ISO2631-5 and ISO2631-1

Condition No.	Vehicle	Surface	Speed [km/h]	Sampling frequency [Hz]	ISO2631-5 S_{ed} (MPa)	ISO2631-1 Av(m/s^2)
1	RV vehicle	Highway	80	160	0.20	0.43
2	RV vehicle	Highway	80	3 kHz	0.24	0.45
3	RV vehicle	Highway	100–120	160	0.21	0.50
4	RV vehicle	Road	40–60	160	0.27	0.43

"100–120 km/h" are compared in ISO 2631-1, an effect from vehicle speed is observed. When the vibration level for "80 km/h" and the vibration level for "100–120 km/h" are compared in ISO 2631-5, there is no significant differ-ence. However, from the evaluation of the effects of vibra-tion on health, both ISO2631-1 and ISO2631-5 indicated the same zone; Health. Moreover, in the "40–60 km/h" case, when the vibration level for the "high way" and for

Table 5. The comparative evaluation of ISO2631-1 and ISO2631-5

Condition No.	Vehicle	Surface	Speed [km/h]	ISO2631-5 Sed [MPa]	ISO2631-1 Av [m/s^2]
1	Agricultural tractor (small size)	Workplace	5	High probability of an adverse health effect	Health risks are likely
2	Agricultural tractor	Road	54	Low probability of an adverse health effect	Caution with potential health risk is indicated
3	Agricultural tractor	Road	21.6	Low probability of an adverse health effect	Caution with potential health risk is indicated
4	Agricultural tractor (large size)	Workplace	3.2	Probability of an adverse health effect	Caution with potential health risk is indicated
5	Agricultural tractor	Road	30.5	Probability of an adverse health effect	Health risks are likely
6	Agricultural tractor	Road	20	Low probability of an adverse health effect	Caution with potential health risk is indicated
7	RV vehicle	Highway	80	Low probability of an adverse health effect	Health effects are not clearly documented
8	RV vehicle	Highway	80	Low probability of an adverse health effect	Health effects are not clearly documented
9	RV vehicle	Highway	100–120	Low probability of an adverse health effect	Health effects are not clearly documented
10	RV vehicle	Road	40–60	Low probability of an adverse health effect	Health effects are not clearly documented

the "road" are evaluated in ISO 2631-1, the vibration level for the "high way" is equal or larger than that for the "road". When the vibration level for the "high way" and that for the "road" are evaluated in ISO 2631-5, the vibration level for the "high way" is lower than that for the "road". Although the reason is not clear, the time domain data is not constant because the data is affected by the road surface condition. However, results will need to be acquired through experimental design modifications.

Discussion

Comparison of health effect evaluation by ISO2631-5:2004 and by ISO2631-1:1997

It generally takes several years for health changes caused by whole-body vibration to occur. Both ISO2631-1:1997 and ISO2631-5:2004 are used for health effect evaluation of whole-body vibration. Therefore, it is necessary to compare the two evaluation methods. For the small agricultural tractor in the workplace (Table 5), both ISO2631-1:1997 and ISO2631-5:2004 indicate a high probability of an adverse health effect. Generally, agricultural tractors have no suspension between the wheel and chassis. For the small agricultural tractor there is a shorter pathway for vibration from surface to the seat than for the large agricultural tractor. Therefore, the small agricultural tractor is more dangerous than the large agricultural tractor.

We assumed that vehicle speed would significantly change vibration dose while driving. The vibration dose was measured on the highway and road. However, there was almost no change in the vibration dose as seen in Table 4.

This appears to be due to the vehicle suspension between the wheel and chassis. Also, the asphalt pavement appears to lower the vibration dose measured on the highway and the road.

Generally, ISO2631-1:1997 is applicable to vibration in the frequency range of 0.5 Hz to 80 Hz which is transmitted to the seated body as a whole through the seat pan. ISO2631-5:2004 requires the sampling rate for the x- and y-directions be appropriated for an 80 Hz signal. The z-direction model in ISO2631-5:2004 recommends the sampling rate be a multiple of 160 Hz.

To determine if the sampling frequency of 160 Hz was enough, the data was gathered at a sampling frequency of 3 kHz for the RV vehicle on the highway. The results from the two data sets indicate 0.20 MPa and 0.43 m/s^2 with 160 Hz and 0.24 MPa and 0.45 m/s^2 with 3 kHz as shown in Table 4. It is evident that the vibration dose from ISO2631-5:2004 and that from ISO2631-1:1997 indicate the same health guide zone. From this, the sampling frequency of 160 Hz is considered to be sufficient for evaluating the health response.

Conclusions

These conclusions do not apply to general situations. However, the following remarks are provided as a summary.

(1) For the small agricultural tractor case, the index S_{ed}, Av > 0.8 was exceeded in the workplace using both ISO 2631-1:1997 and ISO2631-5:2004. This means a high probability of an adverse health effect. Therefore, work schedules should be arranged to include vibration-free time.

(2) For the vehicle case, the index S_{ed}, Av < 0.5 was not

exceeded on the highway or the road using both ISO 2631-1:1997 and ISO2631-5:2004. This means a low probability of an adverse health effect. Also, the speed change did not change the vibration dose while driving a vehicle on the highway or the road

(3) The health risk assessment by ISO2631-5:2004 is similar to the evaluation by ISO 2631-1:1997 with respect to health zone.

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