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PULSE FORCE CALIBRATION OF FORCE TRANSDUCERS

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Abstract − Steep pulse responses of force transducers are measured using a method under development. In the method, a mass is made to collide with a force transducer and the impact force is measured highly accurately as the inertial force acting on the mass. 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.

Keywords: dynamic force, inertial mass, inertial force

1. INTRODUCTION

In Recent years, the demands for measuring dynamic forces have increased in severity and variety in many industrial and research applications such as process monitoring, material testing, model analysis and crash testing. However, only static methods, in which transducers are calibrated by static weighting under static conditions, are widely available at present. Methods for dynamic calibration of force transducers are important to meet these requirements.

Although the methods of dynamic calibration of force transducers are not yet well established, there have been a few trials on developing dynamic calibration methods for force transducers. One method, which was proposed and has been developed by Kumme, uses the inertial force of the attached mass generated by a shaker [1,2]. In this method, dynamic force of a single frequency is generated and applied to a force transducer. This method will be effective for evaluating the characteristics of force transducers under the conditions in which calibration is conducted, such as continuous vibration at a single frequency. Park et al. use this method for dynamic investigation of multi-component force-moment sensors [3,4]. However, this method is not suitable for evaluating the impulse response of transducers, which is important particularly in the crash testing of structures, instruments and machines.

The other method was proposed by the author and has been under development [5-11]. Bruns have also started to develop a similar method [12]. This method was first proposed [5] 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 [10] is used, and the velocity of the mass, i.e., the moving part of the bearing, is measured using an optical interferometer. This method was subsequently improved [6,7,8] as a method for determining the instantaneous value of the impact force in the impulse. In this case, the instantaneous value of impact force is measured as the inertial force acting on the mass, by means of measuring the instantaneous acceleration of the mass. The author has shown the possible applications and importance of this method in force measurement [9]. This method was also improved for evaluating the steep impulse responses of force transducers [11]. In the method, 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. 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. Steep impulses with the half-value width of approximately 1 ms and maximum impact force of up to approximately 1 kN are applied to the piezoelectric force transducer and its impulse responses are evaluated with the standard uncertainty of approximately 1.5 $\times$ 10^{-4} Ns, corresponding to 2 $\times$ 10^{-4} (0.02%) of the maximum applied impulse in the experiments. [11].

In this work, the pulse response of a force transducer is measured using the developing method.

2. EXPERIMENT

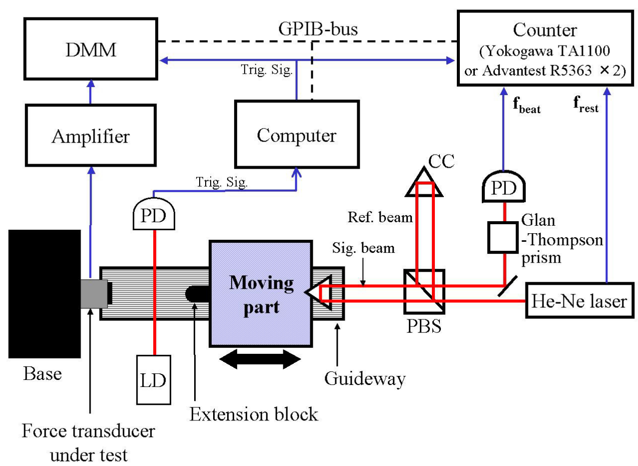

Fig. 1. Experimental set-up

Fig.1 shows a schematic diagram of the experimental set-up for evaluating the impulse response of force transducers. The force transducer under test is firmly attached to the base. 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. A metal block for adjusting the collision position and a cube-corner prism (CC) are attached to the moving part; its total mass, M, is 4.5000 kg. No dumper is used for moderating the steepness of the impulse generated by the collision.

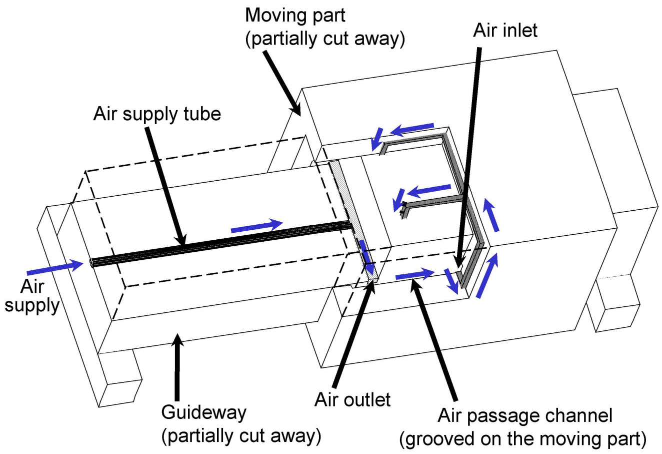

Fig. 2. The schematic of the pneumatic linear bearing

Fig.2 shows the schematic of the pneumatic linear bearing, "Air-Slide TAAG10A-01" (NTN Co., Ltd., Japan). The compressed air supplied from outside is firstly introduced into the guideway rather than directly into the moving part. The reason for this is to avoid pressure piping on the moving part. Then air comes out from air outlets at the center of the guideway, and introduced into the air inlets at the center of the moving part through the air passage channels grooved on the inner surface of the moving part along the direction of motion. In the design, airflow between the guideway and the moving part is always bilaterally symmetric except in the air passage channels. This is for suppressing the static force acting on the moving part. The stroke of the moving part is approximately 100 mm, the maximum weight of the moving part is approximately 30 kg, the thickness of the air film without weight is approximately 8 μm, the stiffness of the air film is approximately 80 N/mm, and the straightness of the guideway surface is approximately 0.1 μm/100mm.

A force transducer using semiconductor strain gauges is used for the experiment. The nominal force of the transducer is approximately 200 N. The force transducer was statically calibrated with the standard relative uncertainty of approximately 1 % against the nominal force.

The output signal of the force transducer is measured by means of a digital multi-meter with memory with a sampling interval of 0.02 ms.

The momentum change of the moving part is measured as the product of mass and the velocity change. The velocity is measured as the Doppler shift frequency of the signal beam of a laser interferometer, f_{Doppler}, which can be expressed as

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

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

where λ_{air} is the wavelength of the signal beam under the experimental conditions, f_{beat} is the beat frequency, i.e., the frequency difference between the signal beam and the reference beam, f_{rest} is the rest frequency which is the value of f_{beat} when the moving part is at a standstill, and the direction of the coordinate system for the velocity, the acceleration and the force acting on the moving part is towards the right in Fig.1.

A Zeeman-type two-frequency He-Ne laser is used as the light source. The frequency difference between the signal beam and the reference beam, i.e., the beat frequency, fbeat, is measured from an interference fringe which appears at the output port of the interferometer; it varied around frest, approximately 2.6 MHz, depending on the velocity of movement.

To measure the frequency, three electric counters, two R5363 (manufacturer: Advantest Corp., Japan) and one TA1100 (manufacturer: Yokogawa Electric Corp., Japan), are prepared and connected to the computer by means of the GP-IB bus. The electric counter TA1100 has just introduced in the laboratory and only used in the experiment in the section of "4. DISCUSSION".

An electric frequency counter (model: R5363; manufactured by Advantest Corp., Japan) continuously measures and records the beat frequency, fbeat, 14000 times with a sampling interval of T=400/ fbeat, and stores the values in memory. This counter continuously measures the interval time of every 400 periods without dead time. The sampling period of the counter is approximately 0.15 ms at the frequency of 2.6 MHz. Another electric counter measures the rest frequency, frest, using the electric signal supplied by a photodiode embedded inside the He-Ne laser.

Measurements of the digital multimeter (HP 3458A), the electric counter (R5363) and the electric counter (TA1100) are triggered by means of an external synchronizing signal. This signal is initiated by means of a light switch, a combination of a laser-diode and photodiode. A sharp trigger signal is then generated by means of a digital-to-analog converter.

In the experiment, the moving part of the linear bearing is made to collide with the force transducer with velocity v_1 m/s; it rebounds with velocity v_2 m/s. The impulse responses of force transducers are determined by comparing the impulse obtained by integrating the output signal of the transducer, $F_{\mathrm{transducer}}$, with the momentum change of the moving part measured by the optical interferometer,

$$M (v_2 - v_1).$$

3. RESULTS

Fig.3 shows the change in velocity of the moving part detected by the optical interferometer and change in impact force detected by the force transducer. The velocities before and after the collision, v_1 and v_2, are calculated as the mean value during the periods whose duration is 10 ms and whose ends are 1 ms apart from the ends of the impulse, $\mu_{v,1}$ and

$\mu_{v,2}$. In this case, the calculated velocities before and after the collision, v_1 and v_2, are -0.0147 ms^{-1} and 0.0114 ms^{-1}, respectively. The absolute value of the velocity is reduced by 35% due to the collision, and the corresponding part of the motion energy is dissipated as heat energy. In this case, the change in momentum is approximately 0.118 kg ms^{-1}. On the other hand, the time integration of the impact force, which is detected by the force transducer calibrated under the static condition, is approximately 0.116 kg ms^{-1}. In this case, the relative difference between the impulse measured by the transducer and the momentum change measured by the optical interferometer against the maximum value of the impact force, $\frac{\left(\int F_{transducer} dt\right)}{M(v_2 - v_1)} - 1$, is approximately 0.017 (1.7%).

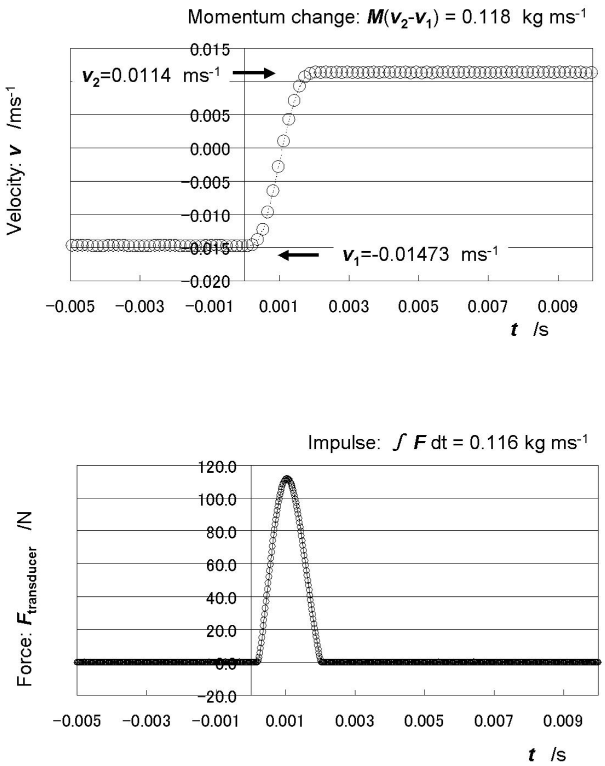

Fig. 3. Change in velocity of the moving part detected by the optical interferometer and change in impact force detected by the force transducer. Mass of the moving part M = 4.5000 kg

Fig.4 shows the relative difference between the impulse measured by the transducer and the momentum change measured by the optical interferometer against the maximum value of the impact force. In the figure, the relative difference between the impulse measured by the transducer and the momentum change measured by the optical interferometer has a constant value of approximately –0.01 (-1%) in the range of the maximum value of the impact force between approximately 40 N to 120 N.

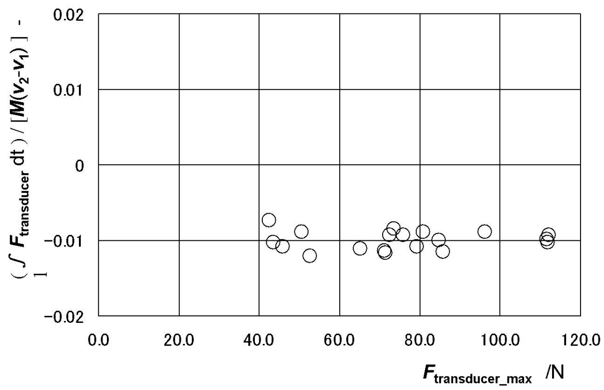

Fig. 4. Relative difference between the impulse measured by the transducer and the momentum change measured by the optical interferometer against the maximum value of the impact force

Fig.5 shows the half value width, W_{hf} s, against the maximum value of the impact force measured by the force transducer, $F_{transducer}$ N. From the experiments, the half-value width, W_{hf} s, is approximately 1 ms.

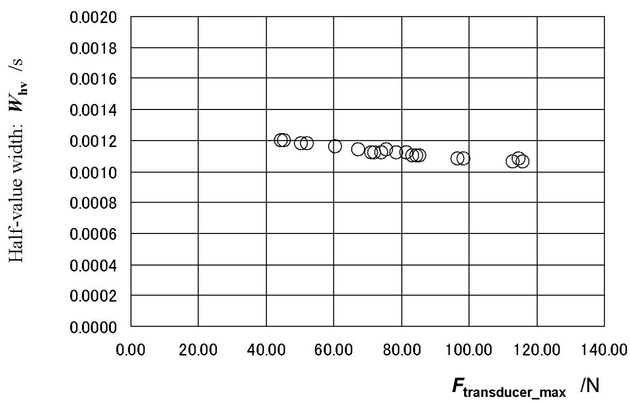

Fig. 5. Half-value width against the maximum value of the impact force

4. DISCUSSION

In the above described experiment, the time integration form is used for evaluating the response against the steep impulse whose half value width is around or less than 1 ms.

Fig. 6 shows the instantaneous value of the impact force measured by the optical interferometer, $F_{inertial}$ N, and that measured by the force transducer, $F_{transducer}$ N. The collision experiment corresponding to this figure is the same as that corresponding to Fig. 3. The inertial force acting on the moving part, $F_{inertial}$, i.e., impact force measured by the optical interferometer, is calculated as the product of the acceleration, α, and the mass, M. The acceleration is calculated by differentiating the velocity, v. The time resolution obtained by the frequency counter R5363 is found to be insufficient for evaluating the instantaneous value of the impact force.

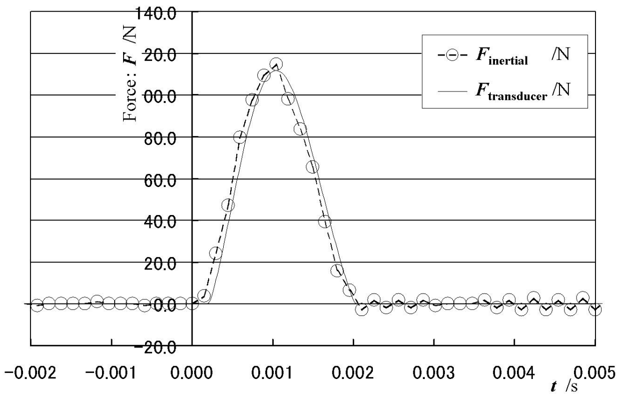

Fig. 6. The instantaneous value of the impact force measured by the developing method using the frequency counter R5363, $\boldsymbol{F}_{\mathbf{inertial}}$, and the impact force measured by the force transducer, $\boldsymbol{F}_{\mathbf{transducer}}$.

Fig 7 shows the instantaneous value of the impact force measured by the developing method using the frequency counter R5363 and TA1100. The time resolution can be improved by using the counter TA1100. However, the uncertainty evaluation for the measurement has not been done.

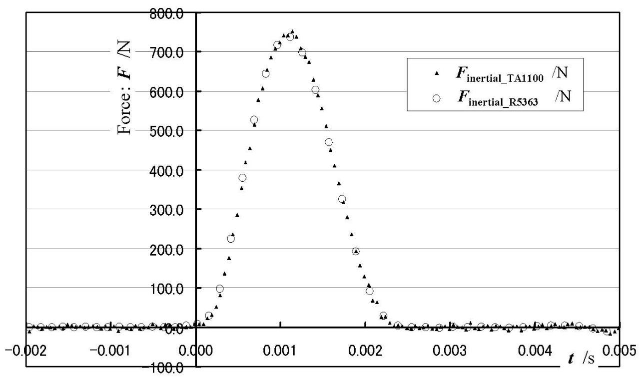

Fig. 7. The instantaneous value of the impact force measured by the developing method using the frequency counter R5363 and TA1100.

In the near future, the following subjects will be pursued.

a) Improving the time resolution
b) Evaluating the uncertainty
c) How to apply the method to practical use

5. CONCLUSION

Steep pulse responses of force transducers are measured using a method under development. In the method, a mass is made to collide with a force transducer and the impact force is measured highly accurately as the inertial force acting on the mass. 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.

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