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Balance for Measuring Mass Under Microgravity Conditions

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A method for efficiently and accurately measuring mass under conditions of weightlessness is proposed using the law of conservation of momentum. In this method, the velocities of two different uniform motion states of an object and the reference mass are measured highly accurately using an optical interferometer. For the preparatory experiments on earth, an instrument, with which linear motion of constant velocity is realized using pneumatic linear bearings, is developed. The combined standard uncertainty in mass measurements from 4 to 18 kg by a single collision is estimated to be about $u_c = 0.012$ kg, which corresponds to 0.07% (7×10^{-4}) of the maximum value of 18 kg. For a mass-measurement instrument employed under microgravity conditions, a design for the instrument and a measurement procedure are proposed.

Introduction

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

Mass is measurable as inertial mass by means of acceleration. If mass is measured when acceleration is present, the uniformity and constancy of acceleration must be considered. If the acceleration field is not sufficiently uniform, the density distribution of the object must be considered. If this is not sufficiently constant, the velocity distribution of the object must be considered.

There are some research studies on mass measurement under microgravity conditions. The following principles have been proposed:

1) Use of the characteristic frequency of vibration[1–4]: This method has been widely studied, and its advantage is that it requires a short measurement time. However, as the acceleration field is neither uniform nor constant, both density and velocity distributions of the object must be considered. Therefore, it is difficult to measure masses of nonrigid objects such as elastic objects, grains, and liquids.

2) Use of centrifugal force[3,5]: The advantage of this method is that it uses a constant acceleration field. Its disadvantages are the requirements of a long measurement duration and a large-sized instrument to realize a uniform artificial acceleration field. Determining the position of the center of gravity is the most difficult problem because of the nonuniformity of the acceleration field and nonuniformities of shapes and densities of general objects. If the changes in shape and density are sufficiently small during the measurement, the position of the center of gravity can be determined by giving two discrete arm lengths. The reported[5] uncertainty in measuring a rigid object of about 500 g on earth is on the order of about 2×10^{-4}. This method has potential for yielding highly accurate measurements of a rigid object when a weight-changing system and a reference mass are used.

3) Use of the law of conservation of momentum[3,6,7]: In this method, the momentum change of the object is measured by means of the impulse detected by a force transducer or the momentum change of the reference mass, under the conditions that the law of conservation of momentum is satisfied. In our first proposal,[6] although the velocity of the object is accurately measured by means of an optical interferometer, the momentum change of the object is measured as the impulse acting on a force transducer. In the preparatory experiment on earth, the relative combined standard uncertainty in mass measurements from 2 to 11 kg in a single impact measurement is estimated to be about $u_{c,r} = 0.6 \times 10^{-2}$ (0.6%). For more accurate measurements, we have proposed an improved method in which the impulse is measured using the reference mass instead of the force transducer, which was the largest source of error in the previous experiments. We have also been researching methods based on the law of conservation of momentum, for evaluating the impulse response of force transducers[8] and for determining the instantaneous value of the impact force in crash testing.[9] Pneumatic linear bearings can be used for realizing linear motion on earth with sufficiently small friction.[10]

Experiment

Figure 1 shows the schematic diagram of the experimental setup based on the law of conservation of momentum. Pneumatic linear bearings (Air-Slide TAAG10A-02 manufactured by NTN Co., Ltd., Japan), are attached to tilting stages whose tilt angles are measured using an autocollimator. The maximum weight of the movable part of each bearing is approximately 30 kg, the thickness of the air film is approximately 8 μm, the stiffness of the air film is larger than 70 N/μm, and the straightness of the guideway is better than 0.3 μm/100 mm. The angles of the tilting stages are set so that the movable parts are independently at standstill at the contact position. The masses of the movable parts of the two linear bearings, slide A and slide B, can be adjusted by means of attached masses. The velocity of each movable part is measured as the Doppler-shift frequency of the signal beam of a laser interferometer, and the frequency is measured using electric frequency counters. A Zeeman-type two-frequency He–Ne laser is used as the light source.

The movable parts of the linear bearings are made to collide with each other. The conservation of momentum is expressed as

$$M_A v_{A,1} + M_B v_{B,1} = M_A v_{A,2} + M_B v_{B,2} \tag{1}$$

where M_A and M_B are the masses of the movable parts of slide A and slide B and v_A and v_B are the velocities of the movable parts of slide A and slide B, respectively. The subscripts 1 and 2 represent the conditions for before and after the collision, respectively.

If the mass of slide A, M_A, is calibrated beforehand and the velocities, v_A and v_B, are measured, the mass of the movable part of slide B, M_B, can be calculated as

$$M_B = -(v_{A,1} - v_{A,2})M_A/(v_{B,1} - v_{B,2}) \tag{2}$$

In the experiment, the movable part of slide A with the initial velocity, $v_{A,1}$, is made to collide with the movable part of slide B in the

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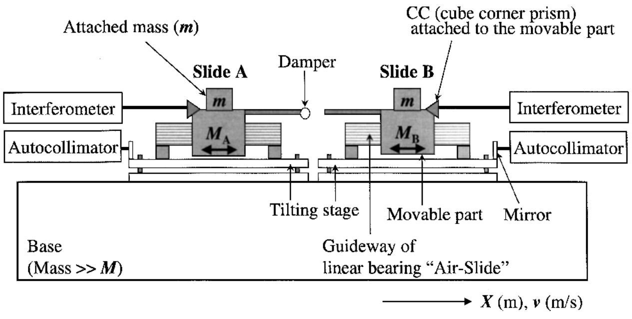

Fig. 1 Experimental setup.

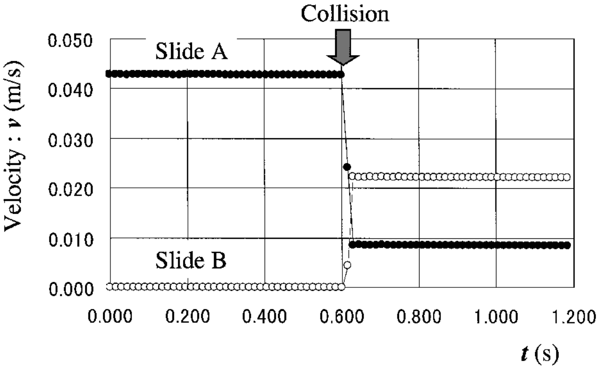

Fig. 2 Velocity change of the moving parts (calibrated masses of the moving parts: $M_{A,C} = 11.782$ kg, $M_{B,C} = 18.128$ kg).

stationary state, $v_{B,1} = 0$. After the collision, the two movable parts separate with the velocities, $v_{A,2}$ and $v_{B,2}$, respectively. A urethane damper 5 mm in thickness is used to reduce the vibration caused by the collision.

We conducted experiments in which the initial velocity of the movable part of slide A and the mass of the movable part of slide B are changed. The initial velocity of the movable part of slide A is given manually by an experimenter. The calibrated mass of the movable part of slide B, $M_{B,C}$, can be assigned any one of four different values of approximately 4.3, 11.7, 11.8, or 18.1 kg by changing the attached metal mass, whereas the calibrated mass of the movable part of slide A, $M_{A,C}$, is fixed at approximately 11.8 kg. In each case, the masses of the movable part of slide A and slide B are calibrated using a conventional balance with a standard uncertainty of about 0.002 kg (0.01% of 18 kg). The velocities of the movable parts, $v_{A,1}$, $v_{B,1}$, $v_{A,2}$, and $v_{B,2}$, are determined as those immediately before or immediately after the collision by means of the linear regression of the 10 data points.

Results

Figure 2 shows the velocity change of the movable parts of slide A and slide B in a measurement. The movable part of slide A, with the initial velocity $v_{A,1} = 0.043$ m/s, is made to collide with the movable part of slide B in the stationary state, $v_{B,1} = 0.000$ m/s. After the collision, the two movable parts separate with the velocities $v_{A,2} = 0.009$ m/s, and $v_{B,2} = 0.022$ m/s, respectively. The momentum changes for slide A and slide B due to collision are approximately −0.4026 (kg m/s) and 0.4024 (kg m/s), respectively. The difference between the momentum slide A loses and the momentum slide B gains is approximately 0.0003 (kg m/s), which corresponds to approximately 0.07% of the momentum change for each slide. On the other hand, the kinetic energies slide A loses and slide B gains are 0.011 and 0.005 m/s^2, respectively. This energy dissipation of approximately 0.006 m/s^2 is thought to occur inside the damper.

Figure 3 shows the difference between the estimated mass $M_{B,E}$ and the calibrated mass $M_{B,C}$ of the movable part of slide B $(M_{B,E} - M_{B,C})$ against the momentum change of the movable part of slide A, $M_{A,C}\ (v_{A,2} - v_{A,1})$, where the subscripts E and C denote estimated and calibrated, respectively. This difference has a mean value of about 7.8 g, and a standard deviation of about 10.2 g.

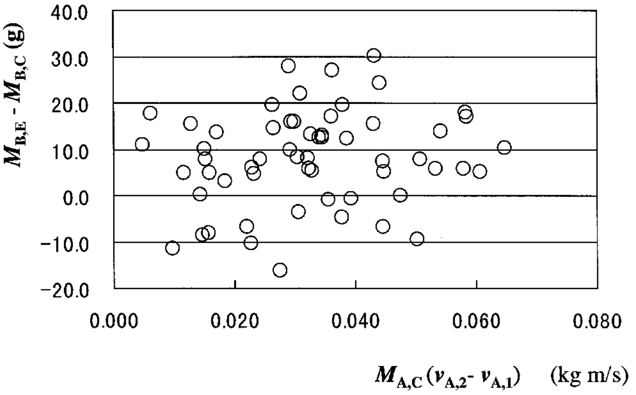

Fig. 3 Difference between the estimated and calibrated masses of the movable part of slide B plotted against the momentum change of the movable part of slide A.

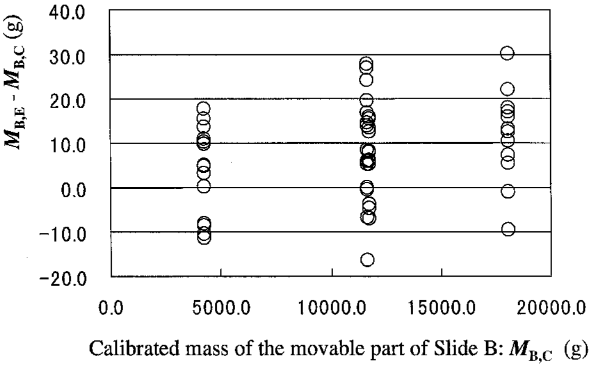

Fig. 4 Difference between the estimated and calibrated masses of the movable part of slide B plotted against its calibrated mass.

Figure 4 shows the difference between the estimated and calibrated masses of the movable part of slide B, $(M_{B,E} - M_{B,C})$, plotted against its calibrated mass, $M_{B,C}$. The root mean square (rms) value of the difference between the estimated mass and the calibrated mass, $(M_{B,E} - M_{B,C})$, is approximately 12.7 g, and the standard uncertainty in the calibrated mass is less than 2 g. Therefore, the combined standard uncertainty in measuring masses of rigid objects between 4 to 18 kg in a single impact measurement is estimated to be about 12.9 g. It corresponds to 0.07% of the maximum value of $M_{B,C}$ of 18.128 kg.

These relatively large magnitudes in the mean value and the uncertainty are thought to come from the attitude vibrations of the movable parts. We see two possible causes. One is the increase and scattering of the frictional force from the guideway part fixed to the base, which acts on the movable part. Another is the change of the relative position of the center of gravity of the movable part against the optical center of the cube corner prism. After the collision, this frictional force sometimes seems to become much larger (up to 10 times) than the measurement results[8] under quiet conditions. To use pneumatic linear bearings for obtaining very small friction, the frictional characteristics under dynamic conditions must be investigated further.

Space Balance

The experimental setup using the pneumatic linear bearings can be used for measuring mass under microgravity conditions, although the pneumatic linear bearings are heavy and occupy a large volume. As for the use of the law of conservation of momentum, microgravity conditions, such as the conditions in the ISS, seem to be ideal for realizing an isolated system composed of the object mass and the reference mass. There seems to be some room for considering a mass-measurement instrument without heavy pneumatic bearings. The following issues need to be considered: 1) How should the velocities of the center of gravity of the two masses be measured? 2) How should the external forces acting on the object mass and the reference mass be eliminated?

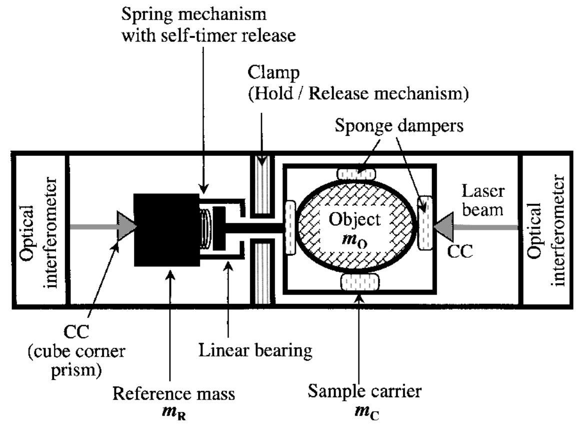

Fig. 5 Proposed balance for measuring mass under microgravity conditions.

Considering these issues, we propose a design for a mass-measurement instrument, which we have termed "space balance," and a measurement procedure. Figure 5 shows a schematic diagram of the proposed balance for accurate and easy mass measurements under microgravity conditions. The carrier, of mass m_C, which holds the object, of mass m_o, by means of sponge dampers, is connected to the reference mass m_R, guided by an ordinary linear bearing with some friction. The measurement procedure is as follows:

Stage 1: When the clamps are released, the carrier and the reference mass are suspended in space without any mechanical contact with the base. Their total angular momentum and linear momentum are almost zero initially and maintain the exact initial values during the measurement if no external force is applied.

Stage 2: The spring-mechanism action is initiated by a self-timer, and the carrier and the reference mass are separated by an internal force; in other words, by the action and reaction forces between the carrier and the reference mass.

Stage 3: If the frictional force of the linear guide F_F is constant or sufficiently small after the spring separates from the carrier, the relative motion between the carrier and object decreases quickly due to the sponge dampers, and they move as one:

$$(m_C + m_o)a_C = -m_R a_R = F_F \tag{3}$$

or

$$(m_C + m_o)\,\mathrm{d}v_C = -m_R\,\mathrm{d}v_R \tag{4}$$

where a_C, a_R, $\mathrm{d}v_C$, and $\mathrm{d}v_R$ are the accelerations of the carrier and reference mass and the velocity changes from the initial values, respectively. The former equation is based on the principle of action and reaction, and the latter equation, which is just a time integration of the former one, is based on the law of conservation of momentum.

The mass of the object m_o is determined as

$$m_o = -(a_R/a_C)m_R - m_C \tag{5}$$

or

$$m_o = -(\mathrm{d}v_R/\mathrm{d}v_C)m_R - m_C \tag{6}$$

The reference and the carrier masses, m_R and m_C, are calibrated in advance. Only one velocity direction is sufficient to determine the mass of the object.

The linear guide is adopted to restrict the relative motion of the carrier holding the object and the reference mass to the linear motion with one degree of freedom. If the reference mass is launched from the carrier without a linear guide, the attitude change and the relative position of the center of gravity with respect to the measurement point must be carefully considered.[11] The measurement points (that is, the optical centers of the cube corner prisms) are positioned for maximal alignment with the centers of gravity of the carrier with the object and the reference mass. This is performed to minimize the sine error caused by angular motion, which occurs due to the initial value of the total angular momentum at the time of stage 1, and the relative rotational motion between the carrier and the object initiated at the time of the stage 2. Some means for monitoring attitude change against the tolerable value, which is set beforehand, may be necessary to ensure high accuracy.

If the vibration of the sponge dampers and/or the spring mechanism cannot be ignored, the acceleration must be measured at the center of oscillations even for the measurement of a rigid object. For nonrigid objects such as liquids, powders, or grains, the acceleration must be measured at the center of oscillations. In this case, the nonrigid objects should be tightly placed in an appropriate container, to make the oscillation period sufficiently small compared with the measurement period. For measuring the mass of an astronaut, it is suitable to use a bed with a constraint band as the carrier, with a linear guide connected to the head or foot of the bed.

For designing the hold/release mechanism, weight changers employed in the accurate balances for the prototype kilogram might be a good reference.

For highly accurate measurements, the air frictional force as an external force and the refractive index of air must be considered, in addition to the above factors. One solution may be evacuating the entire system. Of course, in this case, the mass change of the object caused by adsorption and absorption of gases must be considered.[12]

Conclusions

We propose a method, based on the law of conservation of momentum, for efficiently and accurately measuring mass under conditions of weightlessness. For the preparatory experiments on earth, an instrument, with which linear motion of constant velocity is realized using pneumatic linear bearings, is developed. The combined standard uncertainty in mass measurements from 4 to 18 kg by a single collision is estimated to be about $u_c = 0.012$ kg, which corresponds to 0.07% (7×10^{-4}) of the maximum value of 18 kg. For a mass-measurement instrument employed under microgravity conditions, a design for the instrument and a measurement procedure are proposed.

References

[1]Thornton, W., and Ord, J., "Specimen Mass Measurement," NASA TR N74-11867, 1974.

[2]Oakey, W. E., and Lorenz, R., "Survey and Experimental Testing of Nongravimetric Mass Measurement Devices," NASA TR N77-26456, 1977.

[3]Beyer, N., Lomme, J., McCollough, H., Price, B., and Weber, H., "Proposal for an Astronaut Mass Measurement Device for the Space Shuttle," NASA TR N95-14854, 1995.

[4]Ono, T., Uozumi, H., Honda, O., and Nagata, K., "Mass-Measurement Under Weightless Conditions by the Frequency-Controlled Method," *Measurement*, Vol. 22, No. 3–4, 1997, pp. 87–95.

[5]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*, European Space Research and Technology Center, Noordwijk, The Netherlands, 1998, pp. 93–98.

[6]Fujii, Y., Fujimoto, H., and Namioka, S., "Mass Measurement Under Weightless Conditions," *Review of Scientific Instruments*, Vol. 70, No. 1, 1999, pp. 111–113.

[7]Mizuno, T., Minowa, J., and Araki, K., "Mass Measurement Based on the Law of Conservation of Momentum," *Proceedings of the 38th SICE Annual Conference*, Society for Instrumentation and Control Engineering of Japan, Tokyo, 1999, pp. 865–868.

[8]Fujii, Y., and Fujimoto, H., "'Measurements of Frictional Characteristics of a Pneumatic Linear Bearing," *Meas. Sci. Technol.*, Vol. 10, No. 5, 1999, pp. 362–366.

[9]Fujii, Y., and Fujimoto, H., "Proposal for an Impulse Response Evaluation Method for Force Transducers," *Meas. Sci. Technol.*, Vol. 10, No. 4, 1999, pp. N31–33.

[10]Fujii, Y., Isobe, D., Saito, S., Fujimoto, H., and Miki, Y., "A Method for Determining the Impact Force in Crash Testing," *Mechanical Systems and Signal Processing* (to be published).

[11]Fujii, Y., Shiota, F., Miki, Y., Nakayama, K., and Morokuma, T., "Vertical Displacement Determination of a Levitated Superconducting Mass," *IEEE Transactions on Instrumentation Measurement*, Vol. 48, No. 2, 1999, pp. 200–204.

[12]Fujii, Y., Shiota, F., Miki, Y., Nezu, Y., Makishita, T., and Hara, K., "A Buoyancy-Free Mass Comparator with Precision Better than 10^{-6} for Use in a Superconducting Magnetic Levitation System," *IEEE Transactions on Instrumentation and Measurement*, Vol. 46, No. 2, 1997, pp. 609–612.

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