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Dynamic Calibration Methods for Force Transducers

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Abstract: Three Methods for evaluating the dynamic response of force transducers against varying force are described in this paper. In all methods, the inertial force of a mass is used as the known dynamic force, and this reference force is applied to a force transducer under test. The inertial force is measured highly accurately as the product of the mass and the acceleration. An aerostatic linear bearing is used to obtain linear motion with sufficiently small friction acting on the mass (i.e., the moving part of the bearing). Three experimental setups were built for the dynamic calibration against an impact force, an oscillation force and a step force. Ways of establishing dynamic calibration methods are also discussed.

Keywords: metrology & standards, mechanical quantities measurements, dynamic force, dynamic calibration, force sensor, varying force, inertial force, impact force, oscillation force, step force, optical interferometer, pneumatic linear bearing

1. INTRODUCTION

Recently, the need for measuring dynamic forces have increased in various industrial and research applications such as process monitoring, material testing, motion control and crash testing. However, only static methods, in which transducers are calibrated with static weights under static conditions, are widely available at present. Methods for dynamic calibration of force transducers are important to fulfill these needs. The required uncertainty of a dynamic calibration method should be approximately 0.1 % at the best, considering the fact that commercial force measuring systems are usually statically calibrated with the uncertainty of approximately 0.1 % or worse. However, the establishment of a dynamic calibration method with an uncertainty level of a few percent will be a significant contribution to the field of force measurement.

Although procedures for dynamic calibration of force transducers are not yet well established, there have been a few attempts to develop dynamic calibration methods for force transducers. These attempts can be divided into three categories, namely, methods for calibrating transducers against an impact force, methods for calibrating transducers against an oscillation force, and methods for calibrating transducers against a step force.

As for the procedure for calibrating transducers against an impact force, the author has proposed and developed a method [1-6]. Bruns and Kobusch have also recently developed a similar method for calibrating transducers by using an impact force [7]. 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 a change in the momentum of the mass. To obtain linear motion, with sufficiently small friction acting on the mass, a pneumatic linear bearing [2,3] 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 [4] as 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 measured as the inertial force acting on the mass, by means of measuring the instantaneous acceleration of the mass. This method was also improved [5] as a method for determining the response against a steep impulse with a half value width of approximately 1 ms. The author has discussed the possible applications and importance of this method in force measurement [6]. The impact response of a force transducer embedded inside an impact hammer has been evaluated [7].

As for the trials for calibrating transducers against an oscillation force, Kumme has proposed and developed a method, in which the inertial force of a mass attached to a force transducer is used [9,10]. In this method, both the mass and the transducer are shaken at a single frequency using a shaker, and the inertial force of the mass is applied to the transducer. The inertial force of part of the transducer itself must be taken into account, to evaluate the characteristics of the transducer under typical conditions in which it is fixed to a stable base. Park et al. use this method for dynamic investigation of multi-component force-moment sensors [11,12]. The author has also proposed a method for calibrating force transducers against an oscillation force, in which the force transducer under test is firmly fixed to a stable base [13].

As for the trials for calibrating transducers using a step force, the author first proposed a method in reference [14]. In the method, the reference force, which is suddenly applied to the force transducer under test, is the combined gravitational and inertial force acting on the object. At the beginning of the evaluation, the object is suspended just above the transducer with the use of a wire; then the object is allowed to fall on to the transducer by cutting the wire. To realize perpendicular motion with sufficiently small friction, a pneumatic linear bearing is used. The inertial force acting on the object is measured highly accurately by measuring the velocity of the mass using an optical interferometer. On the other hand, the step force response of force transducers has recently become a topic of much interest. For example, there is research dealing with the dynamic characteristics of force transducers under step load [15]. In this method, the real force is approximately estimated from the output signal without the known reference force. Strictly speaking, there are no other dynamic calibration methods using a step force, in which a known step force is used as the reference, except the method proposed by the author.

Summarizing the present situation, dynamic calibration methods for force transducers are not yet established and are still being developed. The author has proposed all three types of dynamic calibration methods that are for the impact response calibration, the oscillation response calibration and the step response calibration. Proposing a method integrating the different calibration methods and proposing an appropriate set of parameters for describing the dynamic characteristics of general transducers will be very important in the next stage.

All the three methods proposed by the author are based on the Levitation Mass Method (LMM). In this paper, the present status and the future prospects of the LMM as the dynamic force calibration method are discussed.

2. THE LEVITATION MASS METHOD (LMM)

The principle of the proposed methods is shown in Fig.1. In the Levitation Mass Method, the inertial force of a mass is used as the known dynamic force and this reference force is applied to a force transducer under test. The inertial force is measured as the product of the mass and the acceleration. The acceleration of the mass is accurately measured using an optical interferometer. An aerostatic linear bearing is used to obtain linear motion with negligible friction acting on the mass, i.e., the moving part of the bearing.

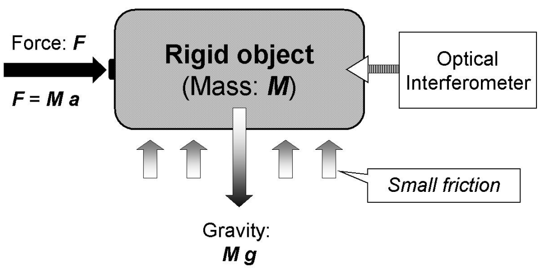

Figure 1 Principle of the Levitation Mass Method (LMM)

Recently, a pendulum mechanism for use as a substitute of an aerostatic linear bearing has been developed [16]. An algorithm of evaluating the frequency fro the waveform recorded using a digitizer has also been proposed [17]. By introducing a pendulum mechanism instead of the expensive aerostatic linear bearing and a low cost digitizer instead of the expensive electronic frequency counter, a low cost instrument based on the LMM can be developed.

The LMM has also been applied to the field of small force measurement [18] and the field of material testing [19,20].

In this paper, the methods for evaluating the dynamic response of force transducers against a varying force are described, and ways for integrating the three different methods are discussed.

3. CALIBRATION METHODS FOR TYPICAL DYNAMIC FORCES

The three types of dynamic calibration methods based on the LMM, which are for the impact response calibration [1,4,5], the oscillation response calibration [12] and the step response calibration [13], are described here.

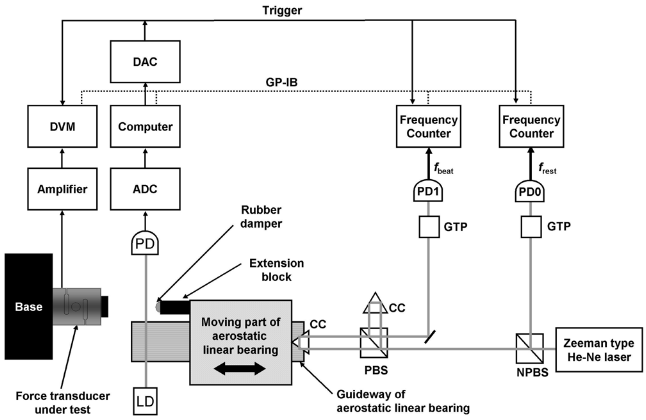

Figure. 2. Experimental setup. Code: CC= cube corner prism, PBS= polarizing beam splitter, NPBS= non- polarizing beam splitter, GTP= Glan-Thompson prism, PD= photo diode, LD= laser diode, ADC=analog-to-digital converter, DAC= digital-to-analog converter, PC= computer.

3.1. Impact Response Calibration Method

Figure 2 shows the experimental setup for measuring the impact force applied to the force transducer being tested. An impulse is generated and applied to the transducer by colliding the moving part of the pneumatic linear bearing to the transducer. An initial velocity is given to the moving part manually. The width and the intensity of the impulse are adjusted by changing the rubber damper and the initial speed of the moving part. The output signal of the force transducer is recorded using digital voltmeter with a sampling interval of 0.2ms.

A Zeeman-type two-frequency He-Ne laser is used as the light source of the optical interferometer. The interferometer has two photo-detectors; PD0 and PD1. The frequency difference between the two orthogonal polarization states emitted from the laser, f_{rest}, is monitored using a Glan-Thompson prism (GTP) and the first photo-detector, PD0.

The velocity of the mass, v, is measured as the Doppler shift frequency, $f_{Doppler}$, which can be expressed as follows:

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

$$f_{Doppler} = - (f_{beat} - f_{rest}),$$

where λ_{air} is the wavelength of the signal beam under the experimental conditions, f_{beat} is the beat frequency, which is the frequency difference between the signal beam and the reference beam and appears as the beat frequency at PD1, and f_{rest} is the rest frequency which is the value of f_{beat} when the moving part of the aerostatic bearing is at a standstill.

The frequency f_{beat} appearing at PD1 is measured using an electric frequency counter (model: R5363; manufactured by Advantest Corp., Japan). It continuously measures and records the beat frequency, f_{beat}, 1000 times with a sampling interval of $T=400/f_{beat}$, and stores the values in its memory. The sampling period of the counter is approximately 0.15 ms at a frequency of 2.7 MHz. The other counter of the same model measures the frequencies f_{rest} appearing at PD0. From the measured Doppler shift frequency, the velocity, acceleration and inertial force of the mass are calculated.

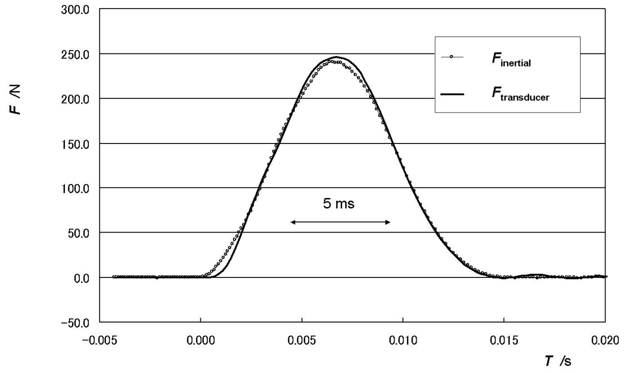

Figure 3 Results of impact force calibration

Figure 3 shows the response of the transducer to an impulse with the half value width of approximately 6.7 ms. The output signal of the transducer, $\boldsymbol{F}_{\mathbf{transducer}}$, seems to vibrate at its characteristic frequency during and after the application of the impulse.

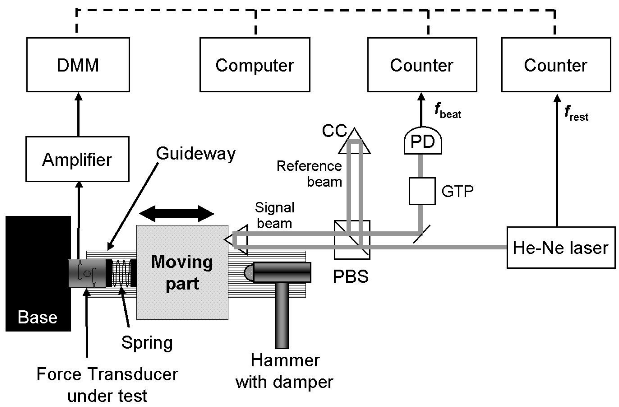

Figure 4 Experimental setup for oscillation force calibration

3.2. Oscillation Response Calibration Method

Figure 4 shows the experimental setup for evaluating the continuous oscillation response of force transducers [12]. A steel spring connects the force transducer to a mass. The force transducer is firmly attached to the base. A pneumatic linear bearing is used to obtain linear motion with sufficiently small friction acting on the mass. The inertial force of the mass is used as the standard oscillation force and is compared with the output signal of the force transducer, when the mass-spring system is continuously oscillating. The initial kinetic energy of the spring-mass system is given by manually hitting the mass using a hammer. The inertial force acting on the mass is measured highly accurately by measuring the velocity of the mass using an optical interferometer.

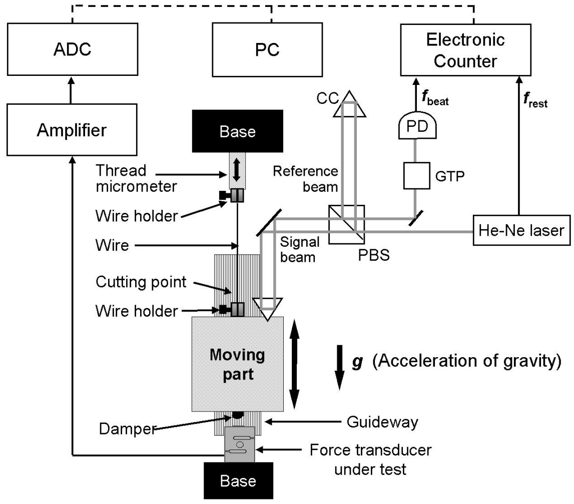

Figure 5 Experimental setup for step force calibration

3.3. Step Response Calibration Method

Figure 5 shows the experimental setup for evaluating the step response of force transducers [13]. A mass, $\boldsymbol{M}$ kg, is suspended using a stainless steel wire, just above a force transducer under test. The initial distance between the object and the force transducer is adjusted using a thread micrometer attached to the upper base. Both ends of the wire are held using wire holders attached to the micrometer and the object.

To realize a vertical motion with sufficiently small friction, a pneumatic linear bearing is also used. The velocity of the mass is measured highly accurately using an optical interferometer. The measurement procedure is as follows: at the beginning, the object is raised, using the wire, just above the transducer; then the object is dropped on to the transducer by cutting the wire using a wire cutter. A rubber damper is attached to the contact point of the object in order to moderate the steepness of the step force. The inertial force acting on the mass is calculated from the velocity of the mass.

4. DISCUSSIONS

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.

To calibrate force transducer under dynamic conditions, the following two subjects will have dominant effects.

(1) Response of the transducer against varying force: This is obviously the main subject of calibration.
(2) Response of the transducer against its acceleration: It is very important to determine where and how the transducers are supported and attached. If the

acceleration of the transducer itself cannot be neglected, the inertial force of some part of the transducer should affect its output.

According to the principle of calibration that calibration must be performed under the same conditions as that of the actual usage, the dynamic force calibration procedure must cover all the conditions under which force transducers are supposed to be used. However, this is almost impossible for dynamic force calibration since there are infinitely many shapes of varying force. If the validity of applying the frequency response obtained form the oscillation force calibration to any other types of force such as impact force, step force and randomly varying force could be proved and if the effect of the inertial mass of some part of the transducer itself could be properly evaluated, a complete dynamic calibration method can be developed using some types of calibration method, such as the methods described above. However, to exactly prove that validity (of applying the frequency response obtained form the oscillation force calibration to any other types of force such as impact force), the reference force used in the calibration must cover all the conditions under which force transducers are supposed to be used.

The first generation of dynamic calibration methods for force transducers will be established in the future as follows,

(1) Dynamic responses of force transducers against some typical types of dynamic forces, such as impact force, oscillation force and step force, are shown in the data sheet of the transducer provided by the manufacturers.
(2) Response of the transducer against the acceleration field in which the transducer is placed will be examined and shown in the data sheet.
(3) Correction method for inertial force of some portion of the transducer itself might be developed and shown in the data sheet.

As for (3), the electrical and mechanical responses of a force transducer against impact forces are measured using 2 axes optical interferometer based on the LMM [21].

5. CONCLUSIONS

The present status and the importance of the dynamic calibration method for force transducers are discussed. Among the attempts to develop the dynamic calibration methods, the advantages of the Levitation Mass Method (LMM), which has been invented and developed by the author, are discussed. Three Methods for evaluating the dynamic response of force transducers against typical varying forces are reviewed. In all methods based on the LMM, the inertial force of a mass is used as the known dynamic force, and this reference force is applied to a force transducer under test. The inertial force is measured highly accurately as the product of the mass and the acceleration. An aerostatic linear bearing is used to obtain linear motion with sufficiently small friction acting on the mass (i.e., the moving part of the bearing). Ways of establishing dynamic calibration methods are also discussed.

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