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1	Vibration Analysis during Grass Harvesting According to ISO Vibration
2	Standards
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### 12 Abstract

This research evaluated the working efficiency and comfort of operation by measuring 13vibration acceleration of tractors during grass harvesting. A real-time kinematic global 14positioning system and an inertial measurement unit installed in a tractor normally used by 1516farmers during grass harvesting were used to acquire tractor vibration acceleration data. 17Analysis of the position and vibration acceleration data of tractors by a Fourier transformation yielded a power spectrum of vibration acceleration at each frequency (1–10 Hz) and position. 18The root mean square of vibration acceleration at each frequency (1-10 Hz) was calculated 19 with the center frequency of the 1/3 octave bands (1.0, 1.25, 1.6, 2.0, 2.5, 3.15, 4, 5, 6.3, 8, 2021and 10 Hz) based on ISO standards. To evaluate the working efficiency in the grassland, geographical information system maps were generated using the power spectrum of vibration 22

1 acceleration and the limit on working time for each frequency that negatively affected the tractor driver. The vibration acceleration in the longitudinal  $(a_x)$  and lateral  $(a_y)$  directions at  $\mathbf{2}$ the center frequency of the 1/3 octave band below 2.0 Hz exceeded the fatigue-decreased 3 proficiency and reduced the comfort boundaries stipulated in ISO 2631 (1974). In the area 4 where working characteristics are severe, the vibration acceleration in the vertical direction  $\mathbf{5}$  $(a_{z})$  is high. The vibration acceleration in the  $a_{z}$  direction at the center frequency of the 1/3 6 octave band (5–10 Hz) clearly indicates discomfort during grass harvesting and a decrease in  $\overline{7}$ the work efficiency beyond one hour. The total vibration acceleration  $(a_y)$  at the center 8 9 frequency of 5.0 Hz of the 1/3 octave band served to evaluate comfort in the whole field during grass harvesting—the  $a_v$  value is higher than that at other frequencies. The area with 10 11 severe working characteristics showed a higher  $a_v$  value at the center frequency of 8.0 Hz than that at other frequencies. 12

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14 Keywords: RTK-GPS, IMU, ISO standard, Fourier transformation, 1/3 octave band center
 15 frequency, vibration acceleration

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### 17 **1. Introduction**

18

There are three effects of vibration on the human body: psychological, physiological, and work efficiency. The physiological effect has the most direct impact on people. In 1976, Japan enacted regulations on vibrations based on ISO/DIS 2631 (1974). Those regulations covered basic issues such as using the vibration level to indicate standard values, and the use of measured values in the vertical direction of the vibration level, following JIS C 1510 (1995)
as the measurement standard.

With significant development of a wide range of machines due to industrialization, 3 noise-related regulations have broadened in range and detail. For example, ISO 2631-1(1997) 4 and ISO/DIS 8041(2003) revised the standards for full human body vibration and hand-arm  $\mathbf{5}$ vibrations. In the Japanese industry standards, JIS 7760-1(2004) and 7760-2(2004), which are 6  $\overline{7}$ the basic requirements for measurement, the method and evaluation of full-body vibrations 8 were revised in 2004 based on ISO/DIS 8041(2003) and ISO 2631(1997). The vibration 9 regulations for agricultural machines, ISO 5008(1979), specify the method to measure the operator's full-body vibration for agricultural tractors and field machines. Using these 10 standards, many studies have reported the effects of vibrations of agricultural tractors on 11 human health and the comfort of many kinds and sizes of tractors with different tires and 1213transmissions and offered methods for estimating tractor vibration (Kennes et al., 1999; Servadio et al., 2007) 14

Sam and Kathirval (2006) reported that the four primary harmful effects of vibration are degraded health, impaired activities, impaired comfort, and motion sickness. Kumar et al. (2001) investigated the strength of tractor vibrations and their effects on humans, such as back injuries or waist pain. They used standards based on ISO 2631(1985) and ISO 5008 (1979). Pope and Hansson (1992) reported that tractors generate vibrations with a frequency of 1–7 Hz, which are harmful to the human body, and generate those as high as 4–8 Hz, which can cause waist pain or spinal injuries.

In this study, we acquired vibration and position information during actual grass harvesting work using a real-time kinematic global positioning system (RTK-GPS) and an inertial measurement unit (IMU). We used a Fourier transform to convert the strength of vibration, by
frequency and location, to work information and generated a geographical information system
(GIS) map for the frequency range 1–10 Hz, which negatively affects humans during tractor
work. We analyzed this GIS map to determine the locations where the vibration intensity in
the 1–10 Hz frequency range exceeded ISO standards, thereby affecting work. We discussed a
new method of evaluating work comfort. This study analyzed vibrations based on ISO
2631(1974), ISO 5008(1979), JIS B 7761-1, 2(2004), and JIS F 0907(2003).

8

### 9 2. Materials and methods

### 10 2.1 Experimental setup

The field experiment was performed at Hamanaka, Hokkaido grassland in 2007. The total 11 area of the grassland is 3.6 ha, but the GIS map covered only an area of 2.4 ha, where the 1213vibration during grass harvesting was actually measured using a Kubota MD 107 (78 kW) 14tractor. During grass harvesting, a mower conditioner with a mowing width of 3 m was 15attached to the tractor and vibration data was collected while driving at a work speed of 3.0 m  $s^{-1}$ . This speed was the normal practical speed for this operation. The working speed was 16almost constant. The data sets recorded during turning were omitted and only those of straight 1718paths were used for analysis. We interviewed the operator to determine the regions where he felt it was difficult to work. We will refer to the combination of factors, including the risk of 1920the tractor rolling over on the operator, an increase in the drag of the mower conditioner, and unstable work postures of an operator during harvesting, as workability. Fig. 1 shows the MD 2122107 harvesting grass at the Hamanaka grassland and Table 1 shows the tractor's main 1 specifications.

 $\mathbf{2}$ An RTK-GPS (MS750, Trimble Navigation Ltd., Sunnyvale, CA) and an IMU (Japan Aviation Electronics Industry Ltd., Tokyo, Japan) installed in a tractor normally used by 3 farmers during actual grass harvesting measured the positions and vibrations. A virtual 4 reference station (VRS)/RTK-GPS receiver with 2-cm precision acquired the position data at  $\mathbf{5}$ 6 a data frequency of 20 Hz. The acceleration in the  $a_x$ ,  $a_y$ , and  $a_z$  directions was measured by  $\overline{7}$ the IMU with a frequency of 25 Hz. The acceleration data in the three directions was 8 corrected by subtracting gravity. These data were stored in a laptop through an RS-232C 9 interface. Fig. 2 shows the locations of the installed sensors. For studying vibration acceleration, the location of the vibration acceleration sensor is most important. ISO 10 8041(2003) and JIS B 7760-1(2004) stipulate that the sensor should be installed in the same 11 plane as the seat surface for measurement. In this study, however, installing the vibration 1213acceleration sensor on the seat interfered with the operator during harvesting; thus, it was installed on the side of the operator's seat to perform measurements without obstructing the 1415work.

Fig. 3 illustrates the tractor's working trajectory, measured by the RTK-GPS during grass harvesting at Hamanaka. The area enclosed by the red triangle indicates poor workability.

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- 19

#### 20 2.2 Preprocessing of tractor vibration acceleration data

As shown in Fig. 3, the length of one working path is about 200 m. Windowing the complete vibration acceleration data in a single path, as shown in Fig. 4, associated the position with spectral information. After performing a discrete Fourier transform, the center of

1 the window serves as the representative position. In this study, we used 256 samples within  $\mathbf{2}$ the window at a sampling frequency of 25 Hz. Because the vibration acceleration data was acquired at a work speed of 3 m s<sup>-1</sup> and 25 Hz, the sampling distance corresponds to a special 3 distance of about 0.12 m. Thus, the frequency and intensity measurements of vibration 4 acceleration in the test space are accurate to within 0.12 m. The 256 samples used for the  $\mathbf{5}$ Fourier transform correspond to the data acquired during 10.24 s and include the vibration 6 acceleration data for a distance of about 30 m. A Hanning window function, used as in Eq. (1),  $\overline{7}$ 8 diminished the effect of the sampling data on both ends. Fig. 4 shows the application of a 9 Hanning window function on a specified number of vibration acceleration data samples acquired from straight-line work and the sampling data interval. 10

11 
$$h(n) = \begin{cases} \sqrt{\frac{2}{3}}(1 - \cos(\frac{2\pi n}{N-1})) & (0 \le n \le N-1) \\ 0 & (1) \end{cases}$$

### 12 3.2 Transformation of vibration acceleration data to multidimensional spatial data

This study analyzed the vibration acceleration power spectrum using a discrete Fourier transform based on the power spectral density function of JIS F 0907(2003) specifications as in Eqs. (2) and (3).

$$16 f_i = i\Delta f = \frac{i}{T_s} (2)$$

17 
$$S_{a}(f_{i}) = (\Delta f) \cdot \frac{1}{N} \left| \sum_{l=1}^{n} x_{l} e^{-2\pi i f_{i} l} \right|^{2}, \qquad (3)$$

18 where  $f_i$  is the *i*th frequency,  $\Delta f$  is the bandwidth representing the frequency resolution, 19 and  $T_s$  is the time duration for the Fourier transform. This study used 256 data samples for a 20 discrete Fourier transform at a frequency of 25 Hz; thus,  $T_s$  was 10.24 s and  $\Delta f$  was 21 0.09766 Hz. *N* is the number of vibration acceleration data samples. The root mean square 1 (r.m.s.) of the vibration accelerations is calculated as

ISO 2631(1974) defines the vibration acceleration intensity level of fatigue as the deterioration of work efficiency according to the vibration acceleration in the  $a_x$ ,  $a_y$ , and  $a_z$  directions at a center frequency of the 1/3 octave band. This study calculated the weighted rms of the vibration acceleration in the longitudinal  $(a_{xwrms})$ , lateral  $(a_{ywrms})$ , and vertical directions  $(a_{zwrms})$  using Eqs. (5), (6), and (7), respectively, and compared the values with ISO 2631(1974).

9 
$$a_{xwrms} = k_x \left[ \sum_i (W_{ai} a_{x_i})^2 \right]^{\frac{1}{2}}$$
 (5)

10 
$$a_{Y_{wrms}} = k_y \left[ \sum_i (W_{ai} a_{y_i})^2 \right]^{\frac{1}{2}}$$
 (6)

11 
$$a_{Zwrms} = k_z \left[ \sum_i (W_{ai} a_{z_i})^2 \right]^{\frac{1}{2}}$$
 (7)

Here  $k_x$ ,  $k_y$ , and  $k_z$  are coefficients that depend on measurement methods for the 12longitudinal (x), lateral (y), and vertical directions (z), respectively.  $W_{ai}$  is the vibration 13acceleration coefficient at the 1/3 octave band with the center frequency  $f = 10^{i/10}$  Hz.  $a_{x_i}$ , 14 $a_{y_i}$ , and  $a_{z_i}$  are the *i*th r.m.s. acceleration in the three directions. In this study, because the 15IMU is installed on the floor of the tractor,  $k_x$ ,  $k_y$ , and  $k_z$  were 0.25, 0.25, and 0.4, 16respectively. With these weighting coefficients, the acceleration on the seat can be estimated 17from the acceleration on the floor (ISO 2631-1, 1997). In addition,  $W_{ai}$  calculates the 18vibration acceleration coefficient defined in ISO 5008(1979) at each selected frequency. The 19

synthesized vibration acceleration was calculated using Eq. (8). This is composed of the
longitudinal, lateral, and vertical components obtained using Eqs. (5), (6), and (7),
respectively, to examine the level of comfort during grass harvesting (JIS F 0907, 2003).

<sup>5</sup> The position and acceleration were measured simultaneously during grass harvesting. <sup>6</sup> Because the position data recorded with the GPS included time data, analysis of the vibration <sup>7</sup> acceleration and position data using this method enables us to determine the intensity <sup>8</sup> spectrum of the vibration acceleration at any time, as shown in Fig. 5. We used this method <sup>9</sup> over the whole grassland area to investigate the spatial characteristics of machine vibration <sup>10</sup> during grass harvesting.

11

### 12 **3. Results and discussion**

 $a_{v} = \sqrt{a_{xwrms}^2 + a_{ywrms}^2 + a_{zwrms}^2}$ 

# 3.1 Characteristics of vibration acceleration in the longitudinal (a<sub>x</sub>) and lateral (a<sub>y</sub>) directions

Fig. 6 illustrates the deterioration of work efficiency due to fatigue and the vibration strength level of comfort along the three axes with the 1/3 octave band specified in ISO 2631(1974) as the center frequency. As shown in Fig. 6, the vibration strength level of fatigue and deterioration of work efficiency is low in the  $a_x$  and  $a_y$  directions in the range 1–2 Hz; that in the  $a_z$  direction is low in the range 4–10 Hz. The lowest frequency on each axis negatively affects fatigue, work efficiency, or comfort.

In this study, therefore, we discuss the characteristics of tractor vibration during grass harvesting at 1/3 octave band center frequencies from 1.0 to 10 Hz in the  $a_x$ ,  $a_y$ , and  $a_z$ . The vibration strength level at which fatigue work efficiency deteriorates was mapped for

(8)

1 each frequency in the range 1.0–10 Hz for the whole field. After analyzing the vibration
2 characteristics during grass harvesting, we diagnosed the machine workability on the
3 grassland.

Fig. 7 compares the average vibration acceleration in the  $a_x$  direction. The level of 4 vibration strength work efficiency decreases in the 1/3 octave band center frequency range  $\mathbf{5}$ 1.0–10 Hz for the whole field and areas with poor workability. The gray and white points are 6 the averaged vibration acceleration values in the  $a_x$  direction for the entire field and the area  $\overline{7}$ 8 pointed out by the operator having poor workability, respectively. As shown in Fig. 7, the average of vibration acceleration for the whole field reached 3.033 m s<sup>-2</sup> at 1.0 Hz. 9 Calculating the work time from the average value of the vibration acceleration of the whole 10 field, we get 25 min below 2.0 Hz, where work fatigue increases and work efficiency 11 decreases. Even in the crucial areas identified by the operator, the vibration acceleration is 1213highest at 1.0 Hz, and the work time, based on fatigue work efficiency at 1.0 Hz, 1.25 Hz, and 2.0 Hz decreases below 6 min. Table 2 shows the statistics of vibration acceleration in the  $a_x$ 14 direction for the whole field and poor workability areas for the center frequency. 15

Fig. 8 shows the GIS map of the maximum vibration acceleration in the  $a_x$  direction for 16the center frequency range 1.0-10 Hz. Over the whole field, the maximum vibration 17acceleration in the  $a_x$  direction exceeded 1.0 m s<sup>-2</sup>, and for specific areas, it exceeded 4.0 m 18 $s^{-2}$ . Within poor workability areas, many areas exhibit maximum vibration acceleration in 19 excess of 5 m s<sup>-2</sup>. Fig. 9 shows the GIS map of the entire field for each 1/3 octave band center 20frequency and illustrates the maximum vibration acceleration. The center frequency of the 1/321octave band that showed maximum acceleration in the  $a_x$  direction is below 2.0 Hz. Note 22that the maximum vibration acceleration at 1.0 Hz covers 80% of the entire field. Even in 23

poor workability areas, the maximum vibration acceleration at the center frequency of 1.0 Hz
 exceeds 90%.

Fig. 10 shows the GIS map created by calculating the maximum vibration acceleration for 3 the entire field in the  $a_x$  direction (as shown in Fig. 8) from the vibration strength level for 4 the deterioration of work efficiency from fatigue, as specified in ISO 2631(1974). The work  $\mathbf{5}$ time limit for the maximum vibration acceleration in the  $a_x$  direction is mainly distributed 6  $\overline{7}$ below 1 min for the whole field owing to the 1/3 octave band center frequency of 1.0 Hz, as 8 shown in Fig. 9. These results show that, in this experiment, the vibration acceleration in the 9 direction of movement caused operator fatigue or deterioration of work efficiency at work times below 1 min owing to a center frequency of 1.0 Hz. 10

Fig. 11 compares the average vibration acceleration in the  $a_v$  direction and the vibration 11 strength level of work efficiency for the whole field and poor workability areas. The gray 1213points are the average values of vibration acceleration for the whole field; the white points are the averages of vibration acceleration in the  $a_y$  direction. The average vibration acceleration 14for the field reached a maximum of 2.478 m s<sup>-2</sup> at 1.0 Hz; below the 1/3 octave band 15vibration center frequency of 2.0 Hz, the vibration acceleration exceeded 1.150 m s<sup>-2</sup>—higher 16 than that above 2.0 Hz. In the area of poor workability, the vibration acceleration was also 17higher at 1.0 Hz and 2.0 Hz than at the other frequencies. Calculating the work time limit 18based on the average vibration acceleration yielded a work time below 25 min for the whole 19field at a center frequency below 2.0 Hz; in areas of poor workability, work times below 1 20min at 1.0 Hz and 2.0 Hz resulted in fatigue or deterioration of work efficiency. Table 3 shows 21the statistical values for vibration acceleration in the  $a_y$  direction for the whole field and 2223areas of poor workability at each 1/3 octave band center frequency.

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Fig. 12 shows the GIS map of the maximum vibration acceleration in the  $a_y$  direction for 1 the 1/3 octave band center frequencies 1.0–10 Hz. The maximum vibration in the  $a_y$  $\mathbf{2}$ direction for the whole field was mainly distributed in areas over  $1.0 \text{ m s}^{-2}$ . In the white line 3 triangle area within the poor workability area, the maximum vibration acceleration exceeds 4 1.4 m s<sup>-2</sup> throughout, while areas over 2.2 m s<sup>-2</sup> also exist. Fig. 13 shows the GIS map of 1/3  $\mathbf{5}$ 6 octave band center frequencies of 1.0-10 Hz, showing the maximum vibration acceleration for each area of the field. As shown in Fig. 13, the 1/3 octave band center frequency showing 78 the maximum vibration acceleration exceeds 90% of the whole field area at frequencies below 1.6 Hz. Areas of poor workability showed tendencies similar to those of the whole field. Fig. 9 14 shows the GIS map of the calculated work time limit that causes fatigue or deterioration of 10 11 work efficiency using the maximum vibration acceleration in the  $a_{y}$  direction, according to 12ISO 2631(1974). The work time limit for the maximum vibration acceleration in the  $a_y$ 13direction is mainly distributed below 1 min for the whole field owing to the effect of the 1/3 octave band center frequencies below 2.0 Hz; similar results were observed in areas of poor 1415workability.

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### 17 **3.2** Characteristics of vibration acceleration in the vertical direction $(a_z)$

Fig. 15 compares the average vibration acceleration in the  $a_z$  direction and the vibration strength level of fatigue work efficiency for the whole field and poor workability areas for the 1/3 octave band center frequencies in the range 1.0–10 Hz. The gray points are the average values of vibration acceleration for the whole field calculated for each center frequency. The white points are the average values of the vibration acceleration in the  $a_z$  direction in areas of poor workability. As shown in Fig. 15, the average vibration acceleration showed high values  $0.909 \text{ ms}^{-2}$  and  $0.985 \text{ ms}^{-2}$  at 1.0 Hz and 2.0 Hz, respectively. In addition, the average of vibration acceleration at center frequencies 5.0–10 Hz with low deterioration of work efficiency was above 0.7 m s<sup>-2</sup>.

At the 1/3 octave band center frequency range 5.0–10 Hz, workability decreases to 1 h. In areas of poor workability, the average vibration acceleration is the highest at 1.0 Hz and 2.0 Hz. The work time in the range 4.0–10 Hz with low vibration strength of work fatigue efficiency deterioration is below 2.5 h. Table 4 summarizes the statistical values of the vibration acceleration in the  $a_z$  direction of the whole field and areas of poor workability for each center frequency.

Fig. 16 shows the GIS map of the maximum vibration acceleration in the  $a_z$  direction for center frequencies 1.0–10 Hz. The maximum vibration for the whole field in the  $a_z$  direction was mainly distributed in areas over 0.6 m s<sup>-2</sup>. In the poor workability area, the maximum vibration acceleration exceeds 1.2 m s<sup>-2</sup>.

15Fig. 17 shows the 1/3 octave band center frequency map with the maximum vibration acceleration in the  $a_z$  direction for the whole field. The center frequency of the 1/3 octave 16band with the maximum vibration acceleration in the  $a_z$  direction is broadly distributed from 171.0 to 10 Hz; however, 80% of the field was at 4.0-10 Hz. Even in the identified poor 18workability areas, the center frequencies were broadly distributed in the 1.0–10 Hz range. Fig. 1918 shows a GIS map obtained by calculating the maximum vibration acceleration in the  $a_{z}$ 20direction from the vibration strength level according to deterioration of work efficiency, as 21specified by ISO 2631(1974). In Fig. 18, the work time for the vibration acceleration in the 22 $a_{z}$  direction at which work efficiency decreased was 1 h in the whole field and poor 23

1 workability areas.

 $\mathbf{2}$ 

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## We used the composite vibration acceleration along the three axes to evaluate the level of comfort, according to the specifications in JIS B 7760-1(2004) and JIS B 7760-2(2004). This was achieved by calculating the composite vibration acceleration. In this paper, the maps for the center frequencies of 5 and 8 Hz are shown because these two maps show the distinguished difference between normal and poor workability areas. Table 5 summarizes the comfort evaluation method according to the composite vibration acceleration specified in JIS B 7760-1(2004) and JIS B 7760-2(2004).

**3.3** Evaluation of comfort by composite vibration acceleration along the three axes

In Fig. 19, the composite vibration acceleration and degree of comfort at the center 11 frequency of 5.0 Hz are shown as a GIS map for each whole field. Fig. 19(a) shows that 12composite vibration accelerations over  $1.0 \text{ m s}^{-2}$  are widely distributed in the whole field. In 13particular, the composite vibration value of the grass harvesting areas pointed out by the 14operator as high exceeded 2.0 m s<sup>-2</sup>, which was 1.0 m s<sup>-2</sup> higher than that at other locations. 15The comfort evaluation shown in Fig. 19(b) evaluated 70% of the whole field as 16 17"uncomfortable," while it rated the poor workability areas identified by the operator as "considerably uncomfortable." Fig. 20 shows the GIS map evaluating the composite vibration 18 acceleration and comfort at 8.0 Hz; Fig. 20(a) shows that the area with a composite vibration 19acceleration of over 0.6 m s<sup>-2</sup> is widely distributed over the field. The poor workability areas 20showed a high composite vibration value of 1.2 m s<sup>-2</sup>, and thus, they were evaluated as being 2122"considerably uncomfortable."

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### 1 4. Conclusions

In this study, we used a system made up of an RTK-GPS and an IMU installed on a farm  $\mathbf{2}$ 3 tractor to simultaneously acquire vibration acceleration and location information during actual grass harvesting. The vibration strength acquired through a Fourier transform was analyzed on 4 the basis of the location information. A GIS map was created for the 1–10 Hz frequency band,  $\mathbf{5}$ which negatively influences workers using the tractor. The analysis determined whether the 6 vibration of any frequency exceeded ISO standards, thereby affecting workability and  $\overline{7}$ efficiency; moreover, the machine workability on the grassland was evaluated. A Fourier 8 transform was applied to the vibration acceleration in the  $a_x$ ,  $a_y$ , and  $a_z$  directions, and 9 10 they were combined with location information to generate a GIS map representing the vibration strength. We compared the 3-axis vibration acceleration for each 1/3 octave band 11 center frequency with the vibration strength levels that cause fatigue or deterioration of work 12efficiency according to ISO 2631(1974) and provided GIS mapping of the work time limits. 13

14 As a result, it was observed that the level of fatigue increased or the work efficiency deteriorated for work times of 6 min below 2.0 Hz for the vibration acceleration in the  $a_x$ 15and  $(a_x)$  directions. On the other hand, with the vibration acceleration in the  $a_z$  direction, 16 machine workability deteriorated significantly when the work time exceeded 1 h at 5.0-10 Hz. 17A GIS map of work comfort was generated on the basis of the composite vibration 18 19 acceleration calculated from the 3-axis vibration acceleration for the 1/3 octave band. These results demonstrate that the method of acquiring vibration acceleration data and the frequency 20analysis of vibration acceleration, as spatial information implemented in this study, are 21effective in identifying and evaluating machine workability in the whole field. 22

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Tractor specifications.

	Model No.	Kubota MD 107
	Driving method	4WD
	Model No.	Kubota F5802-L
Engine	Displacement [cc]	5832
Engine	Max. power [kW/rpm]	78/2400
	Max. torque [kg·m/rpm]	39.9/1300
	Overall length [mm]	4210
	Overall width [mm]	2040
Dimensions	Overall height [mm]	2695
	Wheelbase [mm]	2565
	Weight [kg]	3860
Times	Front	13.6-24-6PR
Tires	Rear	16.9-38-8PR
Transmission	Speeds	F16/R16

Statistical values of vibration acceleration in the longitudinal direction  $(a_x)$  for the whole field and poor workability areas.

Frequency	Whole field $[m s^{-2}]$			Whole field $[m s^{-2}]$ Poor workability area $[m s^{-2}]$				s <sup>-2</sup> ]
[Hz]	Avg.	Max.	Min.	S. E.	Avg.	Max.	Min.	S. E.
1.00	3.033	9.855	0.016	1.265	4.183	8.723	1.793	1.540
1.25	1.224	4.785	0.020	0.616	1.435	4.673	0.084	1.099
1.60	1.352	4.676	0.042	0.670	0.462	1.494	0.054	0.343
2.00	1.210	3.333	0.060	0.483	1.352	2.115	0.717	0.298
2.50	0.976	2.493	0.063	0.407	0.190	0.748	0.008	0.142
3.15	0.774	2.780	0.064	0.278	0.121	0.801	0.007	0.141
4.00	0.712	2.416	0.046	0.246	0.761	1.141	0.286	0.206
5.00	0.574	2.848	0.062	0.194	0.640	0.974	0.252	0.166
6.30	0.534	3.704	0.072	0.204	0.665	1.432	0.401	0.234
8.00	0.594	3.826	0.050	0.215	0.651	0.991	0.351	0.118
10.00	0.802	4.260	0.061	0.269	0.654	0.950	0.390	0.130

Statistical values of vibration acceleration in the lateral direction  $(a_y)$  for the whole field and

poor workability areas.

Frequency	Whole field $[m s^{-2}]$				Poor workability area [m s <sup>-2</sup> ]			
[Hz]	Avg.	Max.	Min.	S. E.	Avg.	Max.	Min.	S. E.
1.00	2.478	7.789	0.024	1.079	3.105	5.929	1.560	0.900
1.25	1.209	5.779	0.017	0.641	0.738	8.141	0.029	1.050
1.60	1.341	4.699	0.027	0.636	0.909	5.072	0.078	1.051
2.00	1.510	4.981	0.039	0.585	2.104	3.336	1.187	0.559
2.50	0.775	4.933	0.031	0.359	0.456	2.737	1.524	0.612
3.15	0.553	2.129	0.032	0.212	0.266	1.665	0.007	0.384
4.00	0.448	2.104	0.043	0.184	0.642	1.402	0.231	0.298
5.00	0.352	2.018	0.040	0.163	0.606	1.397	0.255	0.308
6.30	0.409	3.974	0.049	0.205	0.650	1.428	0.323	0.268
8.00	0.439	2.536	0.054	0.177	0.693	1.307	0.341	0.206
10.00	0.536	2.725	0.067	0.178	0.649	0.887	0.423	0.113

Statistical values of vibration acceleration in the vertical direction  $(a_z)$  for the whole field and poor workability areas for each center frequency.

Frequency	Whole field $[m s^{-2}]$				Poor workability area [m s <sup>-2</sup> ]			s <sup>-2</sup> ]
[Hz]	Avg.	Max.	Min.	S. E.	Avg.	Max.	Min.	S. E.
1.00	0.909	3.461	0.012	0.415	1.148	1.839	0.778	0.220
1.25	0.528	1.821	0.018	0.275	0.168	0.862	0.003	0.136
1.60	0.656	2.510	0.018	0.305	0.292	2.161	0.003	0.377
2.00	0.985	3.517	0.042	0.370	1.338	2.261	0.517	0.404
2.50	0.674	1.979	0.041	0.279	0.139	0.543	0.010	0.102
3.15	0.587	1.841	0.053	0.198	0.110	0.608	0.009	0.144
4.00	0.580	1.744	0.059	0.209	0.844	1.335	0.422	0.204
5.00	0.823	2.216	0.094	0.279	1.060	1.540	0.546	0.165
6.30	0.783	3.669	0.152	0.228	0.970	1.299	0.627	0.139
8.00	0.697	2.249	0.233	0.185	0.967	1.371	0.660	0.116
10.00	0.924	2.379	0.188	0.218	1.057	1.645	0.747	0.152

Comfort evaluation according to composite vibration acceleration.

Range of composite vibration acceleration	Comfort evaluation
Under 0.315 $[m s^{-2}]$	Not uncomfortable
0.315–0.65 [m s <sup>-2</sup> ]	A little uncomfortable
0. 5–1.0 [m s <sup>-2</sup> ]	Somewhat uncomfortable
0.8–1.6 [m s <sup>-2</sup> ]	Uncomfortable
1.25-2.5 [m s <sup>-2</sup> ]	Considerably uncomfortable
More than 2.5 $[m s^{-2}]$	Extremely uncomfortable



Fig. 1 Grass harvesting at Hamanaka grassland.



Fig. 2 Installation of the tractor vibration data-acquisition system.



Fig. 3 Working trajectory of the tractor during grass harvesting and workability investigation locations.



Fig. 4 Applying the Hanning window function to the sampling data



Fig. 5 Vibration strength at each frequency according to the Fourier transformation.



(a) Longitudinal and lateral direction.



Fig. 6 Vibration strength levels of fatigue work efficiency decrease along the three axes.



Fig. 7 Vibration strength levels of fatigue work efficiency decrease according to the vibration acceleration in the longitudinal direction  $(a_x)$ .



Fig. 8 GIS map of the maximum vibration acceleration in the longitudinal direction  $(a_x)$  for

### 1–10 Hz.



Fig. 9 GIS map of the 1/3 octave band centre frequency distribution for maximum vibration acceleration in the longitudinal direction  $(a_x)$ .



Fig. 10 GIS map of work time limit for vibration acceleration in the longitudinal direction  $(a_x)$ .



Fig. 11 Vibration strength levels of fatigue work efficiency decrease according to the vibration acceleration in the lateral direction  $(a_y)$ .



Fig. 12 GIS map of the maximum vibration acceleration in the lateral direction  $(a_y)$  for 1–10





Fig. 13 GIS map of the 1/3 octave band center frequency distribution for maximum vibration acceleration in the lateral direction  $(a_y)$ .



Fig. 14 GIS map of work time limit for vibration acceleration in the lateral direction  $(a_y)$ .



Fig. 15 Vibration strength levels of fatigue work efficiency decrease according to vibration acceleration in the vertical direction  $(a_z)$ .



Fig. 16 GIS map of maximum vibration acceleration in the vertical direction  $(a_z)$  for 1–10 Hz.



Fig. 17 GIS map of the 1/3 octave band center frequency distribution for the maximum vibration acceleration in the vertical direction ( $a_z$ ).



Fig. 18 GIS map of work time limit for vibration acceleration in the vertical direction  $(a_z)$ .



(b) Comfort evaluation using the composite vibration acceleration at 5.0 Hz

Fig. 19 GIS map of composite vibration acceleration at the1/3 octave band centre frequency of 5.0 Hz and a comfort evaluation.



(b) Comfort evaluation using the composite vibration acceleration at 8.0 Hz.Fig. 20 GIS map of composite vibration acceleration at the 1/3 octave band center frequency of 8.0 Hz and a comfort evaluation.