Trans. Japan Soc. Aero. Space Sci.
Vol. 50, No. 170, pp. 251–257, 2008

The Space Scale: An Instrument for Astronaut Mass Measurement

By Yusaku FUJII[1] and Kazuhito SHIMADA[2]

[1]*Department of Electronic Engineering, Faculty of Engineering, Gunma University, Kiryu, Japan*
[2]*Space Medicine Group, Japan Aerospace Exploration Agency (JAXA) Tsukuba Space Center, Tsukuba, Japan*

(Received December 11th, 2006)

A practical, high-precision method for measuring the mass of an astronaut under microgravity conditions is proposed. Using an instrument called the "Space Scale", the velocities of a target object and a reference mass are measured with high accuracy by optical interferometry. The two are connected by a linear ball bearing and have separate linear-motion states, with some acceleration due to friction in the linear ball bearing. For this paper, a ground instrument was developed in which linear motion of the whole mechanical system is achieved with negligible external force by means of a pneumatic linear bearing. The effect of linear ball bearing friction that involves the target object and the reference mass is theoretically negligible, as we proved experimentally in this study. We conclude that an operational model for in-orbit use, which takes advantage of an optical interferometer, would be extremely compact and accurate.

Key Words: Space Station, Microgravity, Metrology and Standards, Inertial Mass, Inertial Force, Optical Interferometer, Non-Rigid Object

1. Introduction

Human activities in space are expected to intensify and diversify with advances in space station factories and laboratories. Highly accurate and efficient measurements of physical quantities will be required.[1] Among the four major SI basic units (m, kg, s, and A), only mass (kg) cannot be measured under microgravity conditions using instruments employed on Earth, such as the balance and load cell, because these instruments require a uniform, steady gravitational acceleration field. Highly accurate and/or highly efficient mass measurements of objects in various states will be required on spacecraft such as the International Space Station (ISS). However, only a few low-accuracy and low-efficiency methods have been developed to date.

One can measure the mass of a target object as inertial mass by applying acceleration or force to it. If the mass is measured when acceleration is present, the uniformity and constancy of the acceleration must be considered. If the acceleration field is not sufficiently uniform or constant, then the distribution of both density and acceleration inside the object must be considered to determine the effect of the inertial force of the object.

Some research studies have focused on mass measurement under microgravity conditions. The following principles have been proposed.

1.1. Use of oscillated motion[2–5]

With the methods categorized in this group, the characteristic frequency of a spring-mass system is typically used. The advantage is the shortness of measurement time. Since the acceleration field is neither uniform nor constant, both density and acceleration distributions of the object must be considered. With these methods, it is difficult to measure the mass of non-rigid objects such as an elastic body, grains, or liquids. In general, the vibration generated by the instrument, which is transferred to the structure of the spacecraft, should be minimized.

1.2. Use of centrifugal force[4,6]

The advantage of the methods categorized in this group is the use of a constant acceleration field. The disadvantages lie in the requirement of a long measurement duration and a large instrument size in order to produce a sufficiently strong artificial acceleration field. Determining the position of the center of mass (COM) is the most difficult problem because of the non-uniformity of the acceleration field, and the various shapes and densities of the general object. If the change in shape and density is sufficiently small during the measurement, the position of the COM can be determined by taking two discrete arm lengths. The reported uncertainty[6] in measuring a rigid object of 500 g on Earth is on the order of 2×10^{-4}.

1.3. Use of linear accelerated motion[4,7–10]

The methods categorized in this group use the velocity change (i.e. acceleration) of the object that is being linearly accelerated with negligible friction. In our method,[8] the velocity of the object is accurately measured by means of an optical interferometer, and the momentum change of the object is measured by the impulse acting on a force transducer. In a preparatory experiment on Earth, the relative combined standard uncertainty in mass measurements from 2 kg to 11 kg in a single impact measurement was estimated to be $u_{c,r} = 0.6 \times 10^{-2}$ (0.6%). For more accurate measurement, we have proposed an improved method[9] in which the impulse is measured using a reference mass instead of a force transducer, which was the largest source of error in the previous experiments. The combined standard uncertainty in mass measurements from 4 kg to 18 kg for a single collision is estimated to be $u_c = 0.012$ kg, which corresponds to 0.07% (7×10^{-4}) of the maximum value of

18 kg. The authors have named the proposed instrument the Space Balance.[8,9] In a recently proposed instrument for astronaut body-mass measurement,[10] the tensile force of a rubber cord is applied to the astronaut under test, and the force is measured using a force transducer.

The proposed Space Balance is based on the Levitation Mass Method (LMM) that was previously proposed and developed by the first author. In this method, the inertial force of a mass levitated using a pneumatic linear bearing is used as a reference force to be applied to the objects being tested (i.e., force transducers, materials, or structures). The inertial force of the levitated mass is measured using an optical interferometer. The first author modified it as the calibration methods for all three categories of dynamic force: impact-force calibration,[11] oscillation-force calibration,[12] and step-force calibration.[13] The first author also applied the LMM for investigating the frictional characteristics of pneumatic linear bearings.[14,15] Finally, the authors applied the Levitation Mass Method for material testing, such as evaluating material viscoelasticity under an oscillating load[16] and under an impact load,[17] and the generation and measurement of micro-Newton level forces.[18]

In previous studies by the first author,[8,9] the proposed mass measurement instrument, the Space Balance, used a linear ball bearing to connect the target object and the reference mass. A ground experiment was conducted using two pneumatic linear bearings to verify the measurement principle, based on the law of conservation of momentum.[9] In this paper, a modified and improved variant of the Space Balance, which was designed for measuring the body mass of astronauts, is proposed as the "Space Scale". In the Space Scale, a linear ball bearing is also used to connect the target object and the reference mass, and the mass of the object is measured by optical interferometry. No force transducer is used in the proposed Space Scale. To fulfill the medical requirements for the body-mass measurement of astronauts, the design has been significantly altered from the previously proposed Space Balance.

In this paper, the effect of friction in the linear ball bearing that connects the target object with the reference mass is experimentally determined. The advantages and points to be considered for the proposed Space Scale are then discussed.

2. Space Scale

Figure 1 depicts the proposed astronaut body-mass measuring instrument, the Space Scale. The holder of mass $m_{\rm H}$ is attached to the astronaut to be measured (mass $m_{\rm O}$); it is also connected to the reference mass $m_{\rm R}$ guided by an ordinary linear bearing with some friction. The velocity of the holder $v_{\rm H}$ and the velocity of the reference mass $v_{\rm R}$ are measured using optical interferometers. Interferometer-1 measures $v_{\rm R}$, and Interferometer-2 measures $(v_{\rm H} - v_{\rm R})$. The measurement procedure is as follows.

Stage 1

The system consists of the holder, the astronaut, and the reference mass. After instrument deployment, the system is suspended in cabin space without any mechanical contact with other objects. The reference point for interferometry CC1 is then released in the microgravity cabin. The total angular and linear momentum maintain the exact initial values during the whole measurement procedure, since no external force is applied.

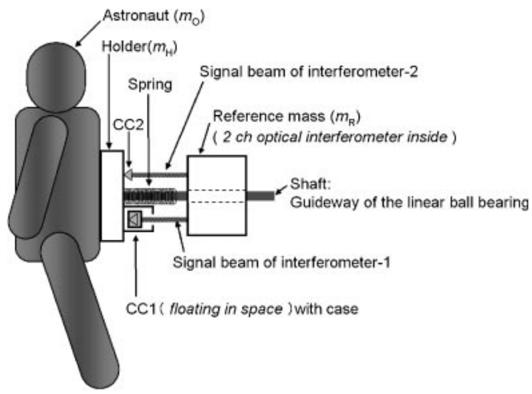

Fig. 1. Space scale for astronaut mass measurement.

Stage 2

The spring-mechanism action is initiated, and the holder that captures the astronaut and the reference mass are separated by an internal force (i.e., the action and reaction forces between the holder with the astronaut and the reference mass).

Stage 3

If the astronaut is sufficiently rigid, the holder and the astronaut move as a single body.

$$(m_{\rm H} + m_{\rm O})\delta v_{\rm H} + m_{\rm R}\delta v_{\rm R} = 0,$$

where $\delta v_{\rm H}$ and $\delta v_{\rm R}$ are the velocity changes of the holder and the reference mass from the initial values. The equation is based on the law of conservation of momentum.

The mass of the astronaut $m_{\rm O}$ is determined as:

$$m_{\rm O} = -(\delta v_{\rm R}/\delta v_{\rm H})m_{\rm R} - m_{\rm H}.$$

The reference and the holder masses, $m_{\rm R}$ and $m_{\rm H}$, are calibrated in advance. A single velocity direction is sufficient to determine the mass of the astronaut.

The explanation above is valid even for a non-rigid object if the COM velocity is measured. Please note that the position of measurement points (i.e., the optical centers of the cube corner prisms) and that of the COMs do not coincide. The fluctuation of the relative position of the measurement point and the COM, due to elastic vibration or attitude change of the object, could be a source of large uncertainty. In the proposed Space Scale, the effect of the fluctuation of the relative position of the measurement point and the COM on the measurement results is minimized.

(1) Only the time region when the velocities are almost constant is used for the analysis. The region near the impact is not used because, in this location, the fluctuation of the relative position of the measurement point and the COM is thought to be large.
(2) The average values of velocity are used for the analy-

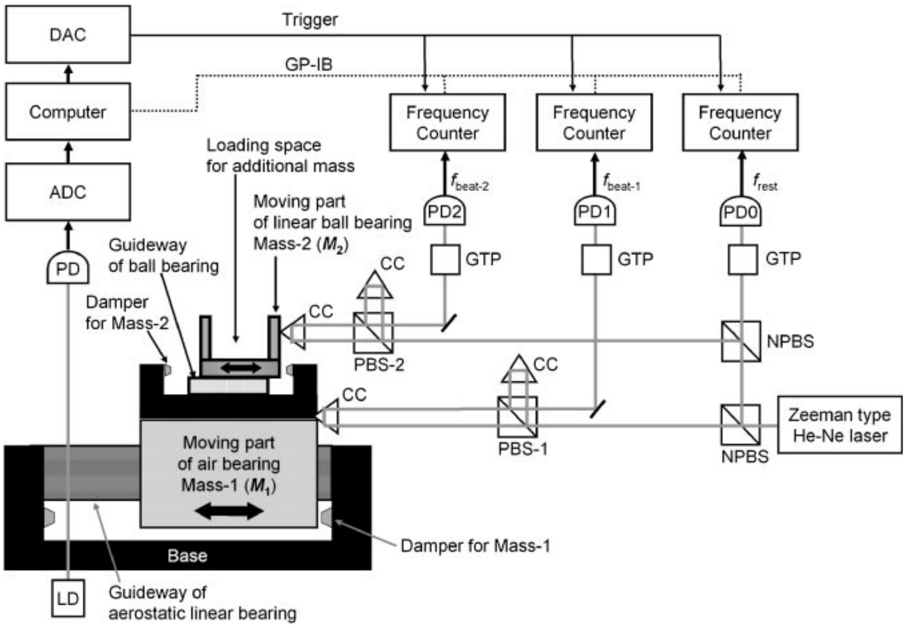

Fig. 2. Experimental setup.
Code: CC, cube corner prism; PBS, polarizing beam splitter; NPBS, non-polarizing beam splitter; GTP, Glan-Thompson prism; PD, photo diode; LD, laser diode; DAC, digital-to-analog converter; ADC, analog-to-digital converter; PC, computer.

sis in order to reduce the effect of fluctuation of the relative position of the measurement point and the COM. The effect of vibrating components and the change in the object shape and attitude can be canceled by averaging the data over a sufficiently long time. Therefore, the linear bearing must be long enough to satisfy this requirement.

In the proposed Space Scale, other considerations are also applied as follows.

(1) The momentum change of the astronaut before and after impact is measured by the momentum change of the reference mass instead of the impulse measured by a force transducer.
(2) The COM of the astronaut and the COM of the reference mass should lie on a line parallel to the longitudinal axis of the linear bearing. For this reason, the holder is attached around the astronaut's waist, which is close to the human body COM.
(3) The optical interferometers are placed inside the reference to maximize the quantity of the reference mass and to minimize the whole mass of the instrument.
(4) In the region of time when the velocities are almost constant, the effect of the small frictional force inside the linear ball bearing on the measurement result is thought to be negligible by the principle of action and reaction.

Clearly, many considerations have been given to the design of the Space Scale to realize an accurate and easy measurement using a simple and compact instrument.

3. Experiment

Figure 2 presents a schematic diagram of the setup for the ground experiment. A pneumatic linear bearing (model: Air-Slide TAAG10A-02, manufactured by NTN Co., Ltd., Japan) is used to ensure linear motion of the whole mechanical system with minimal friction. The pneumatic bearing is attached to a tilting stage. The maximum weight of the moving part is 30 kg; the air film is 8 μm thick, the air film stiffness exceeds 70 N/μm, and the straightness of the guideway is better than 0.3 μm/100 mm. The frictional characteristics are determined by a previously reported method.[14,15] The mass of the moving part of the aerostatic linear bearing, Mass-1, acts as the reference mass calibrated beforehand. The mass of reference M_1 is 2.8094 kg.

A small linear ball bearing (model: LS, manufactured by THK Co., Ltd., Japan) is placed on the moving part of a pneumatic linear bearing. The mass of the moving part of the small linear ball bearing, Mass-2, acts as the object to be measured. The total mass of object M_2 takes five values (0.2130 kg, 0.3051 kg, 0.3971 kg, 0.4893 kg, and 0.5823 kg) using additional masses.

A Zeeman two-frequency He-Ne laser is used as the light source for the optical interferometer. The interferometer has three photo-detectors (PD0, PD1, and PD2). The frequency difference between the two orthogonal-polarization states emitted from the laser, f_{rest}, is monitored using a Glan-Thompson prism (GTP) and the first photo-detector, PD0.

The velocity of Mass-1, v_1, is measured as a Doppler shift frequency, $f_{\text{Doppler-1}}$, which can be expressed as

$$v_1 = \lambda_{\text{air}}\,(f_{\text{Doppler-1}})/2,$$

$$f_{\text{Doppler-1}} = -(f_{\text{beat-1}} - f_{\text{rest}}),$$

where λ_{air} is the wavelength of the signal beam under the experiment conditions; $f_{\text{beat-1}}$ is the beat frequency, which is the frequency difference between the signal beam and the reference beam appearing at PD1; and f_{rest} is the rest frequency, which takes the value of $f_{\text{beat-1}}$ when the moving

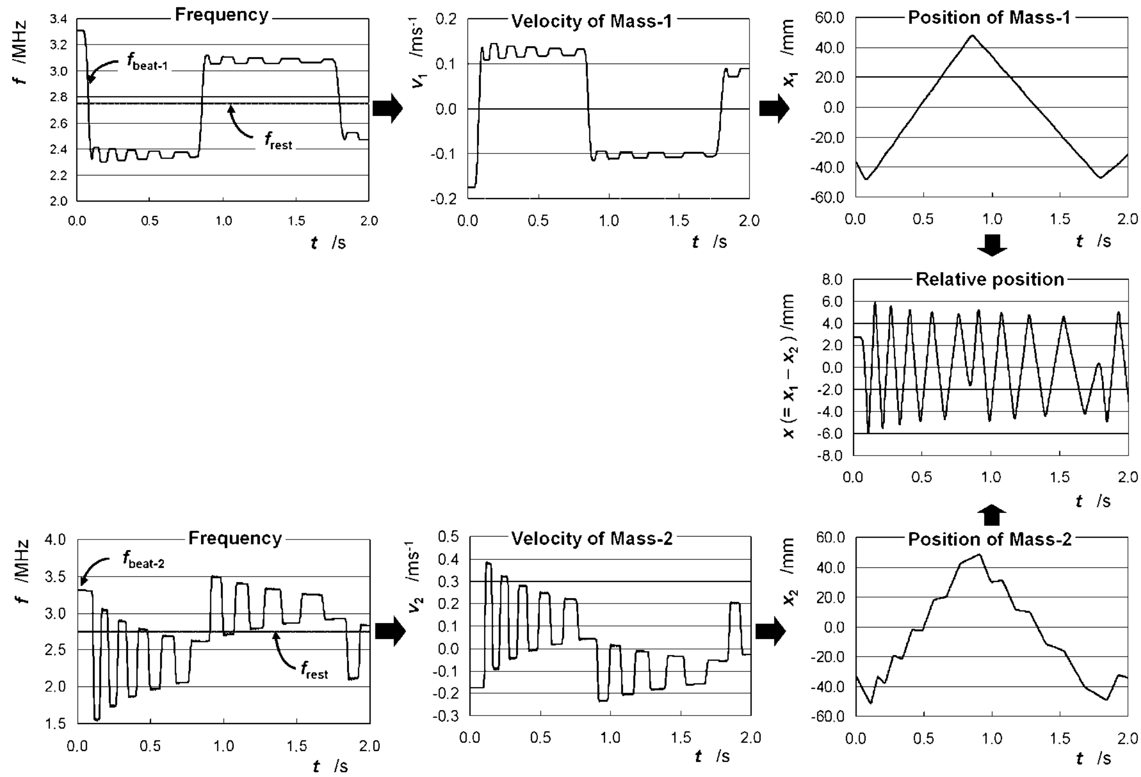

Fig. 3. Calculation of velocity and position from frequency ($M_2 = 0.213$ kg).

part of the pneumatic bearing is at a standstill. The linear-polarization component transmitted through the polarizing beam splitter PBS-1, having a higher frequency than the other linear polarization, is used as the signal beam. The direction of the coordinate system for the velocity, acceleration, and force acting on the moving part is towards the right (Fig. 2). The position of mass x_1 is numerically calculated from the velocity v_1. Here, v_2, the velocity of Mass-2, which is attached to Mass-1 via the ball bearing, is measured as a Doppler shift frequency, $f_{\text{Doppler-2}}$, which can be expressed as:

$$v_1 = \lambda_{\text{air}}\ (f_{\text{Doppler-2}})/2,$$

$$f_{\text{Doppler-2}} = -(f_{\text{beat-2}} - f_{\text{rest}}).$$

The beat frequency $f_{\text{beat-2}}$ is measured using PD2. The position x_2 of the moving part of the ball bearing is numerically calculated from the velocity. The position of the moving part of the ball bearing relative to the moving part of the air bearing, $x = x_1 - x_2$, is calculated.

The frequency $f_{\text{beat-1}}$ appearing at PD1 is measured using an electronic frequency counter (model: R5363; manufactured by Advantest Corp., Japan). The counter continuously measures and records the beat frequency, $f_{\text{beat-1}}$, making 2,000 measurements with a sampling interval of $T = 4{,}000/f_{\text{beat-1}}$, and stores the values in its memory. The counter continuously measures the interval time over 4,000 periods without dead time. The sampling period of the counter is 1.5 ms at a frequency of 2.8 MHz. Two other counters of the same model measure the frequencies f_{rest} and $f_{\text{beat-2}}$ appearing at PD0 and PD2. These counters measure the frequencies without dead time. The sampling interval, T, can be exactly calculated using the measured frequency, f, and the expression $T = 4{,}000/f$.

Measurements using the three electronic counters (R5363) are triggered by means of a sharp trigger signal generated using a digital-to-analog converter (DAC). This signal is initiated by means of a light-controlled switch; a combination of a laser diode and photo diode.

In the measurement, Mass-1 is manually given an initial velocity; it travels toward the left until it rebounds at the left damper attached to the base. Just before Mass-1 reaches the left damper, the laser diode-photo diode (LD-PD) switch turns on, initiating measurements by the frequency counters. During the period that Mass-1 is moving in a single direction, Mass-2 rebounds with Mass-1, creating a relative reciprocating motion for several cycles with an amplitude of 5 mm. In the experiment, five sliding measurements are conducted during the period Mass-1 is moving back and forth, one for each value of M_2 (i.e., 0.2130 kg, 0.3051 kg, 0.3971 kg, 0.4893 kg, and 0.5823 kg).

4. Results

Figure 3 presents the procedure by which the position and velocity are calculated from the measured frequency. The result for $M_2 = 0.2130$ kg is depicted. During the 2.0 s measurement period, Mass-1 moves back and forth. As Mass-1 moves in one direction, Mass-2 undergoes a relative reciprocating motion for four cycles with an amplitude of 5 mm. (See the graph of the relative position $x = x_1 - x_2$.) The amplitude is changed due to the elastic deformation of the side dampers.

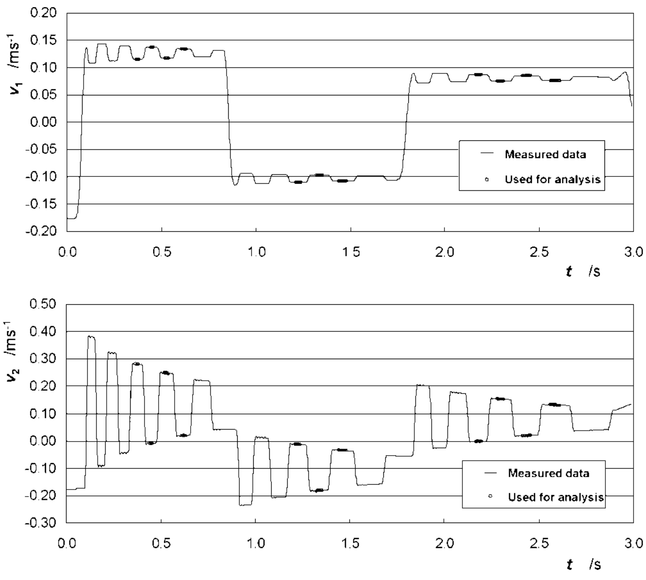

Fig. 4. Change in velocity of Mass-1 and Mass-2 ($M_2 = 0.213$ kg).

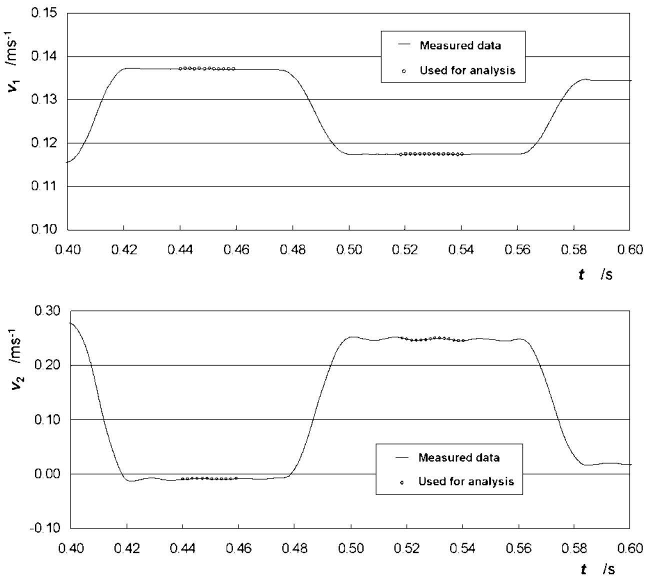

Fig. 5. Detail of change in velocity of Mass-1 and Mass-2 ($M_2 = 0.213$ kg).

Figure 4 plots the velocity change of Mass-1 v_1 and Mass-2 v_2 between $t = 0.00$ s and $t = 3.00$ s. The experiment data is the same as in Fig. 3. To reduce the effect of the mechanical vibration caused by the collision between Mass-1 and Mass-2 and the collision of Mass-1 and the dampers, the data measured near the collision are not used for the analysis. In the following analysis, the data are used if the relative position is in the range of $-1.5\,\text{mm} < x_1 - x_2 < 1.5\,\text{mm}$ and the position of Mass-1 is in the range of $-30\,\text{mm} < x_1 < 30\,\text{mm}$. The mass of Mass-2 is estimated using the average of the measured velocities. In the figure, the measured data used for estimating M_2 are denoted by circles. Three pairs, two pairs, and three pairs of the adjacent measured velocities are obtained during each free sliding of Mass-1.

Figure 5 plots the details of the velocity change of Mass-1 v_1 and Mass-2 v_2 between $t = 0.40$ s and $t = 0.60$ s. The experiment data are the same as in Figs. 3 and 4. The velocity change of Mass-1 due to the collision with Mass-2, δv_1, is calculated as the difference between before ($v_{1,0}$) and after ($v_{1,1}$) the collision. The velocities of Mass-1 before and after the collision, $v_{1,0}$ and $v_{1,1}$, are calculated as the mean value of the instantaneous values measured for $-1.5\,\text{mm} < x_1 - x_2 < 1.5\,\text{mm}$ and $30\,\text{mm} < x_1 < 30\,\text{mm}$. The velocity change of Mass-2 due to the collision with Mass-1 is calculated in the same way as that of Mass-1. In Fig. 5, the velocity change of Mass-1 δv_1 and the velocity change of Mass-2 δv_2 are calculated as:

$$\delta v_1 = v_{1,1} - v_{1,0} = 0.1173 - 0.1370 = -0.0197\ (\text{ms}^{-1}),$$

$$\delta v_2 = v_{2,1} - v_{2,0} = 0.2476 - (-0.0088) = 0.2564\ (\text{ms}^{-1}).$$

Therefore, the mass of Mass-2 is calculated as:

$$M_{2,\text{meas}} = -(\delta v_1/\delta v_2)M_1 = 0.2159\,\text{kg}.$$

The relative measurement error E_r is calculated as:

$$E_r = (M_{2,\text{meas}} - M_{2,\text{cal}})/M_{2,\text{cal}} = 0.0138\ (1.38\%).$$

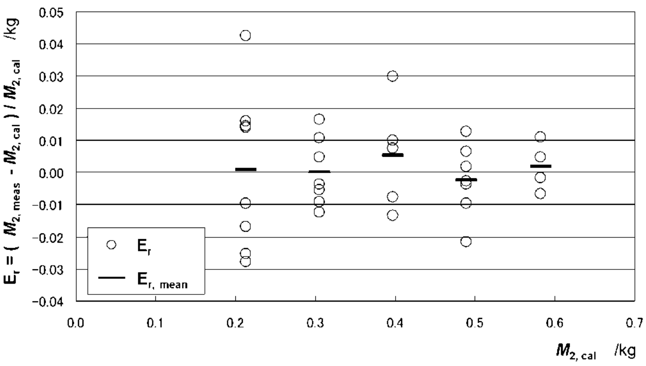

Fig. 6. Relative measurement error against the calibrated mass.

Figure 6 plots the relative error against the calibrated mass for all five series of measurements using $M_{2,\text{cal}} = 0.2130$ kg, 0.3051 kg, 0.3971 kg, 0.4893 kg, and 0.5823 kg. In the figure, the mean values of E_r for corresponding values of $M_{2,\text{cal}}$ are also plotted. The mean values, $E_{r,\text{mean}}$, for $M_{2,\text{cal}} = 0.2130$ kg, 0.3051 kg, 0.3971 kg, 0.4893 kg, and 0.5823 kg are 0.0009 (0.09%), 0.0010 (0.10%), 0.0052 (0.52%), −0.0024 (0.24%), and 0.0018 (0.18%), respectively. The standard deviation of $E_{r,\text{mean}}$ is 0.0025 (0.23%), the mean value is 0.0011 (0.11%), and the root mean square (rms) value is 0.0027 (0.27%).

5. Discussion

In Fig. 5, the relatively large vibration in the free sliding region is clearly observed only in the velocity of Mass-2, v_2. The velocity changes due to the force acting between the two objects are proportional to the inverse value of its mass. Therefore, this vibration in v_2 is thought to be due to the vibration of the attitude of Mass-2. The linear ball bearing used here allows some attitude change of the moving part, Mass-2. The position of the COM and that of the measurement point (optical center of the cube corner prism) of Mass-2 do not coincide.

The measurement time is short in this experiment. In the experiment using $M_{2,\mathrm{cal}} = 0.2130$ kg (Fig. 4), eight estimated values of $M_{2,\mathrm{meas}}$ are obtained from a run that is 3.0 s long. The standard deviation of the estimated values of $M_{2,\mathrm{meas}}$ is large. However, the mean value of $M_{2,\mathrm{meas}}$ obtained during 3.0 s period is close to the calibrated value (Fig. 6). The rms value of $E_{\mathrm{r,mean}}$ in the experiment is 0.0027 (0.27%). These results indicate that the random error in a single measurement is relatively large, but the bias error is relatively small. The random error can be reduced by average operation. This result proves that the friction of the linear ball bearing and the attitude change of the masses do not significantly affect the measurement result.

The relative displacement δL is the distance between the measurement points (i.e., the optical center of the cube corner prism attached to the astronaut) and the COM of the astronaut. Using a longer L (linear bearing length) is beneficial for reducing the effect of δL on the measurement results. For example, when $\delta L = 3$ mm and $L = 1.5$ m, the effect of δL on the measurement result is 0.2%. A measurement accuracy of 0.2% may be easily obtained without any special subject body restraint. To achieve an accuracy of 0.1% or better, some type of body restraint would be necessary.

In this experiment, the mean values for two adjacent points measured at the time when Mass-2 is in the COM-1 are used to estimate the mass of Mass-2. The velocity of Mass-2, v_2, varies with a relatively large amplitude, thought to be due to the pitching motion of the linear ball bearing employed. Two factors, the use of almost-instantaneous values and the large amplitude of the values picked up from the wave, result in a relatively large value of 1.6% for the standard deviation of each measurement error and a small mean value of 0.08% for the total measurement error, E_{r}.

The authors believe that the total mass of the Space Scale can be decreased to as little as 2 kg through the use of an LD interferometer, assuming that a general-purpose laptop computer is available aboard the ISS for calculations.

For this particular experiment, the reference mass is greater than the object mass. Relative measurement accuracy does not change significantly when the object mass is greater than the reference mass, based on the principle of the measurement (i.e. $m_{\mathrm{O}} = -(\delta v_{\mathrm{R}}/\delta v_{\mathrm{H}})\, m_{\mathrm{R}} - m_{\mathrm{H}}$). A metal block is used as the reference for this study; however, any reasonably rigid object whose mass is determined prior to flight, or even theoretically estimated during flight, can be used. The ISS manifest would not be affected if flying with a dedicated weight is prohibited.

If the COM of the astronaut and the COM of the reference mass do not lie on a line parallel to the longitudinal direction of the linear bearing, the attitude of the linear bearing will change. This change is due to the law of conservation of angular momentum, and it occurs even if the initial value of the angular momentum of the whole system is zero. A large attitude change of the linear bearing leads to faulty measurement. Therefore, in the design of the Space Scale, the holder is attached around the waist of the astronaut, which is close to the human body COM. Practically, if some trial-and-error attempts are allowed, the proposed Space Scale can be used for measuring mass whose approximate location of the COM is not well known. In real procedures, visual observations of the attitude change of the bearing during the measurement would be necessary.

Concerning the problems of garbage in space, the proposed Space Scale can be used not only for measuring the mass of the garbage container, but also for locating the COM of the container by measuring the mass of garbage sub-packages.

The Space Scale does not use hazardous materials except for batteries. Its ease of operation and accuracy could be verified quite easily on a parabolic-flight airplane (microgravity up to 25 s) because of its short measurement duration. If body elasticity is an accuracy issue, the astronaut could be secured onto the ISS Crew Medical Restraint System. The authors believe that it would not be necessary to do so, as various body positions could be tried and verified on a parabolic-flight airplane. The instrument does not need to be rack-mounted; thus, it can be operated in any module of the ISS. Overall, the Space Scale is a strong candidate for replacing existing body mass measurement devices, and is also suitable for garbage COM location for the Progress, the H-II Transfer Vehicle (HTV), and the Automated Transfer Vehicle (ATV).

6. Conclusions

A practical, high-precision method for measuring the body mass of an astronaut under microgravity conditions is proposed. Using an instrument called the Space Scale, the velocities of a target object and a reference mass are measured with high accuracy using optical interferometry. The two are connected by a standard linear ball bearing and have separate linear-motion states, with some acceleration due to friction in the linear ball bearing. The ground instrument was developed so that the linear motion of the whole mechanical system is achieved with negligible external force by means of a pneumatic linear bearing. The effects of friction in the linear ball bearing between the target object and the reference mass are theoretically negligible, as we have proven experimentally in this study. It is therefore concluded that an operational model for in-orbit use that takes advantage of an optical interferometer would be extremely compact and accurate.

Acknowledgments

This study was partially supported by a research-aid grant from of the Japan Space Forum (JSF) and the Grant-in-Aid for Scientific Research (B) 19360185 (KAKENHI 19360185).

References

1) Shimada, K.: Extra Vehicular Activity—Advanced Operations and Suit Technology, *Jpn. Soc. Aeronaut. Space Sci.*, **47** (1999),

pp. 191–196 (in Japanese).
2) Thornton, W. and Ord, J.: Specimen Mass Measurement, NASA Tech. Report, N74-11867, 1974.
3) Oakey, W. E. and Lorenz, R.: Survey and Experimental Testing of Nongravimetric Mass Measurement Devices, NASA Tech. Report, N77-26456, 1977.
4) Beyer, N., Lomme, J., McCollough, H., Price, B. and Weber, H.: Proposal for an Astronaut Mass Measurement Device for the Space Shuttle, NASA Tech. Report, N95-14854, 1995.
5) Ono, T., Uozumi, H., Honda, O. and Nagata, K.: Mass-Measurement under Weightless Conditions by the Frequency-Controlled Method, *Measurement*, **22**, 3 (1997), pp. 87–95.
6) Rivetti, A., Martini, G., Alasia, F., Birello, G., Gatti, L. and Solitro, F.: An Inertial, Low-Capacity Balance to be Accomodated on Board the International Space Station, Proceedings of the 2nd European Symposium on the Utilization of the International Space Station, ESTEC, Noordwijk, The Netherlands, 1998, pp. 93–98.
7) Smith, D. and Kaufman, K.: Space Linear Acceleration Mass Measurement Device (Slammd) for the Human Research Facility (Hrf), *SAE Transactions*, **107**, 1 (1998), pp. 589–609.
8) Fujii, Y., Fujimoto, H. and Namioka, S.: Mass measurement under Weightless Conditions, *Rev. Sci. Instrum.*, **70**, 1 (1999), pp. 111–113.
9) Fujii, Y., Fujimoto, H., Watanabe, R. and Miki, Y.: Balance for Measuring Mass under Microgravity Conditions, *AIAA J.*, **39** (2001), pp. 455–457.
10) Fujii, Y. and Shimada, K.: Instrument for Measuring the Mass of an Astronaut, *Meas. Sci. Technol.*, **17** (2006), pp. 2705–2710.
11) Fujii, Y.: Measurement of Impulse Response of Force Transducers, *Rev. Sci. Instrum.*, **72** (2001), pp. 3108–3111.
12) Fujii, Y.: A Method for Calibrating Force Transducers against Oscillation Force, *Meas. Sci. Technol.*, **14** (2003), pp. 1259–1264.
13) Fujii, Y.: Proposal for a Step Response Evaluation Method for Force Transducers, *Meas. Sci. Technol.*, **14** (2003), pp. 1741–1746.
14) Fujii, Y.: Measurement of Force Acting on a Moving Part of a Pneumatic Linear Bearing, *Rev. Sci. Instrum.*, **74** (2003), pp. 3137–3141.
15) Fujii, Y.: Frictional Characteristics of an Aerostatic Linear Bearing, *Tribol. Int.*, **39** (2006), pp. 888–896.
16) Fujii, Y. and Yamaguchi, T.: Method for Evaluating Material Viscoelasticity, *Rev. Sci. Instrum.*, **75** (2004), pp. 119–123.
17) Fujii, Y. and Yamaguchi, T.: Proposal for Material Viscoelasticity Evaluation Method under Impact Load, *J. Mater. Sci.*, **40** (2005), pp. 4785–4790.
18) Fujii, Y.: Microforce Materials Tester, *Rev. Sci. Instrum.*, **76** (2005), 065111-1-7.