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Astronaut mass measurement using linear acceleration method and the effect of body non-rigidity

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Astronaut's body mass is an essential factor of health monitoring in space. The latest mass measurement device for the International Space Station (ISS) has employed a linear acceleration method. The principle of this method is that the device generates a constant pulling force, and the astronaut is accelerated on a parallelogram motion guide which rotates at a large radius to achieve a nearly linear trajectory. The acceleration is calculated by regression analysis of the displacement versus time trajectory and the body mass is calculated by using the formula $m=F/a$. However, in actual flight, the device is instable that the deviation between runs could be 6–7 kg. This paper considers the body non-rigidity as the major cause of error and instability and analyzes the effects of body non-rigidity from different aspects. Body non-rigidity makes the acceleration of the center of mass (C.M.) oscillate and fall behind the point where force is applied. Actual acceleration curves showed that the overall effect of body non-rigidity is an oscillation at about 7 Hz and a deviation of about 25%. To enhance body rigidity, better body restraints were introduced and a prototype based on linear acceleration method was built. Measurement experiment was carried out on ground on an air table. Three human subjects weighing 60–70 kg were measured. The average variance was 0.04 kg and the average measurement error was 0.4%. This study will provide reference for future development of China's own mass measurement device.

astronaut, mass measurement, linear acceleration, body non-rigidity

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Among the fundamental physical quantities, such as time, mass, temperature, and length, mass is probably the only quantity that is unmeasurable in space using conventional methods. As human beings are staying longer and longer in space, measuring mass in the microgravity environment, especially the human body mass, is in great need because body mass is a fundamental index for human health care. Astronauts suffer body mass loss in space due to loss of water, muscle, and nutrition, and too much mass loss over time or a sudden change in body mass implies a possible illness of astronauts. And also, measuring body mass in microgravity provides valuable data for microgravity life science research, such as the study of microgravity effect on human metabolism and bone loss.

1 Mass measurement methods

Conventional methods could not function in a microgravity environment because they actually measure the weight induced by earth gravity. In space environment, other principles have to be employed. The current mass measurement methods for use in microgravity can be divided into four types.

Natural frequency of oscillation [1–3]. The measuring mass is oscillated and the oscillation frequency or the time period of each oscillation is measured. The system stiffness (spring constant) is known or pre-calibrated, and the mass can be calculated by comparing the frequency with that of a reference mass, or by using the equation:

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$$T = 2\pi\sqrt{\frac{m}{k}}, \tag{1}$$

where T is the period of oscillation, and k is the system stiffness.

Preservation of momentum [4,5]. This method is implemented by collision. A reference mass m_r and the measuring mass m collide with each other and velocity change of the two masses after collision is measured. The mass is then calculated by using the equation:

$$m\Delta v = m_r \Delta v_r, \tag{2}$$

where Δv_r is the velocity change of the center of mass (C.M.) of reference mass, and Δv is the velocity change of C.M. of the measuring mass.

Centrifugal force of rotation [6–8]. The measurement of mass is rotated at a certain radius and angular velocity. The centrifugal force is measured by a force transducer and the angular velocity is easily controlled at a certain value, such that the mass can be calculated by using the equation:

$$m = \frac{F}{\omega^2 r}, \tag{3}$$

where ω is the angular velocity, F is the centrifugal force, and r is the rotational radius of C.M..

Linear acceleration [9–11]. The measurement of mass is accelerated along a linear trajectory by applying a pulling force or directly controling the accelerating motion. The acceleration and applied force are measured and the mass is calculated by using the Newton's Second Law:

$$m = \frac{F}{a}, \tag{4}$$

where a is the acceleration of C.M., and F is the corresponding applied force.

The linear acceleration method is so far the most promising method while the other three methods have difficulties in measuring non-rigid objects, especially a non-rigid object as large as human body. The reason is that non-rigid object oscillates unwantedly during motion, and the C.M. may change, making it impossible to measure certain quantities of the C.M., like the velocity and position. As for the linear acceleration method, if the acceleration were controlled constant, it would be an exact simulation of earth gravity, for the constant force, weight, is replaced by another inertial force. Therefore, the method theoretically works for all kinds of subjects, rigid and non-rigid, solid and liquid.

The latest NASA space linear acceleration mass measurement device (SLAMMD) on the ISS employs the linear acceleration method. The device generates a known constant pulling force to achieve constant acceleration. The acceleration is calculated by regression analysis of displacement and the corresponding time.

2 Linear acceleration method and device

A prototype device of this kind was built based on the SLAMMD design with several improvements.

The device consists of a constant force generator, a parallelogram motion guide, body restraints, an optical angle encoder, a load cell, and a microcontroller. The device configuration is shown in Figure 1.

The constant force generator generates a constant pulling force and accelerates the human body constantly. The human body is attached to body restraints and guided by a parallelogram motion guide. The optical angle encoder detects the acceleration a, the load cell measures the applied

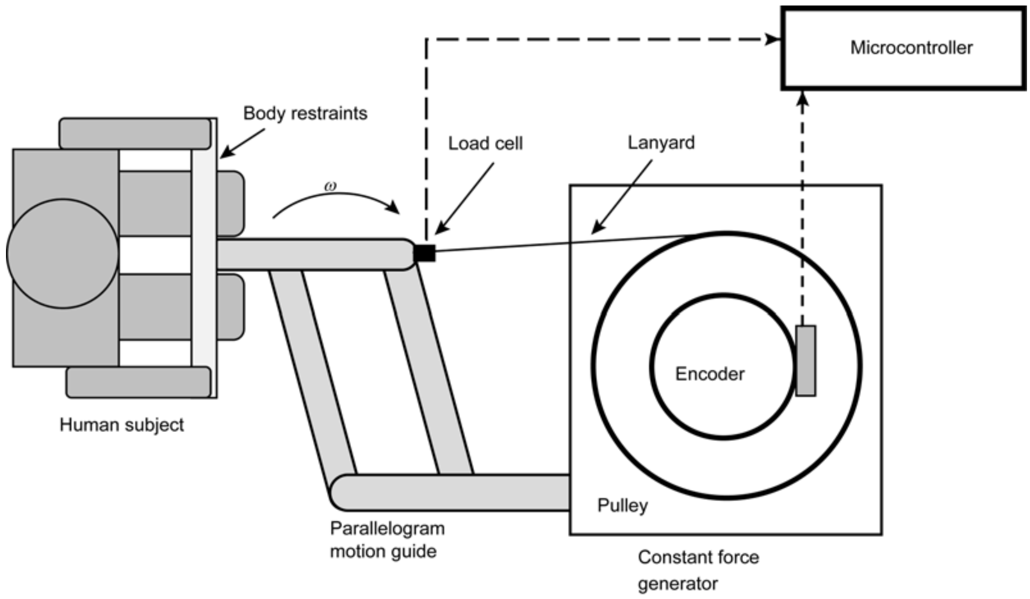

Figure 1 Configuration of linear acceleration device.

force F, and the microcontroller calculates the mass m.

The constant force generator is a spring-cam structure as shown in Figure 2. The cam profile is specially designed so that when springs extend, the pulling force applied to the cam increases and the radius of cam decreases, resulting in a constant torque on the shaft and further resulting in a constant force on the co-shafted pulley.

With the rotation of motion guide, a human body runs a circular path instead of a linear one. Within a small rotation angle, angular acceleration is constant and the circular trajectory is a good approximation of a linear one.

The optical encoder outputs rectangular impulses as pulley rotates. By timing each impulse, a series of displacement, S, and corresponding time, T, can be recorded. The acceleration is calculated by second order polynomial regression analysis of S-T trajectory using standard least square method.

The load cell can simultaneously measure the pulling force in the moving direction. The measurement of force is synchronized with an optical encoder and the average of the pulling force is calculated for mass calculation. The load cell is also used for in-flight calibration because the major changing factor is the pulling force. In this way, the pulling force for mass calculation is always the latest actual value, and no particular calibration procedure is needed, which would significantly simplify the in-flight operation of the device compared with the SLAMMD.

The SLAMMD was launched in 2007. On the ISS, it undertook several performance studies but no operational studies. The theory is perfect. But in actual flight, SLAMMD measurements are not stable enough. Results of different runs can be greatly different. As much as 6 kg of deviation has been experienced [12]. Also, the operation of SLAMMD is complicated. A complete install takes around 20 min. The in-flight calibration is also time consuming. The SLAMMD has not been used for several years [13].

3 Effect of body non-rigidity

The non-rigidity of human body is the major cause of errors and instability.

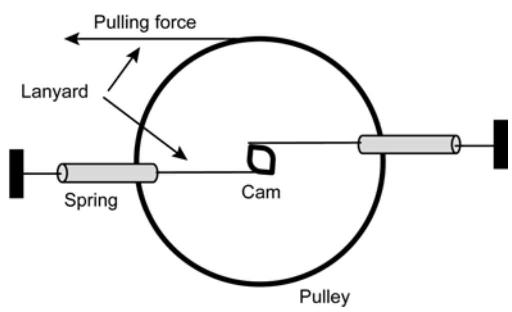

Figure 2 Principle of the constant force generator.

The acceleration in eq. (4) has to be that of C.M.. For a non-rigid object, C.M. is unknown, and the acceleration of C.M. cannot be directly measured. In fact, the device measures the acceleration of body restraints instead. When suddenly accelerated, non-rigid parts will fall behind rigid parts and a human body will slosh and jitter. This makes C.M. changeable and the measured acceleration is different from that of C.M.. When given enough motion time and motion distance, a non-rigid object will eventually settle to reach a uniform acceleration. However, meters of motion distance may be needed [11], which is unacceptable in space. Therefore the body non-rigidity is still a problem to cope with.

The effect of human body non-rigidity can be described in the following aspects.

3.1 Non-rigidity of non-musculoskeletal parts

This mainly refers to the oscillation of inner organs of humans, such as heart and lungs. These parts are soft and have no strong force to support them inside the human body. This can be described as the dynamic response of a human body. NASA suggested a single mass-spring model [14] to describe a human body, as shown in Figure 3(a). A human body is composed of 80% of rigid mass and 20% of non-rigid mass. Connecting the two masses is a spring and a dashpot. The model has an undamped natural frequency of 2 Hz and a damping coefficient of 0.5. The value of k and b can be derived as:

$$k=\left(2\pi f\right)^2 m\approx 157.9m,\quad b=2\zeta\left(2\pi f\right)m\approx 12.6m,$$

where m is the body mass. Figure 3(b) shows a simulation of the acceleration curve of the two masses, where the pulling force is 20 N and the mass is 80 kg. The acceleration of

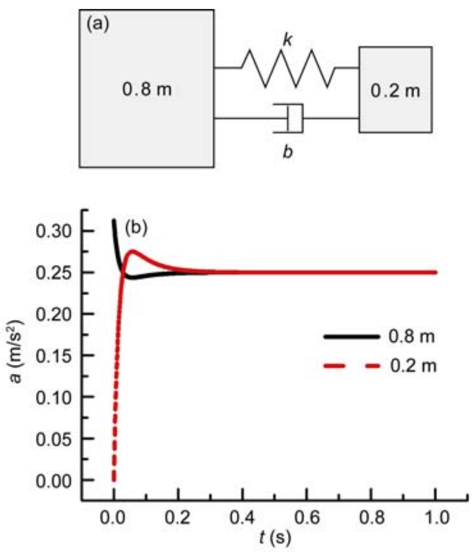

Figure 3 (a) A possible body model suggested by NASA; (b) settle time for this model.

rigid part is ahead of that of C.M., while the acceleration of non-rigid part falls behind. About 0.3 s is needed for the body to settle. Assume the acceleration of rigid part is accurately measured and used for calculation, the deviation from the acceleration of C.M. would be approximately 2.5%. For other models [15], settle time would be more complicated.

3.2 Non-rigidity of musculoskeletal parts

This refers to relative motion of body joints, such as head, spine, arms, and legs. A human body has to be attached to certain body restraints to be accelerated and measured. Practically only a few parts can be attached. The other parts will show different motion status and thus errors occur for the measurement of C.M..

Figure 4 shows how a body is restrained for the SLAMMD. Only the knees, hands, and chin are in direct contact with the body restraints. Upon acceleration, the trunk of body will fall behind. When the human subject senses the acceleration, he will increase muscle strength to pull the trunk to maintain original posture. Thus an oscillation will occur.

To observe the effect, a rigid subject and eight human subjects were measured on the prototype. Figure 5 shows a comparison of measured acceleration curves. The curve of rigid mass is nearly a horizontal straight line while those of human body are much curvier. Low frequency oscillation can be observed in the figure. Judging from eight tested human subjects, the oscillation frequency is around 7 Hz and deviation is around 0.05 m/s^2 (approximate 25%). This factor is individual dependent and may even change from

Figure 4 SLAMMD body restraints.

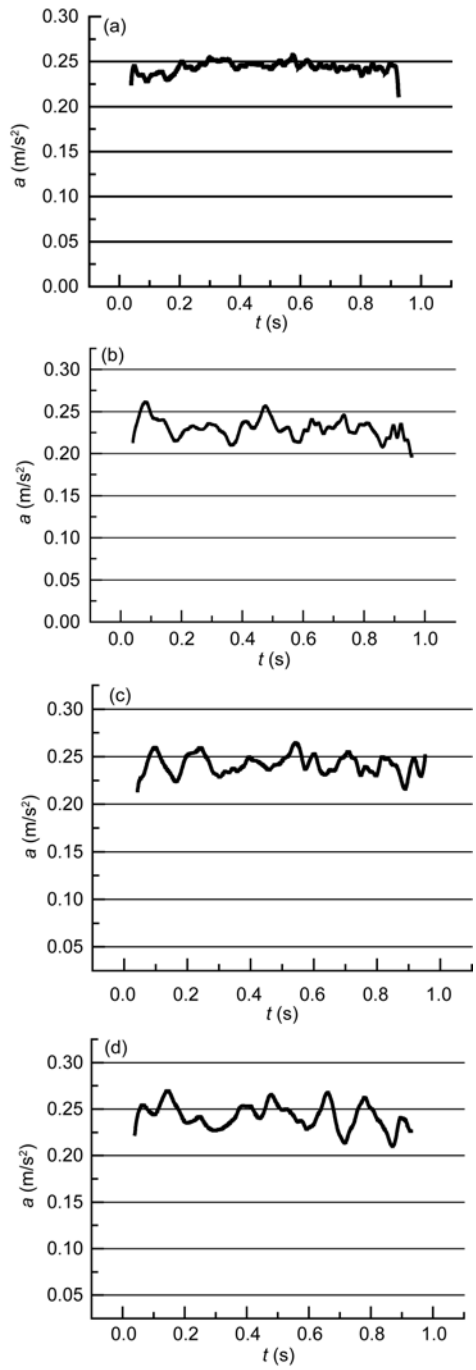

Figure 5 (a) Typical acceleration curve of rigid subject; (b)–(d) typical acceleration curve of different human subjects with similar body mass.

run to run for the same subject.

4 Improvement and experiments

The improvement of body restraints is the best way to reduce the effect of non-rigidity.

The major non-rigid parts of human body are the abdominal, head, and arms and legs. The principle of body restraint is to restrain each body part in both forward and backward directions. Moreover, the body should be fully stretched so that little movement can be made.

For the SLAMMD, the human head is only positioned but not restrained. To keep the head on the head support, the abdominal may not firmly contact with the body restraints. Also no hand grips exist and the arms are free to move.

An improved configuration is given in Figure 6. The hip and abdominal are pushed and fixed. Restraints for feet, legs, and arms are a distance away so that the body is fully stretched. The head has no support but is held by his own hands, so that people with different heights can adapt to this configuration.

The performance of this body restraints was tested on ground on an air table. Air tables are widely used in satellite control system simulation [16]. An air table consists of several plate-shaped air bearings and a large flat table. High-pressure air runs beneath the air bearing so that it can move almost frictionlessly on the table. Thus a two degree-of-freedom of microgravity is simulated. Figure 7 shows a picture of air table experiments.

Three human subjects, weighing 69.0, 63.4, and 62.7 kg respectively, were tested using the improved body restraints. Each subject took 6 measurements. The results are given in Figure 8(a). The average variance was about 0.04 kg and average measurement error was about 0.4%. As a comparison, six human subjects, weighing 58.4, 57.6, 55.5, 58.1, 56.9, and 57.7 kg respectively, were tested on another device with SLAMMD type body restraints. Each subject took 3 measurements. The results are given in Figure 8(b). The average variance was about 0.5 kg and average measurement error about 1.4%.

5 Remarks and conclusions

(1) Mass measurement in space has not been well solved.

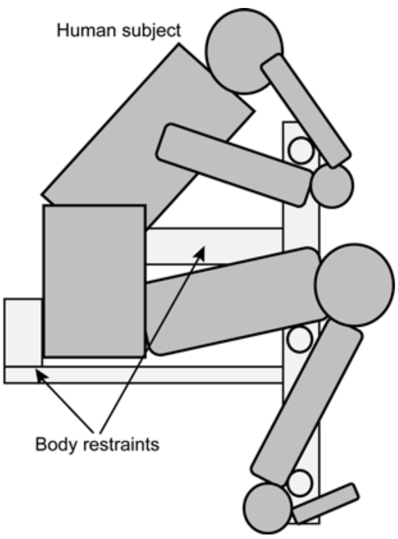

Figure 6 An improved configuration of body restraints.

Figure 7 Air table experiments (subject not in proposed posture).

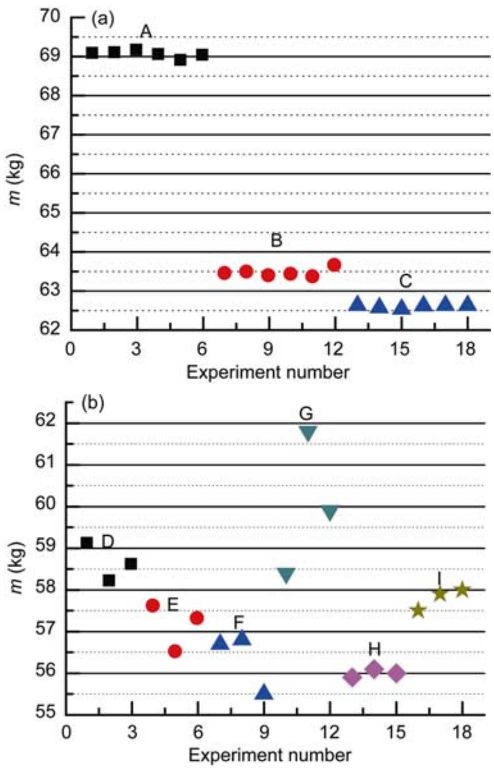

Figure 8 Human subjects measurement results. (a) Using improved posture; (b) using SLAMMD type posture.

Currently, the linear acceleration method is theoretically most suitable for non-rigid objects like human bodies. Prototype tested on ground has shown satisfactory accuracy. The implementation using constant force plus parallelogram guide is optimal and practical for space environment because it requires little energy and operational space. With the availability of more operational space, the linear acceleration method may eventually become as accurate and convenient as those conventional mass measurement methods on ground.

(2) The fundamental source of error is the non-rigidity of human body which results in an oscillation of C.M.. It is difficult to establish a detailed model because it is individual dependent and posture dependent. Better body restraints, which prevent each body part from moving forward nor backward, will significantly improve measurement accuracy and stability. Experiments showed that measurement error of prototype has reduced from about 1.4% to about 0.4%. If operated in real flight, the improved configuration may not work as well as on-ground experiments because the existence of earth gravity will help human subject to maintain his posture. However, significant improvement should be promising.

(3) The training of human subjects is another important factor to reduce measurement error. A well trained subject adapts better to the sudden acceleration motion and is more probable to hold his posture without introducing great distortion in acceleration. Measurement variance and error of subject A was 0.18 kg and 0.98% respectively when he first undertook experiment without any training. After several tens of measurements, measurement variance and error of subject A was 0.06 kg and 0.12% respectively.

(4) As China is planning its own space station, this study will provide reference for future development of China's own measurement device.

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