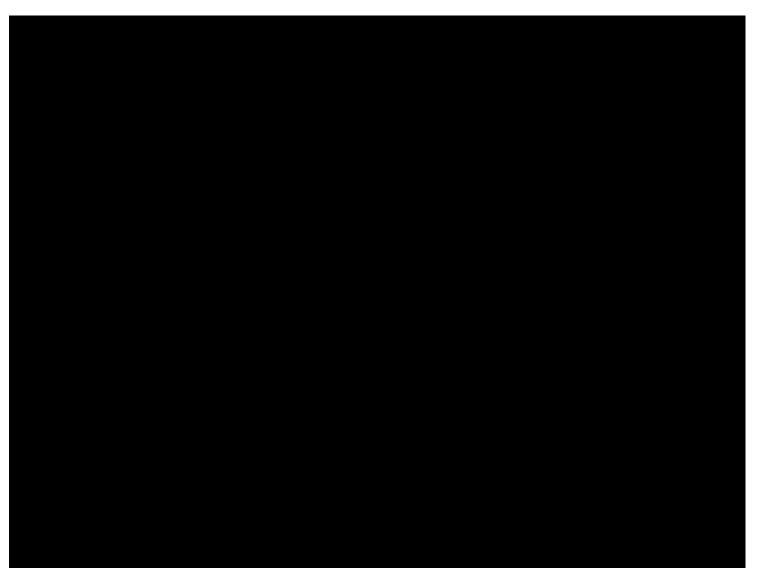




# Introduction of Fujii Lab. by NHK



#### Contents of the Presentation

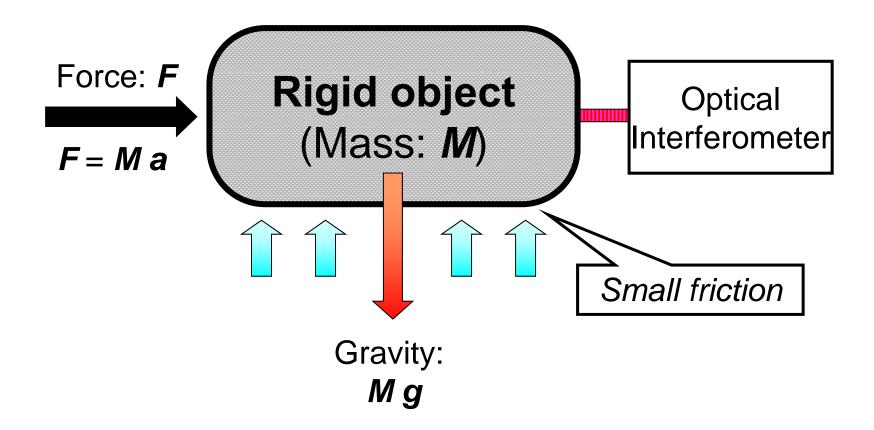
## Introduction to the Levitation Mass Method (LMM)

- Principle of the LMM
- Variations of the LMM
- Example of its application as material tester

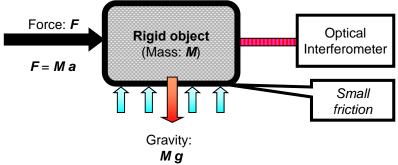
# **History of the LMM**

- Mass measuring instrument for the ISS (Space Balance)
- Dynamic force calibration
- Friction measurement of linear air-bearing
- Material tester

#### The Levitated-Mass Method

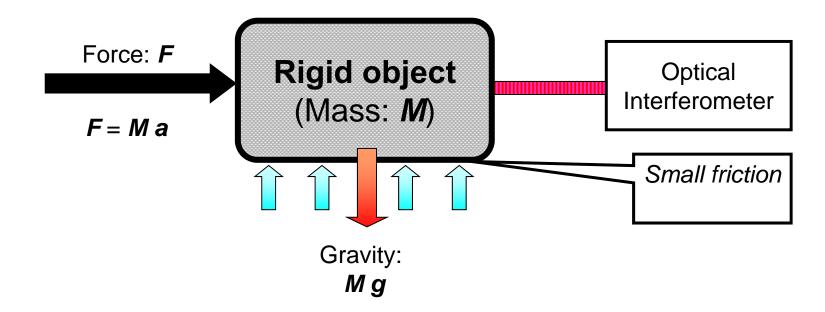


## The Levitation Mass Method Proposed by the Author





#### The Levitation Mass Method Proposed by the Author



Force is measured as the inertial force of a mass levitated with an airbearing.

The Doppler frequency shift of a laser beam reflecting on the mass is accurately measured using an optical interferometer.

The velocity **v**, position **x**, acceleration **a** and inertial force **F** of the mass are calculated from the measured time-varying Doppler shift **f**.

#### Present Problems on Dynamic Force Calibration

There is not any dynamic calibration method for force transducers.



The following two major problems arise when varying force is measured using a force transducer.

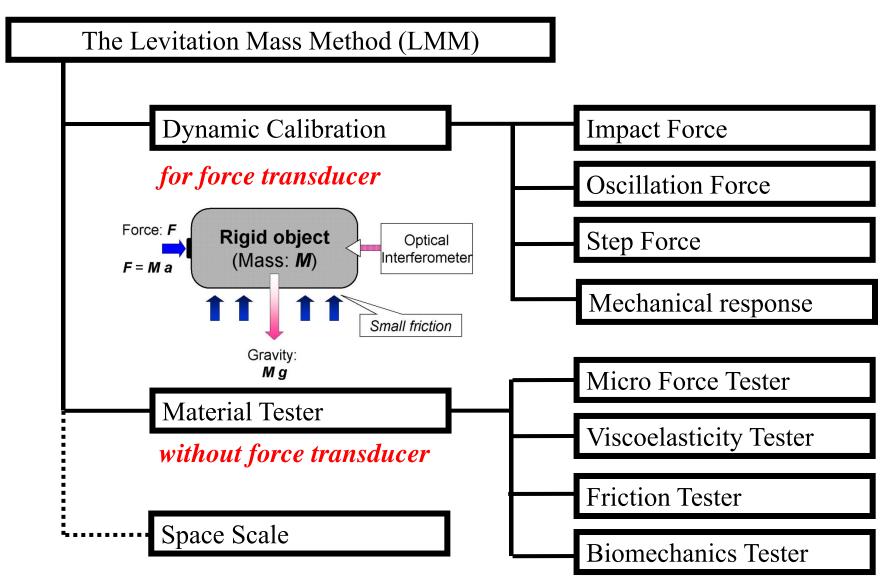
1<sup>st</sup> problem: It is impossible to determine the uncertainty of measured value of the varying force properly.

**2<sup>nd</sup> problem:** It is impossible to determine the distortion of the time axis.

The proposed method is free from these problems.

## Applications of the LMM

The LMM has shown the extreme high performance in the following fields.



# Publications on LMM in Measurement Science and Technology

(2006 Impact Factor: 1.228)

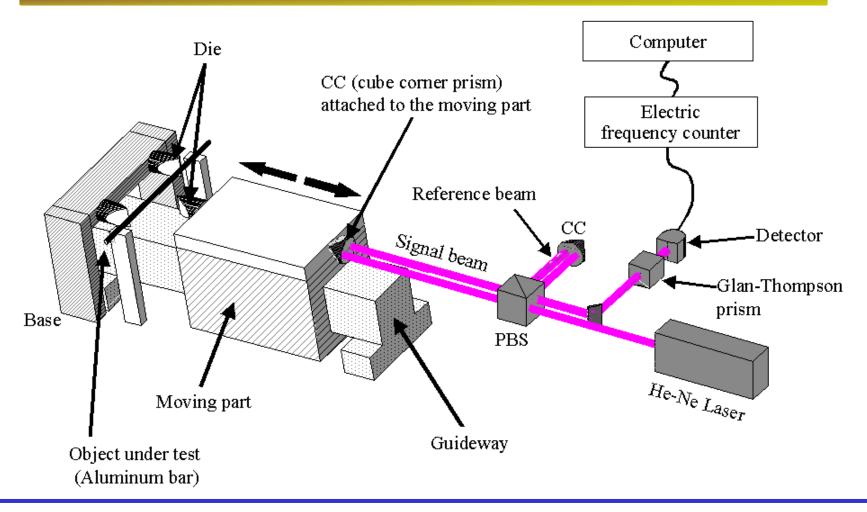
- Y. Fujii and H. Fujimoto, "Proposal for an impulse response evaluation method for force transducers", *Meas. Sci. Technol.*, Vol. 10, No.4 pp. N31-N33, 1999.
- Y. Fujii and H. Fujimoto, "Measurements of frictional characteristics of a pneumatic linear bearing", *Meas. Sci. Technol.*, Vol.10, No.5, pp.362-366, 1999.
- Y. Fujii, K. Ogushi and T. Tojo, "A proposal for a dynamic-response-evaluation method for torque transducers", *Meas. Sci. Technol.*, Vol.10, No.12, pp. N142-N144, 1999.
- Y. Fujii, "Proposal for a step response evaluation method for force transducers", *Meas. Sci. Technol.*, Vol. 14, No.10, pp. 1741-1746, 2003
- Y. Fujii, "A method for calibrating force transducers against oscillation force", *Meas. Sci. Technol.*, Vol. 14, No.8, pp. 1259-1264,2003.
- Y. Fujii, "Measurement of steep impulse response of a force transducer", *Meas. Sci. Technol.*, Vol. 14, No.1 pp. 65-69, 2003.
- Y. Fujii and T. Yamaguchi, "Optical method for evaluating material friction", *Meas. Sci. Technol.*, Vol. 15, No.10, pp. 1971-1976, 2004.
- Y. Fujii and J. Valera, "Impact force measurement using an inertial mass and a digitizer", *Meas. Sci. Technol.*, Vol.17, No.4, pp. 863-868, 2006.
- Y. Fujii, "Method of evaluating the dynamic response of materials to forced oscillation", *Meas. Sci. Technol.*, Vol.17, No.7, pp. 1935-1940, 2006.
- Y. Fujii and K. Shimada, "Instrument for measuring the mass of an astronaut", *Meas. Sci. Technol.*, Vol.17, No.10, pp.2705-2710, 2006.
- Y. Fujii, "Method for correcting the effect of the inertial mass on dynamic force measurements", *Meas. Sci. Technol.*, Vol.18, No.5, pp.N13-N20, 2007.
- Y. Fujii, "Microforce materials tester based on the levitation mass method", *Meas. Sci. Technol.*, Vol.18, No.6, pp.1678-1682, 2007.

# Publications on LMM in Review of Scientific Instruments

(2006 Impact Factor: 1.541)

- (1) Y. Fujii, H. Fujimoto and S. Namioka, "Mass measurement under weightless conditions", *Rev. Sci. Instrum.*, Vol. 70, No.1, pp.111-113, 1999.
- Y. Fujii, "Measurement of impulse response of force transducers", *Rev. Sci. Instrum.*, Vol.72, No.7, pp. 3108-3111, 2001.
- Y. Fujii, "Measurement of force acting on a moving part of a pneumatic linear bearing", *Rev. Sci. Instrum.*, Vol.74, No.6, pp.3137-3141, 2003.
- Y. Fujii and T. Yamaguchi, "Method for evaluating material viscoelasticity", *Rev. Sci. Instrum.*, Vol.75, No.1, pp.119-123, 2004.
- (5) Y. Fujii, "Microforce materials tester", *Rev. Sci. Instrum.*, Vol.76, No.6, 065111, 2005.
- (6) Y. Fujii, "Pendulum for precision force measurement", *Rev. Sci. Instrum.*, Vol. 77, No.3, 035111-1-5, 2006.
- (7) Y. Fujii, "Measurement of the electrical and mechanical responses of a force transducer against impact forces", *Rev. Sci. Instrum.*, Vol.77, No.8, 085108-1-5, 2006.
- (8) Y. Fujii, "Method of generating and measuring static small force using down-slope component of gravity", *Rev. Sci. Instrum.*, Vol.78, No.6, 066104-1-3, 2007.
- (9) Y. Fujii, K. Shimada, M. Yokota, S. Hashimoto, Y. Sugita and H. Ito, "Mass measuring instrument for use under microgravity conditions", *Rev. Sci. Instrum.*, Vol.79, No.5, 056105-1-3, 2008.

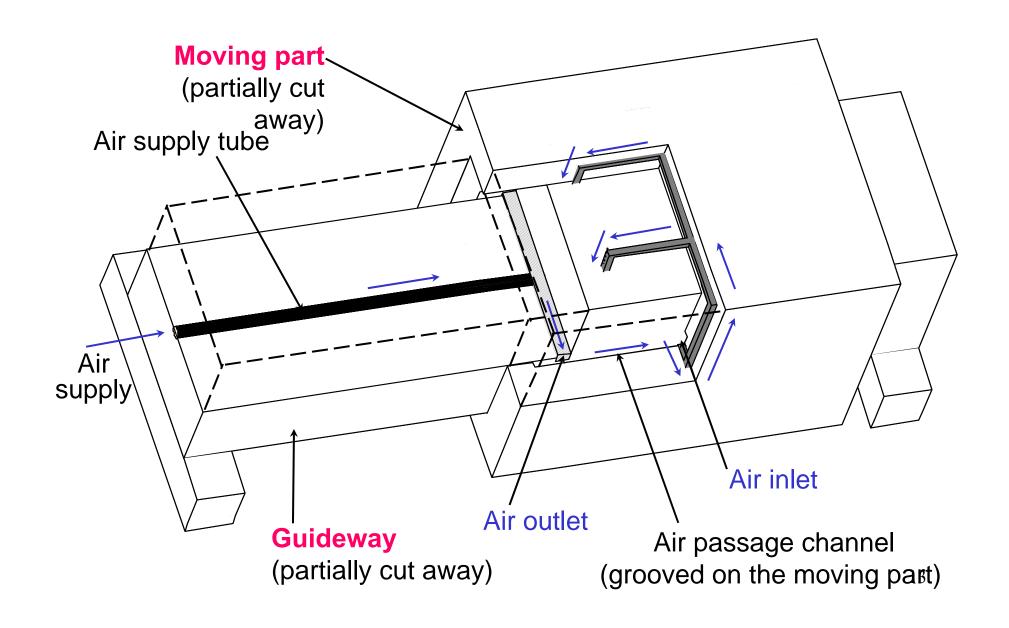
# Dynamic bending tester base on the LMM



Y. Fujii, D. Isobe, S. Saito, H. Fujimoto and Y. Miki, "A method for determining the impact force in crash testing", *Mech. Syst. Signal Pr.*, Vol.14, No.6, pp.959-965, 2000.

Y. Fujii, "Dynamic three-point bending tester using inertial mass and optical interferometer", *Optics and Lasers in Engineering*, Vol.38, No.5, pp.305-318, 2002

# Cut-away view of the bearing



# Data processing

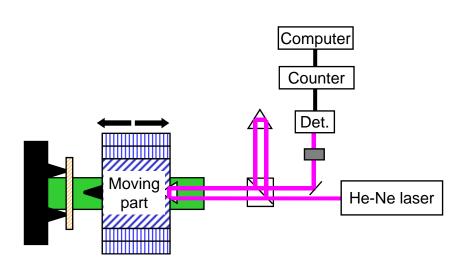
Velocity of the moving part **v** is proportional to Doppler shift frequency

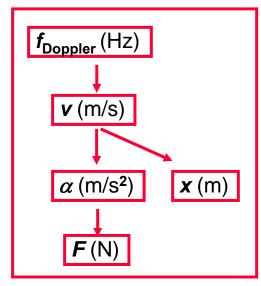
$$\mathbf{v} = \lambda_{\text{air}} (\mathbf{f}_{\text{Doppler}})/2$$
,  
 $\mathbf{f}_{\text{Doppler}} = \mathbf{f}_{\text{beat}} - \mathbf{f}_{\text{rest}}$ 

Acceleration  $\alpha$  (m/s<sup>2</sup>) and position x (m) are calculated from velocity.

Total force acting on the moving part:

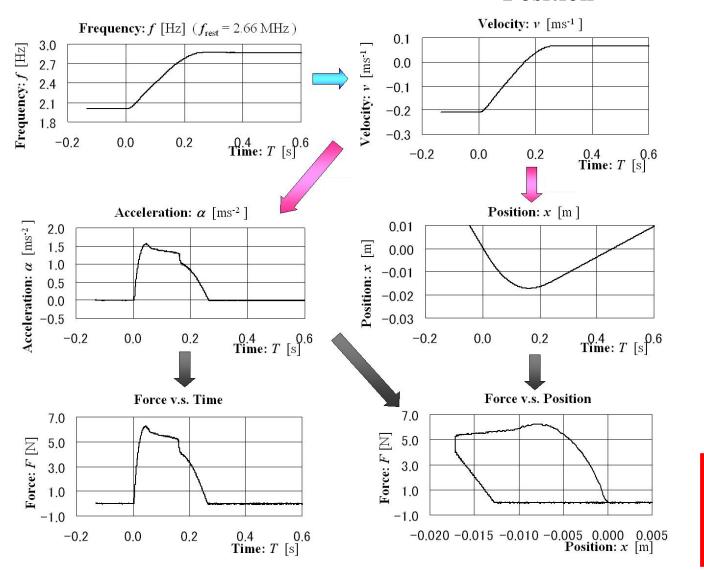
$$F = M\alpha$$
.





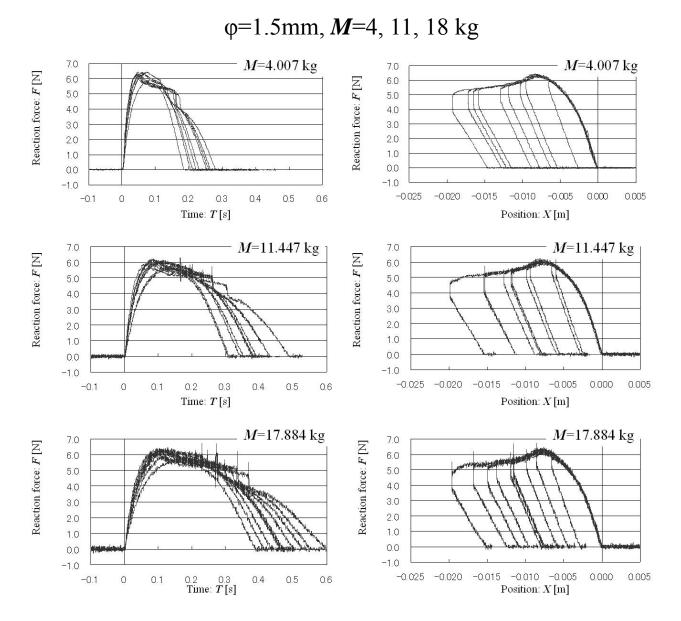
### Result of measurement

# Frequency → Velocity → Acceleration → Force → Position



Uncertainty of measurement: 0.5%

# Result of 3 point dynamic bending test of pure aluminum



# History of the Levitation Mass Method

**Ground Test Setup for Space Balance Dynamic Force Calibration Measurement of Friction of Linear Air-bearing Material Tester without Force Transducers** 

#### Birth of the Levitation Mass Method

# **Ground Test Setup for Space Balance**

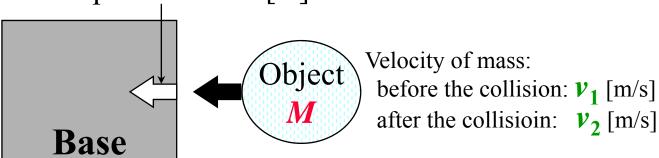
**Dynamic Force Calibration** 

**Measurement of Friction of Linear Air-bearing** 

**Material Tester without Force Transducers** 

#### **Ground Test Setup for Space Balance: Principle**

#### Impact force: **F** [N]



Impulse acted on the base: **F** dt

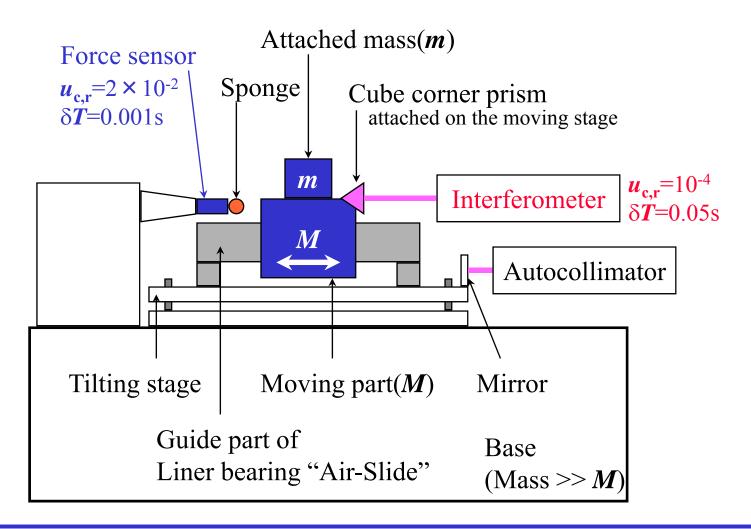
Momentum change:  $M(v_1 - v_2)$ 

$$\int \boldsymbol{F} \, \mathrm{dt} = \boldsymbol{M}(\boldsymbol{v}_1 - \boldsymbol{v}_2).$$

Then the mass of the moving part is estimated as

$$\mathbf{M} = (\int \mathbf{F} \, \mathrm{dt}) / (v_1 - v_2) \equiv \mathbf{M}_{\mathrm{E}}.$$

#### **Ground Test Setup for Space Balance: Experimental Setup**



Y. Fujii, H. Fujimoto and S. Namioka, "Mass measurement under weightless conditions", *Rev. Sci. Instrum.*, Vol. 70, No.1, pp.111-113, 1999.

#### **Ground Test Setup for Space Balance: Experimental Results**

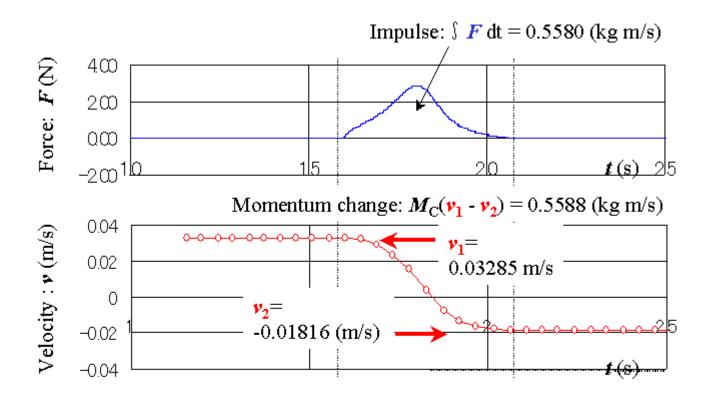


FIG. 2 Impulse on the force sensor and velocity change of the moving part (calibrated mass of the moving part:  $M_C$ =10.955 kg)

#### **Space Balance: Specimen measurement**

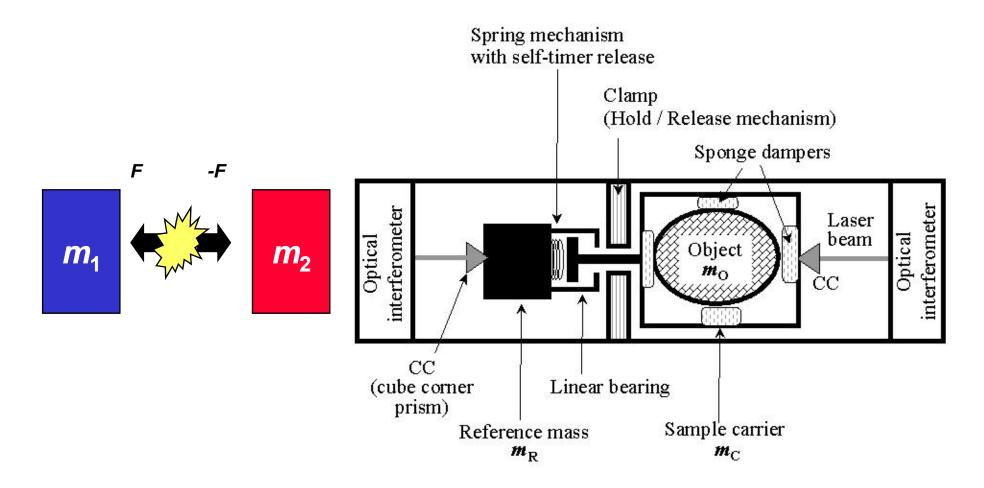


Figure 5 Proposed balance for measuring mass under microgravity conditions.

Y. Fujii, H. Fujimoto, R. Watanabe, Y. Miki, "Balance for measuring mass under microgravity conditions", *AIAA Journal*, Vol.39, No.3, pp.455-457, 2001.

## **Space Balance: Human measurement (1/3)**

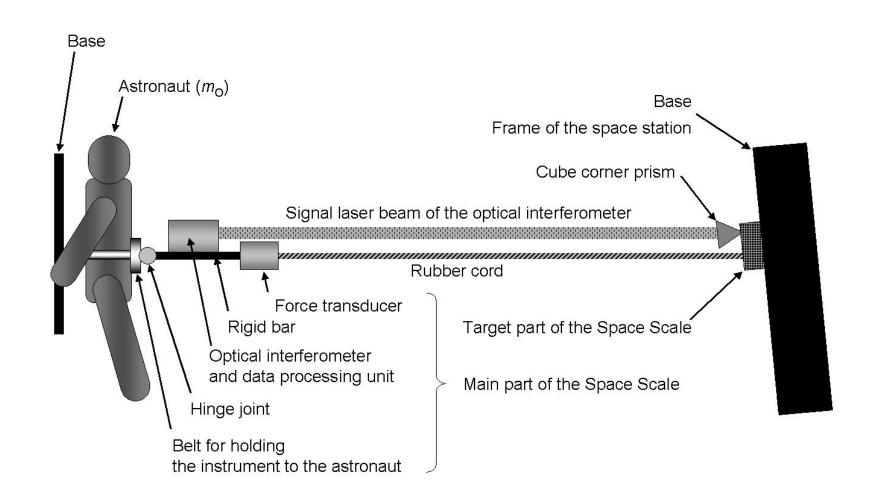


Figure 5 Space Ralance for Astronaut Mass Measurement

Y. Fujii and K. Shimada, "Instrument for measuring the mass of an astronaut", *Meas. Sci. Technol.*, Vol.17, No.10, pp.2705-2710, 2006.

#### **Space Balance: Human measurement (2/3)**

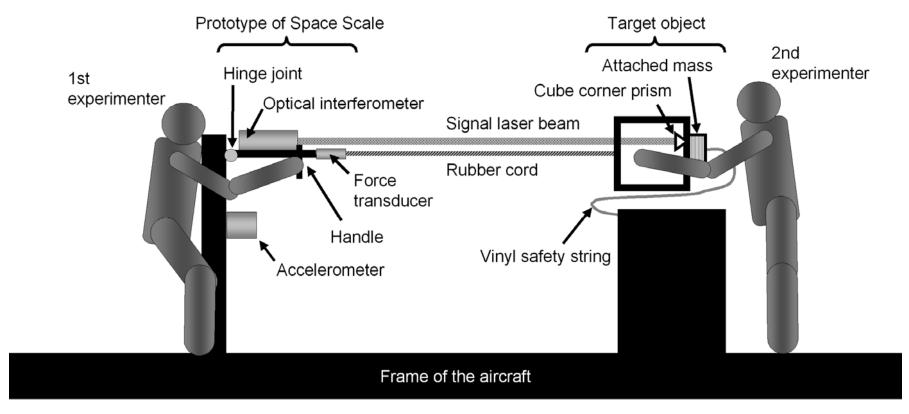


FIG.2. Experimental Setup.

Y. Fujii and K. Shimada, "The space scale: An Instrument for astronaut mass measurement", *Trans. Jpn. Soc. Aeronaut. Space Sci.*, Vol.50, No.170, pp.251-257, 2008.

Y. Fujii, K. Shimada, M. Yokota, S. Hashimoto, Y. Sugita and H. Ito, "Mass measuring<sub>24</sub> instrument for use under microgravity conditions", *Rev. Sci. Instrum.*, 2008.

# **Space Balance: Human measurement (3/3)**

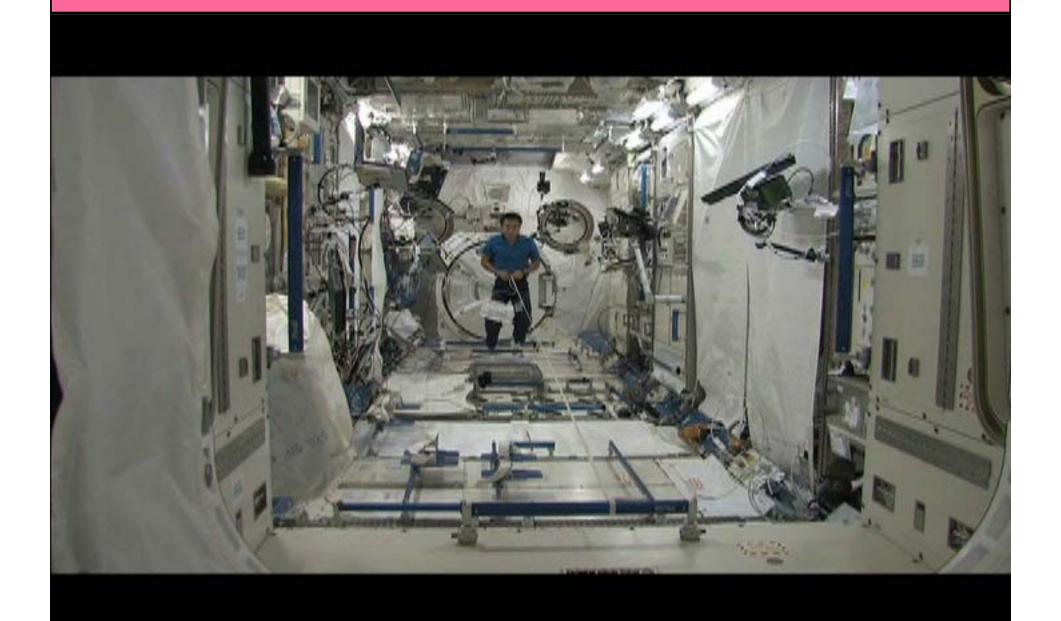




video

0G for 18 seconds Gulfstream II

# **Space Balance: Experiment in the International Space Station**



#### **Ground Test Setup for Space Balance: Problems Arising!**

How to know the uncertainty of force?

How to know the friction of air bearing?

# Applied to Dynamic Force Calibration

# **Ground Test Setup for Space Balance**

**Dynamic Force Calibration** 

**Measurement of Friction of Linear Air-bearing** 

**Material Tester without Force Transducers** 

#### **Dynamic Force Calibration: Background 1**

There is not any dynamic calibration method for force transducers.



The following two major problems arise when varying force is measured using a force transducer.

1<sup>st</sup> problem: It is impossible to determine the uncertainty of measured value of the varying force properly.

2<sup>nd</sup> problem: It is impossible to determine the distortion of the time axis.

#### **Dynamic Force Calibration: Background 2**

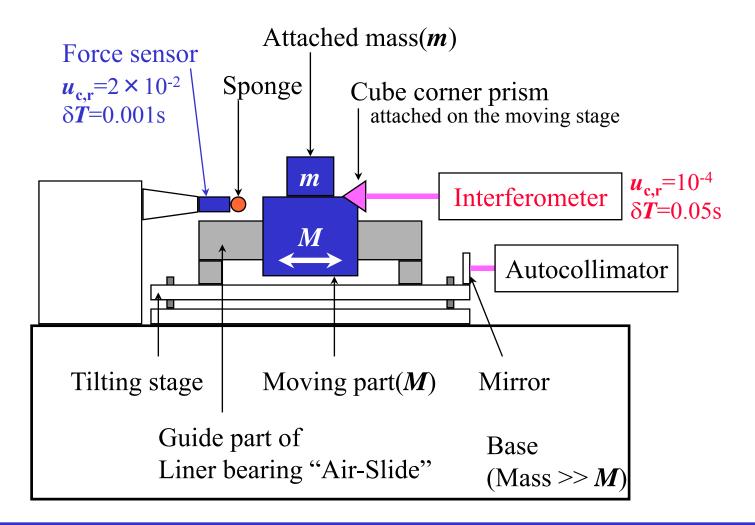
At present, the resonance frequency of the transducer is the only parameter that is available for evaluating the dynamic characteristics of the transducer.

It is usually believed that force transducers with higher resonance frequencies can measure dynamic forces with a smaller uncertainty.

However, this belief has no logical basis.

Therefore, dynamic calibration methods using known reference varying forces are urgently required.

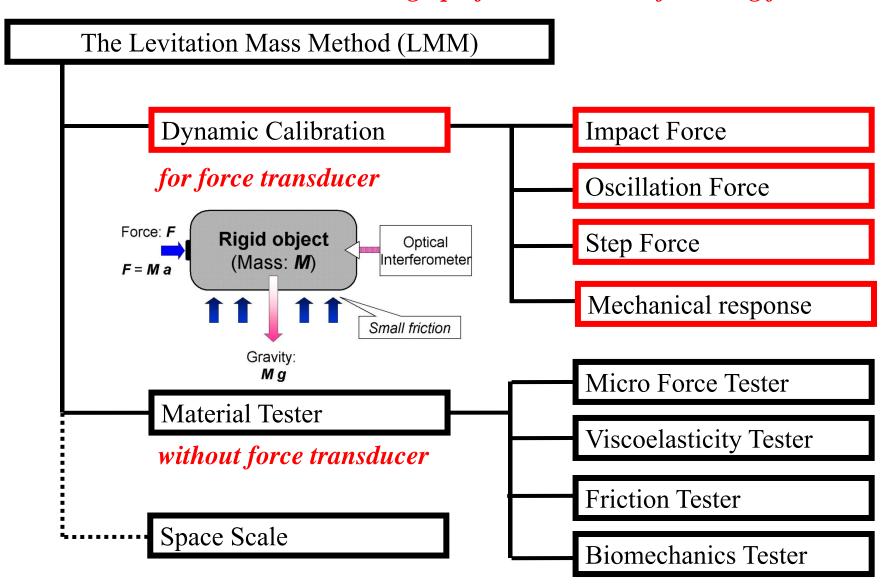
## **Dynamic Force Calibration: Experimental Setup**



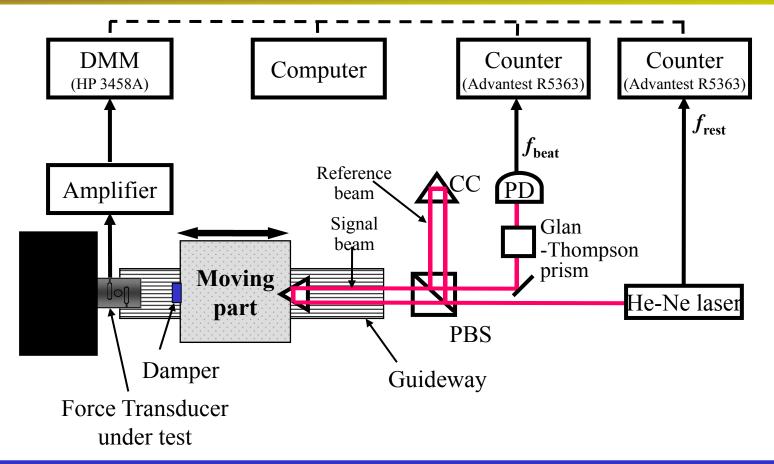
Y. Fujii and H. Fujimoto, "Proposal for an impulse response evaluation method for force transducers", *Meas. Sci. Technol.*, Vol. 10, No.4 pp. N31-N33, 1999.

## Applications of the LMM

The LMM has shown the extreme high performance in the following fields.



# Impact Force Calibration: Experimental Setup

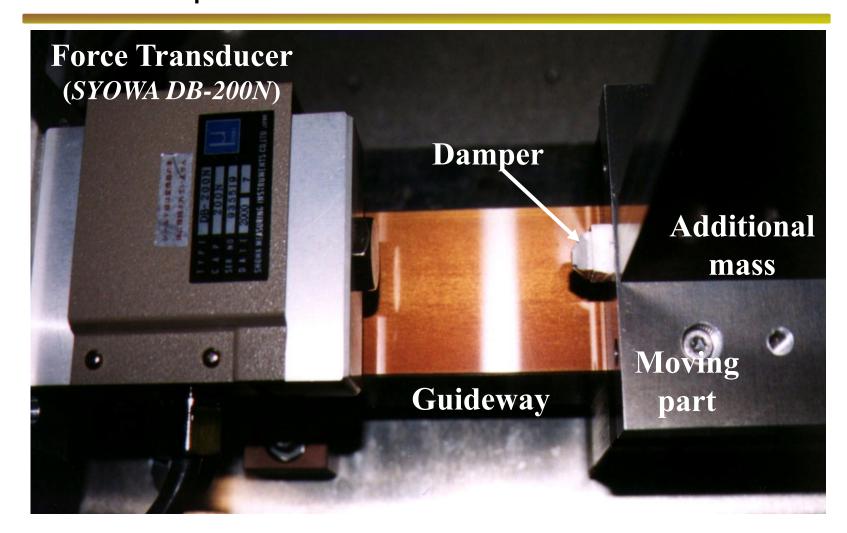


Y. Fujii, "Measurement of impulse response of force transducers", *Rev. Sci. Instrum.*, Vol.72, No.7, pp. 3108-3111, 2001.

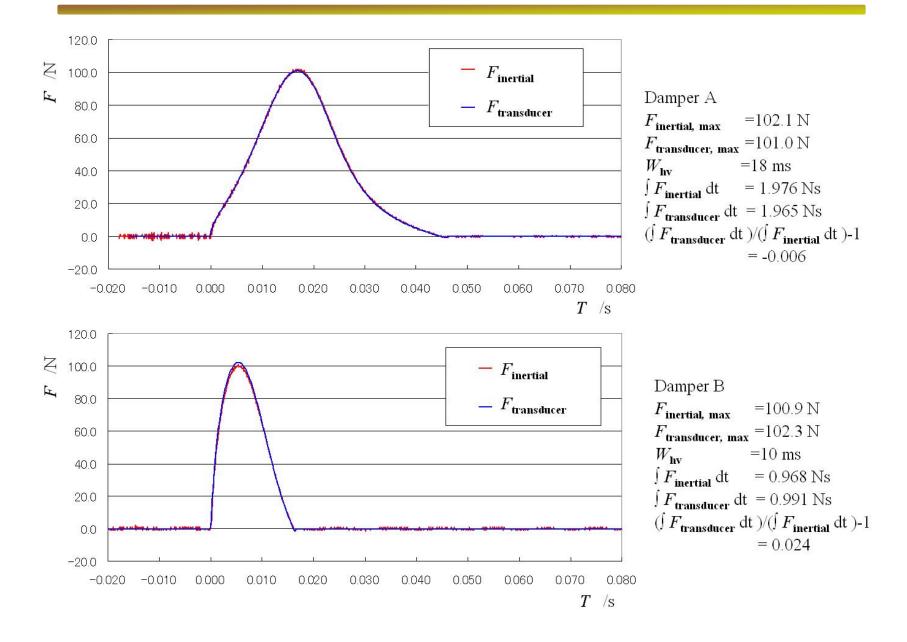
Y. Fujii, "Evaluation of impulse response of commercial force transducers", *Measurement*, Vol.33, No.1, pp.35-45, 2003.

Y. Fujii, "Measurement of steep impulse response of a force transducer", *Meas. Sci. Technol.*, Vol. 14, No.1 pp. 65-69, 2003.

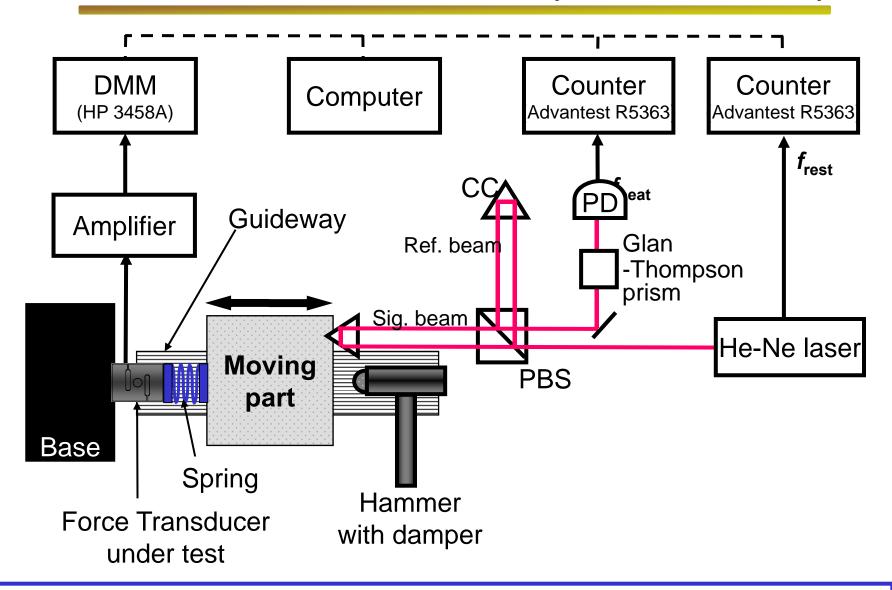
# Impact Force Calibration: Photo



# Impact Force Calibration: Results

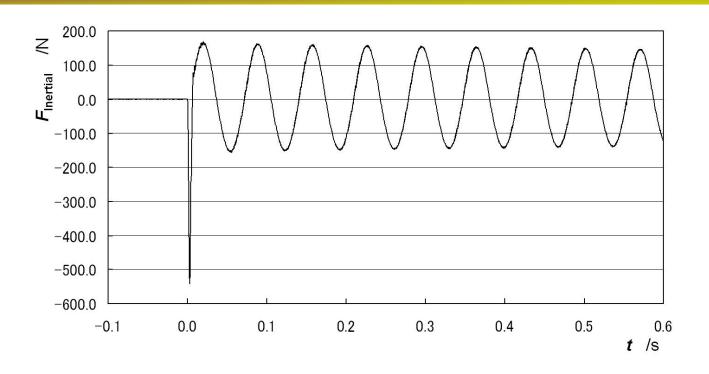


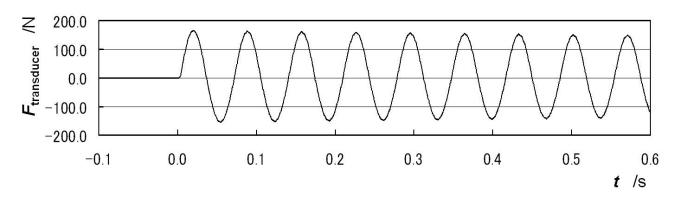
# Oscillation Force Calibration: Experimental Setup



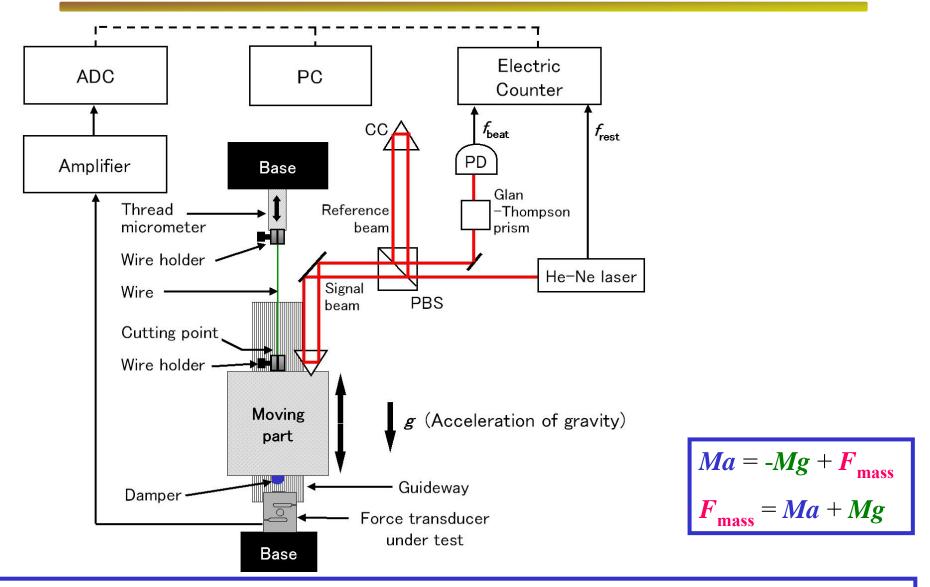
Y. Fujii, "A method for calibrating force transducers against oscillation force", *Meas. Sci. Technol.*, Vol. 14, No.8, pp. 1259-1264,2003.

## Oscillation Force Calibration: Results



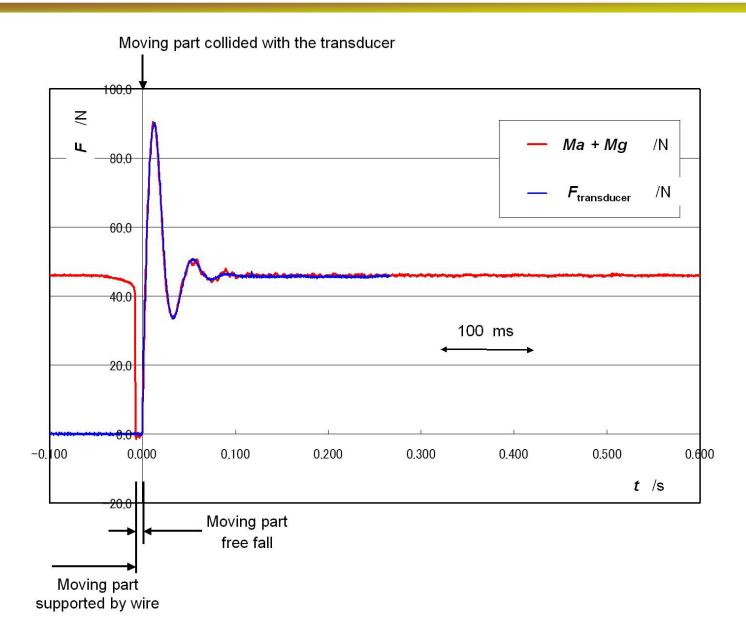


# Step Force Calibration: Experimental Setup



Y. Fujii, "Proposal for a step response evaluation method for force transducers", *Meas* 3 *ci. Technol.*, Vol. 14, No.10, pp. 1741-1746, 2003

# Step Force Calibration: Results



## **Inertial Force Correction**

# Electrical and Mechanical Response measurement

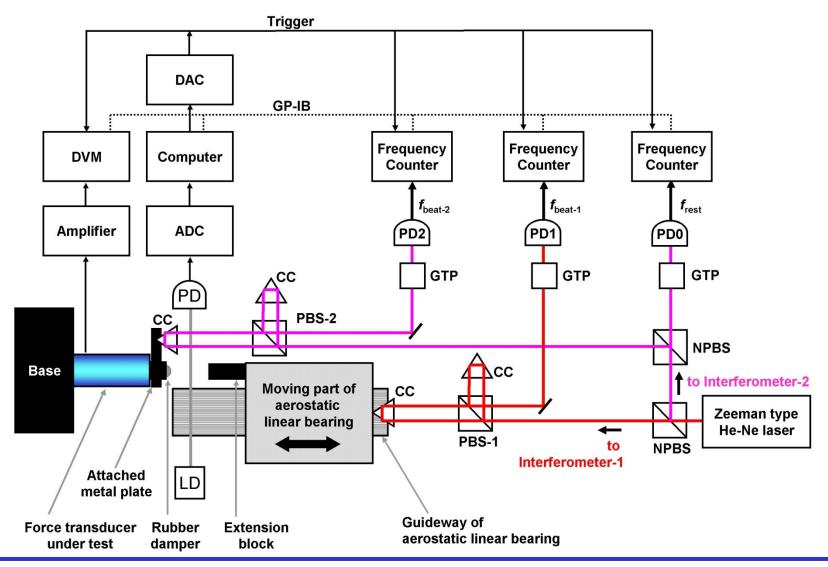


## **Inertial Force Correction**



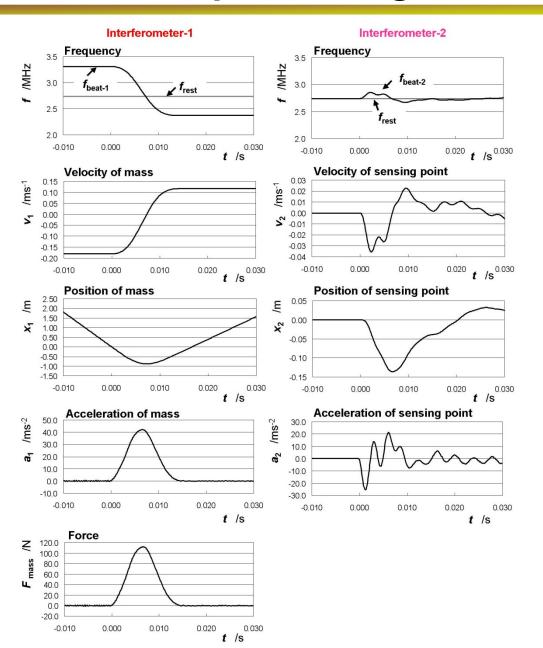
# Target of Development

# **Experimental Setup**

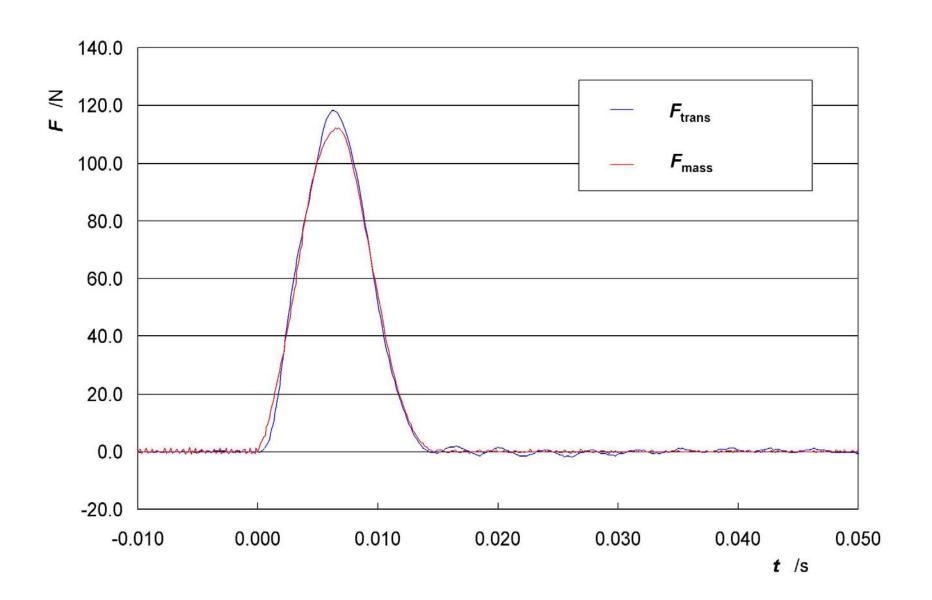


Y. Fujii, "Measurement of the electrical and mechanical responses of a force transducer1 against impact forces", *Rev. Sci. Instrum.*, Vol.77, No.8, 085108-1-5, 2006.

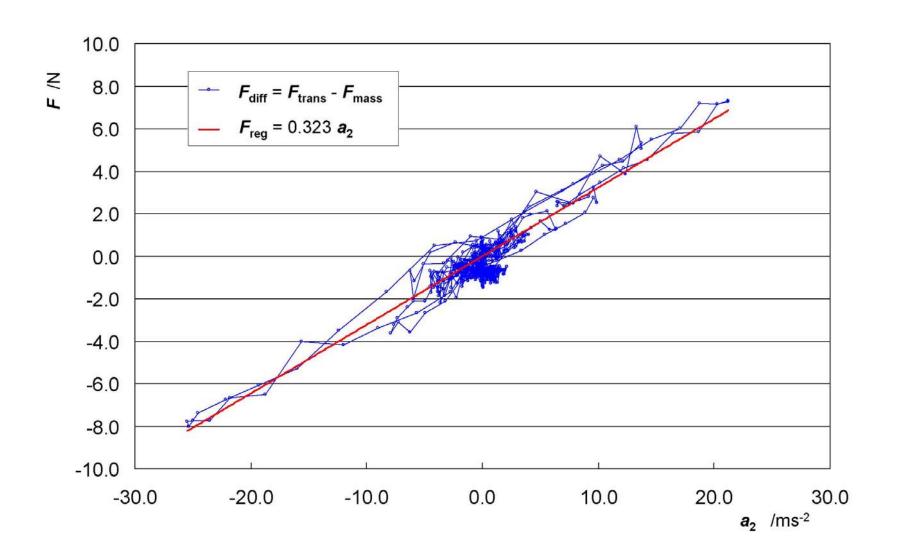
# **Data processing**



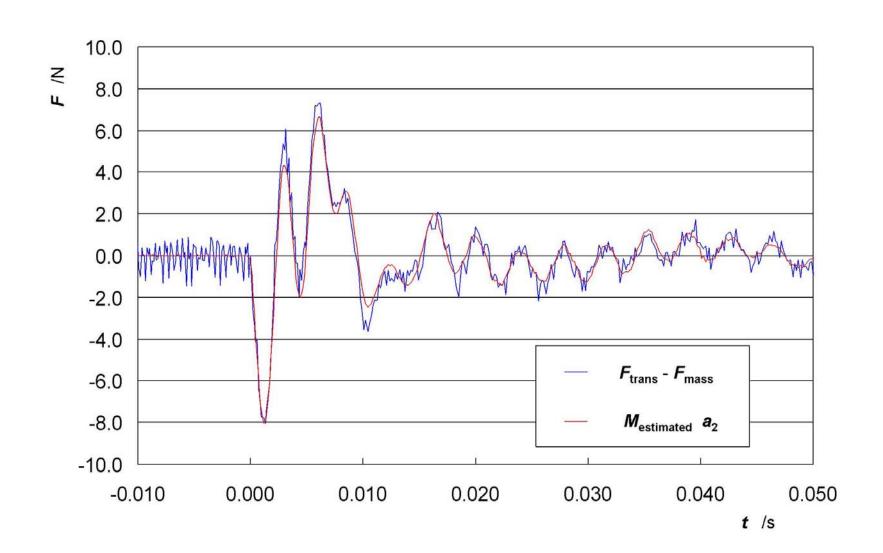
# Relationship between $F_{\text{trans}}$ and $F_{\text{mass}}$



Relationship between the acceleration of the sensing point and the difference between the values measured by the transducer and those measured by the proposed method.



Difference between the values measured by the transducer and those measured by the proposed method, and the estimated inertial force of the sensor element.



#### **Inertial Force Correction**

# Electrical and Mechanical Response measurement

Dynamic error can be well explained as the inertial force of the transducer itself.

It is almost proportional to acceleration of the sensing point of the transducer  $a_2$ .

Since the deformation of the transducer is almost proportional to the force,  $a_2$  is thought to be proportional to  $d^2F_{trans}/dt^2$ 



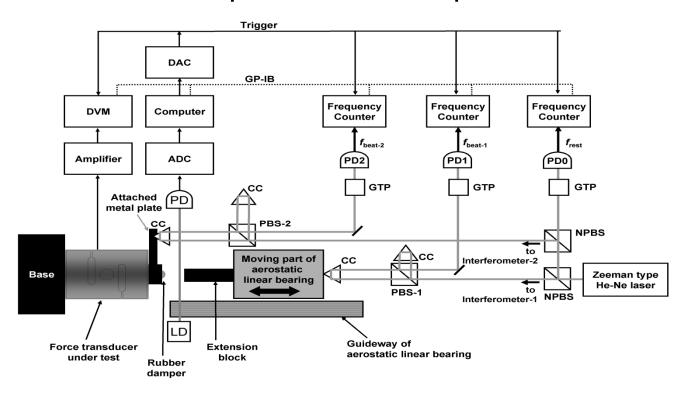
Inertial Force Correction Using Output of Transducer



Target of Development

# **Inertial Force Correction (1.1)**

## **Experimental Setup**



Y. Fujii, "Measurement of the electrical and mechanical responses of a force transducer against impact forces", Rev. Sci. Instrum., Vol.77, No.8, 085108-1-5, 2006.

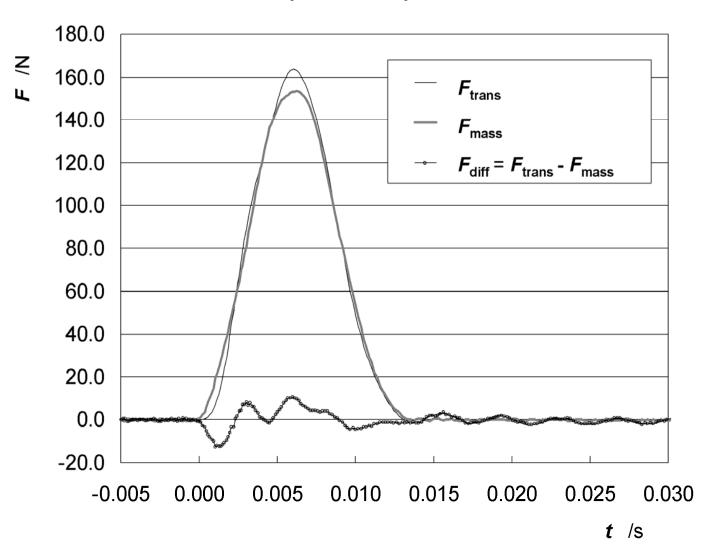
Y. Fujii, "Method for correcting the effect of the inertial mass on dynamic force measurements", Meas. Sci. Technol., Vol.18, No.5, pp.N13-N20, 2007.

Y. Fujii, "Toward establishing dynamic calibration method for force transducers", IEEE Trans. Instrum. Meas., Vol.58, No.7, pp.2358-2364, 2009.

Y. Fujii and K. Maru, "Self-Correction Method for Dynamic Measurement Error of Force Sensors", Experimental Techniques, (in press).

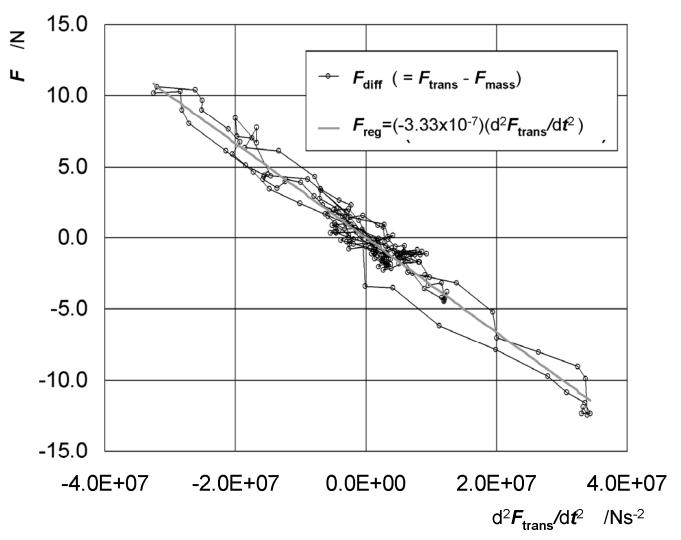
# **Inertial Force Correction (1.2)**

## Impact response



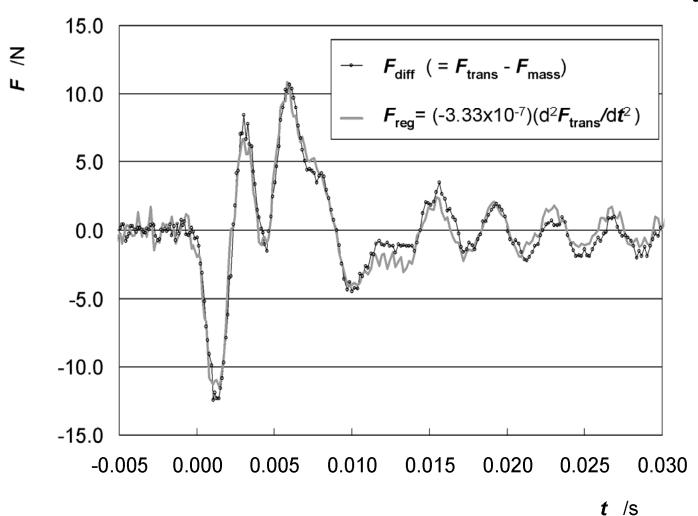
# **Inertial Force Correction (1.3)**

Relationship between the measurement error and the differential coefficient of the second order of  $F_{trans}$ 



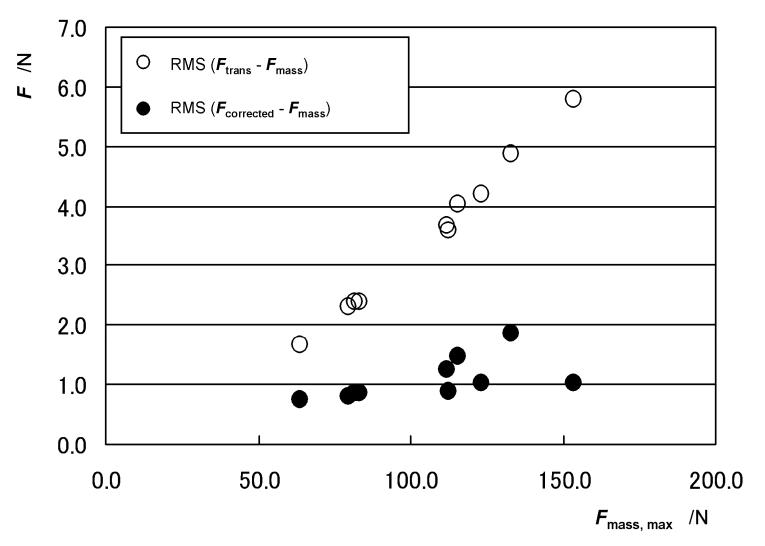
# **Inertial Force Correction (1.4)**

Relationship between the measurement error and the differential coefficient of the second order of  $F_{\rm trans}$ 



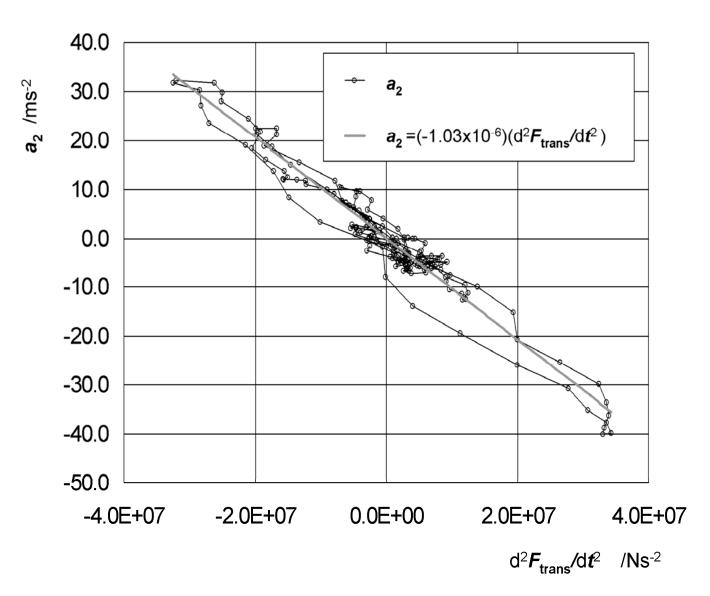
# **Inertial Force Correction (1.5)**

Root mean square values of the errors of the measured force with and without the inertial force correction



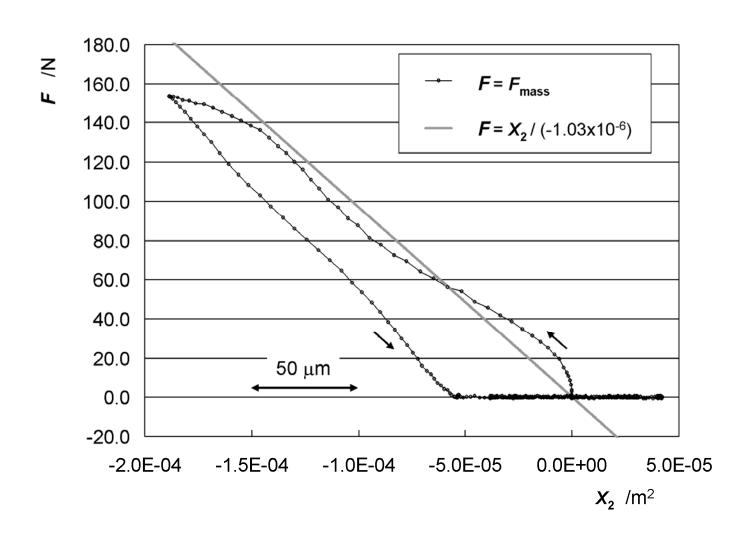
## **Inertial Force Correction (1.6)**

Acceleration at the sensing point  $a_2$  and  $d^2F_{trans}/dt^2$ 



# **Inertial Force Correction (1.7)**

## Mechanical response of the transducer



# Target of development

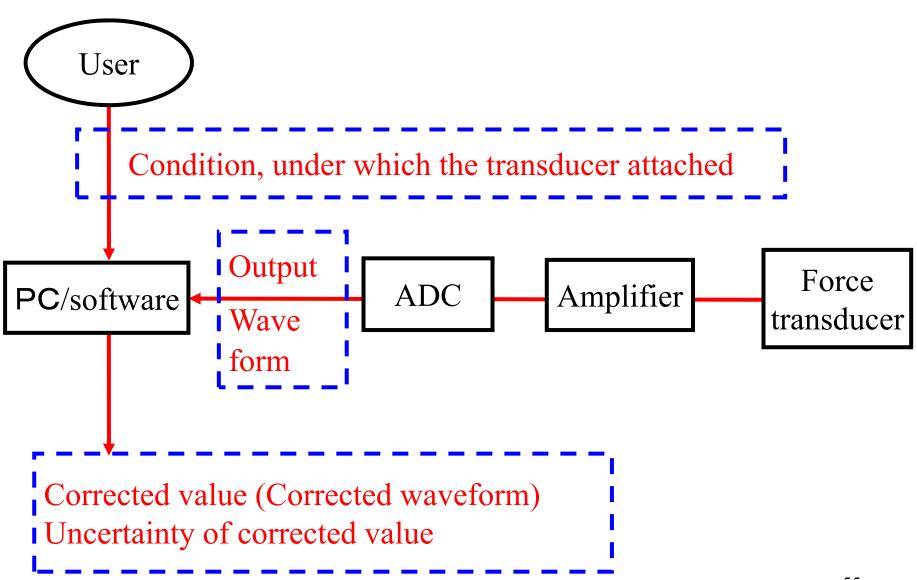
## **Target**

Development of the software, which corrects the error caused by the inertial mass of the transducer itself and evaluates the uncertainty of the measured value with and without the correction.

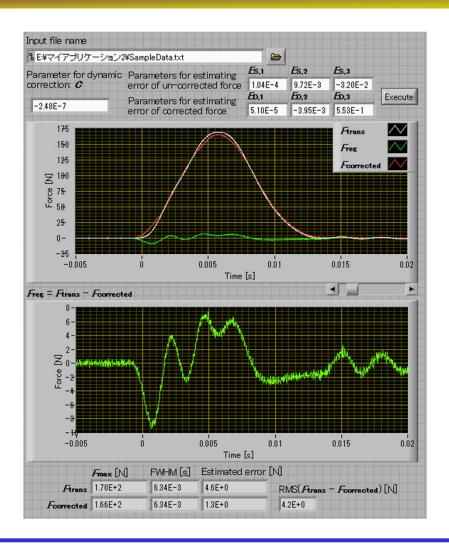
#### **Condition**

For the first prototype, the force transducer should be firmly attached to the stable base.

# Concept of developing software



# Software for Correcting Dynamic



N. Miyashita, K. Watanabe, K. Irisa, H. Iwashita, R. Araki, A. Takita, T. Yamaguchi and Y. Fujii, "Software for Correcting the Dynamic Error of Force Transducers" *Sensors*, Vol.14, No.7, pp.12093-12103, 2014.

#### **Ground Test Setup for Space Balance: Problems Arising!**

How to know the friction of air bearing?

# Applied to Friction Measurement of Air-bearing

**Ground Test Setup for Space Balance Dynamic Force Calibration Measurement of Friction of Linear Air-bearing Material Tester without Force Transducers** 

## Measurement of Friction of Linear Air-bearing: Background

Aerostatic linear bearings have the two major features:

- (1) High accuracy in motion
- (2) Low friction.

For the former feature, i.e. high accuracy in motion, these bearings and linear motors are widely used in combination in the most precise machine tools and instruments in which precise linear motion is required.

There have been some studies on this feature.

The latter feature, i.e. low friction, has not attracted the close attention of engineers and researchers in the field. 
No method was available!

However it will ultimately become the center of interest for improving the accuracy of motion control in the near future.

## Measurement of Friction of Linear Air-bearing: Experimental

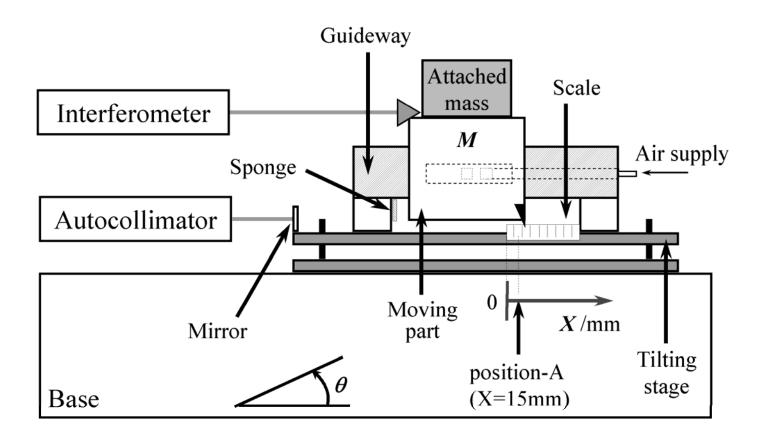
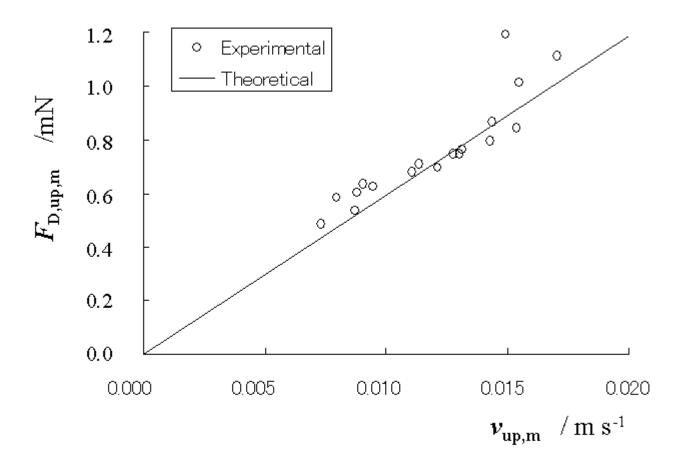


Figure 2. Experimental setup

Y. Fujii and H. Fujimoto, "Measurements of frictional characteristics of a pneumatic linear bearing", *Meas. Sci. Technol.*, Vol.10, No.5, pp.362-366, 1999.



Dynamic frictional force acting on the moving part

## Measurement of Friction of Linear Air-bearing: Variation 1

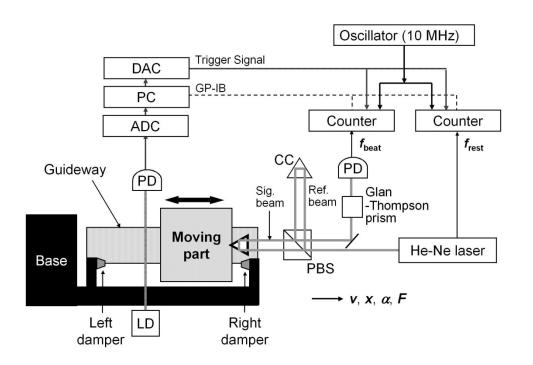


Figure 1. Experimental setup

Figure 5. Change in resultant force acting on the moving part against position (1st set of measurements)

Y. Fujii, "Frictional characteristics of an aerostatic linear bearing", *Tribol. Int.*, Vol.39, No.9, pp.888-896, 2006.

## Measurement of Friction of Linear Air-bearing: Variation 2

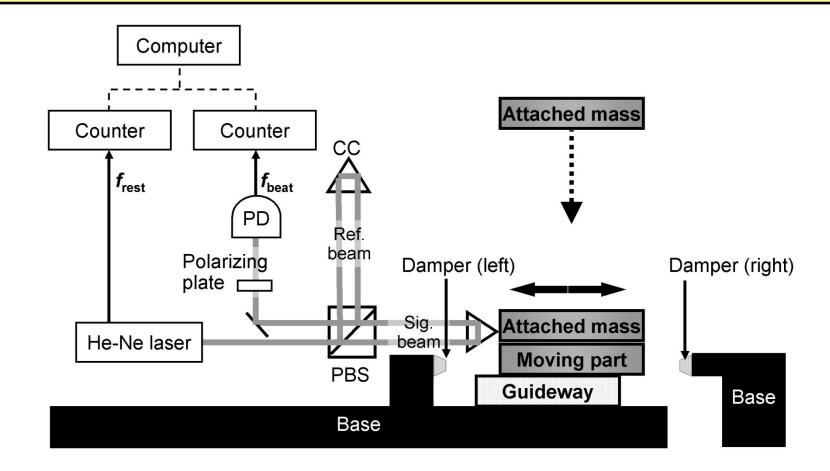


Figure 1 Experimental Setup

Y. Fujii, "An optical method for evaluating frictional characteristics of linear bearings", *Optics and Lasers in Engineering*, Vol.42, No.5, pp.493-501, 2004.

# Applications to Material Tester

No dynamic calibration methods have been established.

It is very difficult to evaluate the uncertainty of force measured using force transducers embedded in material testers.

#### **Question?**

Can the experimental setup for dynamic force calibration be used for material test?

#### YES!

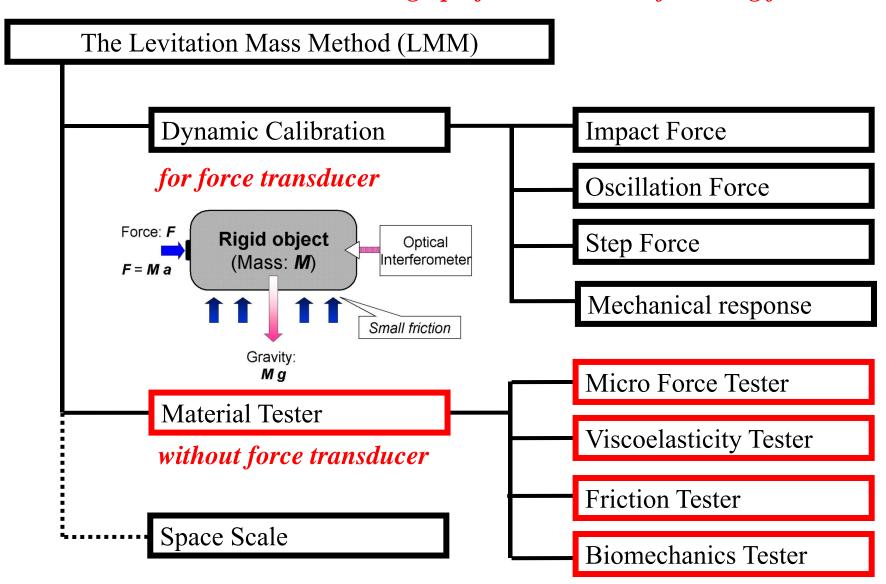
If the transducer under test is replaced by a material, then the mechanical properties of the material can be evaluated with the SAME experimental setup.

## History of the Levitation Mass Method

**Ground Test Setup for Space Balance Dynamic Force Calibration Measurement of Friction of Linear Air-bearing Material Tester without Force Transducers** 

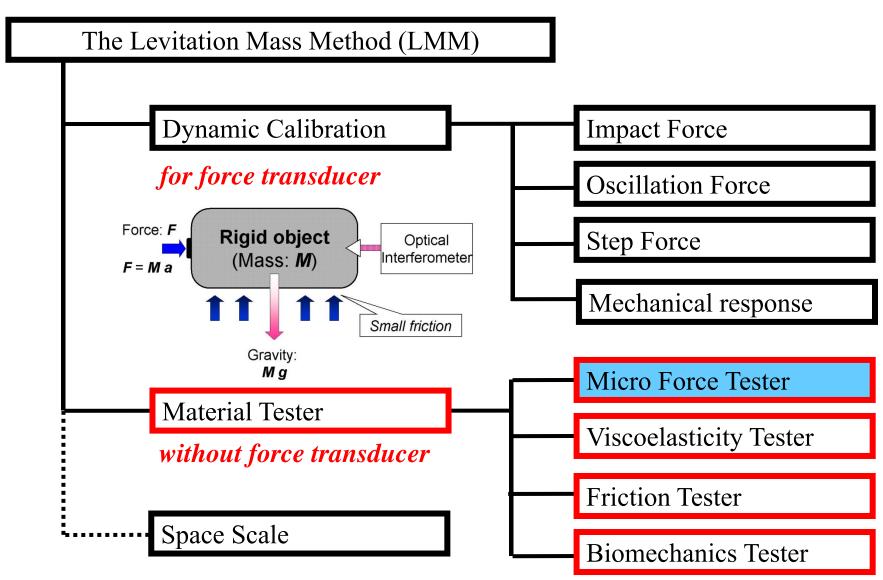
## Applications of the LMM

The LMM has shown the extreme high performance in the following fields.



## Applications of the LMM

The LMM has shown the extreme high performance in the following fields.



## Difficulties in Measuring Small Force

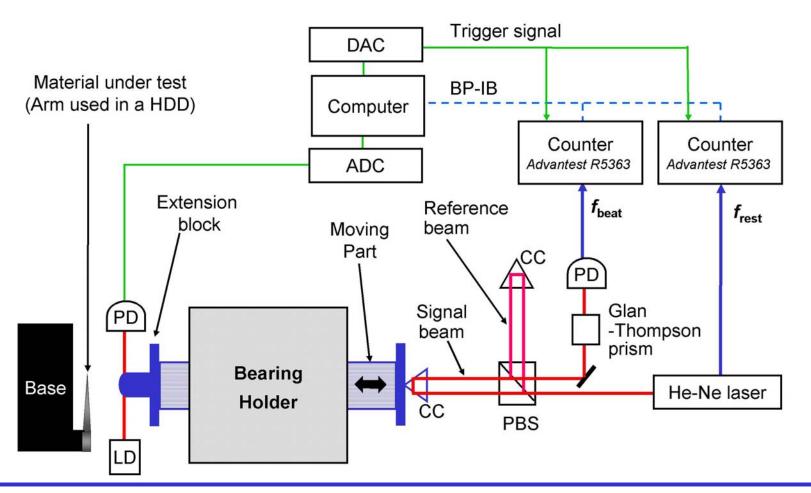
Recently, the requirements for evaluating small force in the range of 1mN to 1N have increased in various industrial and research applications. However, it is sometimes very difficult to generate and evaluate small force properly.

The Difficulties in measuring small force mainly come from the two facts as follows.



- (1) Any method for measuring micro-Newton level forces has not yet been established even for static forces. Some methods for supporting a direct realization of micro-Newton level forces linked to the International System of Units (SI) below 1 N are currently being developed by some national standard laboratories.
- (2) Small force to be generated and/or measured is usually a varying force and any dynamic calibration technique for force sensors has not yet been established. Some methods are now being developed. In other words, this fact means that both the uncertainty evaluation for the measured value of the small force and the uncertainty evaluation for the time of the measurement are very difficult.

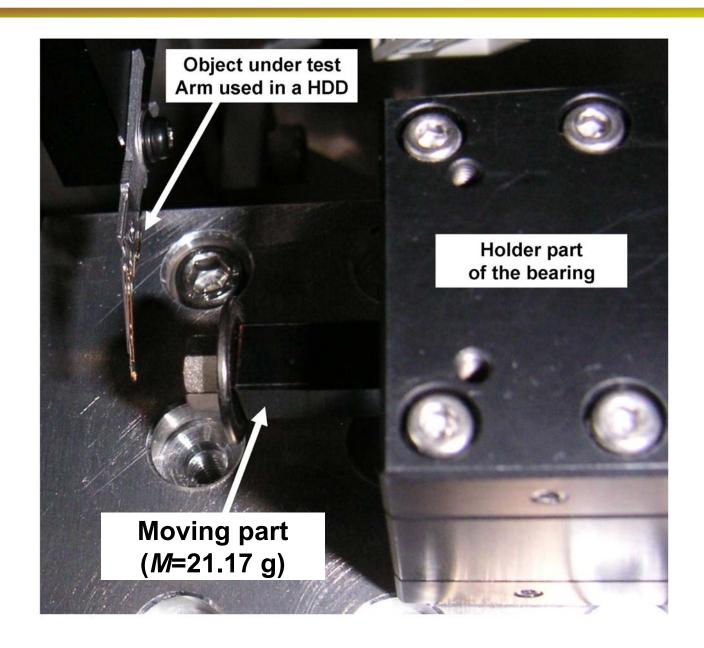
## Microforce measurement: Experimental Setup



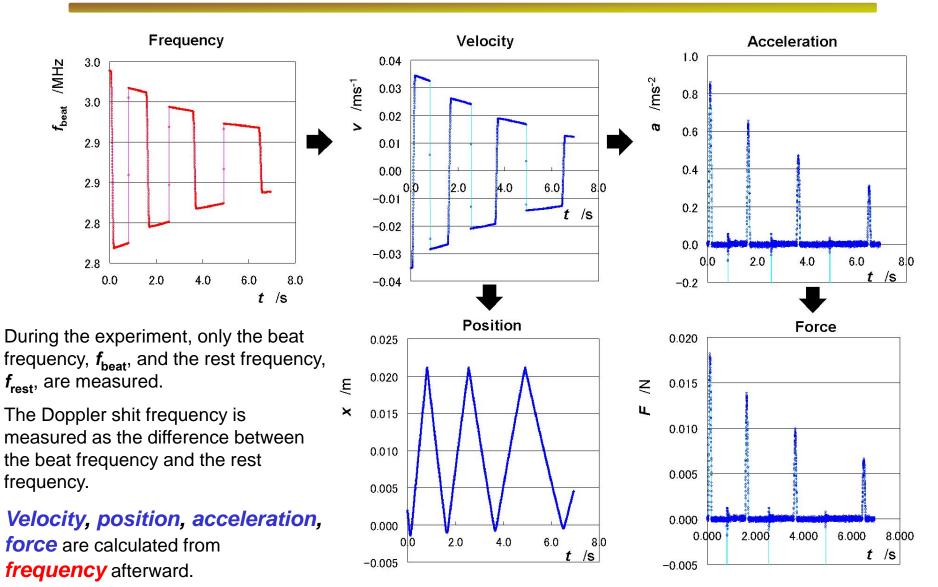
Y. Fujii, "Method for generating and measuring the micro-Newton level forces", *Mech. Syst. Signal Pr.*, Vol.20, No.6, pp.1362-1371, 2006.

Y. Fujii and D.W. Shu, "Impact force measurement of an actuator arm of a hard disk drive", *Int. J. Impact Eng.*, Vol.35, No.2, pp.98-108, 2008.

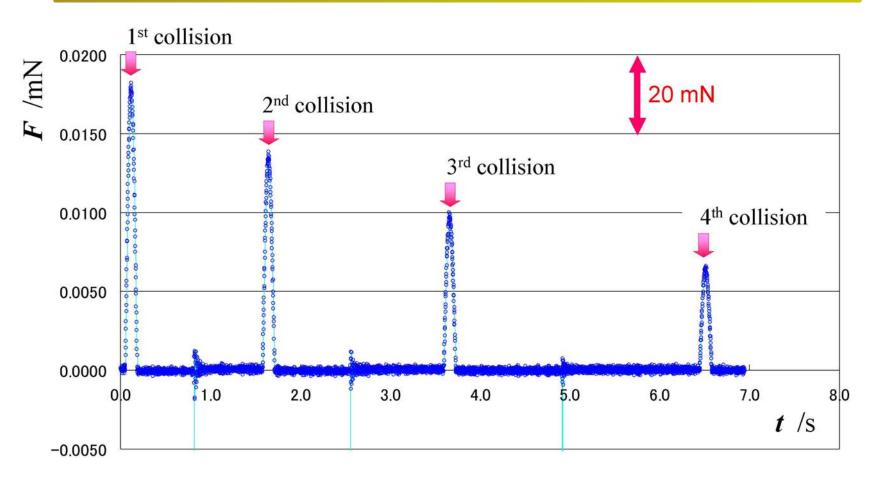
#### Microforce measurement: Photo



# Microforce measurement: Data processing procedure: Calculation of velocity, position, acceleration, force from frequency



#### Microforce measurement: Results



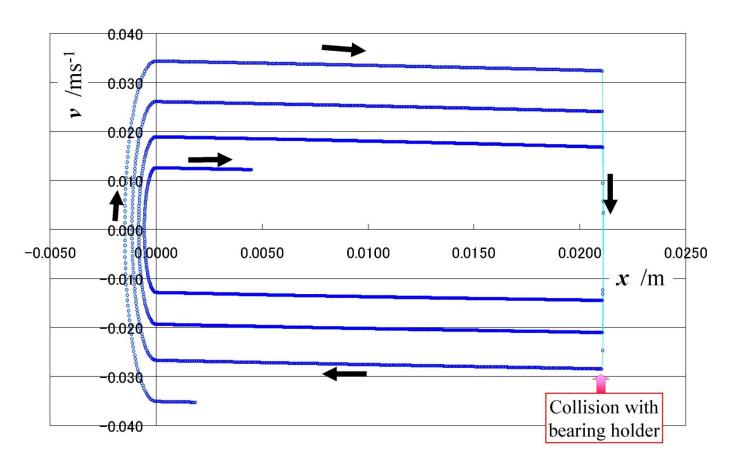
The force acting on the material from the mass is expressed as  $-\mathbf{F}$  according to the law of action and reaction.

The moving part moves back and forth between the material under test and the left-hand side-face of the bearing holder.

The steep negative peaks represent its collision to the bearing holder.

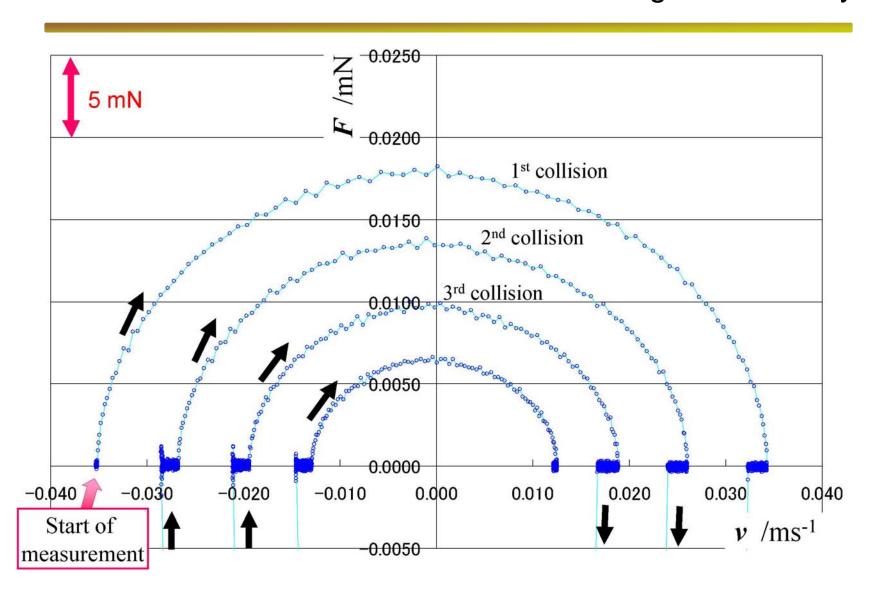
The force has some values even during the free sliding motion of the moving part, x > 0. The variation of force during the free sliding motion is thought to mainly come from the dynamic frictional force acting inside the bearing.

## Microforce measurement: Measured Velocity against Position



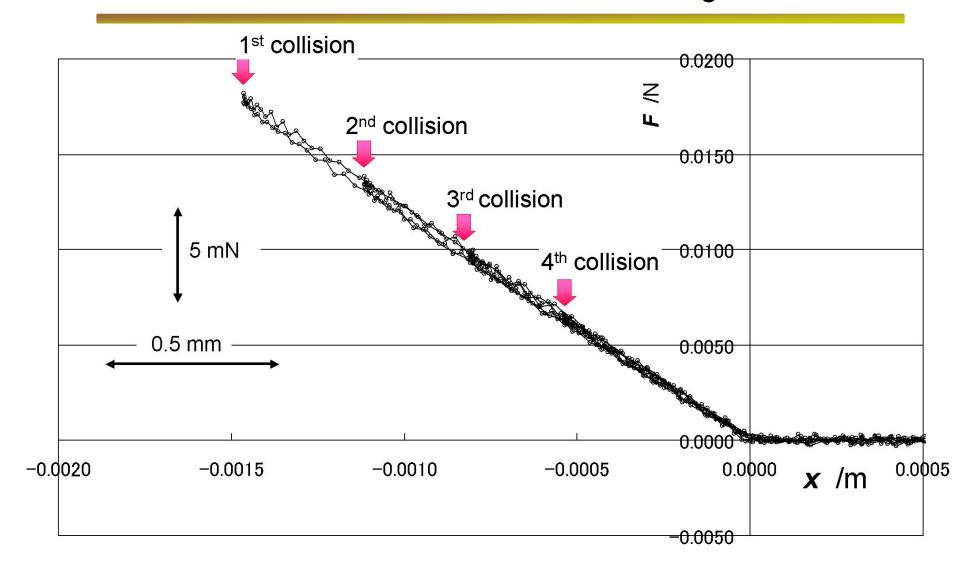
During the free motion of the moving part, the effect of the dynamic frictional force acting on the moving part during the free travel is clearly observed.

## Microforce measurement: Measured Force against Velocity



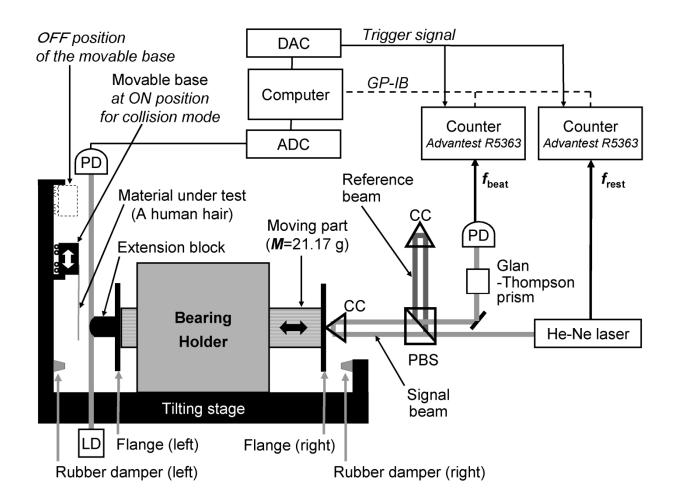
The lead of the force against velocity, which is caused by the viscosity of the material, is NOT clearly observed.

# Microforce measurement: Measured Force against Position



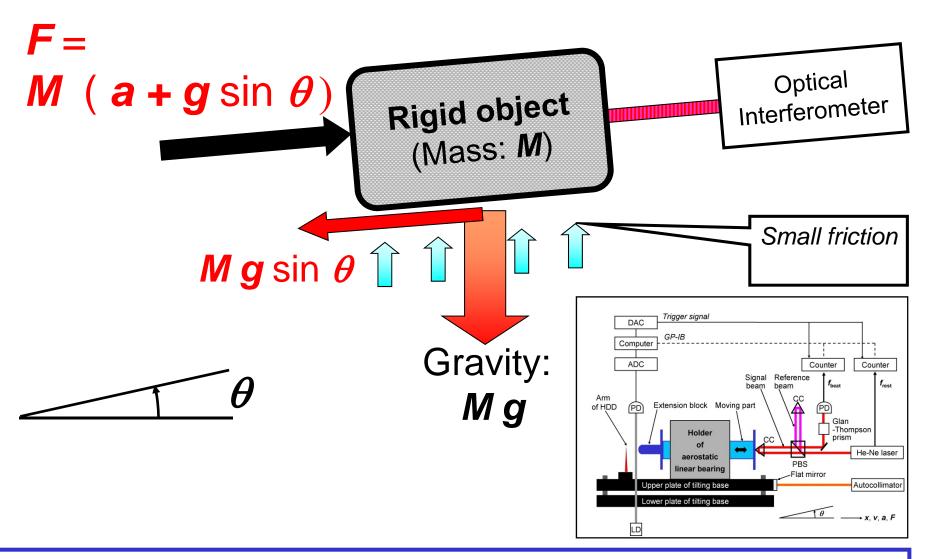
The spring constant is almost constant during the experiment with 4 collisions.

#### Microforce measurement: Friction Correction



Experimental setup with in-SITI observation function for evaluating the force acting inside the bearing

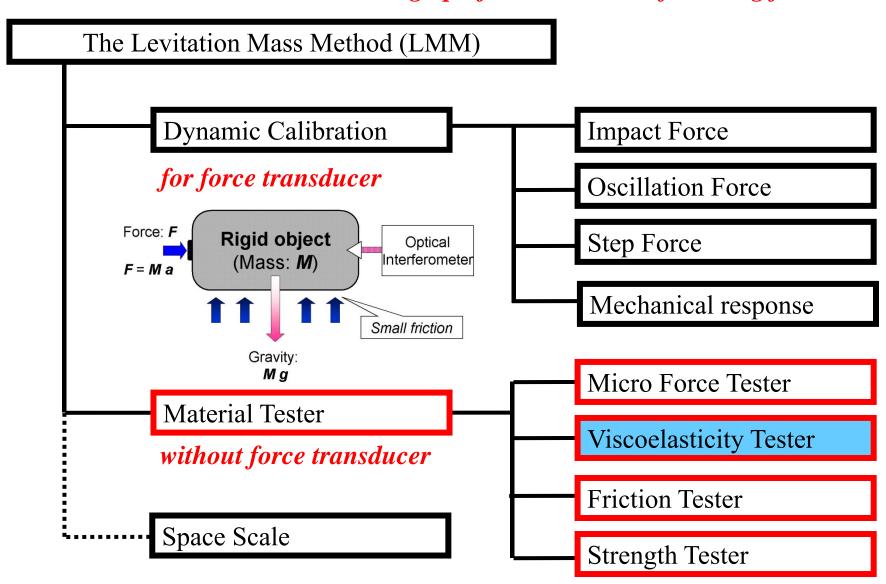
#### Microforce measurement: Static Small Force



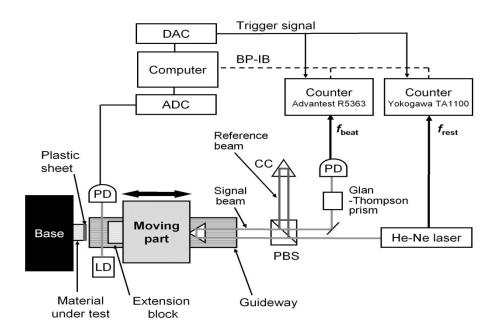
Y. Fujii, "Method of generating and measuring static small force using down-slope component of gravity", *Rev. Sci. Instrum.*, Vol.78, No.6, 066104-1-3, 2007.

# Applications of the LMM

The LMM has shown the extreme high performance in the following fields.



## Viscoelasticity Tester: Impact load



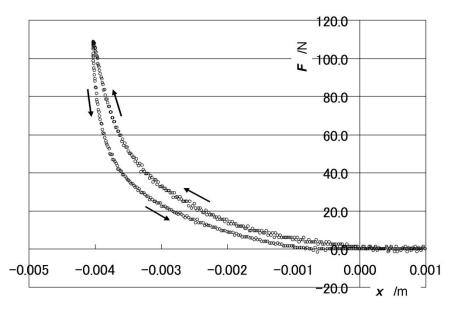


Figure 1. Experimental setup

Figure 4 Change in force against position

Y. Fujii and T. Yamaguchi, "Proposal for material viscoelasticity evaluation method under impact load", *Journal of Materials Science*, Vol.40, No.18, pp.4785 – 4790, 2005.

## Viscoelasticity Tester: Oscillation load

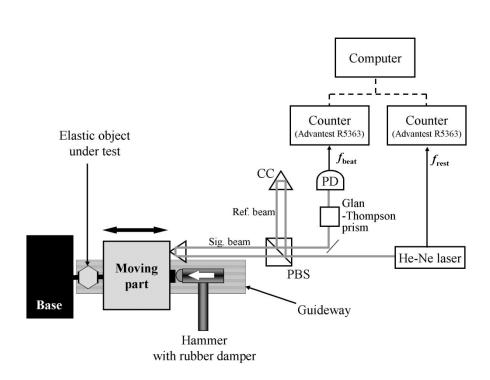


Figure 1. Experimental setup

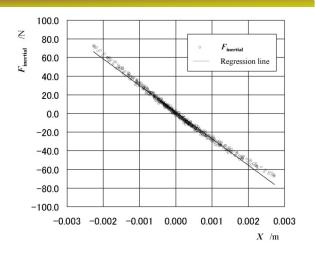


Figure 4 Relationship between force and position

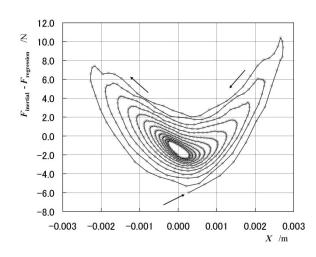


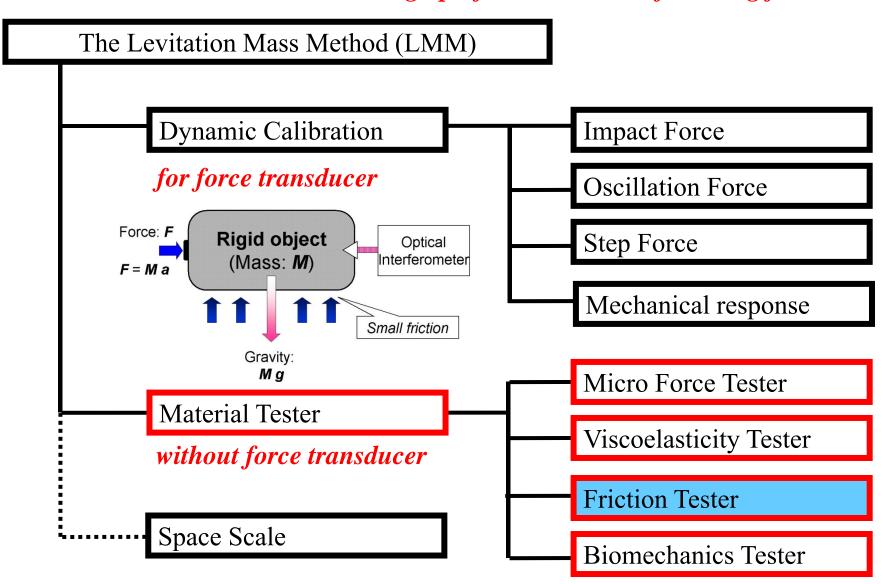
Figure 5 Relationship between relative force and position

80

Y. Fujii and T. Yamaguchi, "Method for evaluating material viscoelasticity", *Rev. Sci. Instrum.*, Vol.75, No.1, pp.119-123, 2004.

# Applications of the LMM

The LMM has shown the extreme high performance in the following fields.



#### **Friction Tester**

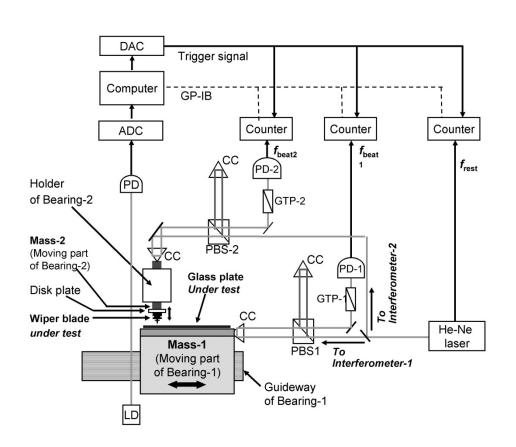


Figure 1. Experimental setup

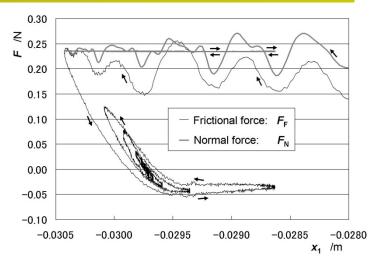


Figure 6 Change in friction and normal force around stopping region

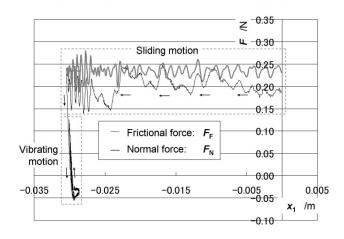
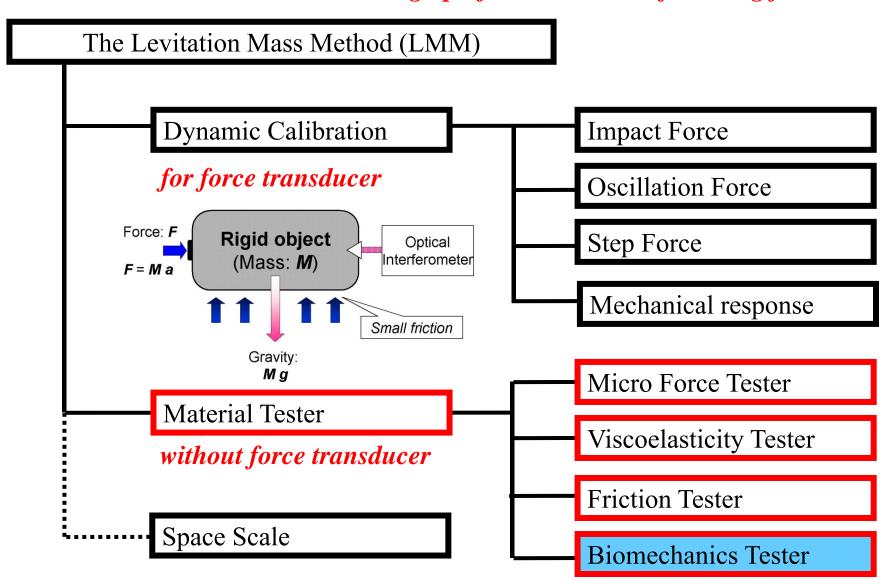


Figure 5 Change in friction and normal force against position of Mass-1

Y. Fujii, "Method for measuring transient friction coefficients for rubber wiper blades on glass surface", *Tribol. Int.*, Vol.41, No.1, pp.17-23, 2008.

# Applications of the LMM

The LMM has shown the extreme high performance in the following fields.



# Biomechanics Tester: Force controllability of human finger

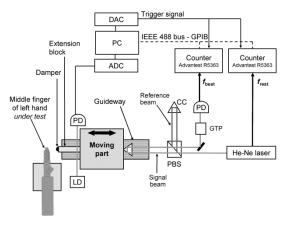


Fig. 1. Experimental setup. Code:CC= cube corner prism, PBS= polarizing beam

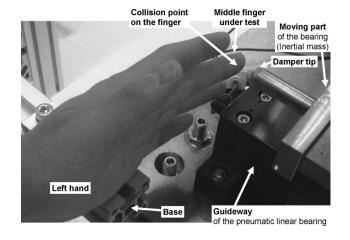
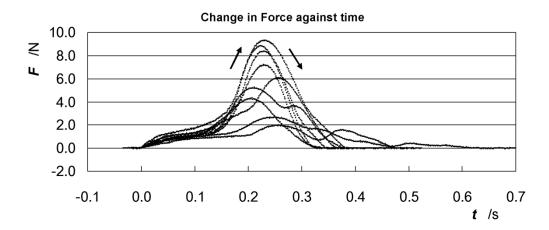


Fig. 2 Photograph of the test section



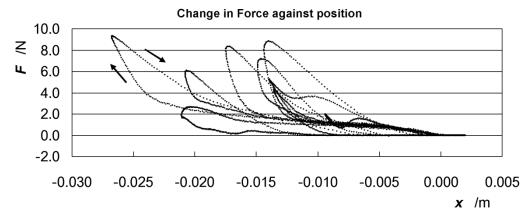
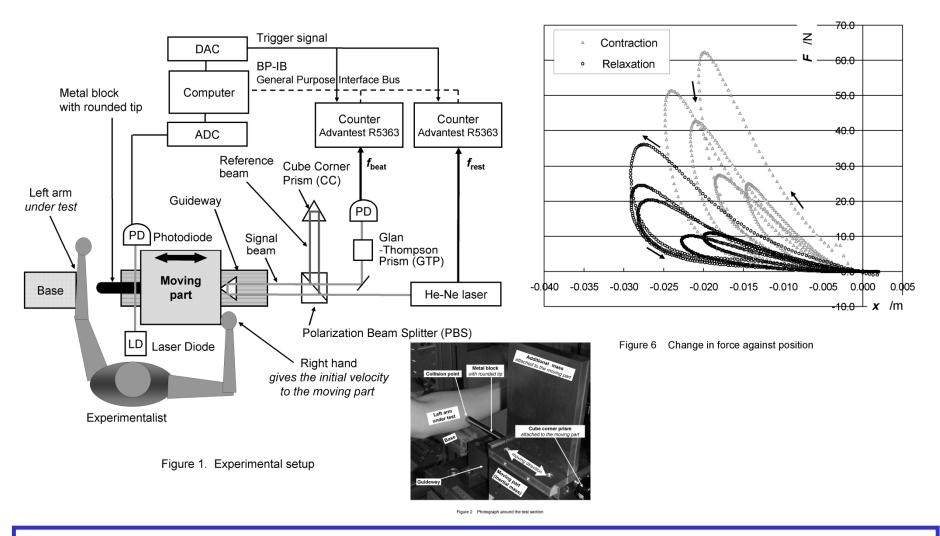


Fig. 7. Response with eyes closed (9 collision measurements)

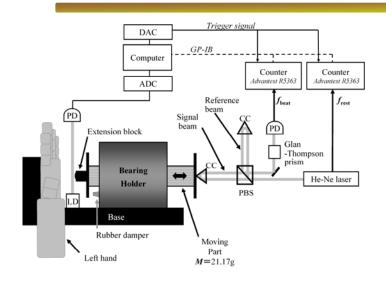
Y. Fujii and T. Yamaguchi, "Method of evaluating the force controllability of human finger", *IEEE Trans. Instrum. Meas.*, Vol.55, No.4, pp.1235-1241, 2006.

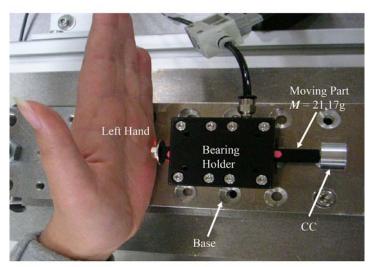
# Biomechanics Tester: Force controllability of human finger

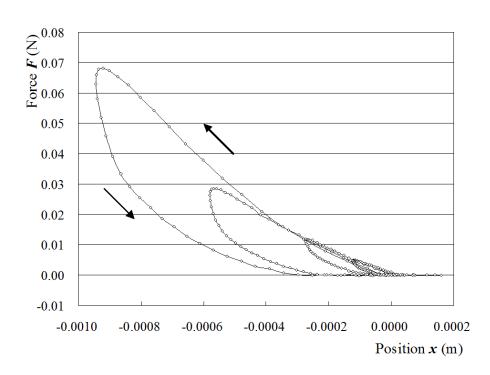


Y. Fujii, T. Yamaguchi and J. Valera, "Impact response measurement of a human arm", *Exp. Techniques*, Vol.30, No.3, pp.64-68, 2006.

## mechanical response of human palm to small impact force

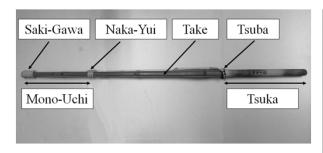


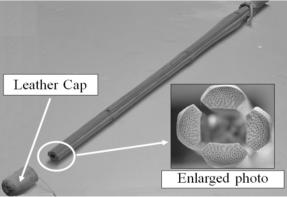


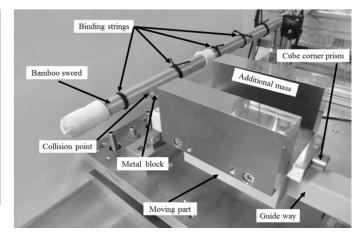


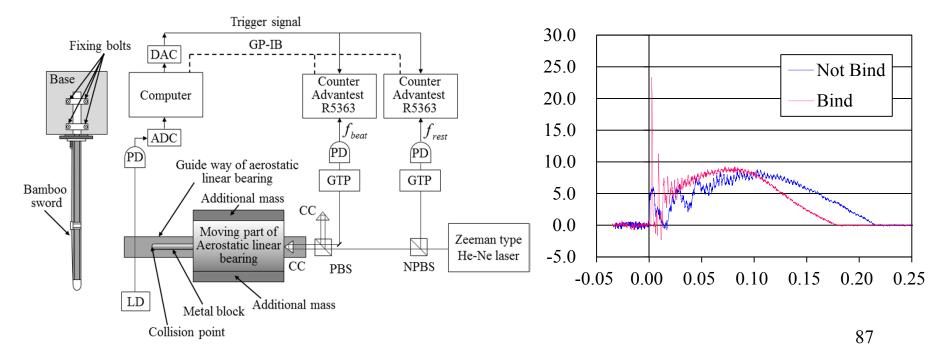
H. Ito and Y. Fujii, "Evaluation of Mechanical Response of Human Palm to Small Impact Force", *Electronics and Communications in Japan*, Vo.92, No.1, pp.18-23, 2009.

## Impact response measurement of a bamboo sword

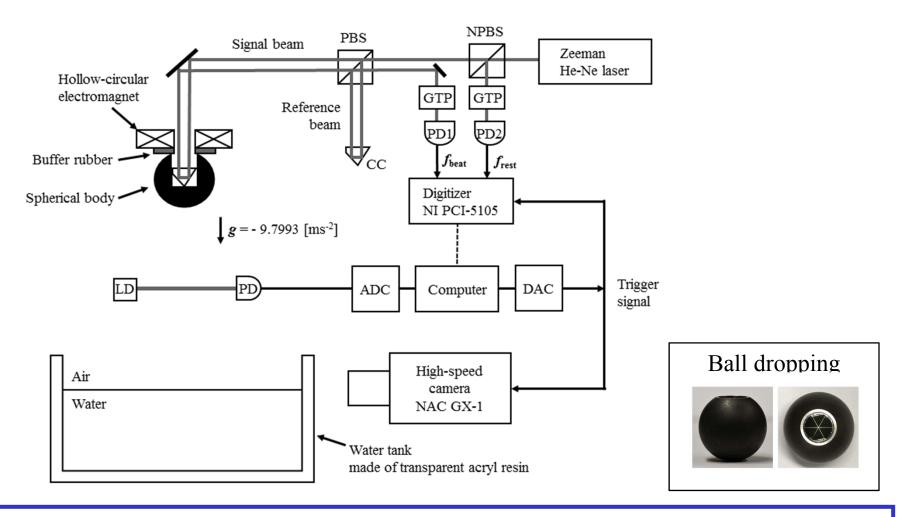






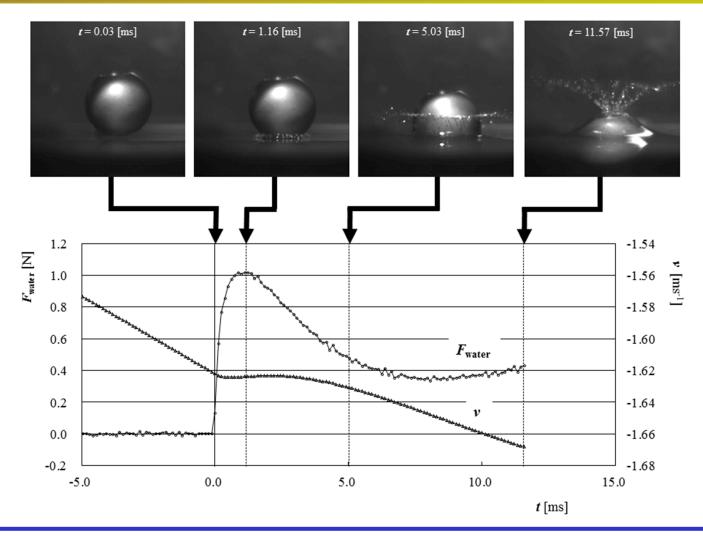


# Impact tester using a dropping ball (1/2)



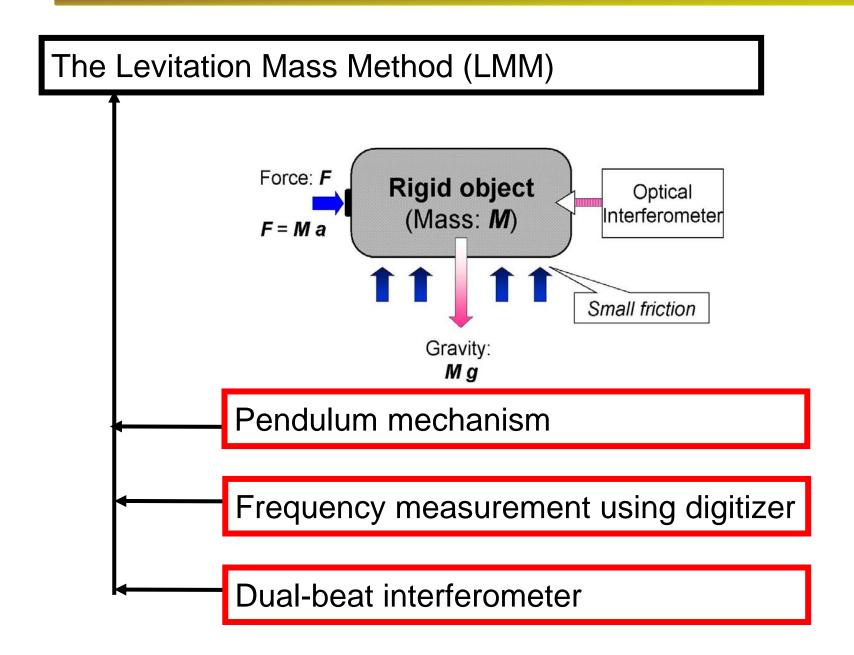
R. Araki, A. Takita, T. Ishima, H. Kawashima, N. Pornsuwancharoen, S. Punthawanunt, E. Carcasona, and Y.Fujiii, "Impact force measurement of a spherical body dropping onto a water surface", *Rev. Sci. Instrum.*, Vol.85, 075108, 2014.

# Impact tester using a dropping ball (1/2)

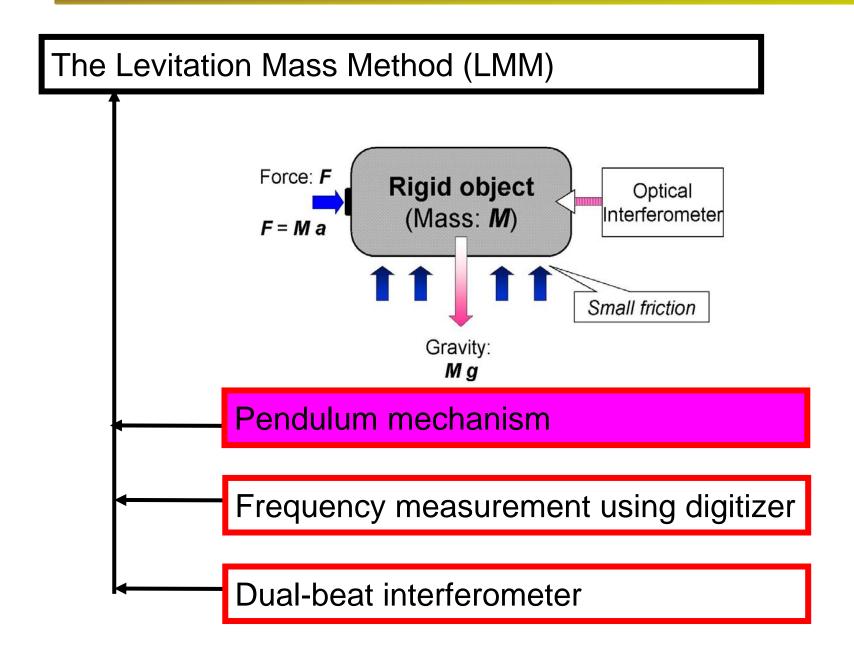


R. Araki, A. Takita, T. Ishima, H. Kawashima, N. Pornsuwancharoen, S. Punthawanunt, E. Carcasona, and Y.Fujiii, "Impact force measurement of a spherical body dropping onto a water surface", *Rev. Sci. Instrum.*, Vol.85, 075108, 2014.

# Some technologies for improving the LMM



# Some technologies for improving the LMM



#### Pendulum mechanism

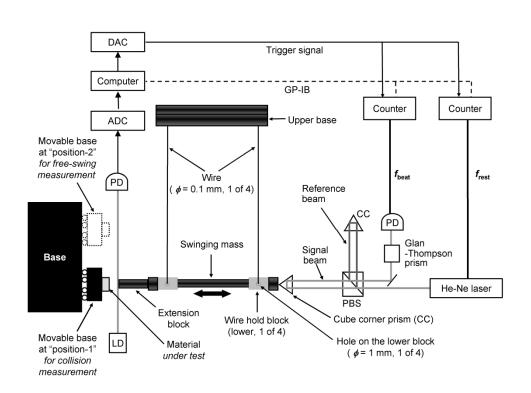


Figure 1. Experimental setup

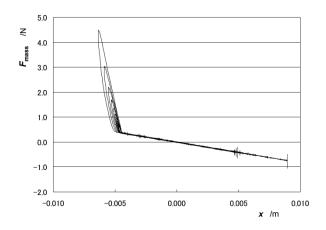


Figure 6 Change in force against position in collision measurement

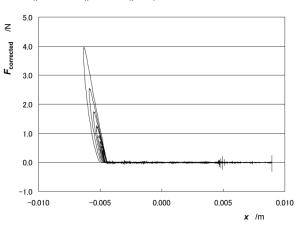
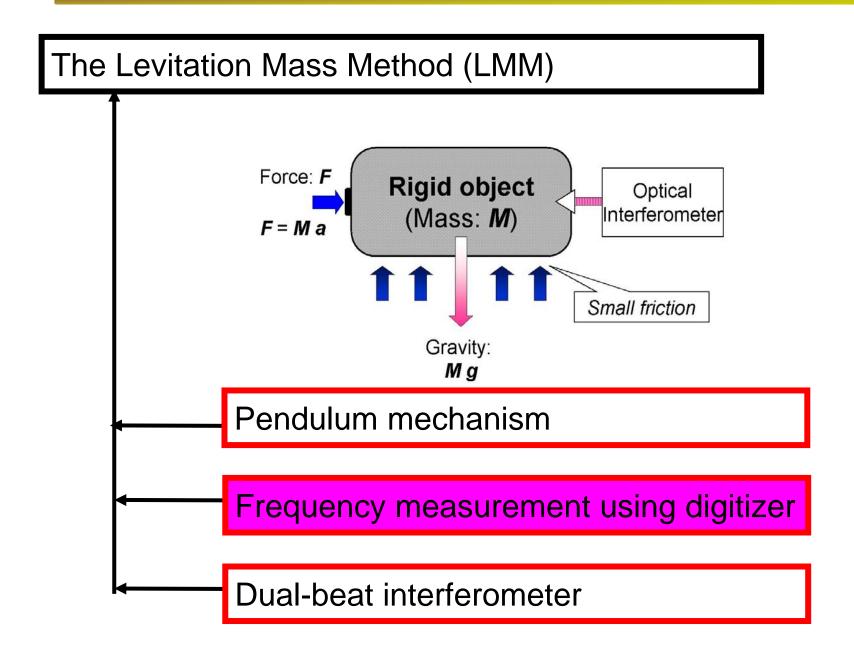


Figure 7 Change in corrected force against position in collision measurement

Y. Fujii, "Pendulum for precision force measurement", *Rev. Sci. Instrum.*, Vol. 77, No.3, 035111-1-5, 2006.

# Some technologies for improving the LMM

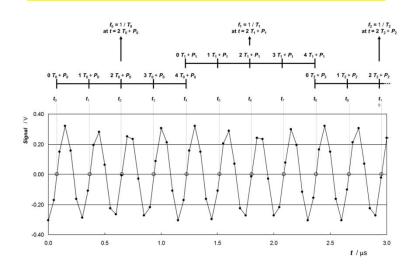


## Frequency measurement using digitizer (1)

#### Zero-crossing Averaging Method (ZAM)

# 

#### **Zero-crossing Fitting Method (ZFM)**



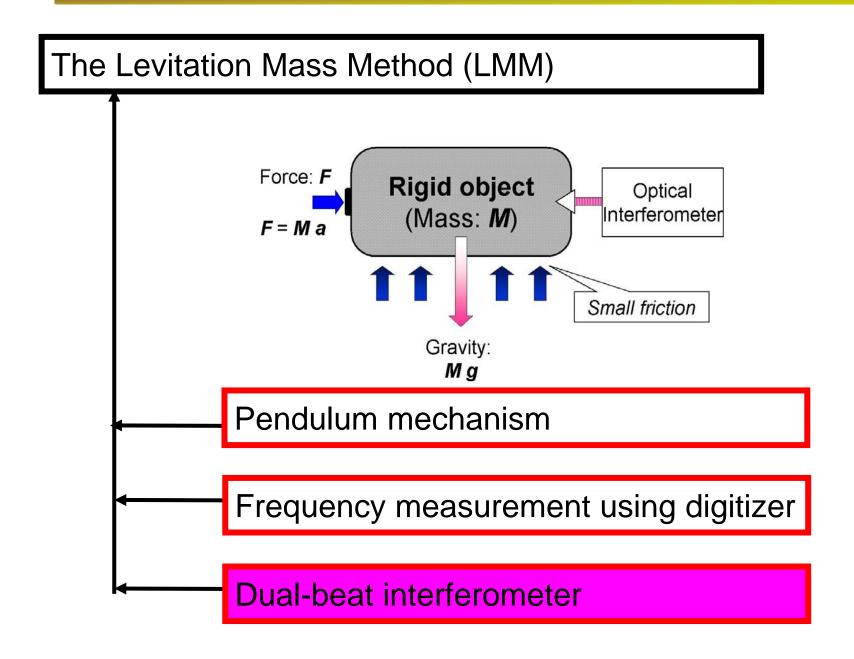
Y. Fujii and J. Valera, "Impact force measurement using an inertial mass and a digitizer", *Meas. Sci. Technol.*, Vol.17, No.4, pp. 863-868, 2006.

Y. Fujii, "Impact response measurement of an accelerometer", *Mech. Syst. Signal Pr.*, Vol.21, No.5, pp.2072-2079, 2007.

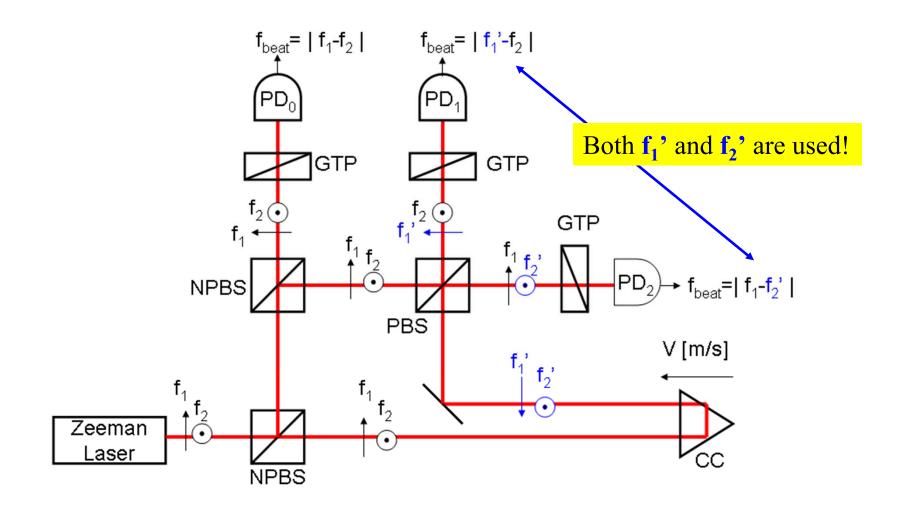
Y. Fujii and J. P. Hessling, "Frequency estimation method from digitized waveform", *Experimental Techniques*, Vol.33, No.5, pp.64-69, 2009.

T. Jin, A. Takita, S. Mitatha, P. P. Yupapin, H. Z. Jia, W. M. Hou and Y. Fujii, "Method for acceleration measurement using a laser Doppler interferometer", *Meas. Sci. Technol.*, Vol. 24, No.7, 077001, 2013.

# Some technologies for improving the LMM

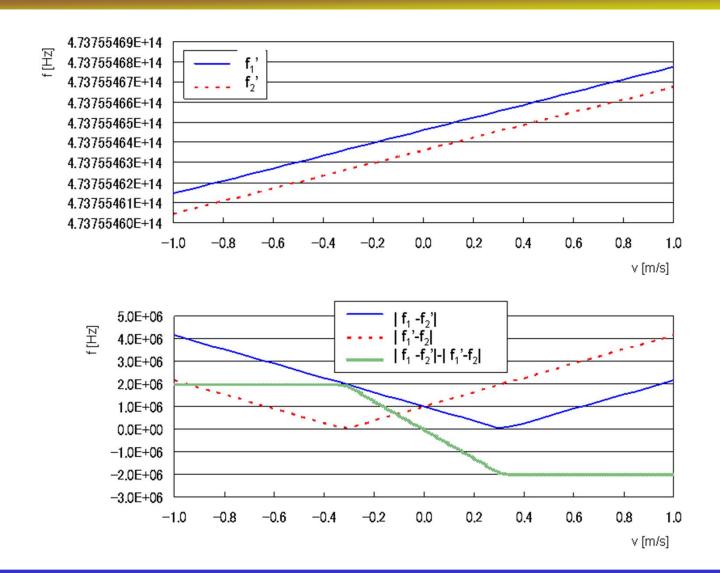


## Dual-beat interferometer for high-speed measurement (1/2)



A. Takita, H. Ebara, Y. Fujii, "Dual beat-frequencies laser Doppler interferometer", *Rev. Sci. Instrum.*, Vol.82, 123111, 2011.

## Dual-beat interferometer for high-speed measurement (2/2)



A. Takita, H. Ebara, Y. Fujii, "Dual beat-frequencies laser Doppler interferometer", *Rev. Sci. Instrum.*, Vol.82, 123111, 2011.

### Conclusions 1/2

The author has proposed a method, the Levitation Mass Method (LMM). In this method, the inertial force of a mass levitated using a aerostatic linear bearing is used as the reference force applied to the objects being tested, such as force transducers, materials and structures.

In the LMM, only the motion-induced time-varying beat frequency is measured during the measurement, and all the other quantities, such as velocity, position, acceleration and force, are numerically calculated afterwards.

This results in the good synchronization between the obtained quantities. In addition, force is directly calculated according to its definition, that is, the product of mass and acceleration.

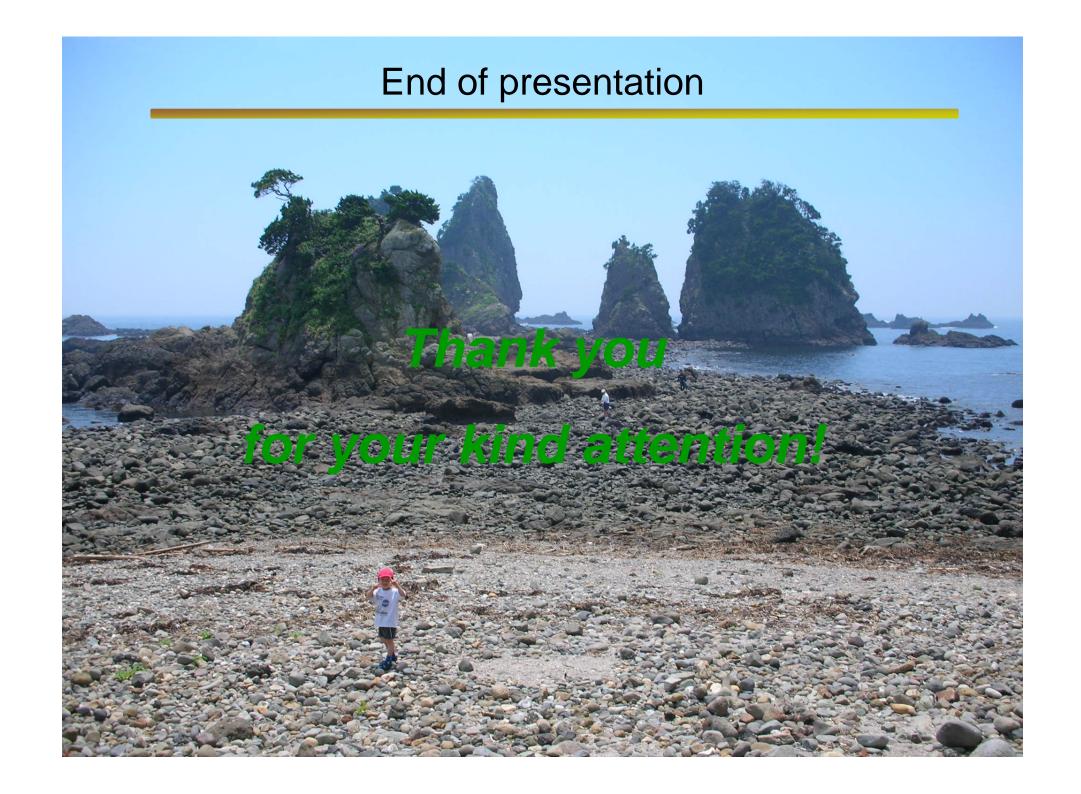
## Conclusions 2/2

The author would like to develop the following technologies and make them being commercialized.

Dynamic calibration method for force transducers: With this, the correction and the uncertainty evaluation of the measured forces with arbitrary waveform can be possible.

High precision material tester based on the LMM: In the tester, only the Doppler shift frequency is measure. Neither a force transducer nor a position sensor is used. Force is calculated according to its definition, that is the product of mass and acceleration.

There is still much room for further improvement as described in the paper.

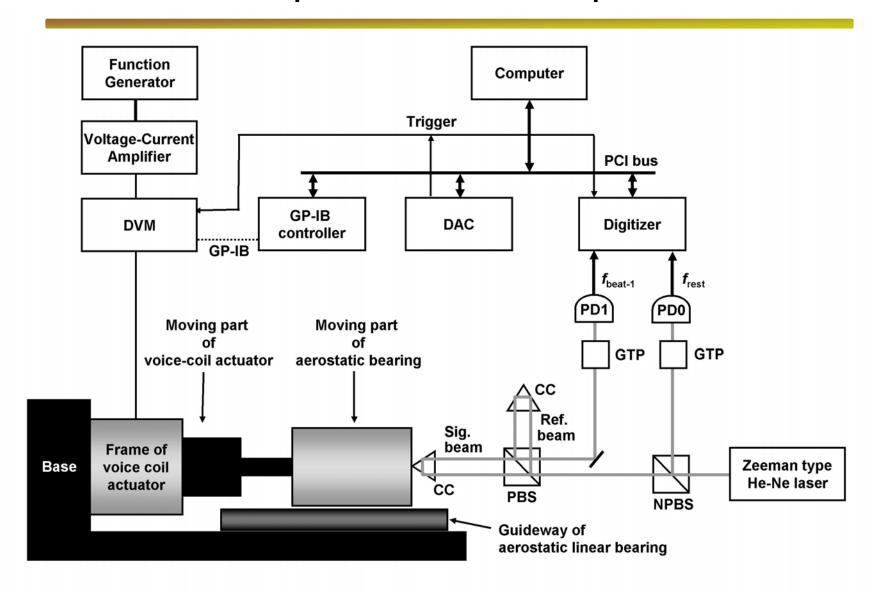


# Scope of the research

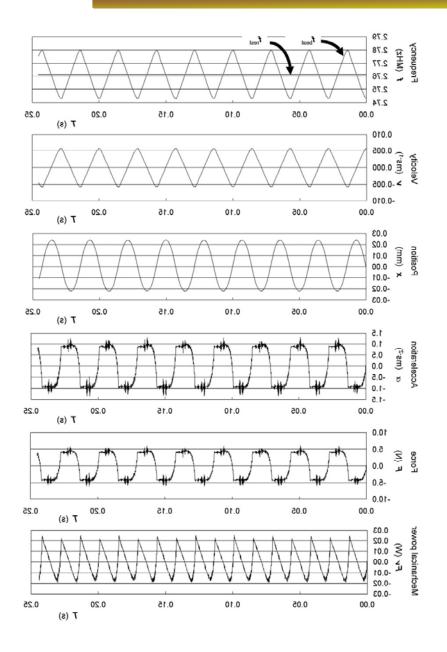
The electrical and mechanical characteristics of a voice coil linear motor under moving conditions are evaluated using a method based on the Levitation Mass Method (LMM).

The force generated by the actuator is measured as the inertial force of the mass, which is levitated with sufficiently small friction using a pneumatic linear bearing.

# **Experimental Setup**



# Mechanical Quantities

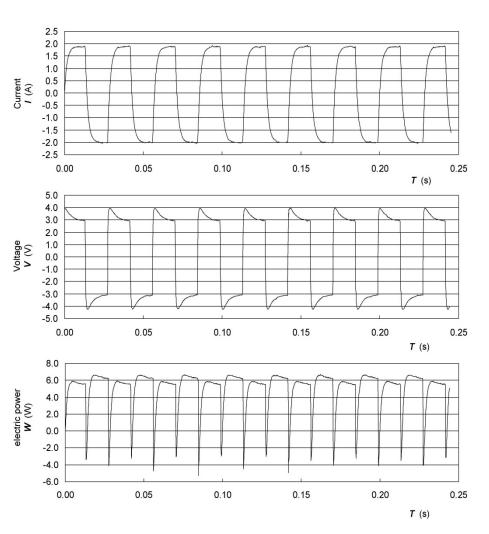


First, the frequency is calculated from the digitized output signal of the optical interferometer.

Then the velocity, position, acceleration, force, and mechanical power are calculated from the frequency.

In the figure, approximately 8 periods of the reciprocating motion are observed.

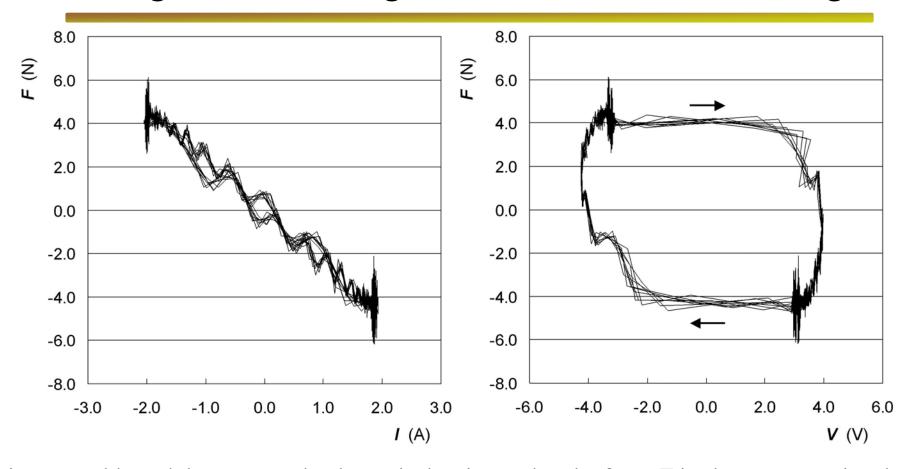
# **Electrical Quantities**



Although the function generator supplies a square wave of 35 Hz to the voltage-current amplifier,

the current exhibits a dull waveform, while the voltage exhibits an overshoot waveform.

# Change in force against current and voltage

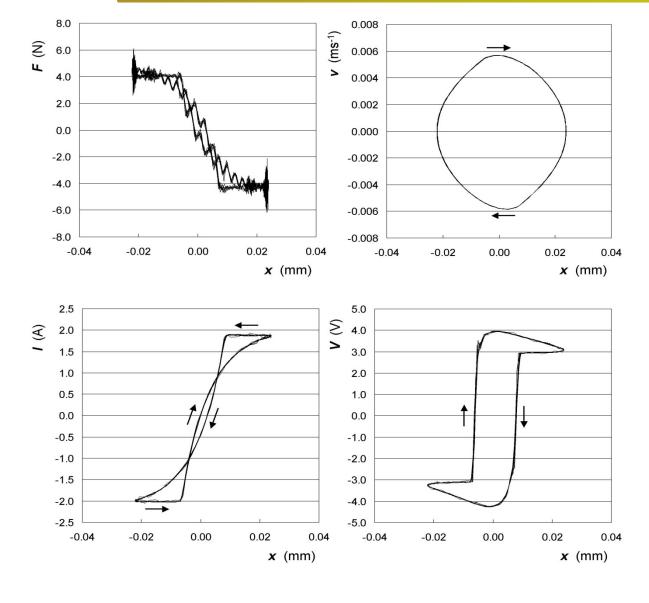


It is reasonable and the same as the theoretical estimate that the force F is almost proportional to the current I. The regression line is F = -2.3I - 0.14.

Fine structures are observed in the curves and they coincide well during the 8 periods of the reciprocating motion.

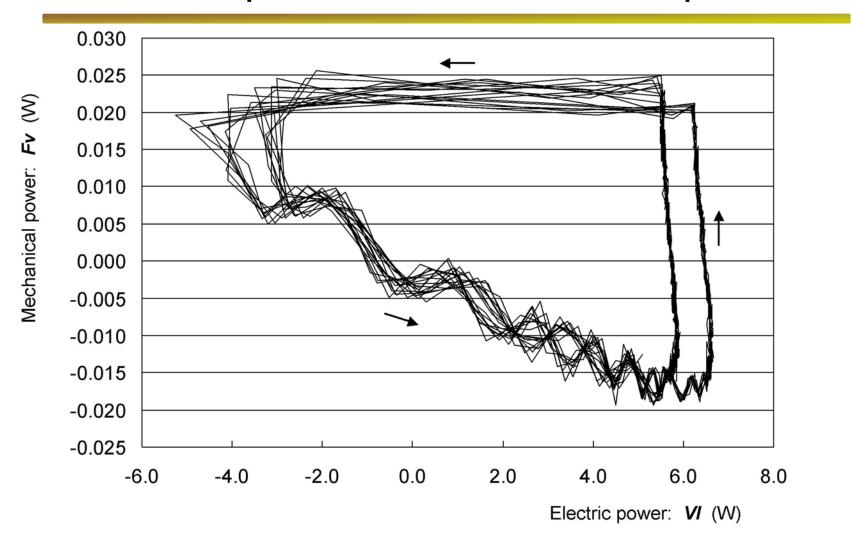
This indicates an accurate performance of the experimental setup and a high reproducibility of the measurements.

## Change in force, velocity, current, and voltage against position



The reproducibility of these results is very high during the 8 periods of the reciprocating motion.

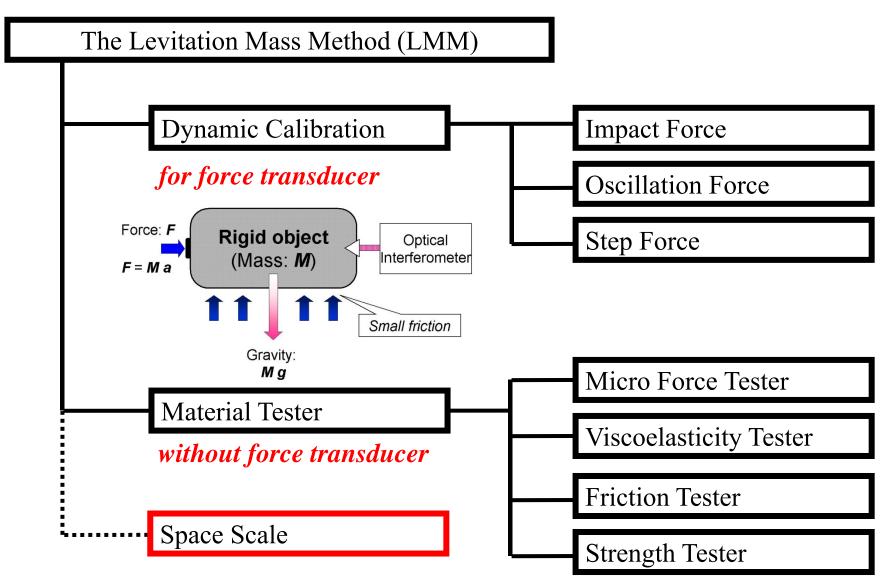
#### Eelectric power and mechanical power



The energy efficiency of the motor is very poor. The reproducibility of these results is very high during the 8 periods of the reciprocating motion.

#### Applications of the LMM

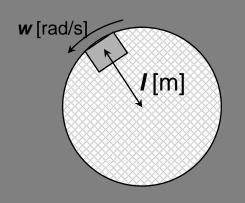
The LMM has shown the extreme high performance in the following fields.

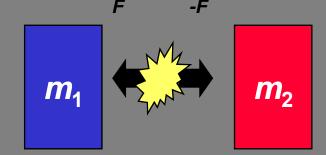


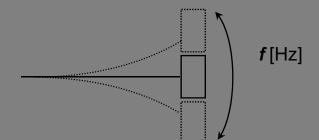
#### International Space Station (ISS)









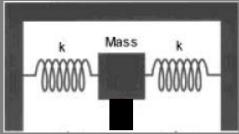


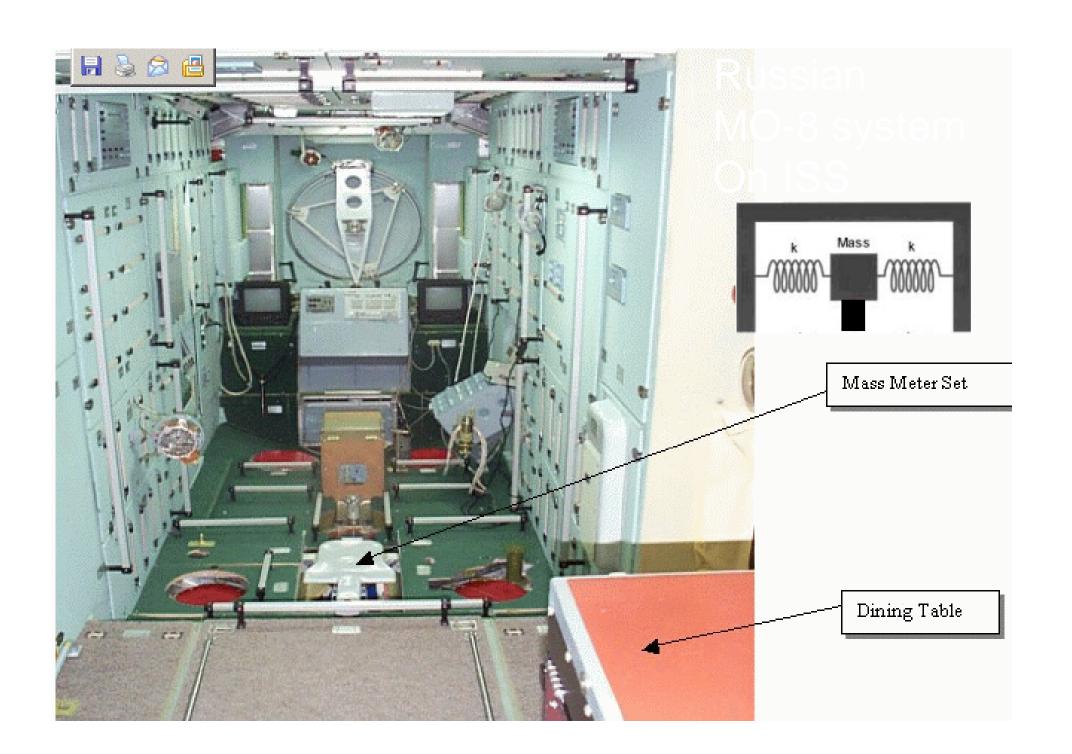
# Body mass measurement is a medical requirement for ISS crew

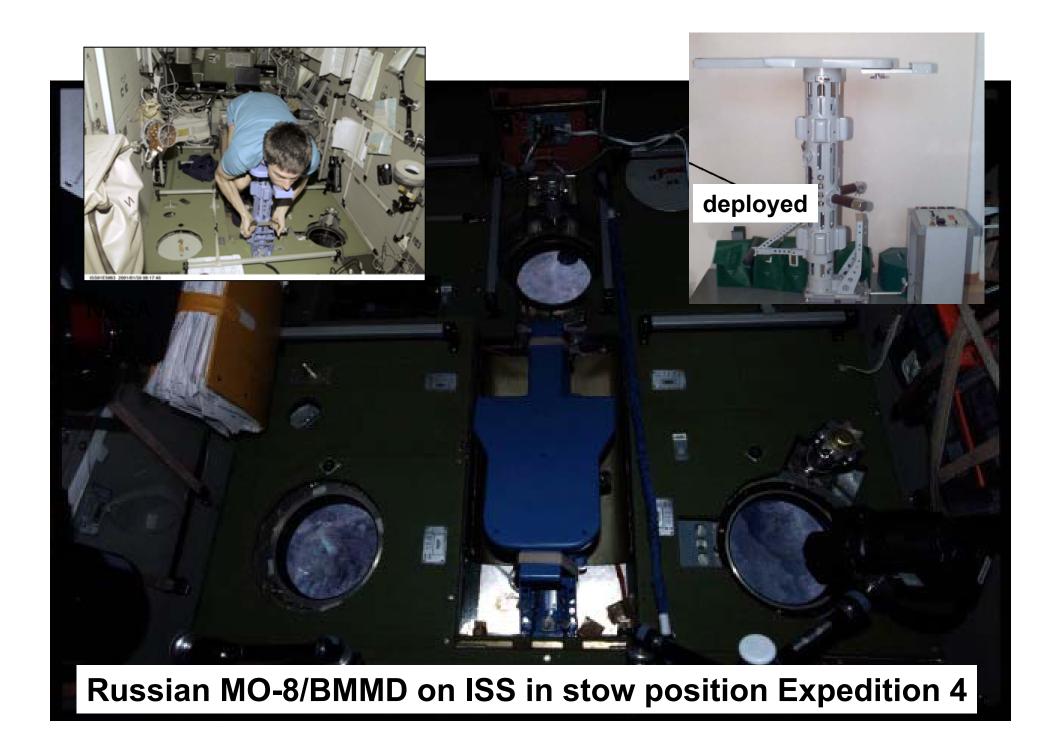
body mass range 40-110kg precision 0.2kg (0.5 % - 0.2 %)







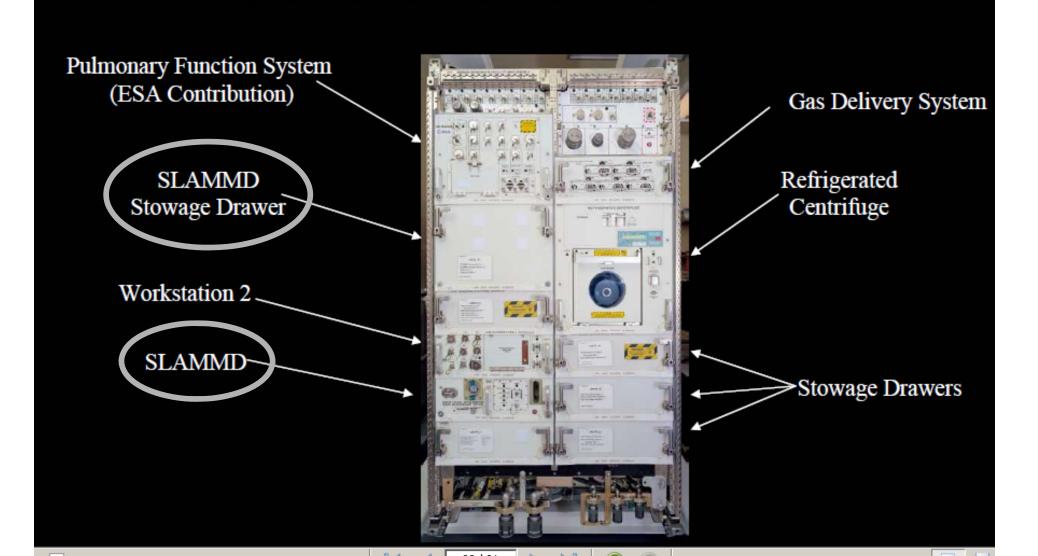






### NASA's new body mass device - SLAMMD HRF Rack 2 (Launch Configuration)





#### SLAMMD on ISS Exp.12 – 16 Dec. 2005



SLAMMD on ISS Exp.12 – 16 Dec. 2005







#### we can probably do better, by

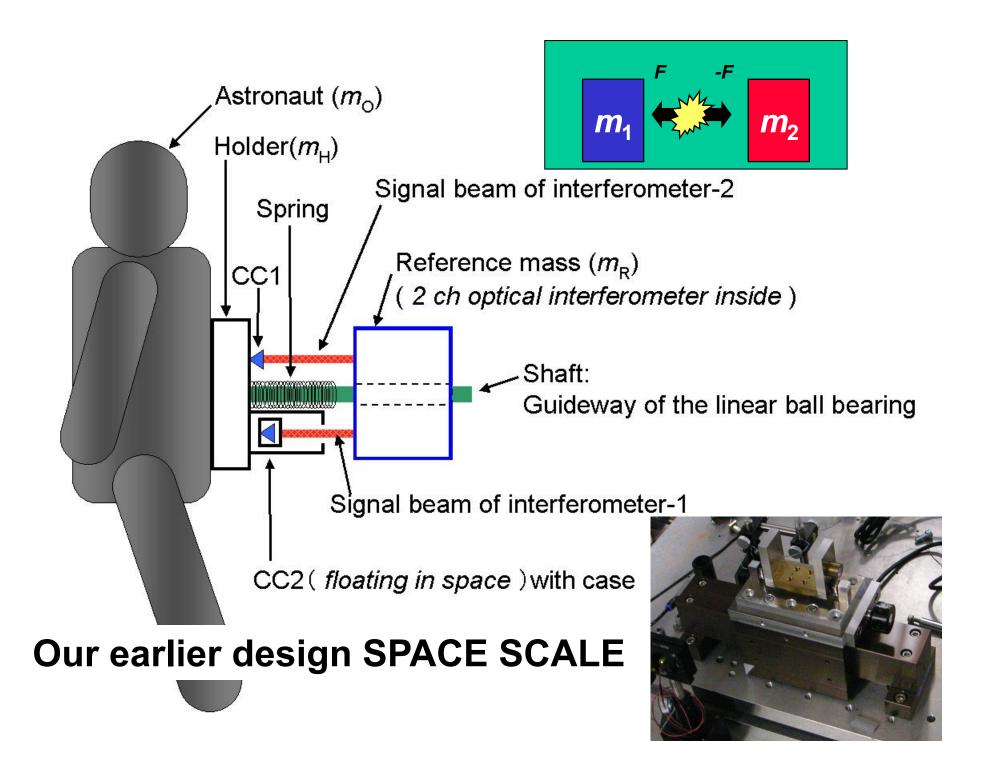


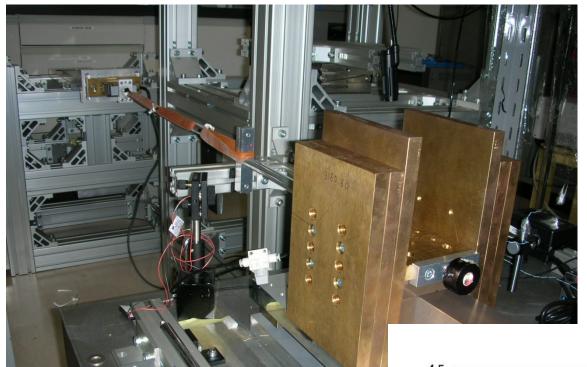
ISS and Atlantis solar to By Thierry Legault www.astrophoto.fr

#### SPACE SCALE

- [1] Y. Fujii, H. Fujimoto and S. Namioka, "Mass measurement under weightless conditions", *Rev. Sci. Instrum.*, Vol. 70, No.1, pp.111-113, 1999.
- [2] Y. Fujii, H. Fujimoto, R. Watanabe, Y. Miki, "Balance for measuring mass under microgravity conditions", *AIAA Journal*, Vol.39, No.3, pp.455-457, 2001.
- [3] Y. Fujii and K. Shimada, "Instrument for measuring the mass of an astronaut", *Meas. Sci. Technol.*, Vol.17, No.10, pp.2705-2710, 2006.
- [4] Y. Fujii and K. Shimada, "The space scale: An Instrument for astronaut mass measurement", *Trans. Jpn. Soc. Aeronaut. Space Sci.*, Vol.50, No.170, pp.251-257, 2008.
- [5] Y. Fujii, K. Shimada, M. Yokota, S. Hashimoto, Y. Sugita and H. Ito, "Mass measuring instrument for use under microgravity conditions", *Rev. Sci. Instrum.*, Vol.79, No.5, 056105-1-3, 2008.
- [6] Y.Fujii, K. Shimada, K. Maru, M. Yokota, S. Hashimoto, N. Nagai and Y. Sugita, "Instrument for Measuring the Body Mass of Astronaut", *Trans. Jpn. Soc. Aeronaut. Space Sci. Space Technol. Jpn.*, (in press)
- [7] Y. Fujii, K. Shimada and K. Maru, "Instrument for Measuring the Body Mass of Astronauts under Microgravity Conditions", *Microgravity Science and Technology*, Vol. 22, No. 1, pp. 115-121, 2010.

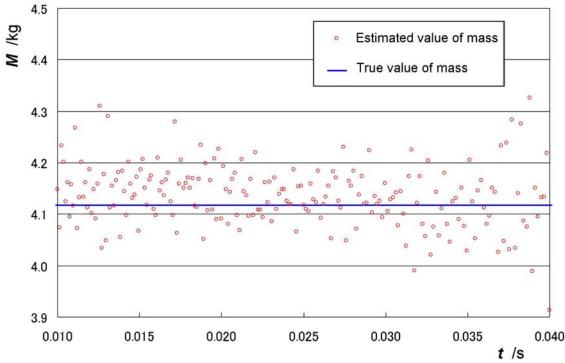


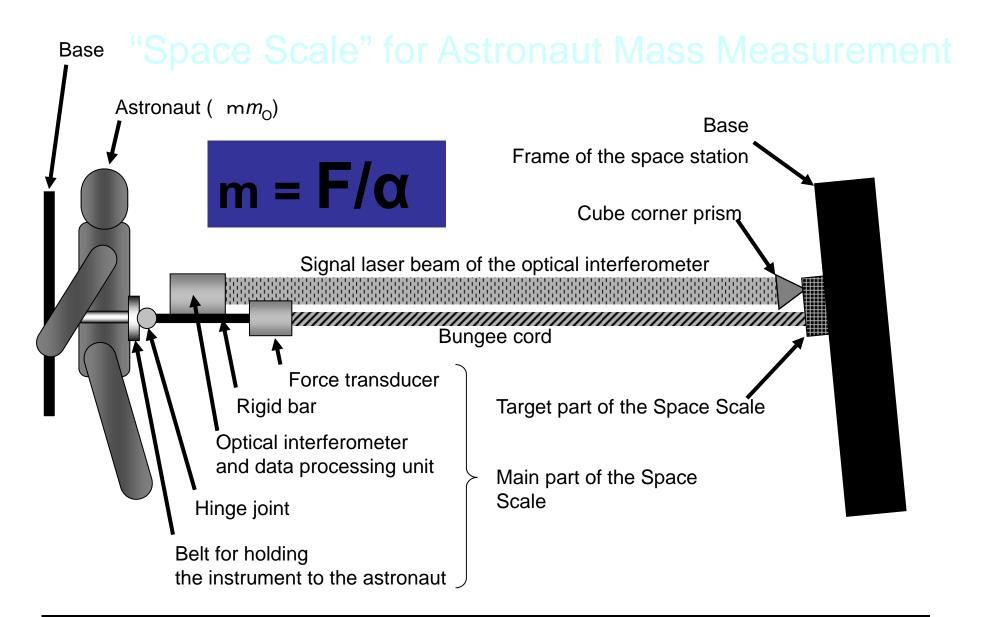




## Ground model study

Precision(1.6%rms) and accuracy(0.4%) were promising to satisfy the body mass measurement requirements.





Our latest SPACE SCALE design on Parabolic Flight Test

#### Parabolic Flight Test at Nagoya Gulfstream II

