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ACCURATE WEIGHING SYSTEM USED UNDER THE VIBRATION-LIKE MOVING CONDITIONS

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Abstract: This paper describes a weighing system used under the conditions in which various movements exist. These various movements are heaving motion, rolling motion, pitching motion, etc. In this paper, these various movements are collectively called as "vibration-like movement". The term of "vibration-like moving conditions" means the conditions in which vibration-like movements exist. In the previous paper [1], the new weighing method was proposed. This method basically requires 4 loadcells which observe the vibration-like moving conditions. These loadcells are called as "dummy loadcell". Installing 3 dummy loadcells properly and estimating two angular velocities, this weighing method is feasible to measure the mass value of a weighed object by means of 3 dummy loadcells. In this paper, the estimating method of these velocities is explained in detail. We manufactured the weighing system which consists of a weighing loadcell and 3 dummy loadcells on trial. Several numerical simulations and experiments by using this weighing system were conducted. It is confirmed that the estimation of the angular velocities is feasible and the accurate weighing under the vibration-like moving conditions is also feasible.

Keywords: accurate mass measurement, system identification, vibration-like moving environment.

1. INTRODUCTION

From the viewpoint of industrial applications, it is important to measure the mass value of an object accurately under the vibration-like moving conditions. In general, the vibration-like movement makes the measurement accuracy worse. Therefore, it is required to develop the weighing method which mitigates the environmental influence of the vibration-like movement. Several weighing methods were proposed under the vibration-like moving conditions, but these methods do not consider the influence of the gravity center of the weighed object [2]-[4].

On the other hand, we proposed the new weighing method under the vibration-like moving conditions in the previous paper [1]. This weighing method considers the position of a gravity center of a weighed object and it basically requires 4 dummy loadcells. However, it is described that the appropriate location of 3 dummy loadcells and the signal processing of 4 loadcells output are feasible

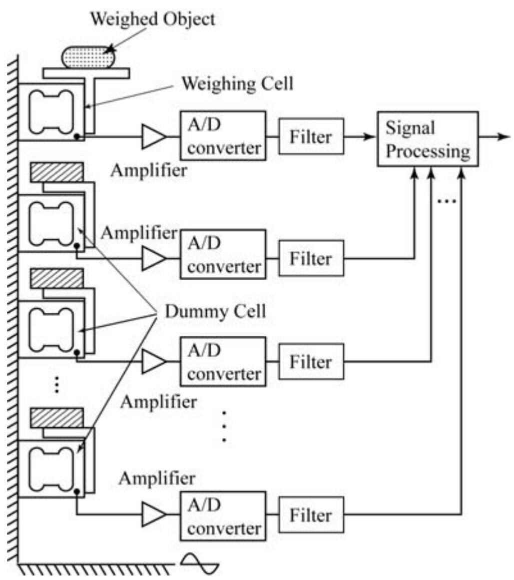

Fig. 1 Weighing System

to estimate the vibration-like movement in the paper.

In this paper, a trial-manufactured weighing system and the estimating procedure of the angular velocities are described in detail. The weighing system consists of a weighing loadcell and 3 dummy loadcells.

It is confirmed that this weighing system to which the proposed weighing method is applied is feasible.

A result of numerical simulations and simple experiments shows that the estimation method of the angular velocities is feasible and the weighing system is effective.

2. WEIGHING SYSTEM USED UNDER THE VIBRATION–LIKE MOVING CONDITIONS

2.1. Weighing method with 4 dummy loadcells

In this section, the weighing method with 4 dummy loadcells is described briefly. Figure 1 shows the schematic of the weighing system. This weighing system consists of a weighing loadcell and 3 or 4 dummy loadcells. In Figs. 1, 5 and 6, a weighing loadcell is described as "Weighing Cell" and dummy loadcell is described as "Dummy Cell". Figure

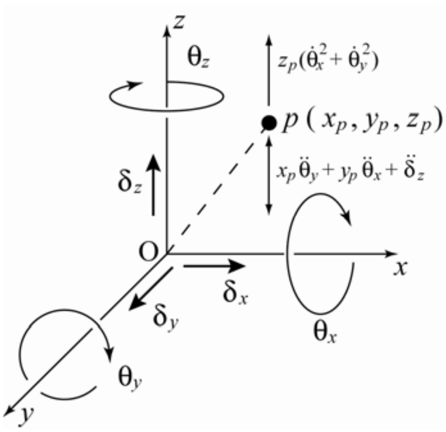

Fig. 2 Coordinate System under Vibration-Like Moving Conditions

2 shows the coordinate system in which these loadcells are installed. A loadcell is vertically installed on a plane which is parallel to the *xy* plane. δ_i represent the translational motion in the direction of *i*-axis($i = x, y, z$). $\theta_i\ (t)$ represent the rotational motion around *i*-axis($i = x, y, z$). The loadcells used in this paper detect the force in the direction of *z*-axis. The gravity center of a loadcell is abbreviated to "GCL". Similarly, "GCDL(GCWL)" is an abbreviation of the gravity center of dummy(weighing) loadcell. Supposing that the position of GCL is located at the point $p(x_p, y_p, z_p)$, the following accelerations influence the output of the loadcell.

- The tangential accelerations $y_p\ddot\theta_x(t), x_p\ddot\theta_y(t)$
- The centrifugal accelerations $z_p\dot\theta_x^2(t), z_p\dot\theta_y^2(t)$
- The translational acceleration $\ddot\delta_z(t)$

Since the strain of a loadcell is very small, the influence of the strain on the change in position of GCL is ignored. The output signal of the loadcell $u_p(t)$ is written as

$$u_p(t) = Em\boldsymbol{P}^T\boldsymbol{B}(t)\,. \tag{1}$$

where,

$$\boldsymbol{P}^T(t) = \begin{bmatrix} x_p & y_p & z_p & 1 \end{bmatrix}, \tag{2}$$

$$\boldsymbol{B}^T(t) = \begin{bmatrix} \ddot\theta_y(t) & \ddot\theta_x(t) & \dot\theta_x{}^2(t)+\dot\theta_y{}^2(t) & g_{xy}(t)+\ddot\delta_z(t) \end{bmatrix} \tag{3}$$

E and *m* is the output sen-sitivity and the mass value of the loadcell, respectively, and ^{T} expresses transposition. $g_{xy}(t)$ is the vertical component to *xy* plane of the acceleration due to gravity *g*. $\hat{\boldsymbol{B}}(t)$ is the estimated value of the matrix $\boldsymbol{B}$ and is derived from Eq. (4) .

$$\hat{\boldsymbol{B}}(t) = (\boldsymbol{D}^{-1}\boldsymbol{U}_d(t)/E_2m_2) \tag{4}$$

where, $^{-1}$ represents an inverse matrix,

$$\boldsymbol{D} = \begin{bmatrix} x_{d1} & y_{d1} & z_{d1} & 1 \\ x_{d2} & y_{d2} & z_{d2} & 1 \\ x_{d3} & y_{d3} & z_{d3} & 1 \\ x_{d4} & y_{d4} & z_{d4} & 1 \end{bmatrix}, \tag{5}$$

$$\boldsymbol{U}_d = \begin{bmatrix} u_{d1}(t) & u_{d2}(t) & u_{d3}(t) & u_{d4}(t) \end{bmatrix}. \tag{6}$$

$d_i\ (x_{di}, y_{di}, z_{di})$ ($i = 1, 2, 3, 4$) represent the positions of GCDL and u_{di} ($i = 1, 2, 3, 4$) represent the output of the dummy loadcells. Suppose that the output sensitivities and mass value of the dummy loadcell are the same. As a result, $\hat{\boldsymbol{B}}(t)$ is derived from the position of GCDL and the output signal of the dummy loadcells. The output signal of the weighing loadcell $u_k(t)$ is represented Eq. (7) as follows;

$$u_k(t) = \hat{\boldsymbol{B}}^T(t)\ \boldsymbol{C}^T\,, \tag{7}$$

$$\boldsymbol{C} = \begin{bmatrix} a & b & c & d \end{bmatrix}^T. \tag{8}$$

$$a = E_1m_1x_k\,, b = E_1m_1y_k$$
$$c = E_1m_1z_k\,, d = E_1m_1$$

Here E_1 and m_1 is the output sensitivity and the mass value of the weighing loadcell, respectively. The position of GCWL is (x_k, y_k, z_k). Regarding $u_k(t)$ and $\boldsymbol{B}(t)$ as an output signal and input signals of a linear system, the vector $\boldsymbol{C}$ is estimated by means of system identification algorithm [6].

As shown in Eq. (8), the parameter *d* of $\boldsymbol{C}$ does not depend on the position of GCWL. The estimated mass value of the weighed object $\hat{m}_1$ is obtained from this estimated parameter *d* as in the following equation;

$$\hat{m}_1 = d/E_1\,. \tag{9}$$

2.2. Weighing method with 3 dummy loadcells

Now giving our attention to Eq. (1), the output signal of a loadcell $u_p(t)$ is a linear combination of the four components of $\boldsymbol{B}(t)$. The element in row 3 of $\boldsymbol{B}(t)$ is the sum of the angular velocities squared ($\dot\theta_x^2(t)+\dot\theta_y^2(t)$) and the element in row 1 and 2 of $\boldsymbol{B}(t)$ are angular accelerations ($\ddot\theta_x(t)$, $\ddot\theta_y(t)$). Therefore, if the following conditions are satisfied, 3 dummy loadcells are enough to estimate the vibration-like movement. The conditions are as follows;

- z_{di} of 3 dummy loadcells are equal to 0.
- $\dot\theta_x(0)$ and $\dot\theta_y(0)$ are estimated from the output of 4 loadcells.

Supposing that z_{di} is equal to 0, the 3rd element of $\boldsymbol{B}(t)$ does not influence the output of the dummy loadcells. Therefore, Eq. (10) estimates the following vector $\boldsymbol{B}_3(t)$.

$$\boldsymbol{B}_3{}^T(t) = (\boldsymbol{D}_3{}^{-1}\boldsymbol{U}_{d3}(t)/E_2m_2) \tag{10}$$

$$\boldsymbol{B}_3{}^T(t) = \begin{bmatrix} \ddot\theta_y(t) & \ddot\theta_x(t) & g_{xy}(t)+\ddot\delta_z(t) \end{bmatrix} \tag{11}$$

Here, the elements of $\boldsymbol{B}_3(t)$ is the vector which has the elements of $\boldsymbol{B}(t)$ except row 3(See Eq. (11)).

It is assumed that the dummy loadcells are installed at the points of $(x_{di}, y_{di}, 0)$ ($i = 1, 2, 4$), matrix $\boldsymbol{D}_3$ is defined as follows;

$$\boldsymbol{D}_3 = \begin{bmatrix} x_{d1} & y_{d1} & 1 \\ x_{d2} & y_{d2} & 1 \\ x_{d4} & y_{d4} & 1 \end{bmatrix}$$

The vector $\boldsymbol{U}_{d3}(t)$ represents the output vector of 3 dummy loadcells.

$$U_{d3}(t) = [u_{d1}(t) \quad u_{d2}(t) \quad u_{d4}(t)]^T \quad (12)$$

On the other hand, the position of z_k changes in each mass measurement, because the shape and mass value of each weighed object changes. As a result, $\left(\dot{\theta}_x^2(t) + \dot{\theta}_y^2(t)\right)$ influences the output of the weighing loadcell. Therefore, estimation of $\boldsymbol{C}$ in Eq. (7) requires derivation of $\hat{\boldsymbol{B}}(t)$. Since $\dot{\theta}_i(t)$ (i = x, y) are the integral of $\ddot{\theta}_i(t)$ in continuous time, $\left(\dot{\theta}_x^2(t) + \dot{\theta}_y^2(t)\right)$ is written as follows;

$$\dot{\theta}_x{}^2(t) + \dot{\theta}_y{}^2(t) = \left\{\int_0^t \ddot{\theta}_x(t)\mathrm{d}t\right\}^2 + \left\{\int_0^t \ddot{\theta}_y(t)\mathrm{d}t\right\}^2. \quad (13)$$

Equation (13) is rewritten as the following equation in discrete time;

$$\dot{\theta}_x{}^2(j) + \dot{\theta}_y{}^2(j) = \left\{\dot{\theta}_x(0) + \sum_{k=1}^{j}\ddot{\theta}_x(k)T\right\}^2 + \left\{\dot{\theta}_y(0) + \sum_{k=1}^{j}\ddot{\theta}_y(k)T\right\}^2$$

$$= \dot{\theta}_x{}^2(0) + 2\sum_{k=1}^{j}\dot{\theta}_x(0)\ddot{\theta}_x(k)T + \left\{\sum_{k=1}^{j}\ddot{\theta}_x(k)T\right\}^2$$

$$+ \dot{\theta}_y{}^2(0) + 2\sum_{k=1}^{j}\dot{\theta}_y(0)\ddot{\theta}_y(k)T + \left\{\sum_{k=1}^{j}\ddot{\theta}_y(k)T\right\}^2$$

$$= \Theta_{ini} + 2\dot{\theta}_x(0)\Theta_x(j) + 2\dot{\theta}_y(0)\Theta_y(j) + \Theta_{sum}(j). \quad (14)$$

where, T is sampling period and

$$\Theta_{ini} = \dot{\theta}_x{}^2(0) + \dot{\theta}_y{}^2(0), \quad (15)$$

$$\Theta_i(j) = \sum_{k=1}^{j}\ddot{\theta}_i(k)T,\ i = x, y, \quad (16)$$

$$\Theta_{sum}(j) = \Theta_x{}^2(j) + \Theta_y{}^2(j). \quad (17)$$

Seeing Eq. (14), the estimation of $\left(\dot{\theta}_x^2(t) + \dot{\theta}_y^2(t)\right)$ requires to compute Θ_{ini}, $\Theta_{sum}(j)$, $\dot{\theta}_i(0)$ (i = x, y).

Firstly, since $\Theta_i(j)$ are derived easily from the product of $\ddot{\theta}_i(j)$ and T. $\Theta_{sum}(j)$ is calculated from the estimates of $\Theta_i(j)$, easily. We consider the estimation of the Θ_{ini}. Let us set a preparation time for estimation of several parameters. During this preparation time, a weighed object is not loaded on the weighing loadcell. Under such condition, we know the mass value of the weighing loadcell and the position of GCWL. Therefore, it is possible to regard the weighing loadcell as 4th dummy loadcell. (In this case, we should not make the z_k equal to the z_{di}, because $\boldsymbol{D}$ in Eq. (5) becomes singular.)

Regarding the weighing loadcell as 4th dummy loadcell, all elements of $\boldsymbol{B}(0)$ in Eq. (4) are computed by using the output signals of 4 loadcells at the starting time. Since Θ_{ini} is equal to the element in row 3 of $\boldsymbol{B}(0)$, we obtain Θ_{ini} by using the estimating algorithm mentioned above.

Finally, we must compute $\dot{\theta}_i(0)$,(i = x, y). During the preparation time, Eq. (4) is rewritten as follows;

$$\boldsymbol{A}_o(j) = \boldsymbol{E}^T(j)\boldsymbol{F}, \quad (18)$$

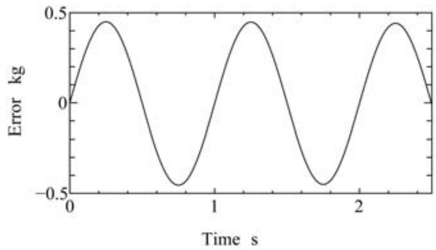

Fig. 3 Simulated Result without Compensation

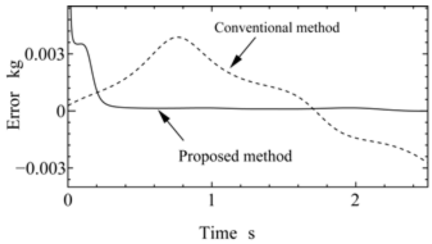

Fig. 4 Comparison of the Proposed method and the Conventional

where,

$$\boldsymbol{A}_o(j) = \dot{\theta}_x{}^2(j) + \dot{\theta}_y{}^2(j) - \Theta_{ini} - \Theta_{sum}(j),$$

$$\boldsymbol{E}^T(j) = [2\Theta_x(j) \quad 2\Theta_y(j)],$$

$$\boldsymbol{F}^T = [\dot{\theta}_x(0) \quad \dot{\theta}_y(0)].$$

As mentioned above, the vectors $\boldsymbol{A}_o$ and $\boldsymbol{E}$ are computed by using the output signals of 4 loadcells. Therefore, it is possible for system identification algorithm to compute the estimate of $\boldsymbol{F}$, regarding $\boldsymbol{A}_o$ and $\boldsymbol{E}$ as output signals and input signals of a linear system, respectively.

As a result, we compute the estimate of $\left(\dot{\theta}_x^2(j) + \dot{\theta}_y^2(j)\right)$ at each sampling time, by using these estimated values $\dot{\theta}_x(0)$, $\dot{\theta}_y(0)$ and Θ_{ini}. During the preparation time, we estimate $\dot{\theta}_i(j)$ (i = x, y). Using these estimated angular velocities, the estimate of $\left(\dot{\theta}_x^2(j) + \dot{\theta}_y^2(j)\right)$ is feasible to be computed at the weighing time after the preparation time.

3. SIMULATIONS

In this section, let us make it clear by numerical simulations that the weighing method with 3 dummy loadcells is feasible. It assumed that 3 dummy loadcells are installed suitably. Suppose that disturbance to output do not exist. The conditions for simulations are as follows;

(x_k, y_k, z_k) = (0.0, 0.05 m, 0.05 m),
(x_{d1}, y_{d1}, z_{d1}) = (0.5 m, 1.0 m, 0.0),
(x_{d2}, y_{d2}, z_{d2}) = (1.0 m, 1.0 m, 0.0),
(x_{d3}, y_{d3}, z_{d3}) = (0.5 m, 0.5 m, 0.0),

E_1, E_2 = 1.0.

Mass value of weighing loadcell m_1 = 1.5 kg
Mass value of dummy loadcells m_2 = 1.0 kg

Vibration-like movement is as follows;

$\theta_x(j) = 0.1 \sin(2\pi \times 0.3\, j\, T)$ rad,

$\ddot{\delta}_z(j) = 0.3\, g \sin(2\pi \times jT)$ m/s^2.

The length of preparation time is 1 s. The sampling period T is 1 ms.

Figure 3 shows a simulated result without compensation. The results with a conventional method and proposed method are shown in Fig. 4. The mass value of the conventional method is calculated from Eq. (19). This conventional method does not considered the position of gravity center of a weighed object. In these figures, the horizontal axis expresses time and the vertical axis expresses measurement error, respectively.

$$m_1 = u_k(j) / E_1 \boldsymbol{K}^T \hat{\boldsymbol{B}}(j), \boldsymbol{K}^T = [0 \quad 0 \quad 0 \quad 1] \qquad (19)$$

The measurement error with the proposed method becomes less than one thousandth after 0.2 seconds. Some cases of mass measurement under various conditions are simulated. The simulated results with the proposed method became similar to the result shown in Fig. 4.

Consequently, the proposed method is feasible to weigh under the vibration-like moving conditions. In simulations, the time required to weigh is about 0.2 seconds.

4. EXPERIMENTS AND CONSIDERATION

4.1. Experimental conditions

Figure 5 gives us the overview of the experimental apparatus. The weighing system consists of a weighing loadcell and 3 dummy loadcells. These loadcells are set on an aluminum board which is a square, 400 mm on a side. The thickness of the board is 10 mm. Figure 6 shows the location of the loadcells on the board.

This board is connected to the shaker by the connecting rod. The shaker oscillates horizontally. The board inclines in synchronization with the oscillation of the shaker. This experimental condition simulates a rolling (or pitching) motion of a ship on the sea.

Figure 6 (a) and (b) show the top and the front view of the experimental apparatus, respectively. The experimental apparatus consists of the elements as listed in Table 1.

The sampling period T is 1 ms and the resolution of A/D conversion is 16 bits in experiments. On each dummy loadcell, the weight with known mass value is loaded. The rectangular tray is fitted with the weighing loadcell. In the experiments, standard weights are loaded on this tray. In the experiments, the shaker oscillates in 0.7 Hz, because the shaker can not oscillate in 0.3 Hz.

Each position of the GCL is shown as follows;

$(x_k, y_k, z_k) = (0.05$ m, 0.368 m, 0.0134 m),
$(x_{d1}, y_{d1}, z_{d1}) = (0.05$ m, 0.05 m, $0.0)$,
$(x_{d2}, y_{d2}, z_{d2}) = (0.264$ m, 0.05 m, $0.0)$,
$(x_{d3}, y_{d3}, z_{d3}) = (0.264$ m, 0.368 m, $0.0)$.

The supplied voltage to the weighing loadcell is 11 V. The tare weight of the weighing loadcell is 0.932 kg.

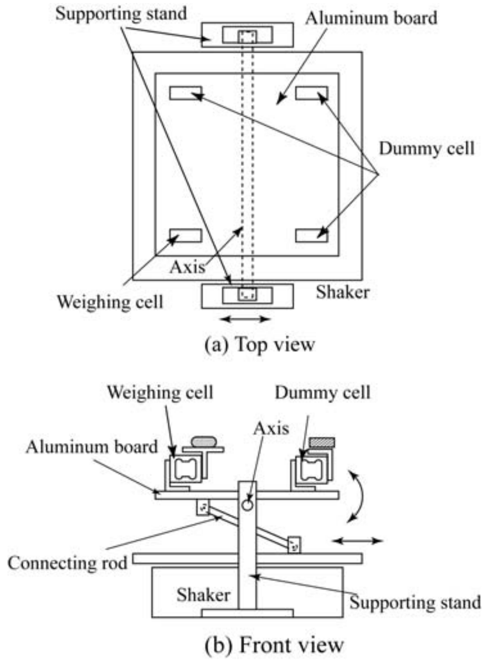

Fig. 5 Experimental apparatus

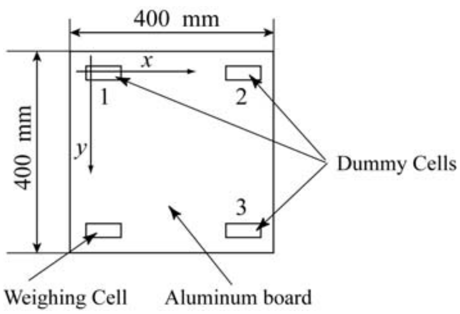

Fig. 6 Location of four loadcells on aluminum board

4.2 Experimental procedure

In this section, the experimental procedure is explained in detail.

1. While the shaker oscillates, the data acquisition starts. About 1 second later, the weight is loaded on the tray of the weighing loadcell. The data is acquired for 3.8 seconds.
2. The preparation time is set to 0.8 seconds. During this preparation time, $\dot{\theta}_x(j)$ and $\dot{\theta}_y(j)$ are estimated by processing the output signals of 4 loadcells.
3. Between 0.8 and 1.5 seconds, the weighing calculation is not conducted, because the influence of loading the object remains. During this time period, the estimation of the angular velocities $\dot{\theta}_x(j)$ and $\dot{\theta}_y(j)$ is continued.
4. After 1.5 seconds elapsed from the start of the data acquisition, the calculation of the mass value starts. At the starting moment of this weighing calculation, angular velocities $\dot{\theta}_x(j)$ and $\dot{\theta}_y(j)$ are substituted for the initial angular velocities $\dot{\theta}_x(0)$ and $\dot{\theta}_y(0)$, respect-

Table 1. Parts of experimental apparatus.

Shaker	**SSV-725(San-esu)**
Weighing loadcell	**UH-36-4-0(Yamato Scale Ltd.)**
Dummy loadcell	**UH-36-2-0(Yamato Scale Ltd.)**
DC Amplifier	**3131 (YOKOGAWA)**
A/D board	**AD-3155(Interface)**
Personal Computer (CPU)	**Dimension 4100 (DELL) (Pentium III, 800 MHz)**

tively. The mass value of the weighed object $\widehat{m}(j)$ is calculated by using the estimated angular velocities $\dot{\theta}_x(j)$ and $\dot{\theta}_y(j)$ at every sampling time.

Signal processing is conducted off-line. The output signals of loadcells are saved in the personal computer.

After that, the angular velocities and the mass value of the weighed object are calculated by means of the recursive least-squares algorithm, respectively.

4.3 Consideration of experimental results

A typical example of the experimental results is shown in Fig. 7. The horizontal axis expresses time and the vertical axis expresses the measurement error, respectively. The origin of the horizontal axis is the starting time of calculating the mass value. The mass value of the weighed object is 1.332 kg. The chain line expresses the result without compensation. The dashed line expresses the result with the conventional method. The solid line expresses the result with the proposed method. The measurement error with the proposed method became less than one thousandth after 0.5 seconds since the mass measurement started. Other experiments with the proposed method showed similar results. Therefore, it is expected that the proposed method measures mass value accurately with 3 dummy loadcells.

10 measurements were conducted on each sample mass whose value was changed from 0.1 up to 0.6 kg at 0.1 kg intervals. That is to say, 60 measurements were conducted in total.

The measurement accuracy was examined by using the mean value of the error ε, the standard deviation σ, and the total error Σ, which are defined as follows:

$$\varepsilon_{ij} = \widehat{m}_{eij} - m_{1i} \tag{20}$$

$$\varepsilon_i = \frac{1}{N}\sum_{j=1}^{N}\varepsilon_{ij} \tag{21}$$

$$\sigma_i = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left(\varepsilon_{ij} - \varepsilon_i\right)^2} \tag{22}$$

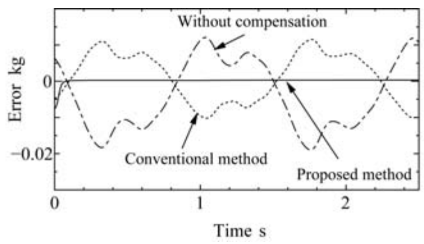

Fig. 7 Experimental results

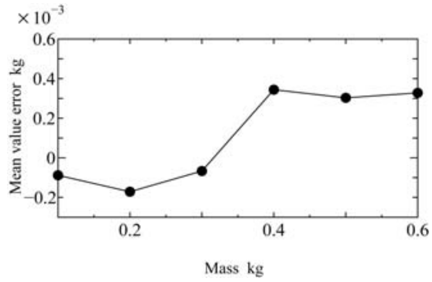

Fig. 8 Experimental results

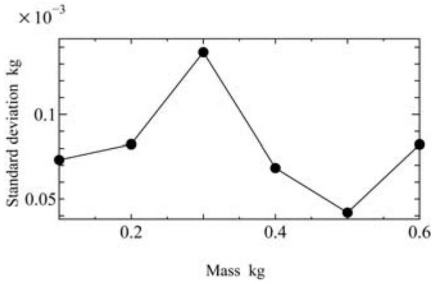

Fig. 9 Experimental results

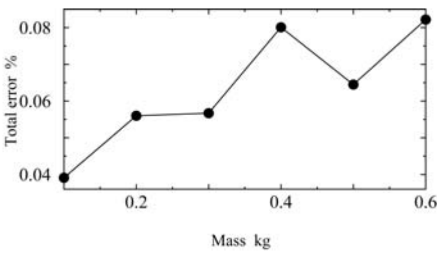

Fig. 10 Experimental results

$$\Sigma_i = \frac{|\varepsilon_i| + 2\sigma_i}{m_{FS}} \times 100 \ \% \tag{23}$$

where N is the total number of measurements(N = 10), and $m_{FS,}$ the value of the full scale, is 0.6 kg. These results of ε, σ, and Σ are plotted in Figs. 8, 9 and 10, respectively.

In the experiments, the total errors are less than 0.1 %. As a result, the weighing system has measuring performance to weigh accurately under the vibration-like moving conditions.

5. CONCLUSIONS

In this paper, we explained the accurate weighing method with 3 dummy loadcells under the vibration-like moving conditions. We manufactured the weighing system which consists of a weighing loadcell and 3 dummy loadcells on trial. This weighing method requires to compute the estimate of $\left(\dot{\theta}_x^{\,2}(t)+\dot{\theta}_y^{\,2}(t)\right)$. We propose the calculating method which estimates $\left(\dot{\theta}_x^{\,2}(t)+\dot{\theta}_y^{\,2}(t)\right)$. The estimation of angular velocities is also required to set the preparation time.

We conducted numerical simulations and experiments by using the trail-manufactured experimental apparatus. In these simulations and experiments, the proposed method accurately computes the estimate of the mass value in about 0.5 sec. It is concerned that the total error with the proposed method becomes less than 0.1 %. Therefore, it is confirmed that the weighing method with 3 dummy loadcells using the trial-manufactured weighing system is feasible.

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