Optical based Precision Measurement System and Its Application on Dynamic Force Measurement

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Abstract. Force is one of the basic quantities of mechanics, which is usually measured using a force transducer. However, the force transducer is usually calibrated by a static method. While the dynamic calibration for the force transducer is not sufficient. Dynamic calibration and measurement are needed to measure and evaluate mechanical parameters of materials in industry and research applications such as material testing, measurement of friction of a material, motion control, and crash testing. Dynamic measurement of force is also very necessary to produce and evaluate force with micro-Newton levels. However, there are difficulties in dynamic measurement, namely: there are difficulties in evaluating the inaccuracies in the measurement of varying forces, then there is difficulty in evaluating the inaccuracy in the time when measuring force. To overcome this problem, an optical-based precision measurement system was developed. This system can measure the force with high accuracy without using a force transducer. In the developed system, a levitated load (moving part) is used as a reference force imposed on the material to be measured for mechanical parameters. The inertial force of the levitated load is calculated accurately as a result of the multiplication between the load mass and its acceleration. In systems that are developed, speed, acceleration, force, and position are calculated accurately from the shift in the laser beam Doppler frequency reflected by the load. So that the measurement accuracy is strongly influenced by the accuracy of frequency calculations. In this system, a special program for zero-crossing-based frequency estimation is also very accurate. The developed system has proven to be able to perform mechanical/dynamic measurements and can evaluate the style with newton-level micro very accurately.

1. Introduction

Newton's law of motion explains the basic concepts of force interaction. A moving mass will experience a change in speed as a function of the force it receives. The moving mass contains energy in the form of momentum. This energy is used as a source of force. This force is called the inertial force which is proportional to the change in momentum of the mass\textsuperscript{[1]}. The optical-based precision measurement system developed is a method that can accurately measure dynamic forces. This method uses the inertia force as the reference force. A load (moving part) with a certain mass is levitated to minimize friction, given initial velocity or force to be the source of inertial force. This method is known as Levitation Mass Method (LMM). Then this mass collides with objects that will be measured by the influence of dynamic force interactions. Optical interferometers are used to measure the movement of the levitated mass\textsuperscript{[2]}. The basic concept of this method can be seen in Figure 1.
The developed system has high accuracy in measurement. In this method, only the beat frequency varies with time due to mass movements measured in measurements, and other quantities such as speed, position, acceleration, and force are calculated numerically later. So that the relationship between the quantities that are fixed is very good.

In practice, the LMM uses levitated mass or pendulum mass[3]. the mass is levitated using an aerostatic linear bearing around the guideway to reduce friction [4]. Figure 2 shows the arrangement of the air bearings of LMM. The guideway is designed to limit the direction of motion only on one axis. This guideway must be ascertained to be straight and precise to maintain uniformity of air cushion on the perimeter. Another way in LMM is to hang the mass using a string (figure 3). The string is arranged in such a way that the axis of the mass movement is in one direction.
Mass movements are measured by utilizing the optical interferometer Doppler effect [5]. In the mass, corner cube is installed which reflects the laser beam parallel to the source. When the mass moves, the length of the laser beam path changes and the reflection frequency also changes. The laser interferometer is set-up in a heterodyne layout where the reference and beam rays as Doppler effects are measured simultaneously. Dual frequency laser is used to avoid the need for high-speed light intensity transducers.

Set up of the laser interferometer to detect mass movement shown in figure 4. The laser beam is split by the Non-Polarizing Beam Splitter (NPBS) into two beams where one beam is read as the initial frequency. The beam path is made using Corner Cube (CC) and Polarizing Beam Splitter (PBS) to produce interference between the reference beam and reflected light. Glan-Thompson Prism is used to filter and polarize the light entering the photodetector. The photodetector is used as a transducer by detecting intensity as a result of the interference process.

\[
f = \left( \frac{1 + \frac{v}{c}}{1 - \frac{v}{c}} \right) f_0
\]

In this case, Einstein's theory of special relativity is not needed to get the formula for light reflected by a moving mirror, because all observations are made in one reference frame. The formula obtained with \(c\) is the speed of light and \(v\) is the velocity of mass which produces a shift in frequency as a
function of the reference frequency. Information about this frequency shift contains a velocity vector, and its relationship can be seen in equation (2).

$$\Delta f = f - f_0 = 2v \frac{f_0}{c} \approx 2v \frac{f_0}{c}$$

(2)

Generally, the laser beam has a very high frequency so to read the frequency, a recorder with a very high speed is needed. One way to reduce this frequency is to use interference, although this will limit the system speed limit.

Figure 5 describes an example of the interference method with the frequency changing in its path and the results of this interference are read by the photodetector. In the photodetector, the frequency limit is the difference between the two beams using Glan-Thompson Prism. By choosing a close working frequency for these 2 beams, low-frequency measurements can be made. So that measurement can be done with a recording system with a low frequency, of course, it will also reduce the cost of measurement.

Figure 5. Interferometer beam path and frequency

$f_{rest}$ is the reference frequency and $f_{beat}$ is the reflection frequency. Doppler shift frequency $f_{doppler}$ is calculated using equation (3).

$$f_{doppler} = -(f_{beat} - f_{rest})$$

(3)

The velocity of the mass which results in the Doppler effect is calculated from $f_{doppler}$ using equation (4). In this equation, $\lambda_{air}$ is the wavelength of the laser beam reflected by the actuator in the experiment.

$$v = \frac{\lambda_{air} f_{doppler}}{2}$$

(4)

The velocity information generated from this interference method is used to obtain the acceleration and position of the mass using equation (5) and equation (6). In this measurement, information about the mass of the moving part is needed to obtain the inertial force based on the definition that force is the product of mass and acceleration as in equation (7). While the inertial force can be measured as a change in mass momentum using equation (8).

$$a = \frac{dv}{dt}$$

(5)
Velocity in LMM is calculated based on Doppler Shift Frequency. Doppler shift, also known as the Doppler Effect, is a change in frequency for an observer (receiver) that moves relative to the source [6]. When the source and observer are at rest, the observer will receive the same frequency as the source. If one of the sources or observer or both moves close to each other, the observer will receive a frequency higher than the frequency generated by the source. On the contrary, if the source and observer keep away from each other, the observer will receive a lower frequency than the frequency generated by the source. Although for both cases, the frequency generated by the source is constant.

Actually, the principle of shifting or changing frequency is clear. The frequency shift is actually not happening, but what happens is phase change. Frequency can be expressed as a phase difference with time.

The distance from the beam that has the length of the wave $\lambda$ is $2r$ that is, the distance of back and forth. Thus, the phase difference between the signal is transmitted and the received signal can be expressed as:

$$\varphi = \frac{2r \cdot 2\pi}{\lambda}$$

(9)

Phase differentiation with time is:

$$\frac{d(\varphi)}{dt} = -\frac{4\pi}{\lambda} \frac{d(r)}{dt}$$

(10)

With $v_r$, the relative velocity of moving parts $v_r = \frac{d(r)}{dt}$, then the frequency can be expressed as:

$$f = \frac{1}{2\pi} \left( -\frac{4\pi}{\lambda} \right) v_r$$

(11)

This frequency is equivalent to the Doppler frequency, so $f_{doppler}$:

$$f_{doppler} = \frac{2}{\lambda} v_r$$

(12)

So that the relative speed of moving parts can be determined.

This paper will explain the application of the development of optical-based precision measurement systems.
2. Micro Force Material Tester
As a micro-force measuring device, the LMM has been used as a method for generating and measuring the force with micro-newton level. Using this method, the mechanical response of a sheet of paper has been evaluated with a maximum impact force of 2 mN. However, the forces acting inside the linear bearing are ignored and other uncertainties have not been evaluated.

Then an in-situ observation technique is used to estimate forces acting in a pneumatic linear bearing. In this method, the force acting on the test material is evaluated accurately by subtracting the force acting in the bearing from the total inertial force of the excited mass. Using this method, the mechanical response of human hair has been evaluated with a maximum immunity of 0.1 mN with an uncertainty of 1.6 uN.

2.1. Set-Up Experiment
Figure 7 shows a schematic diagram of the experimental set up for cantilever bending tests of materials against small impact forces. In this method, mass inertial force is used as a reference force acting on the test material. Pneumatic linear bearings are used to realize linear motion with small friction. Impact force is generated and applied by impacting it.

The initial velocity is given to moving parts manually. The inertial force acting on the mass is accurately measured using an optical interferometer. Hair is used as a test material.

The test material is placed on a movable base, which allows two measurement modes namely collision mode and free sliding mode. The free sliding mode is used to evaluate the forces acting inside the bearing.
The total force acting on the moving part $F_{\text{mass}}$ is divided into two components, namely the force of the test material $F_{\text{material}}$ and other force $F_{\text{bearing}}$.

$$F_{\text{mass}} = F_{\text{material}} + F_{\text{bearing}}$$ (13)

If another force $F_{\text{bearing}}$ can be ignored, the force acting on the material from the moving part is $-M \cdot a$. If $F_{\text{bearing}}$ cannot be ignored, it will be included in the calculation.

$F_{\text{bearing}}$ consists of three components

$$F_{\text{bearing}} = F_{\text{friction}} + F_{\text{airflow}} + F_{\text{gravity}}$$ (14)

Where $F_{\text{friction}}$ is the friction force in the air bearing layer due to the relative motion between moving parts and bearing holders, $F_{\text{airflow}}$ is the friction force in the bearing air layer due to the symmetry of the air flow, and $F_{\text{gravity}}$ is the component of the gravitational force caused by the inclination of the bearing holder towards the horizontal plane.

In the measurement, the total force $F_{\text{mass}}$ is measured as the product of the mass and acceleration. Acceleration is calculated from the moving part's velocity. The velocity is calculated from the result of a Doppler frequency shift from the laser interferometer beam $f_{\text{doppler}}$, which is stated as

$$v = \lambda_{\text{air}} \frac{f_{\text{doppler}}}{2}$$ (15)

$$f_{\text{doppler}} = - (f_{\text{beat}} - f_{\text{rest}})$$ (16)
Where $\lambda_{at}$ is the wavelength of the signal beam in the experimental condition, $f_{beat}$ is a beat frequency that is the difference in frequency between the signal beam and the reference beam, the $f_{rest}$ is rest frequency which is the $f_{beat}$ value when moving-part in a stationary state.

Zeeman type two frequency He-Ne laser is used as a light source. The frequency difference between the signal file and the reference file, $f_{beat}$ is measured by interference fringe on the interferometer output port which varies around the $f_{rest}$, around 2.9 Mhz, depending on the speed of motion.

An electronic frequency-counter measure and records the beat frequency $f_{beat}$ 14.000 times with the sampling interval $T = \frac{40.000}{f_{beat}}$, and stores the value in memory. The counter will always measure the time interval of every 40,000 periods without pauses. The sampling period from the counter approaches 14 ms at a frequency of 2.9 Mhz. Electric counter with the same model is used to measure rest frequency, $f_{rest}$.

Measurements with two electric counters are triggered by using a light switch which is a combination of laser diodes and photodiodes.

2.2. Measurement

2.2.1. Collision Measurement

In collision measurement, mass is made to collide with the test mass and the total force acting on the mass is measured as the result of multiplication between mass and acceleration. Figure 8 shows the data processing procedure. During collision measurement, only beat frequency and rest frequency accurately measured using optical interferometers. Doppler frequency shift is measured as the difference between beat frequency and rest frequency. Velocity, position, acceleration, and force are calculated from the shift in the Doppler frequency.

Figure 8. Procedure for data processing: calculation of velocity, position, acceleration, and force from the frequency

Figure 9 shows the change in total force acting on the mass against the position. The maximum value of the $F_{mass}$ impact force, max, approaches 0.12 mN (1.2 x 102 uN) as shown in the figure, the total force acting on a mass $F_{mass}$ is not small when moving parts collide and reverse direction, in other words, other forces such as $F_{bearing}$, consisting of $F_{friction}$, $F_{airflow}$ and $F_{gravity}$ cannot be ignored.
2.2.2. Free sliding measurement

To evaluate other force $F_{\text{bearing}}$ which consist of $F_{\text{friction}}$, $F_{\text{airflow}}$, and $F_{\text{gravity}}$, then the free-sliding measurements is conducted. In the experiment, the movable base is set to the off position and the moving part is made to move back and forth between the two rubber dampers. The total force acting on moving parts $F_{\text{mass}} = F_{\text{material}} + F_{\text{bearing}}$, is measured in the same way as collision measurement. Then the data where moving parts make contact with the rubber is removed and only data during the free sliding movement is selected. During free sliding movements, the total force $F_{\text{mass}}$ is proportional to other force $F_{\text{bearing}}$.

Figure 10 shows changes in force $F_{\text{bearing}}$ against the position during the free-sliding motion of moving part.
3. Optical Method to Evaluate Friction

Today, the need for measurement of friction between objects increases in various research and industrial applications. Although friction is one of the general and fundamental magnitudes of mechanics, it is often difficult to evaluate it. In general, reducing the effects of friction on industrial needs has a very beneficial effect on the environment, reducing energy lost due to friction and increasing the lifetime of the engine.

The difficulty in measuring friction comes from the fact that friction is generally a varying force and there is no dynamic calibration method for force transducers [7].

By modifying the LMM method, a direct optical-based friction measurement system was developed. In this method, the friction force is measured without using a force transducer.

3.1. Experiment setup

Figure 11 shows a diagram of an experimental set up to evaluate the friction acting between materials. In experiments, friction between miniature cars and iron plates was measured. The miniature of the car has a length of 65 mm with a tire diameter of 10 mm, connected to a force transducer and pressed to an iron plate connected to a moving part of a pneumatic linear bearing. The friction force between miniature cars and iron plates is measured directly as the inertial force of the moving part. Using linear bearings, linear movements with very little friction can be realized.

An initial speed is given to the moving part manually in the left direction of figure 11 at the beginning of the sliding experiment. A corner cube for interferometer and metal block to adjust the collision position associated with moving parts, the total mass of the moving part is 8.9402 kg. The inertial force acting on the mass is measured accurately using an optical interferometer.

The friction acting on miniature cars from iron plates is the same as the inertia force of moving parts, \( F_{\text{inertia}} = -M \cdot a \) based on the law of inertia if other forces such as friction force inside the bearing can be ignored. With this condition, the force acting on the iron plate of the miniature car is the result of mass times and the moving part acceleration that is \( F = m \cdot a \). Acceleration is calculated from the moving part speed. The calculated speed of the measured Doppler frequency shift from the laser interferometer, \( f_{\text{doppler}} \), which is expressed as
where \( \lambda_{air} \) is the wavelength of the signal beam in the experiment, \( f_{beat} \) is the beat frequency, i.e. the frequency difference between the signal beam with the reference beam, \( f_{rest} \) is the rest frequency i.e the value of \( f_{beat} \) when the moving part is at rest.

An S-shaped transducer force transducer is used to measure normal force, which is needed to get the coefficient of friction.

In this experiment, two sets of sliding measurements were carried out. In sliding measurement, moving parts are given an initial speed manually; moving parts will move to the left until they hit the damper connected to the base. During the measurement, there was no slippage on the miniature tires of the cars used.

3.2. Result

Figure 12 shows the data processing procedure from the calculation of velocity, position, acceleration and inertial force of the frequency during the measurement. During a sliding experiment, only the beat frequency \( f_{beat} \) and rest frequency, \( f_{rest} \) which are measured with very high accuracy using optical interferometers to obtain the inertial force of the moving part. The Doppler frequency shift is measured as the difference between beat frequency and rest frequency. The speed, position, acceleration and inertial force of the moving parts are calculated later.

![Figure 12](image12.png)

**Figure 12.** Data processing procedure: calculation of velocity, position, acceleration, and force from the frequency

Figure 13 shows changes in friction force \( F_f \), normal force, \( F_N \), and coefficient of friction, \( \mu (= F_f / F_N) \). Figure 13 shows a sliding measurement similar to figure 12.
Figure 13. Changes in friction force, normal force and coefficient of friction.

Figure 14 shows the friction force changes in two sliding measurements.

Figure 14. Changes in friction in two sliding measurements.

4. Measurement of Astronauts’ Body Mass on Microgravity Condition
In the future, human activities in outer space will be more intensive and varied as the space station and laboratory factories progress. Measurements with high accuracy and precision from physical quantities will be needed. From the 4 physical quantities that are often used such as length, mass, temperature, and current strength. Only mass cannot be measured in a state without weight (without gravity). We can measure mass only if the object we are about to measure has acceleration. For that, we have to measure dynamically.

At the International space station (ISS), information about the mass of astronauts, garbage containers, and scientific specimens is needed. Nowadays, NASA and the Federal Space Agency of Russia have developed and used two instruments to measure the body mass of astronauts on the ISS. However, this instrument is not easy to operate in the space shuttle cabin and its accuracy is not very reliable. The mass can be derived from the value of force, where force is the product of the multiplication between mass and acceleration. To be able to measure mass in microgravity conditions, the force field must be produced artificially and surround the target object[8].
4.1. Set up experiment

Figure 15 is a system developed to measure the mass of astronauts accurately and easily under microgravity conditions. Figure 16 is an experimental set-up in the mass measurements of astronauts.

In this method, a force transducer is used to measure the forces acting on astronauts. Then an optical interferometer measures the acceleration of the astronaut. The force transducer and optical interferometer are placed on a rigid rod. The laser beam and rubber cable are made parallel by using a hinge that connects the rigid rod with the astronaut.

![Figure 15: The basic principle of optical-based measurement of astronauts’ mass](image)

![Figure 16: Experimental setup of optical-based astronaut mass measurements](image)

4.2. Discussion

The advantages of the method developed are as follows:

- The instrument used is simple, lightweight and has a compact structure, does not require an actuator and can be stored in a small place when not in use.
- Only requires the tensional inertia force by astronauts
- Because astronauts float in the air, the mass of astronauts is free from external forces.
- Large displacement during measurement: this reduces the effect of changes in subject posture (i.e. changes in the distribution of astronaut density).
References

[1] T. Jin, A. Takita, M. Djamal, W. Hou, H. Jia, and Y. Fujii, “A method for evaluating the electro-mechanical characteristics of piezoelectric actuators during motion,” Sens. Switz., vol. 12, no. 9, pp. 11559–11570, 2012.

[2] T. Yamaguchi, Y. Fujii, T. Fukushima, N. Tomita, A. Takita, K.-I. Nagai, and S. Maruyama, “Damping response analysis for a structure connected with a nonlinear complex spring and application for a finger protected by absorbers under impact forces,” Mech. Syst. Signal Process., vol. 42, no. 1–2, pp. 88–96, 2014.

[3] J. Ozawa, A. Takita, T. Azami, and Y. Fujii, “Microforce material tester using small pendulum II,” Key Eng. Mater., vol. 497, pp. 169–175, 2012.

[4] K. Kitabata, H. Iwashita, A. Takita, M. Djamal, N. Pornsuwancharoen, and Y. Fujii, “Frictional characteristics measurement of a ceramic aerostatic linear bearing,” Key Eng. Mater., vol. 643, pp. 167–172, 2013.

[5] R. Araki, A. Takita, and Y. Fujii, “Method for frequency estimation by constant gate time,” presented at the Proc. of 2013 3rd Int. Conf. on Instrumentation, Communications, Information Technol., and Biomedical Engineering: Science and Technol. for Improvement of Health, Safety, and Environ., ICICI-BME 2013, 2013, pp. 416–420.

[6] 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, 2013.

[7] M. Djamal, K. Watanabe, K. Irisa, I. A. Prayogi, A. Takita, T. Yamaguchi, and Y. Fujii, “Dynamic characteristics measurements of a force transducer against small and short-duration impact forces,” Metrol. Meas. Syst., vol. 21, no. 1, pp. 59–66, 2014.

[8] K. Shimada and Y. Fujii, “Mass measurement of the astronauts on the International Space Station (ISS) for nutritional control,” presented at the Procedia Engineering, 2012, vol. 32, pp. 18–24.

[9] W. Xie, H. Yin, and J. Shen, “Review and proposition of new dynamic force calibration method,” presented at the Proceedings of 2013 IEEE 11th International Conference on Electronic Measurement and Instruments, ICEMI 2013, 2013, vol. 1, pp. 451–455.

[10] L. Zhang, F. Yang, R. Li, T. Guan, J. He, F. S. Fu, D. Li, and D. Zhang, “A novel impact tester for in situ evaluating the shock reliability of micro-structures,” presented at the Proceedings of the IEEE International Conference on Micro Electro Mechanical Systems (MEMS), 2016, vol. 2016–February, pp. 942–945.