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Performance of Measuring Vibration of MEMS Sensor

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The purpose of this study is to examine the usefulness of an MEMS sensor for measuring vibration of agricultural vehicle by obtaining serial data of vibration acceleration of agricultural vehicle using an MEMS sensor and translational accelerometer and thereby calculating RMS and PSD for comparison and analysis as a step before construction of measuring system which can identify operating conditions of agricultural packaging machinery at all times.

Although there are differences between vertical acceleration RMS and pitching angular acceleration measured by an MEMS sensor and translational accelerometer due to disturbance factors and computation errors, both measurements obtained by the two methods typically increase as vehicle body moves faster.

For PSD, likewise RMS, there were differences in measurements, but peak frequencies were almost matched between the two methods, so it was confirmed that an MEMS sensor could exactly detect vibration characteristics.

Therefore, it was considered that instead of large and costly translational accelerometer, an MEMS sensor which can measure both translational acceleration (back–and–forth, lateral, and vertical) and angular acceleration (rolling, pitching, and yawing) only with a single unit could be properly used in identifying vibration characteristics of agricultural packaging machinery.

Key words: MEMS sensor, power spectral density, six degrees of freedom components of acceleration, vibration measuring

INTRODUCTION

Recently, many studies on application of farming support and agricultural work management system using information and communication technology to management efficiency of agriculture have been progressed and agricultural machinery of high efficiency and high utilization have also been required. This has brought about consideration of the construction of such measuring system as being important that could identify operating information of agricultural vehicle including safety of vehicle body.

Rudimentary operating information of agricultural packaging machinery is exactly about the characteristics of motion of vehicle. In order to identify them, 6 degrees of freedom components of vibration acceleration are required. Previous studies on measuring the vibration of vehicle body of 6 degrees of freedom components of vehicle have been through measuring of translational acceleration of translational accelerometer and rotational acceleration of gyro. However, this method has problems in that measuring system is so large and costly that it could not be regularly used in measuring vibration acceleration and identifying operating conditions of vehicle body (Choe, Jung Seob and E. Inoue, 2001; Inoue E. *et al*., 1990).

Therefore, this study aims to examine the usefulness of MEMS (Micro Electro Mechanical System) sensor, a compact and affordable sensor which has recently received attention, for measuring vibration of agricultural vehicle by obtaining serial data of vibration acceleration using an MEMS sensor and translational accelerometer and thereby calculating and comparing RMS (Root Mean Square) and PSD (Power Spectral Density) as a step before construction of measuring system which can always identify operating conditions of agricultural packaging machinery.

MATERIALS AND METHODOLOGY

Until now, measurement of 6 degrees of freedom vibration components of vehicle have been performed by measuring translational acceleration and rotational acceleration using translational accelerometer and gyro.

However, since such measuring system is not only large in size but also costly in price, there are substantial difficulties in using the system as it is for measuring vibration and operating conditions of agricultural vehicle body at all times.

Hence, this study aims to demonstrate the usefulness of an MEMS sensor, a compact and affordable product of semiconductor processing technology for which research and development have actively progressed in recent years, by obtaining serial data of vibration acceleration of agricultural vehicle body and thereby calculating RMS

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and PSD values and comparing them with those obtained from the existing acceleration measuring system. Detailed specifications of the MEMS sensor and the existing device for measuring 6 degrees of freedom acceleration and experimental methods employed in this study are as follows:

MEMS Sensor (Choe, Jung Seob *et al.*, 2013)

Capacitive acceleration sensor

MEMS (Micro Electro Mechanical Systems) sensor integrates not only electrical circuits but also other components such as sensor or actuator on silicon substrate. As being compact in size and capable of performing advanced functions, it has been widely used in various fields including information and communication, cars, home appliances, industrial machinery, medicine and biotechnology, and environment and safety control.

One of the major MEMS sensors is acceleration sensor which consists of sensing element which senses acceleration and signal processing circuit which amplifies signals from the sensing element and adjusts and outputs them. MEMS sensors are classified into capacitive type, piezoresistive type and thermal detecting type, depending upon the mode of sensing element.

The acceleration sensor selected for this study is of capacitive type which determines acceleration a from x, displacement per hour of a spring of which spring constant is k and which is connected with a pendulum in weight of m. That is, because in $a=kx/m$ which is obtained by combining $F=ma$, Newton's equation of motion, and $F=kx$, Hook's law, k and m are constants, acceleration a can be calculated by determining x, displacement per hour of a spring. The sensing element consists of the operating part and fixing part which have electrodes, respectively. When the operating electrode approaches the fixing electrode, it acts on clock signal applied to the fixing electrode and brings about a potential change in the operating electrode. This potential change is proportionate to the displacement x and acceleration can be converted.

Fig. 1 provides a schematic diagram of the sensing element.

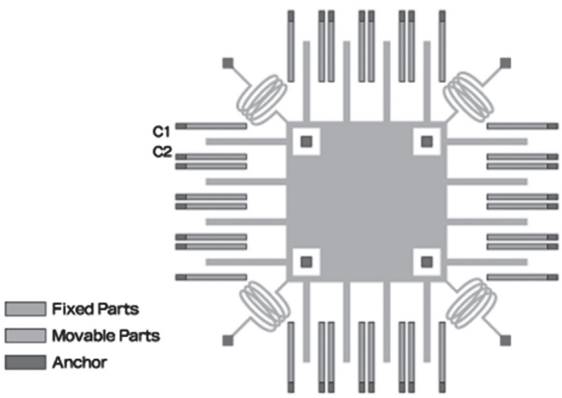

Fig. 1. Schematic diagram of the sensing element of acceleration sensor.
(Source: http://monoist.atmarkit.co.jp/ feledev/articles/basic/mems/mems01.html)

Wireless 9–axis motion sensor

The MEMS sensor used in this study was manufactured by Logical Product, with capacity of 5G/300dps and is wireless 9–axis motion sensor that can receive and transmit data. It can wirelessly measure translational acceleration, rotational angular velocity, and geomagnetic orientation in 3 directions for each measure.

This sensor is very light and compact with total weight of 35 g including the battery, can be easily installed, and only requires minimal installation space. It can also perform remote wireless measurement and data logging. Specified low power communication was selected for the private transceiver device used to transmit and receive command and to receive measurement data and file with the wireless sensor module, which allows wireless communication over about 50 m.

Main specifications of the tested MEMS sensor are shown in Table 1.

Table 1. Main specifications of 9–axis wireless motion sensor

Modulation type	DS–SS
Radio frequency	2405 MHz~2480 MHz, 5 MHz interval
Battery	AAA battery×1
Power consumption	Maximum 230 mV
External dimensions	40 mm×20 mm×55 mm
Weight	Approximately 35 g

Acceleration sensor

Voltage supplied for acceleration sensor in the MEMS sensor is 3.3 V and output of the sensor at 0 G is 1.65 V. Sensor sensitivity is 190.0 mV/g.

Output voltage of the acceleration sensor is AD converted into 12 bits. AD converted value is a straight binary, and full scale is 3.3 V. Therefore, when the output voltage of the sensor is V, AD converted value X_{acc} is as in Eq. 1.

$$X_{acc} = \frac{4095 \times V}{3.3} \quad (1)$$

When acceleration is G, conversion equation is as in Eq. 2. Note that for actual output at 0 G, some offset is included due to factors such as temperature.

$$G = \frac{V - 1.65}{0.19} \quad (2)$$

Angular velocity sensor

Output from angular velocity sensor was filtered by a low pass filter with cutoff frequency of approximately 190 Hz, amplified by 5.6 times using an op–amp, and converted by an AD converter.

The op–amp operates with reference to the reference voltage of gyro sensor (V_{ref} = 1.35 V), and difference between this reference voltage and sensor output is multiplied by 5.6 and entered into the AD converter. Sensor output at 0 deg/sec (deg/sec is hereafter referred to as dps) is 1.35 V. Sensor sensitivity is 0.67 mV/dps.

When output voltage of the sensor is V, AD–converted value X_{gyro} is as in Eq. 3.

$$X_{gyro} = \frac{4095\times V}{3.3} \tag{3}$$

When angular velocity is W, conversion is given by Eq. 4.

$$W= \frac{V-1.35}{5.6\times 0.00067} \tag{4}$$

Based on the abovementioned information, the MEMS sensor was determined to be suitable for this study in that it can measure translational acceleration (back–and–forth, lateral and vertical) and angular acceleration (rolling, pitching, and yawing) only with a single sensor and transmit and receive wireless data

Measuring Device of 6 Degrees of Freedom Vibration Acceleration (Acceleration Box) and Measurement Method (Choe, Jung Seob and E. Inoue, 2001; Inoue E. *et al.*, 1990)

An acceleration box made of an acryl box which was used in measuring vibration acceleration in the existing studies and 12 translational accelerometers is shown Fig. 2. The measurement method of 6 degrees of freedom vibration acceleration component using the acceleration box is described below.

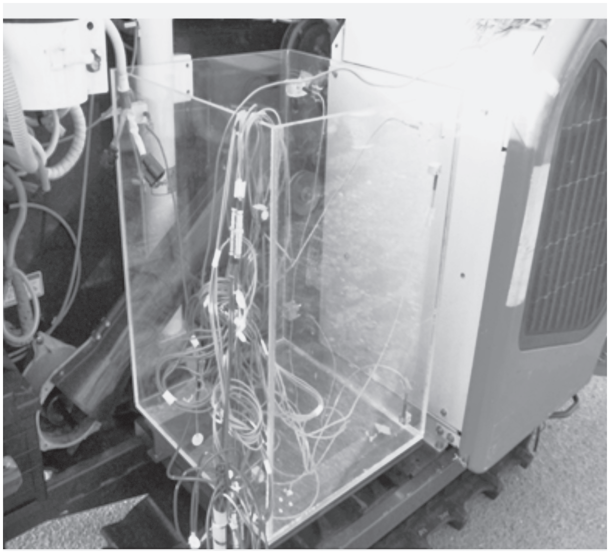

Fig. 2. Acceleration box.

Because translational accelerometer not in the central location of a rigid body senses translational component and rotational component, if the number of translational accelerometers used is i, a measurement by the k^{th} translational accelerometer is given by Equation 5, provided that the coordinate system has three axes with the origin of the central location of rigid body as the inertial principal axes.

$$\alpha_k=(\vec{\alpha}_G\times\vec{e}_k) + (\vec{\theta}\times\vec{\gamma}_k\times\vec{e}_k) + (\vec{\omega}\times(\vec{\omega}\times\vec{\gamma}_k)\times\vec{e}_k) \tag{5}$$

where

α_k : Acceleration of the k^{th} translational accelerometer

$\vec{\alpha}_G$: Translational vector at the central location of vehicle body

$\vec{\theta}$: Rotational angular acceleration vector

$\vec{\omega}$: Rotational angular velocity vector

$\vec{\gamma}_k$: Position vector of the k^{th} translational accelerometer

$\vec{e}_k$: Direction vector of the k^{th} translational accelerometer

The coordinates of the translational accelerometer shall be determined by arranging it as shown in Fig. 3.

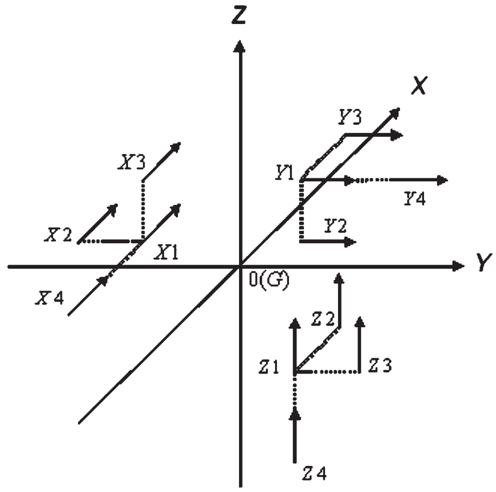

Fig. 3. Arrangement of 12 translational accelerometers. (provided that the origin is the central position of vehicle body)

$$\begin{aligned}
&X1 : (h_{1x}, h_{1y}, h_{1z}),\quad X2 : (h_{2x}, h_{2y}, h_{2z}),\\
&X3 : (h_{3x}, h_{3y}, h_{3z}),\quad X4 : (h_{4x}, h_{4y}, h_{4z}),\\
&Y1 : (m_{1x}, m_{1y}, m_{1z}),\quad Y2 : (m_{2x}, m_{2y}, m_{2z}),\\
&Y3 : (m_{3x}, m_{3y}, m_{3z}),\quad Y4 : (m_{4x}, m_{4y}, m_{4z}),\\
&Z1 : (n_{1x}, n_{1y}, n_{1z}),\quad Z2 : (n_{2x}, n_{2y}, n_{2z}),\\
&Z3 : (n_{3x}, n_{3y}, n_{3z}),\quad Z4 : (n_{4x}, n_{4y}, n_{4z}),
\end{aligned} \tag{6}$$

where

$$\begin{aligned}
&h_{1x}= h_{2x} = h_{3x},\quad h_{1y}= h_{3y} = h_{4y},\quad h_{1z}= h_{2z} = h_{4z}\\
&m_{1x}= m_{2x} = m_{4x},\quad m_{1y}= m_{2y} = m_{3y},\quad m_{1z}= m_{3z} = m_{4z}\\
&n_{1x}= n_{3x} = n_{4x},\quad n_{1y}= n_{2y} = n_{4y},\quad n_{1z}= n_{2z} = n_{3z}
\end{aligned}$$

When the coordinates of each of the translational accelerometers are substituted in Equation 5 and developed, a simultaneous equation 7 with twelve unknowns is produced by which the values of translational accelerometers in X, Y and Z directions can be obtained.

X direction

$$\begin{aligned}
\alpha_{1x}&=\alpha_{gx}+ \dot{\varpi}_y h_{1z} - \dot{\varpi}_z h_{1y}+(\varpi_y h_{1y}+\varpi_z h_{1z})\dot{\varpi}_x-(\varpi_y{}^2+\varpi_z{}^2)h_{1x}\\
\alpha_{2x}&=\alpha_{gx}+ \dot{\varpi}_y h_{1z} - \dot{\varpi}_z h_{2y}+(\varpi_y h_{2y}+\varpi_z h_{1z})\dot{\varpi}_x-(\varpi_y{}^2+\varpi_z{}^2)h_{1x}\\
\alpha_{3x}&=\alpha_{gx}+ \dot{\varpi}_y h_{3z} - \dot{\varpi}_z h_{1y}+(\varpi_y h_{1y}+\varpi_z h_{3z})\dot{\varpi}_x-(\varpi_y{}^2+\varpi_z{}^2)h_{1x}\\
\alpha_{4x}&=\alpha_{gx}+ \dot{\varpi}_y h_{1z} - \dot{\varpi}_z h_{1y}+(\varpi_y h_{1y}+\varpi_z h_{1z})\dot{\varpi}_x-(\varpi_y{}^2+\varpi_z{}^2)h_{4x}
\end{aligned}$$

Y direction

$$\begin{aligned}
\alpha_{1y}&=\alpha_{gy}+ \dot{\varpi}_z m_{1x} - \dot{\varpi}_x m_{1z}+(\varpi_x m_{1x}+\varpi_z m_{1z})\dot{\varpi}_y-(\varpi_x{}^2+\varpi_z{}^2)m_{1y}\\
\alpha_{2y}&=\alpha_{gy}+ \dot{\varpi}_z m_{1x} - \dot{\varpi}_x m_{2z}+(\varpi_x m_{1x}+\varpi_z m_{2z})\dot{\varpi}_y-(\varpi_x{}^2+\varpi_z{}^2)m_{1y}\\
\alpha_{3y}&=\alpha_{gy}+ \dot{\varpi}_z m_{3x} - \dot{\varpi}_x m_{1z}+(\varpi_x m_{1x}+\varpi_z m_{1z})\dot{\varpi}_y-(\varpi_x{}^2+\varpi_z{}^2)m_{1y}
\end{aligned}$$

$$\alpha_{4y}=\alpha_{gy}+\dot{\varpi}_z m_{1x}-\dot{\varpi}_x m_{1z}+(\varpi_x m_{1x}+\varpi_z m_{1z})\dot{\varpi}_y-(\varpi_x{}^2+\varpi_z{}^2)m_{4y} \quad (7)$$

Z direction

$$\alpha_{1z}=\alpha_{gz}+\dot{\varpi}_x n_{1y}-\dot{\varpi}_y n_{1x}+(\varpi_x n_{1x}+\varpi_y n_{1y})\dot{\varpi}_z-(\varpi_x{}^2+\varpi_y{}^2)n_{1z}$$
$$\alpha_{2z}=\alpha_{gz}+\dot{\varpi}_x n_{1y}-\dot{\varpi}_y n_{2x}+(\varpi_x n_{2x}+\varpi_y n_{1y})\dot{\varpi}_z-(\varpi_x{}^2+\varpi_y{}^2)n_{1z}$$
$$\alpha_{3z}=\alpha_{gz}+\dot{\varpi}_x n_{3y}-\dot{\varpi}_y n_{1x}+(\varpi_x n_{1x}+\varpi_y n_{3y})\dot{\varpi}_z-(\varpi_x{}^2+\varpi_y{}^2)n_{1z}$$
$$\alpha_{4z}=\alpha_{gz}+\dot{\varpi}_x n_{1y}-\dot{\varpi}_y n_{1x}+(\varpi_x n_{1x}+\varpi_y n_{1y})\dot{\varpi}_z-(\varpi_x{}^2+\varpi_y{}^2)n_{4z}$$

where

$\alpha_{iX}, \alpha_{iY}, \alpha_{iZ}$: Acceleration measured by translational accelerometers X_i, Y_i, Z_i (i=1~4)
$\alpha_{gx}, \alpha_{gy}, \alpha_{gz}$: Translational acceleration in the X, Y, and Z directions (m/s)
ω_X, ω_Y, ω_Z : Angular velocity of the centers of the X, Y, and Z axes (rad/s)
$\dot{\omega}_X$, $\dot{\omega}_Y$, $\dot{\omega}_Z$: Angular acceleration of the centers of the X, Y, and Z axes (rad/s^2)

From Equation 7, $\alpha_{gx}, \alpha_{gy}, \alpha_{gz}$ translational acceleration in the X, Y, and Z directions of the central position and $\dot{\omega}_X$, $\dot{\omega}_Y$, $\dot{\omega}_Z$, angular acceleration around the inertial principal axes can be determined.

The coordinates of each accelerometer from the origin of the accelerometer box are as follows:

$$\begin{aligned}&X1: (ho_{1x}, ho_{1y}, ho_{1z}),\ X2: (ho_{2x}, ho_{2y}, ho_{2z}),\\ &X3: (ho_{3x}, ho_{3y}, ho_{3z}), X4: (ho_{4x}, ho_{4y}, ho_{4z}),\\ &Y1: (mo_{1x}, mo_{1y}, mo_{1z}),\ Y2: (mo_{2x}, mo_{2y}, mo_{2z}),\\ &Y3: (mo_{3x}, mo_{3y}, mo_{3z}), Y4: (mo_{4x}, mo_{4y}, mo_{4z}),\\ &Z1: (no_{1x}, no_{1y}, no_{1z}),\ Z2: (no_{2x}, no_{2y}, no_{2z}),\\ &Z3: (no_{3x}, no_{3y}, no_{3z}), Z4: (no_{4x}, no_{4y}, no_{4z})\end{aligned} \quad (8)$$

where

$$\begin{aligned}&ho_{1x}=ho_{2x}=ho_{3x}, ho_{1y}=ho_{3y}=ho_{4y}, ho_{1z}=ho_{2z}=ho_{4z}\\ &mo_{1x}=mo_{2x}=mo_{4x}, mo_{1y}=mo_{2y}=mo_{3y}, mo_{1z}=mo_{3z}=mo_{4z}\\ &no_{1x}=no_{3x}=no_{4x}, no_{1y}=no_{2y}=no_{4y}, no_{1z}=no_{2z}=no_{3z}\\ &h1=ho_{2x}-ho_{1x}, h2=ho_{3z}-ho_{1z}, h3=mo_{2z}-mo_{1z}\\ &h4=mo_{3x}-mo_{1x}, h5=no_{2x}-no_{1x}, h6=no_{3y}-no_{1y}\\ &h7=ho_{4x}-ho_{1x}, h8=mo_{4y}-mo_{1y}, h9=no_{4z}-no_{1z}\end{aligned}$$

The coordinates of the position of each accelerometer from the origin of the accelerometer box are expressed in Equations 9 and 10 and their broad positions are as shown in Fig. 4.

$$\begin{aligned}&X1(18, 40, 100),\ X2(18, 400, 100),\\ &X3(18, 40, 500), X4(385, 40, 100)\\ &Y1(360, 18, 60),\ Y2(360, 18, 500),\\ &Y3(40, 18, 60), Y4(360, 440, 60)\\ &Z1(385, 400, 550),\ Z2(25, 400, 550),\\ &Z3(385, 50, 550),\ \mathrm{Z4}(385, 400, 100) \qquad (9)\\ &ho_{1x}=ho_{2x}=ho_{3x}=18,\ ho_{1y}=ho_{3y}=ho_{4y}=40,\\ &ho_{1z}=ho_{2z}=ho_{4z}=100\\ &mo_{1x}=mo_{2x}=mo_{4x}=360,\ mo_{1y}=mo_{2y}=mo_{3y}=18,\\ &mo_{1z}=mo_{3z}=mo_{4z}=60\\ &no_{1x}=no_{3x}=no_{4x}=385,\ no_{1y}=no_{2y}=no_{4y}=400,\\ &no_{1z}=no_{2z}=no_{3z}=550\end{aligned}$$

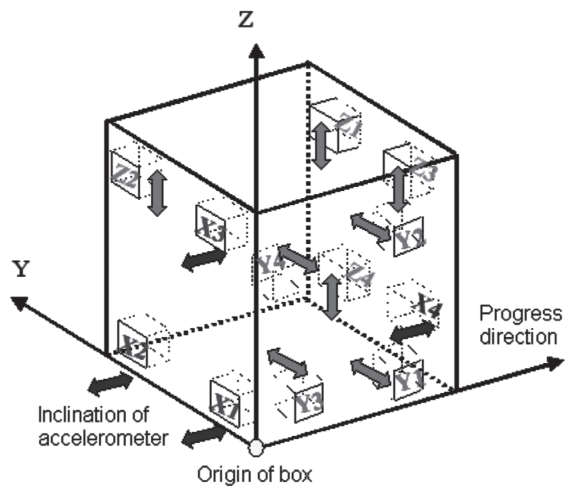

Fig. 4. Layout drawing of each accelerometer.

And, if the coordinates from the position of the vehicle body to be measured (central location, seat location, etc.) to the origin of the accelerometer box installed in the body are set as (X0, Y0, Z0), the coordinates of each accelerometer from the location of the vehicle body to be measured (Xoi, Yoi, Zoi, i = 1~4) become as follows;

$$\begin{aligned}&Xoi(X0+ho_{ix}=h_{ix},\ Y0+ho_{iy}=h_{iy},\ Z0+ho_{iz}=h_{iz})\\ &Yoi(X0+mo_{ix}=m_{ix},\ Y0+mo_{iy}=m_{iy},\ Z0+mo_{iz}=m_{iz})\\ &Zoi(X0+no_{ix}=n_{ix},\ Y0+no_{iy}=n_{iy},\ Z0+no_{iz}=n_{iz})\end{aligned} \quad (10)$$

Using each coordinate as discussed above, 6 degrees of freedom vibration acceleration can be calculated as the following Equations 11 through 16.

The coordinates from X1 to Z4 are the acceleration of 12 translational accelerometers for the acceleration box and shown in Fig. 3 in detail.

Translational acceleration

Front–rear translational acceleration:

$$\alpha_{gx}=X1+h_{1z}\cdot\frac{X1-X3}{h2}+h_{1y}\cdot\frac{X1-X2}{h1}+h_{1x}\cdot\frac{X1-X4}{h7} \quad (11)$$

Lateral translational acceleration:

$$\alpha_{gy}=Y1+m_{1x}\cdot\frac{Y1-Y3}{h4}+m_{1z}\cdot\frac{Y1-Y2}{h3}+m_{1y}\cdot\frac{Y1-Y4}{h8} \quad (12)$$

Vertical translational acceleration:

$$\alpha_{gz}=Z1+n_{1y}\cdot\frac{Z1-Z3}{h6}+n_{1x}\cdot\frac{Z1-Z2}{h5}+n_{1z}\cdot\frac{Z1-Z4}{h9} \quad (13)$$

Angular acceleration

Rolling angular acceleration (X axis):

$$\theta_z=\frac{1}{2}\left(\frac{Y1-Y2}{h3}-\frac{Z1-Z3}{h6}\right) \quad (14)$$

Pitching angular acceleration (Y axis):

$$\theta_y=\frac{1}{2}\left(\frac{X1-X3}{h2}+\frac{Z1-Z2}{h5}\right) \quad (15)$$

Yawing angular acceleration (Z axis):

$$\theta_y = \frac{1}{2}\left(\frac{X1\text{–}X2}{h1} + \frac{Y1\text{–}Y3}{h4}\right) \tag{16}$$

As we have seen in the above, since acceleration measuring system using an acceleration box equipped with 12 translational accelerometers becomes large and costly, it is not appropriate to be used in measuring vibration acceleration of vehicle body at all times.

Experimental method

Experimental devices

The installation locations of head–feeding combine and measuring device are shown in Fig. 5. An acryl acceleration box equipped with 12 translational accelerometers is installed in the place from which a grain tank of the combine has been removed and an MEMS sensor is installed beneath the origin of the acceleration box.

The specifications of head–feeding combine are listed in Table 2

Measurement conditions

Vertical and pitching acceleration were selected which are considered as important in assessing vibration of vehicle body as an items to compare the performance of vibration measurement for an MEMS sensor and translational accelerometer.

Vibration measurement was performed in three times each of the three velocities including low speed (0.7 m/s), medium speed (1.1 m/s) and high speed (1.4 m/s) without manipulation of direction on dry and flat concrete rigid surface to exclude disturbance element.

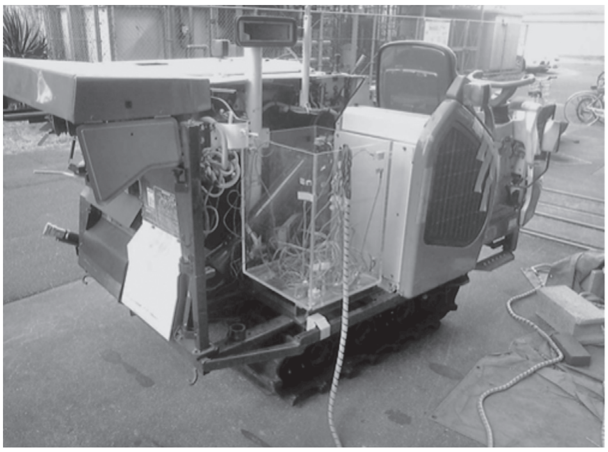

Fig. 5. Installation locations of head–feeding combine and measuring device.

RESULTS AND CONSIDERATION

This study examined the usefulness of an MEMS sensor by calculating RMS and PSD from vertical and pitching acceleration serial data measured by an MEMS sensor and translational accelerometer and comparing them.

Fig. 6 shows vertical acceleration actual measurement value RMS and pitching angular acceleration measurement value RMS according to running speed.

Vertical acceleration RMS was not deviated from general trend, for although the measurement value of the MEMS sensor was as small as about half of the measurement value of translational accelerometer, vehicle moves faster. For pitching angular acceleration RMS, the measurement value of the MEMS sensor was rather higher than that of translational accelerometer from medium speed. Such differences in measurement values of the two measuring devices might be caused by mismatch of measurement location or errors in calculation process but cannot be concluded. Therefore, more intensive measuring device and considerations would be necessary.

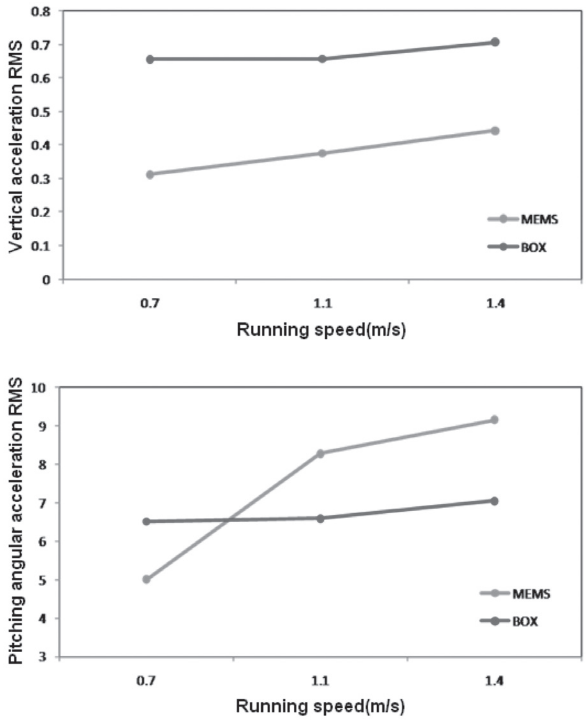

Fig. 6. Vertical acceleration and pitching angular acceleration RMS by measuring device according to running speed.

Table 2. Specifications of head–feeding combine

Body		Engine	Driving part	
Full length;	3120 mm	Type; Water–cooled 4–cycle	Travel speed;	0~1.26 m/s
Full width;	1660 mm	3–cyliner vertical D	Crawler,	
Full height;	1760 mm	Total displacement; 1115 mm^3	Width;	400 mm
Weight;	1255 kgf	Output power/rotation speed;	Ground contact length;	1040 mm
		18.5/2600 ps/rpm	Average ground pressure;	14.8 kPa

Figures 7 through 9 compare actual measurement values of PSD between the two measuring devices by speed.

Figures 10 through 12 compare actual measurement values of pitching angular acceleration PSD of the two measuring devices by speed.

For PSD values, likewise RMS values, the measurement value of the MEMS sensor was as small as one third of that of translational acceleration but peak frequencies were almost matched, indicating that vibration characteristics were sensed very accurately.

PSD peak exactly coincided with tire lug pitch pass

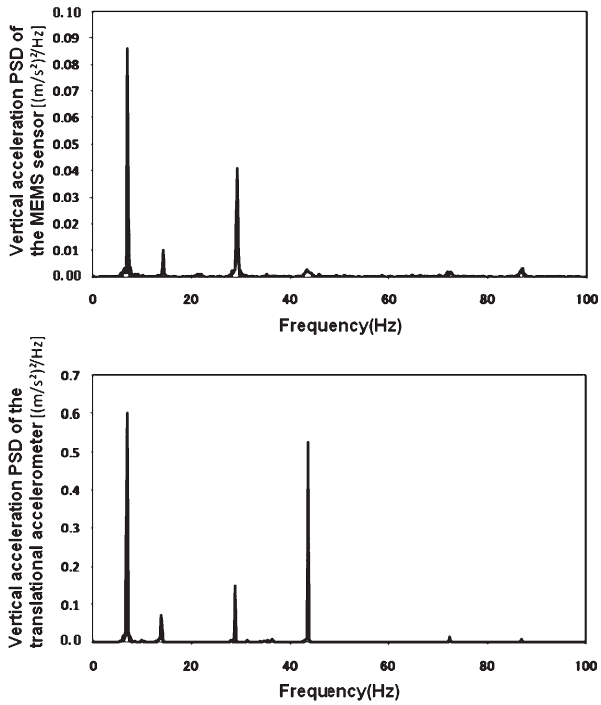

Fig. 7. Vertical acceleration PSD of the MEMS sensor and translational accelerometer at low speed driving (0.7 m/s).

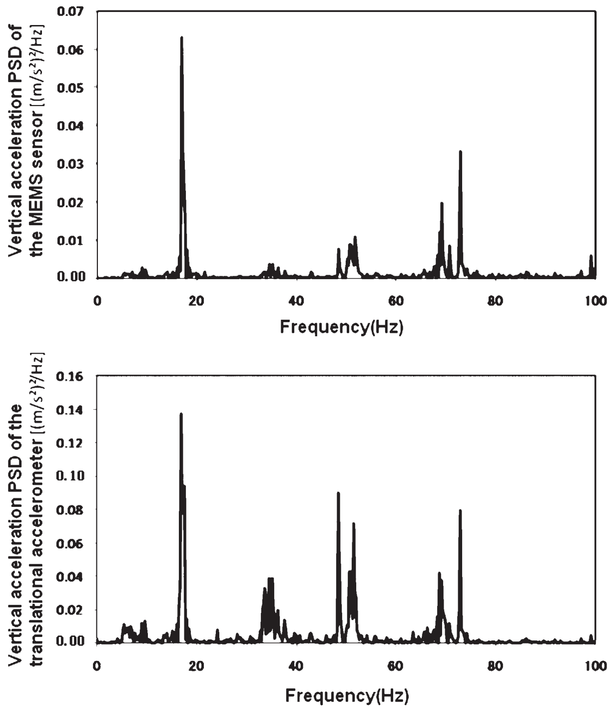

Fig. 9. Vertical acceleration PSD of the MEMS sensor and translational accelerometer at high speed driving (1.4 m/s).

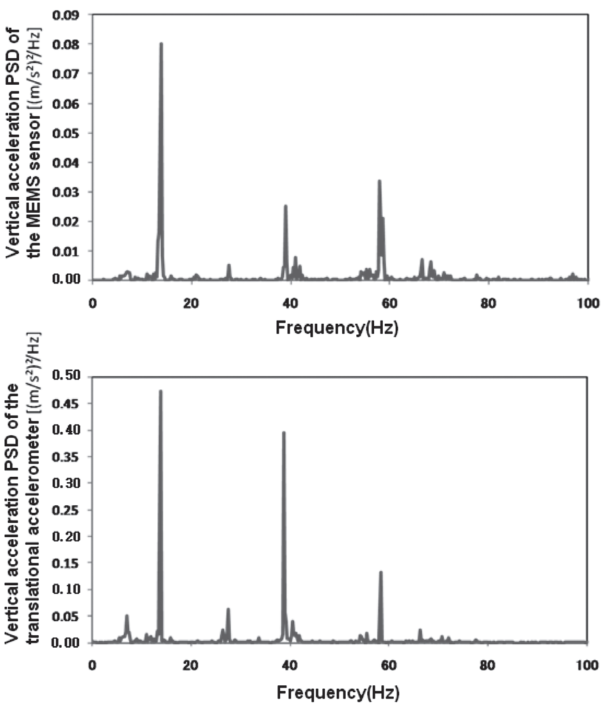

Fig. 8. Vertical acceleration PSD of the MEMS sensor and translational accelerometer at medium speed driving (1.1 m/s).

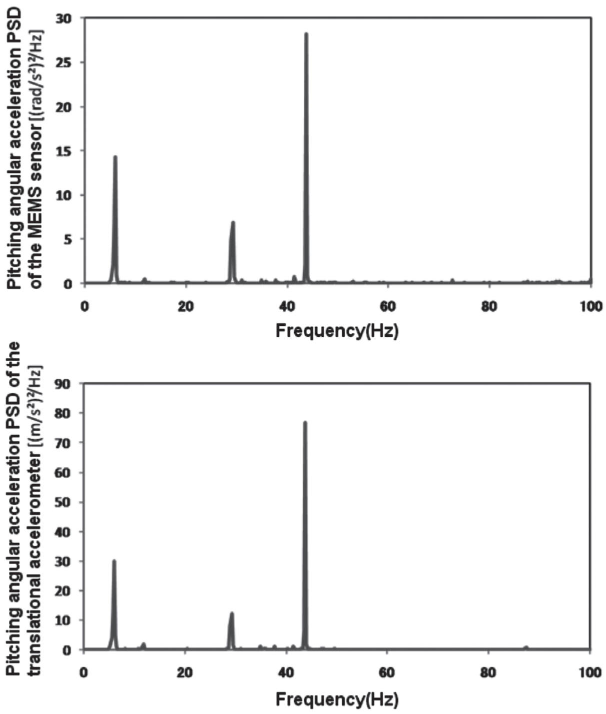

Fig. 10. Pitching angular acceleration PSD of the MEMS sensor and translational accelerometer at low speed driving (0.7 m/s).

frequency and engine vibration frequency. Figures 7 to 12 show that peaks appear at 8 Hz and 30 Hz at low speed, 13 Hz and 40 Hz at medium speed, and 17 Hz and 50 Hz at high speed and are exactly corresponded with lug pitch pass frequency and engine vibration frequency.

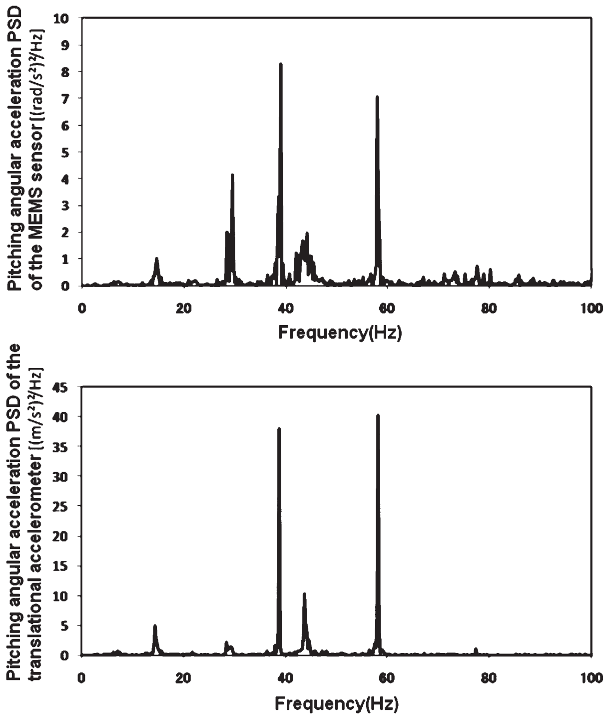

Fig. 11. Pitching angular acceleration PSD of the MEMS sensor and translational accelerometer at medium speed driving (1.1 m/s).

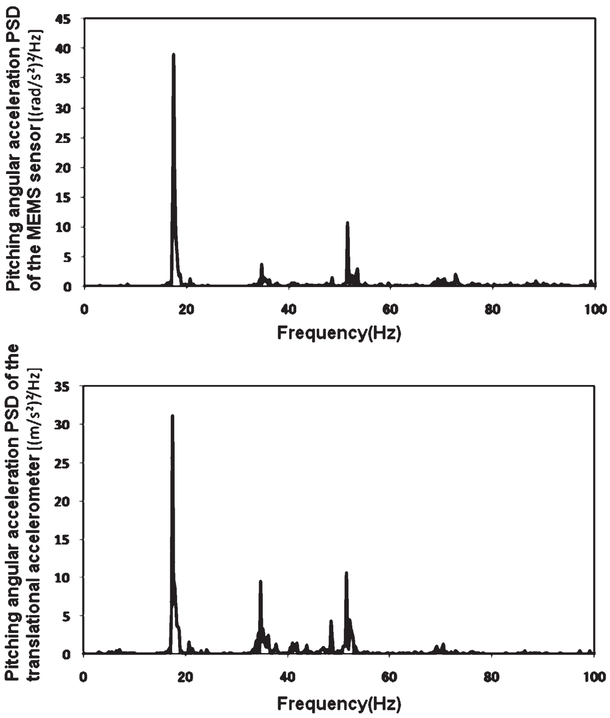

Fig. 12. Pitching angular acceleration PSD of the MEMS sensor and translational accelerometer at high speed driving (1.4 m/s).

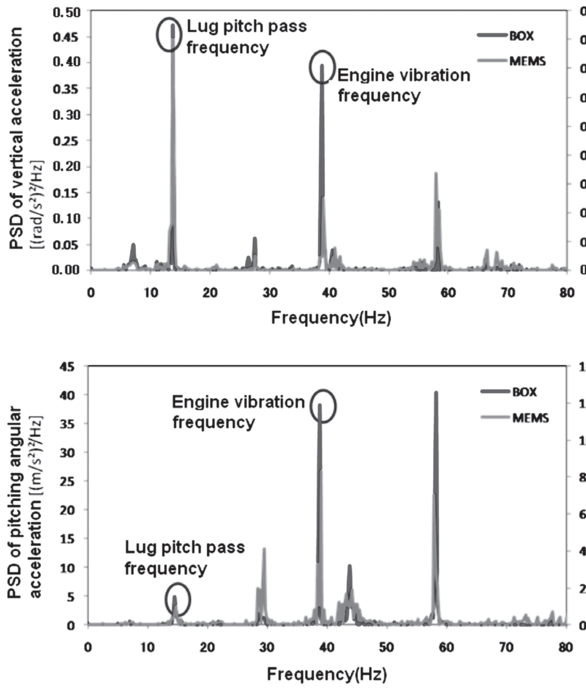

Fig. 13. Combination of PSDs of vertical acceleration and pitching angular acceleration of the MEMS sensor and translational accelerometer in medium-speed traveling.

Fig. 13 provides the combined PSD of actual values of vertical acceleration and pitching angular acceleration measured by the MEMS sensor and translational accelerometer in medium–speed traveling.

Although there are differences in sub–harmonic or harmonic and the sizes are different, it was observed that lug pitch pass frequency of 13 Hz and engine frequency of 40 Hz were almost matched.

As the original purpose of this study is to examine whether the MEMS sensor is useful in assessing vibration characteristics, rather than to exactly measure absolute values of vibration acceleration of vehicle body, it is determined that the MEMS sensor would be very useful in assessing vibration characteristics in that translational acceleration (back–and–forth, lateral and vertical) and angular speed (rolling, pitching, and yawing) can be measured with a single sensor instead of the existing translational accelerometers which are large and costly and carry out wireless transmission and receiving of data.

SUMMARY AND CONCLUSION

The purpose of this study is to examine the usefulness of the MEMS sensor for measuring vibration of agricultural vehicle by obtaining serial data of vibration acceleration of agricultural vehicle using the MEMS sensor and translational accelerometer and thereby calculating RMS and PSD for comparison and analysis as a step before construction of measuring system which can identify operating conditions of agricultural packaging machinery at all times.

The results of this study are summarized as follows:

For vertical acceleration RMS, because the measurement value of the MEMS sensor was as small as about half of that of translational accelerometer but increased as the vehicle moves faster, which does not deviate from general tendency.

For pitching angular acceleration RMS, unlike vertical acceleration, the measurement value of the MEMS sensor was higher than that of translational accelerometer from medium speed, but increased as the vehicle moves faster, which does not deviate from general tendency.

Such differences in measurement values of the two measuring devices might be caused by mismatch of measurement location or errors in calculation process but cannot be concluded. Therefore, more intensive measuring device and considerations would be necessary.

For PSD values, likewise RMS values, the measurement value of the MEMS sensor was as small as one third of that of translational acceleration but peak frequencies were almost matched, indicating that vibration characteristics were sensed very accurately PSD peak exactly coincided with tire lug pitch pass frequency and engine vibration frequency.

As the original purpose of this study is to examine whether the MEMS sensor is useful in assessing vibration characteristics, rather than to exactly measure absolute values of vibration acceleration of vehicle body, it is determined that the MEMS sensor would be very useful in assessing vibration characteristics in that translational acceleration (back–and–forth, lateral and vertical) and angular speed (rolling, pitching, and yawing) can be measured with a single sensor instead of the existing translational accelerometers which are large and costly and carry out wireless transmission and receiving of data.

Further studies should carry out more precise and high–degree vibration assessment by using multiple MEMS sensors or using them in combination with other sensors such as GPS

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