Small mass measurement system for use under microgravity conditions

Koichi Maru a, *, Yusaku Fujii a, Kazuhito Shimada b

 aDepartment of Electronic Engineering, Gunma University, Kiryu Gunma 376-8515, Japan
 bJAXA Houston Office, Japan Aerospace Exploration Agency (JAXA), 100 Cyberonics Blvd., STE201 Huston, TX 77058, USA

Abstract

Small mass measurement system under microgravity conditions is described. The proposed method, based on the Levitation Mass Method, uses the law of conservation of momentum. In the proposed method, the force acting to the base from the Space Balance and the acceleration of the carrier of the object are measured, and the mass is derived based on the Newton equation of motion. Compact instruments for measuring small mass under microgravity conditions are proposed.

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1. Introduction

High precision measurements of physical quantities have been highly required in space-station factories, laboratories, and space exploration programs. 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 and steady gravitational acceleration field. High-accuracy and compact instruments for small mass measurements will be required on space stations such as the International Space Station (ISS). However, only a few low-accuracy 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. Some methods for mass measurement under microgravity conditions have been proposed such as the use of the characteristic frequency of vibration [1-4], the use of centrifugal force [3,5], and the use of the law of conservation of momentum [3,6-9].

In the method using the law of conservation of momentum, the momentum change of the object is measured by means of the impulse detected with 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 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 kg to 11 kg in a single impact measurement is estimated to be about $0.6 \times 10^{-2}$ (0.6%). For more accurate measurements, we have proposed an improved method [7] 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. The combined standard uncertainty in mass measurements from 4 kg to 18 kg by a single collision is estimated to be about 0.012 kg, which corresponds to $0.07\% \ (7 \times 10^{-4})$ of the maximum value of 18 kg. For a mass-measurement instrument employed under microgravity conditions, a design for a measurement procedure the instrument named “Space Balance” have been proposed [6,7].

This method is based on the Levitation Mass Method (LMM), which has been proposed and developed by the second author. In the LMM, the inertial force of a mass levitated by a pneumatic linear bearing is used as the reference force applied to the objects under test. The inertial force of the levitated mass is measured using an optical interferometer. The second author has proposed calibration methods for the dynamic force calibration [8-10], a method for investigating the frictional characteristics of pneumatic linear bearings [11,12], and a method for material testing [13-15]. For the method for generating and measuring a micro-Newton level forces, the force acting on the mass from the material under test of about 0.1 mN was successfully measured with the standard uncertainty of approximately $1.4 \, \mu \text{N}$ [15].

In this paper, a method of small mass measurement system under microgravity conditions is described. The proposed method, based on the LMM, uses the law of conservation of momentum. In the proposed method, the force acting to the base from the Space Balance and the acceleration of the carrier of the object are measured, and the mass is derived based on the Newton equation of motion. Compact instruments for measuring small mass under microgravity conditions are also proposed.

2. Concept

![Fig. 1. Proposed Space Balance for small mass measurement using force transducer and accelerometer.](image)

Figure 1 illustrates the proposed Space Balance for small mass measurement. The carrier which holds the object is connected to the base guided by a linear guide with some friction. Here, the mass of the carrier is $m_c$ and the mass of the object under test is $m_o$. The outside of the guide is attached to a force transducer. The instrument is attached to the base with sufficiently large mass, such as the frame of a space station. In the measurement, the carrier of the object accelerates and separates from the base with sufficiently large mass under the guidance of the linear guide. During the measurement, the force acting to the base from the Space Balance, $F$, is measured with a force transducer, and the acceleration of the carrier of the object, $a$, is measured with an accelerometer attached to the carrier of the object. The mass of the object, $m_o$, is calculated as
The use of the micro-electro-mechanical-systems (MEMS)-type accelerometer would enable us to achieve very compact instrument.

In this structure, the mass can be accurately measured even if some small friction occurs at the linear guide because the friction affects both the force measured with the transducer and Eq. (1) holds even under the existence of the friction.

3. Experiment

Figure 2 illustrates the experimental setup for the preparatory experiment on earth. A pneumatic linear bearing (Air-Slide TAAG10A-02, NTN Co., Ltd., Japan) is used to realize a linear motion of the object with negligibly small friction on earth. The maximum weight of the moving part is approximately 30 kg, the thickness of the air film is approximately 8 μm, the stiffness of the air film is more than 70 N/μm, and the straightness of the guideway is better than 0.3 μm/100 mm. The frictional characteristics are determined using the developed method [11,12]. The bearing is attached to a tilting stage. The angle of the tilting stage is set so that the moving part is at a standstill at the position of contact with the transducer.

![Experimental setup for preparatory experiment.](image)

The moving part of the linear bearing is made to collide with the force transducer (LM-10KA, Kyowa Co. Ltd., Japan). The initial velocity of the moving part is manually given. The moving part travels toward the left until it bounds at the force transducer attached to the base. The origins of the time axis and the position axis are set to be the time and the position where the reaction force applied to the object is detected, respectively. The total mass of the moving part, \( M \), is 4.1182 kg. The mass of the object \( m \) is determined as

\[
m = \frac{F}{a} - m_o.
\]

(1)

where \( F \) is the force measured using the force transducer and \( a \) is the acceleration measured using an optical interferometer.

The output signal of the force transducer is measured with a digital voltmeter (3458A, Agilent Technologies, Inc., USA) with a sampling interval of 0.1 ms. The force transducer is calibrated under static conditions with the relative standard uncertainty of approximately 0.1%. However, the difference between the dynamic characteristics and the static characteristics of the transducer is unknown, since there are no dynamic calibration methods for force transducers available at present.

The main difference between the instrument shown in Fig. 1 and experimental setup is the method for measuring the acceleration. The acceleration of the mass is calculated from the velocity of the moving part by using a heterodyne interferometer. A Zeeman-type two-frequency He-Ne laser is used as the light source, and the frequency
difference between the signal beam and the reference beam, $f_{\text{beat}}$, is measured from an interference fringe appearing at the output port of the interferometer. The velocity is measured as the Doppler shift frequency of the signal beam of a laser interferometer, $f_{\text{Doppler}}$, which can be expressed as

$$v = \frac{\lambda_{\text{air}} f_{\text{Doppler}}}{2},$$

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

where $\lambda_{\text{air}}$ is the wavelength of the signal beam under the experimental conditions, and $f_{\text{rest}}$ is the rest frequency which is the value of $f_{\text{beat}}$ (approximately 2.6 MHz) when the moving part is at a standstill. The $f_{\text{beat}}$ varies around $f_{\text{rest}}$ depending on the velocity of movement. An electric frequency counter (R5363; Advantest Corp., Japan) continuously measures and records the value of $f_{\text{beat}}$ 2000 times with a sampling interval of 400/$f_{\text{beat}}$. This counter continuously measures the interval time of every 400 periods without dead time. The sampling period of the counter is approximately 1.5 ms at a frequency of 2.6 MHz. Another electric counter (TA-1100; Yokogawa Electric Corp., Japan) measures the value of $f_{\text{rest}}$ by using the signal from a photodiode embedded inside the He-Ne laser.

The 10-MHz reference frequency generated by a crystal oscillator in an oil bath is supplied to the digital voltmeter and the two electric counters. Measurements using the digital voltmeter and the two electric counters are triggered by means of a sharp trigger signal generated using a digital to analog converter. This signal is initiated by a light switch.

4. Results

Figure 3 plots the data processing procedure for calculating the velocity $v$ (m/s) and the acceleration $a$ (m/s$^2$) from the Doppler shift frequency $f_{\text{Doppler}}$ (Hz) obtained by the optical interferometer and the electric counter. During the collision experiment, only the beat frequency, $f_{\text{beat}}$ and the rest frequency, $f_{\text{rest}}$, are measured highly accurately using the optical interferometer. The sign of the Doppler shift frequency changes before and after collision due to the change in the direction of motion. The full width at half maximum (FWHM) of the impulse is approximately 32.8 ms.

Figure 4 plots the change in force measured using the force transducer. The maximum value of the measured force is 35.0 N.

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![Graphs showing Doppler shift frequency, velocity, and acceleration](image-url)
Figure 5 plots the value of $F/a$ estimated from force measured using force transducer, $F$, and acceleration measured using optical interferometer, $a$. The value of $F/a$ corresponds to the mass measured by the instrument. The calibrated value of the mass of 4.1182 kg is also indicated in Fig. 5.

Figure 6 plots the value of $F/a$ around the impulse. The average value and the standard deviation of $F/a$ within the FWHM (the time interval from 7.8 ms to 40.6 ms) are approximately 4.130 kg and 0.097 kg, respectively. The difference between the average value of $F/a$ of approximately 4.130 kg and the calibrated value of approximately 4.1182 kg is approximately 0.012 kg. This corresponds to 0.3% of the calibrated value of approximately 4.1182 kg. The root means square (RMS) value of the difference between the instantaneous value of $F/a$ and the calibrated value of 4.1182 kg is approximately 0.098 kg.
Fig. 6. Estimated value of $F/a$ around impulse. The calibrated value of the mass of 4.1182 kg is also shown in this figure.

5. Discussions

Fig. 6 indicates that the estimation of the mass from the instantaneous value of force measured using the force transducer and acceleration measured using the optical interferometer can be well done because RMS value of the difference between the instantaneous value of $F/a$ and the calibrated value of 4.1182 kg is sufficiently small (approximately 0.098 kg; this corresponds to 2.4% of the calibrated value). If the average value of $F/a$ during the period of approximately 30 ms is used, the error is reduced to 0.3%.

The difference between the dynamic characteristics and the static characteristics of the force transducer is thought to be the dominant cause of the measurement error. In the experiment, a relatively sharp impulse with the FWHM of the impulse is approximately 32.8 ms is used. If the impulse is more moderate, the measurement error might be much smaller.

Figure 7 illustrates another structure of the proposed Space Balance. In this instrument, a compact integrated laser Doppler velocimeter (LDV) or linear encoder is attached to the carrier instead of the accelerometer in Fig. 1. In typical accelerometers, the acceleration is derived by measuring the displacement of a balance weight inside the accelerometer. It can cause the uncertainty of the measured acceleration. On the other hand, the instrument using an LDV or linear encoder can directly measure the acceleration of the object as the derivative of the velocity or the second derivative of the displacement. The authors proposed [16] a concept of waveguide-type compact LDVs using...
planar lightwave technology [17-23]. Combining this concept with an integration technique of active devices (laser diodes and photodetectors) has the possibility to achieve very small LDV and linear encoder. It can lead to the possibility for measuring very small mass under microgravity conditions.

6. Conclusion

Small mass measurement system under microgravity conditions is described. The proposed method, based on the Levitation Mass Method, uses the law of conservation of momentum. In the proposed method, the force acting to the base from the Space Balance and the acceleration of the carrier of the object are measured, and the mass is derived based on the Newton equation of motion. Compact instruments for measuring small mass under microgravity conditions are proposed using an accelerometer, LDV, or linear encoder.

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