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Impact force measurement using an inertial mass and a digitizer

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Abstract

A novel method for accurately measuring impact forces with small peak value and steep slope is proposed. In the method, a mass, which is levitated with a pneumatic linear bearing and hence encounters negligible friction, is made to collide with an object under test. The Doppler frequency shift of a laser beam reflecting from the mass is calculated by using an optical interferometer whose output signal waveform is recorded with a digitizer (i.e. a high-speed analogue-to-digital converter). The velocity, position, acceleration and inertial force of the mass are calculated from the measured varying frequency shift. The performance of the proposed method is demonstrated by evaluating the viscoelasticity of a small rubber block under an impact load with small peak value and steep slope.

Keywords: material testing, viscoelasticity, inertial mass, inertial force, optical interferometer, levitation mass method

1. Introduction

Recently, the need for evaluating the mechanical properties of materials and structures under varying loads has arisen in various industrial and research applications such as material testing, motion control and crash testing. In such cases, the force acting on the material under test is measured using a force transducer and the position of the point at which the force is applied is measured using a position transducer. However, force transducers are typically calibrated with standard static methods using static weights and under static conditions. At present there are no standard methods for evaluating the dynamic characteristics of force transducers. This results in two major problems concerning material testing. One is the difficulty in evaluating the uncertainty in the measured value of the varying force. The other is the difficulty in evaluating the uncertainty in the time at which the varying force is applied, because the delay (or lead) of the transducer response against the applied force is unknown.

Force is one of the most basic mechanical quantities and is defined as the product of mass and acceleration. This implies that an accurately known acceleration is required to obtain force accurately and to calibrate force transducers accurately. Acceleration due to gravity g is conveniently used for generating and/or measuring constant force. Constant force can be accurately compared using a conventional balance with a knife-edge or a hinge.

The lack of dynamic calibration methods for force transducers results in the difficulty in determining the uncertainty in measuring a varying or dynamic force using force transducers. Although methods for the dynamic calibration of force transducers are not yet well established, there have been a number of attempts to establish dynamic calibration methods for force transducers.

One method was proposed by the first author and has been under development since then [1–5]. This method was first proposed [1] as an impulse response evaluation method for force transducers; a mass was made to collide with a force transducer and the impulse, i.e., the time integration of the impact force, was measured highly accurately as the change in momentum of the mass. To obtain linear motion with negligible friction acting on the mass, a pneumatic linear bearing [5] was used, and the velocity of the mass, i.e., the moving part of the bearing, was measured using an optical interferometer. This method was subsequently improved [2] to a method for determining the instantaneous value of the impact force in the impulse. In this case, the instantaneous value of the impact force was determined by measuring the instantaneous acceleration of the mass. The method was also modified and improved for calibrating force transducers under

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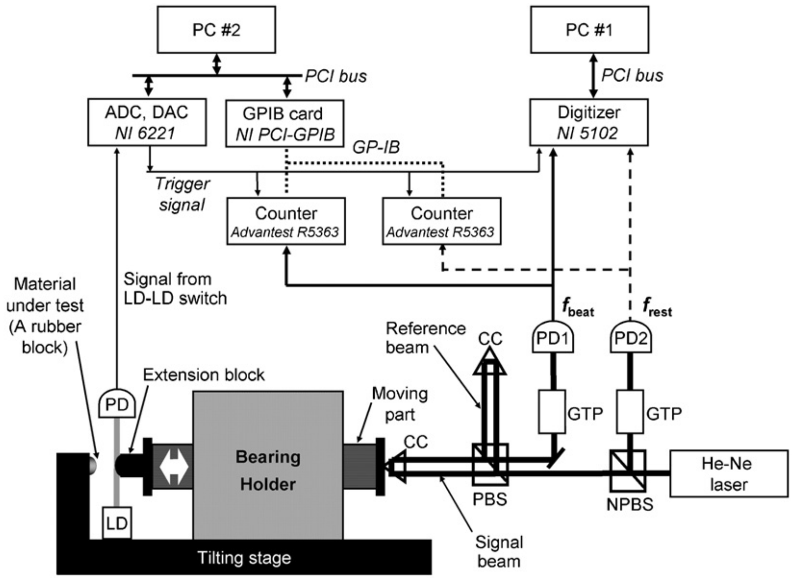

Figure 1. Experimental setup. Key: CC—cube corner prism, PBS—polarizing beam splitter, NPBS—non-polarizing beam splitter, GTP—Glan–Thompson prism, PD—photo diode, LD—laser diode, PC—computer.

oscillatory forces [3] and under step force [4]. Bruns *et al* have also developed a similar method [6].

Another method, which was proposed and developed by Kumme, uses the inertial force of a mass attached to a shaker [7]. In this method, a dynamic force of single frequency was generated and applied to a force transducer. This method is effective for evaluating the characteristics of force transducers under the conditions of calibration, such as continuous vibration at a single frequency. Park *et al* have used this method for the dynamic investigation of multi-component force-moment sensors [8, 9].

Summarizing the present status of measurement of dynamic force, methods have been proposed and developed for the dynamic force calibration of force transducers against some typical types of dynamic forces, such as impact forces, oscillation forces and step forces. However, it has not been established how to apply the results of such dynamic calibration to an arbitrary dynamic force. Its difficulty mainly comes from the fact that the validity of applying the frequency response obtained from the oscillation force calibration to other type of forces such as impact force and step force has not been proved to be valid.

By modifying the above methods [1–5], the first author also proposed a method for evaluating material viscoelasticity [10], a method for generating and measuring micro Newton level forces [11], a method for evaluating material friction [12] and a method for evaluating the frictional force encountered inside general linear bearings [13].

In all the above methods proposed by the first author, the Doppler frequency shift induced by the motion of a mass is measured using electronic frequency counters. However, the performance of commercially available counters sometimes is not sufficient to measure frequency with sufficient resolution and sampling rate. In general, there is a trade-off between resolution and sampling rate. In electronic frequency counters, only a limited portion of the waveform information that is input to them is used to calculate the period and frequency of the waveform. Frequency counters only measure the first and last zero-crossing times of a time interval containing many periods. The rest of the zero-crossing points in the interval are only counted without measuring the actual zero-crossing times. This is an inefficient use of the waveform information that is available.

Instead of electronic frequency counters, high-speed digitizers are sometimes used to record the whole wave profile and the period and the frequency are calculated from the waveform afterwards using computers. In the field of vibration measurement, this technique is widely used for measuring the period and the frequency of the output signal of a laser interferometer [14]. In the field of dynamic force calibration, this technique is also used for the same purpose [15, 16]. The zero crossing is obtained from the digitized waveform using the appropriate curve approximation, such as linear interpolation, polynomial approximation or sine curve fit [14–16].

In this paper, a novel method for accurately measuring impact forces with small peak value and steep slope is proposed. In the method, the entire output signal waveform from the optical interferometer is recorded using a digitizer, i.e. a high-speed analogue-to-digital converter. The Doppler frequency shift of a laser beam reflecting from the moving mass is calculated from the recorded waveform by calculating the time interval between the zero-crossing points of the waveform. In the proposed method, the time of the zero-crossing point is calculated as the average of many adjacent zero-crossing points. The performance of the proposed method is demonstrated by evaluating the viscoelasticity of a small rubber block under small and steep impact loads.

2. Experimental setup

Figure 1 shows a schematic diagram of the experimental setup for evaluating the viscoelasticity of a small object against a small and steep impact. In the method, the inertial force of a moving mass is used as the reference force applied to the material under test. A pneumatic linear bearing is used to obtain linear motion with negligible friction acting on the mass, i.e., the piston-shaped moving part of the bearing. The impact force is generated and applied to the material by collision with the mass. An initial velocity is manually given to the moving part. A corner-cube prism (CC), that forms part of the interferometer, and a metal block with a round-shaped tip (for adjusting the collision position) are attached to the moving part (made of aluminium with square pole shape); its total mass M is approximately 21.17 g. The inertial force acting on the mass is measured highly accurately using an optical interferometer. A small rubber block is used as the material under test and it is weakly glued to the metallic base.

The total force acting on the moving part F is the product of its mass M and its acceleration a:

$$F = Ma. \tag{1}$$

The acceleration is calculated from the time-varying velocity of the moving part.

An optical interferometer was used to accurately measure the velocity. It consisted of a Michelson interferometer in which the mirrors were replaced with corner-cube prisms. One corner-cube was firmly attached to the moving mass and defined as the signal arm of the interferometer. The other corner-cube was at rest and defined as the reference arm. The light source used was a Zeeman-type two-wavelength He–Ne laser in which the two wavelengths had orthogonal polarization. The light from the He–Ne laser was incident on a polarization beam splitter (PBS). One wavelength was transmitted to the signal arm and then reflected from the corner-cube attached to the moving mass. The other wavelength was reflected from the beam splitter and into the reference arm. After propagation in the Michelson interferometer the signal and reference beams were transmitted through a polarizer (a Glan–Thompson prism at 45° to the polarization of the beams, GTP), and hence interfered. The interfering beams were then incident on a detector PD1 and resulted in a beat signal, since the beams had slightly different wavelengths. The rest frequency, f_{rest}, was measured with detector PD2. When the object was at rest, then $f_{\mathrm{beat}} = f_{\mathrm{rest}}$ was approximately 2.7 MHz. However, object motion resulted in a Doppler shift in the signal beam which in turn resulted in a variation of f_{beat}. A digitizer (model: 5102; manufactured by National Instruments Corp., USA) recorded both signals from PD1 and PD2 with a sampling number of 5M samples for each channel and with a sampling rate of 20 MS s^{-1}. The measurement duration of the digitizer is 0.25 s.

The mass velocity was obtained by measuring the induced Doppler shift in the signal beam of the laser interferometer and by using the following equations:

$$v = \lambda_{\mathrm{air}}(f_{\mathrm{Doppler}})/2 \tag{2}$$

$$f_{\mathrm{Doppler}} = -(f_{\mathrm{beat}} - f_{\mathrm{rest}}), \tag{3}$$

where f_{Doppler} is the Doppler shift, λ_{air} is the wavelength of the signal beam in the air, f_{beat} is the beat frequency (i.e., the frequency difference between the signal beam and the reference beam) and f_{rest} is the rest frequency defined above. The positive direction for the velocity, acceleration and force acting on the moving part is towards the right in figure 1.

Simultaneously with the digitizer, an electronic frequency counter (model: R5363; manufactured by Advantest Corp., Japan) measured and recorded the beat frequency f_{beat} 2000 times with a sampling interval of $T = 400/f_{\mathrm{beat}}$, and stored the values in memory. This counter continuously measured the interval time of every 400 periods without dead time. The sampling period of the counter was approximately 0.15 ms at a frequency of 2.7 MHz. Another electronic counter (same model) measured the rest frequency f_{rest}. These counters have previously been used in the levitation mass method [10–12] and they were used here for comparison purposes to determine the accuracy of the proposed method.

The pneumatic linear bearing, 'GLS08A50/25-2571' (NSK Co., Ltd, Japan), was attached to an adjustable tilt stage. The tilt angle of the tilt stage can be adjusted by adjusting three compression and three tension bolts. The mechanism of the tilt stage is not shown in figure 1. According to the design specifications, the maximum value of additional mass that can be attached to the moving part is approximately 1 kg, the range of the movement is approximately 25 mm and the nominal thickness of the air film is approximately 10 μm. The moving part is a rectangular shape with a base of 8 mm × 8 mm and a height of 80 mm. The tilt angle of the upper surface of the bearing holder can be roughly adjusted horizontally with an uncertainty of approximately 0.1 mrad using a bubble level. The slope angle of approximately 0.1 mrad corresponds to the slope component of the gravitational force acting on the moving part of approximately 0.02 mN.

Measurements using the digitizer and the electronic frequency counters were triggered by means of a sharp step signal generated using a digital-to-analogue converter. This trigger signal is initiated by a light switch, which was a combination of a laser diode and a photodiode. When the moving part passes across the laser beam of the light switch, then the trigger signal is generated. To obtain the highest performance from the digitizer, the digitizer was exclusively controlled with a dedicated computer, PC1. The other computer, PC2, controlled all the other instruments, such as the GP-IB board and the ADC board. In the experiment, only one collision measurement was recorded.

3. Algorithm

Figure 2 shows an example of the data processing procedure for calculating the frequencies, f_{beat} and f_{rest}, from the waveforms at detectors PD1 and PD2 which were recorded with the digitizer. The figure shows only the first 121 points out of 5 million points that were recorded during the collision measurement with detector PD1. The figure shows only approximately 17 periods, during the first 6 μs of the collision measurement.

The frequency f_j is determined from the duration of N_j periods P_j, as $f_j = N_j/P_j$ where $j \geqslant 0$. The starting time T_j and the ending time T_{j+1} of the duration P_j are calculated as the average time of $(2n + 1)$ adjacent zero crossings, where n represents the half width of the averaging interval and is an integer that is not negative. This can be better understood by referring to figure 2. The time of the zero crossings, t_i ($i = 1, 2, 3, \ldots$), at which the waveform crosses zero from the negative value to the positive value is determined by linear interpolation using the adjacent two data points. Finally the duration of N_j periods, P_j ($j = 0, 1, 2, \ldots$), is calculated as

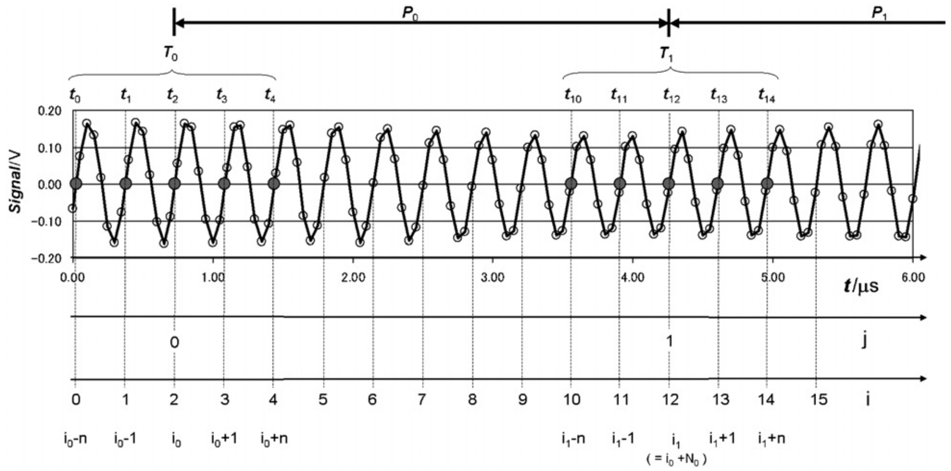

Figure 2. The data processing procedure (in the case of $n = 2$ and $N = 10$): calculation of frequency from the interferometer's output signal.

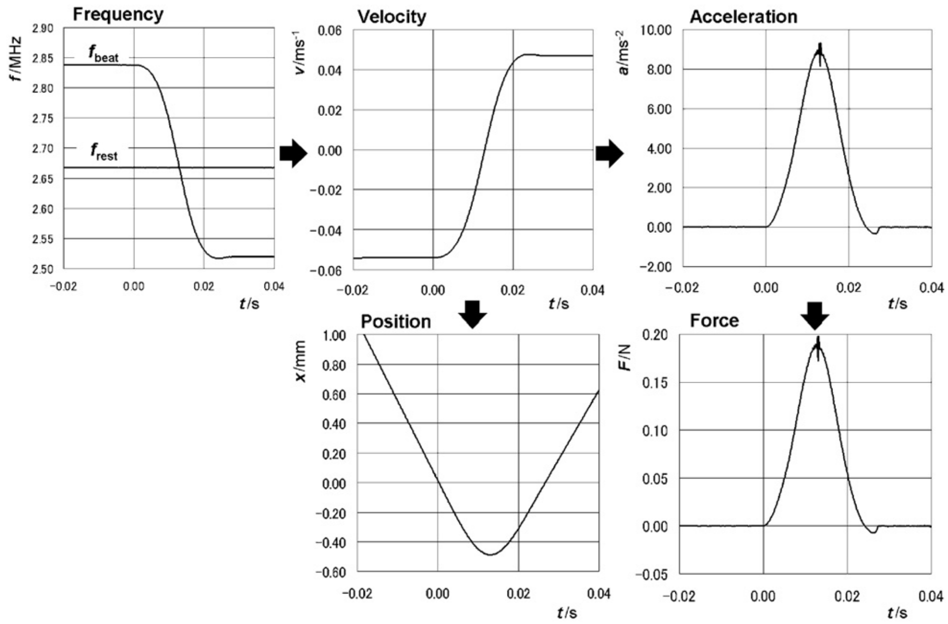

Figure 3. The data processing procedure: calculation of velocity, position, acceleration and force from beat frequency.

$P_j = T_{j+1} - T_j$ and the frequency is given by $f_j = N_j/P_j$. In the example shown in figure 2, N and n are set to be 10 and 2, respectively:

$$T_j = \frac{1}{2n+1}\sum_{i=jN_j}^{jN_j+2n} t_i \tag{4}$$

$$P_j = T_{j+1} - T_j \tag{5}$$

$$f_j = N_j/P_j. \tag{6}$$

In the following measurement of f_{beat}, N_j is made equal to 400 and n is made 100, so that the measurement of f_{beat} with the digitizer can be directly compared to that of the frequency counter. On the other hand, to determine the rest frequency, f_{rest}, the number of periods that define the duration, P_j, is not constant and is adjusted so that the starting time and the ending time of the duration are set as close as possible to those of the beat frequency.

Figure 3 shows the data processing procedure for calculating the velocity, position, acceleration and force from the measured time-varying Doppler shifted frequency. During the measurement, only the beat frequency, f_{beat}, and the rest frequency, f_{rest}, were measured. The Doppler shift is given by the difference between the beat and rest frequencies. The velocity, position, acceleration and frictional force of the mass were calculated at a later stage from the measured beat frequency and the measured rest frequency. The width at half maximum and the peak value of the impact force are approximately 10 ms and 0.2 N, respectively. A slight vibration in the force was observed near its peak. And the negative force due to the adhesive between the rubber block and base was also observed at the end of the collision.

4. Results

Figure 4 shows the change in the force obtained by the proposed method, $F_{\text{digitizer}}$, which is obtained from the instantaneous value of the beat frequency, f_{beat}, and the *instantaneous* value of the rest frequency, f_{rest}. The figure also

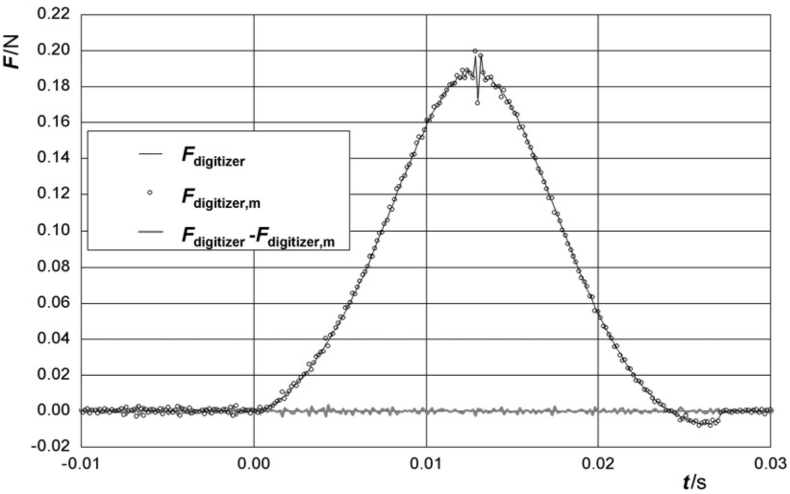

Figure 4. Measured force against time.

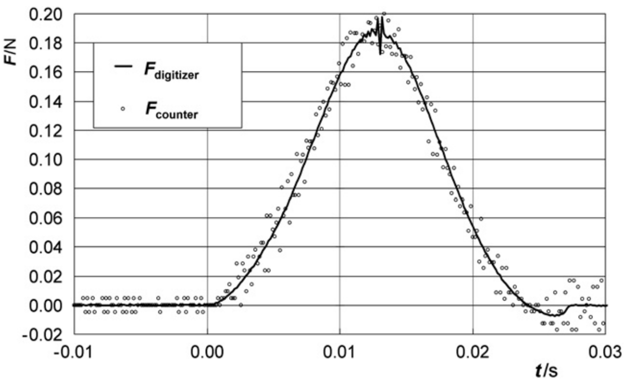

Figure 5. Comparison with the values measured using the electric counters.

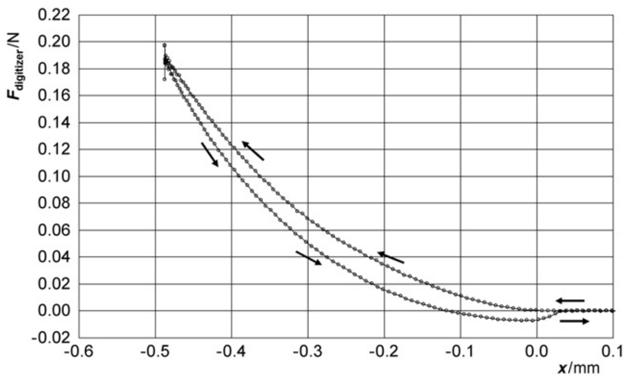

Figure 6. Change in force against position (arrows indicate the order of occurrence).

shows the force calculated, $F_{\text{digitizer,m}}$, using the instantaneous value of the beat frequency, f_{beat}, and the *mean value* of the rest frequency, $f_{\text{rest,m}}$. In addition the difference between $F_{\text{digitizer}}$ and $F_{\text{digitizer,m}}$ is also shown. The difference between $F_{\text{digitizer}}$ and $F_{\text{digitizer,m}}$ is small throughout the measurement period shown in the figure. This fact indicates that the vibration of $F_{\text{digitizer}}$ observed near the peak is not due to laser instability. In other words, they indicate that it does not originate from the change of f_{rest} but is due to the change of f_{beat} only. It should be mentioned that feedback to the laser from unwanted reflections in the optical components was minimized by slightly misaligning the components to improve laser stability.

Figure 5 shows the force measured by the proposed method, $F_{\text{digitizer}}$, and the force measured by the electronic frequency counter, F_{counter}. Although the sampling rates are the same value (corresponding to the time taken by 400 signal periods), the noise in F_{counter} is much larger than that of $F_{\text{digitizer}}$.

Figure 6 shows the change in force against position. The typical profile of viscoelastic materials is observed. The area bounded by the curve represents the energy dissipation. It is approximately 7.4×10^{-6} J and it corresponds to 24% of the initial kinetic energy of the mass.

5. Discussions

A simple averaging technique for evaluating the time of zero crossings has proved to be very effective. In the proposed method for measuring the frequency of the waveform, the two zero-crossing points used in equation (5) are calculated by averaging several zero-crossing points according to equation (4). The effect of the half width of the averaging interval, n, is significant in eliminating fluctuation of the data measured using the digitizer (both time fluctuation and voltage fluctuation). The measurement periods, N_j, also have a significant effect in eliminating fluctuation of the data; however, increasing N_j result in the increase of the sampling interval. On the other hand, increasing n does not result in the increase of the sampling interval. Therefore, the introduction of n is the key to improving both the resolution and the sampling rate.

By introducing n, a high accuracy and high-sampling rate are obtained even when using a low-performance digitizer. In the usual algorithms used, most of the zero crossings are not used for improving the accuracy and are just used to count the number of periods. The proposed processing technique can be introduced as a measuring algorithm for electronic frequency counters and in PC-based measurement software (such as LabVIEW) for improving both the resolution and the sampling rate.

There is still potential for improving the performance by using a larger portion of the measured data. For example, sinusoidal curve fitting using all the measured points in the corresponding period in the waveform would be a very effective way of improving both the time and frequency resolution.

The digitizer used in the experiment is a low performance and inexpensive model. Digitizers with higher performance, for example with the sampling rate of 100 MS s^{-1}, are commercially available. The proposed method using a low-performance model has proved to have a higher performance than the previously developed method using a high-performance electronic frequency counter.

If the waveform distortion from the ideal sine curve is sufficiently small and the wave profile is measured with a sufficiently large sampling rate and sufficiently high sampling resolution, the frequency can be obtained with high accuracy even from a smaller number of periods or even from a time interval smaller than one period. For this, it will be preferable to stabilize the laser further.

As for the force vibration observed in the experiment, it can be related to the shape of the rubber block and the glue characteristics between the block and the base. The mechanism is not clear at this moment, however it is out of the scope of the presented results.

The proposed method not only improves the accuracy of the measurement and the sampling rate, but also results in an instrument of much lower cost. In previous experiments, very high-performance frequency counters were required to obtain the force with acceptable accuracy and sampling rate.

6. Conclusions

A novel method for accurately measuring small and steep impact force has been proposed. In the method, a mass, which was levitated with a pneumatic linear bearing and which encountered negligible friction, was made to collide with an object under test. The Doppler frequency shift of a laser beam reflecting from the moving mass was calculated from the output signal of an optical interferometer whose waveform was recorded with a digitizer. The high performance of the proposed method is shown by evaluating the viscoelasticity of a small rubber block under small and steep impact load. The present status and the future prospects were discussed.

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