Method for evaluating mechanical response of human skin against micro impact force

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Abstract. Method for evaluating mechanical response of human skin against micro impact force is proposed. The method is a variation of the Levitation Mass Method, which has been proposed and developed by the author. In the method, a mass that is levitated with a pneumatic linear bearing, and hence encounters negligible friction, is made to collide with an object under test, such as a skin of human hand. During the collision the Doppler frequency shift of the laser beam reflecting from the mass is accurately measured using an optical interferometer. The velocity, the position, the acceleration and the inertial force of the mass are calculated from the measured time-varying Doppler frequency shift. The method is characterized by the fact that preparation of the test is very easy and the testing time is very short.

1. Introduction
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 quite difficult to generate and evaluate small force, properly.

The difficulties in measuring small force mainly come from the facts as followings,
(1) No National Measurement Institute supports a direct force realization linked to the International System of Units (SI) below 1 N even for static force [1].
(2) Small force to be generated and/or measured is usually a varying force and any dynamic calibration technique for force sensors has not established [2]. In other words, this fact means that the uncertainty evaluations both for the measured value of the small force and for the time of the measurement are very difficult.

Force, which is one of the most basic mechanical quantities, is defined as the product of mass and acceleration as:

\[ F = Ma \]

where \( F \) is the force acting on an object, \( M \) is the mass of the object, and \( a \) is the acceleration of the center of the gravity of the object. This means that a well-defined acceleration is required to generate force accurately and to calibrate force transducers accurately.

Acceleration due to gravity, \( g \), is convenient and usually used for generating and/or measuring constant force. There is an attempt [1] for developing a method for generating and measuring micro constant force directly linked to SI by modifying the Watt Balance Method [3]. There is another attempt for developing a method for generating and measuring micro constant force, in which a combination of an electric balance and a lever mechanism is used as a scale [4].

However there are no working methods for calibrating force transducers under dynamic conditions.
Only static methods, in which transducers are calibrated by static weighting under static conditions, are widely available at present. Therefore, it is very difficult to determine the uncertainty in measuring a varying force or dynamic force using force transducers. Usually it is widely believed that force transducers with higher resonant frequency are suitable for measuring the dynamic force with higher frequency. However, that is irrational, of course.

Although the methods of dynamic calibration of force transducers are not yet well established, there have been a number of trials aiming at establishing the dynamic calibration methods for force transducers.

One method was proposed by the author and has been under development [2,5,6]. This method, that is the Levitation Mass Method, was first proposed [2] as an impulse response evaluation method for force transducers; a mass is made to collide with a force transducer and the impulse, i.e., the time integration of the impact force, is measured highly accurately as a change in momentum of the mass. To realize linear motion with sufficiently small friction acting on the mass, a pneumatic linear bearing [5] is used, and the velocity of the mass, i.e., the moving part of the bearing, is measured using an optical interferometer.

The other method, which was proposed and has been developed by Kumme, uses the inertial force of the attached mass generated by a shaker [7,8,9]. In this method, dynamic force of a single frequency is generated and applied to a force transducer. This method is effective for evaluating the characteristics of force transducers under the conditions in which calibration is conducted, such as continuous vibration at a single frequency.

The Levitation Mass Method has been applied to the field of the material testing, such as the dynamic three-point bending test [10], the viscoelasticity test [11], the friction test [12] and the material test against micro-Newton level forces [13].

In this paper, the mechanical response of human skin against micro impact force is evaluated by means of modifying the Levitation Mass Method.

2. Experimental setup
Fig. 1 shows a schematic diagram of the experimental setup for generating and measuring the small impact force applied to a skin of the palm of human hand. Fig.2 shows a photograph around the test section. A pneumatic linear bearing is used to realize linear motion with sufficiently small friction acting on the mass, i.e., the moving part of the bearing. Impact force is generated and applied to the skin under test by colliding the mass. An initial velocity is given to the moving part manually. A cube-corner prism (CC) for interferometer and a metal block with a round-shaped tip for adjusting the collision position are attached to the moving part; its total mass, \( M \), is approximately 21.17 g. The inertial force acting on the mass is measured highly accurately using an optical interferometer.
Zeeman-type two-frequency He-Ne laser is used as the light source.

The force acting on the material from the moving part is equal to the inertial force of the moving part, \( F_{\text{inertial}} = -Ma \) according to the law of inertia if other forces, such as the frictional force inside the bearing, can be ignored. In this condition, the force acting on the moving part from the material is the product of mass and acceleration of the moving part, i.e. \( F = Ma \). The acceleration is calculated from the velocity of the moving part. The velocity is calculated from the measured value of the Doppler shift frequency of the signal beam of a laser interferometer, \( f_{\text{Doppler}} \), which can be expressed as

\[
 v = \lambda_{\text{air}} \left( \frac{f_{\text{Doppler}}}{2} \right) ,
\]

\[
 f_{\text{Doppler}} = -(f_{\text{beat}} - f_{\text{rest}}),
\]

where \( \lambda_{\text{air}} \) is the wavelength of the signal beam under the experimental conditions, \( f_{\text{beat}} \) is the beat frequency, i.e., the frequency difference between the signal beam and the reference beam, \( f_{\text{rest}} \) is the rest frequency which is the value of \( f_{\text{beat}} \) when the moving part is at a standstill.

Figure 3. Data processing procedure: calculation of velocity, position, acceleration and force from frequency

An electric frequency counter (model: R5363; manufactured by Advantest Corp., Japan) continuously measures and records the beat frequency, \( f_{\text{beat}} \), 14000 times with a sampling interval of \( T = \frac{4000}{f_{\text{beat}}} \), and stores the values in memory. This counter continuously measures the interval time of every 4000 periods without dead time. The sampling period of the counter is approximately 1.5 ms at a frequency of 2.7 MHz. Another same-model electric counter measures the rest frequency, \( f_{\text{rest}} \), using the electric signal supplied by a photodiode embedded inside the He-Ne laser. Measurements using the two electric counters are triggered by means of a sharp trigger signal generated using a digital to analog converter. This signal is initiated by means of a light switch, a combination of a laser-diode and a photodiode.

The pneumatic linear bearing, “GLS08A50/25-2571” (NSK Corp, Japan), is attached to an adjustable tilting stage. The maximum tolerable mass of the moving part is approximately 1 kg and the thickness of the air film is approximately 10 mm.

In the experiment, 1 set of collision measurement with 5 continuous collisions with the skin of human hand is conducted. In 1 set of measurement, the mass performs reciprocating motion between the skin under test and the rubber damper shown in Fig.1.

3. Results and Discussion

Fig. 3 shows the data processing procedure in a collision experiment. In the figure, only the 1st collision out of 5 collisions is shown. During the experiment, only the beat frequency, \( f_{\text{beat}} \), and the rest frequency, \( f_{\text{rest}} \), are measured highly accurately using an optical interferometer. The velocity, the
position, the acceleration and the inertial force of the mass are calculated from the frequency afterward. Fig. 4 shows the change in force acting on the mass from the material, \( F = Ma \), against position during the whole set of measurement. The origins of the position axis is set to be zero at the point the force acting from the skin is firstly detected. The cause of variations of the beginning positions of 5 impulses is that the hand slightly moves during the set of the 5 collision measurements. The area bounded the trajectory of each collision measurement equals to the work done by the mass. This is due to viscoelasticity of the skin.

Fig.5 shows the change in force against position during only the 5th collision measurement, in which the smallest impulse is applied to the skin. The maximum value of the force is approximately 4.3 mN.

The relationship between the mechanical properties, the change of color of the skin, the health conditions and the variations between individuals will be investigated in the near future. In the investigation, a digital video camera will be introduced to record the color of the skin around the collision area.

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