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IMPACT RESPONSE MEASUREMENT OF A FORCE TRANSDUCER

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Abstract: A method for measuring the impact response of force transducers is proposed. In this method, a mass is made to collide with a force transducer, and the instantaneous value of the force acting on the sensing point of the transducers is determined by measuring the instantaneous value of the acceleration of the inertial mass. To realize linear motion with sufficiently low friction acting on the mass, a pneumatic linear bearing is used, and the velocity of the mass, the moving part of the bearing, is measured using an optical interferometer. An impact force with half value width of approximately 5ms to 20ms is applied to a semiconductor strain gauge force transducer, and the values measured by the transducer and by this method are compared.
Keywords: force transducer, dynamic characteristics, impact, impulse, interferometer, pneumatic linear bearing, air slide, conservation of momentum

1 INTRODUCTION

Force transducers are widely used in dynamic conditions in many industrial and research applications such as process monitoring, material testing and crash testing. Dynamic calibration of force transducers, which are usually calibrated by static weighing under static conditions, is necessary for such applications.

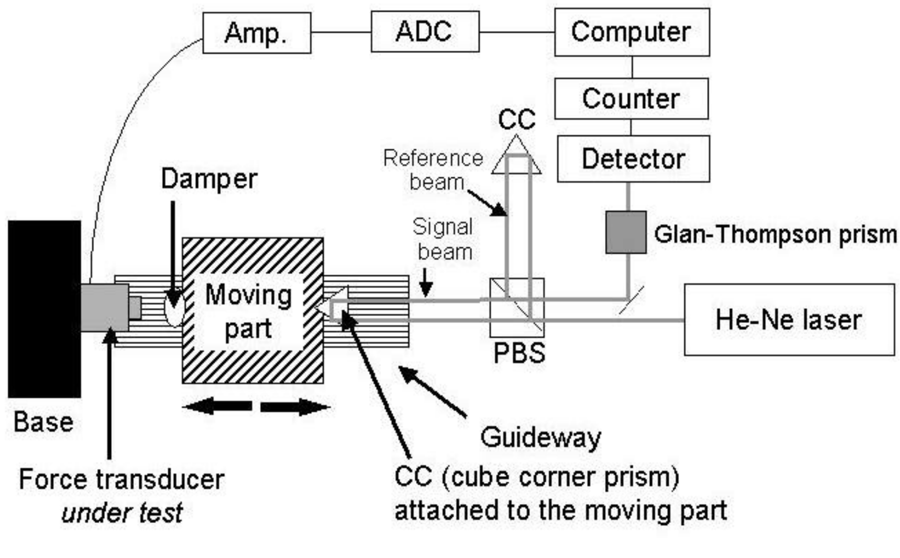

Figure 1. Schematic of the experimental setup

A few methods have been proposed for this purpose. One method [1-3] uses the inertial force of the attached mass generated by a shaker. In this method, a shaker shakes the force transducer being tested continuously. This method will be effective for evaluating the characteristics of force transducers under the conditions in which the calibration is conducted, such as the condition of continuous vibration with a single frequency. To evaluate the uncertainty involved when applying this method for impact detection, the use of a different method will enable elimination of any overlooked influencing parameters.

On the other hand, we have proposed a method based on the law of conservation of momentum for evaluating the dynamic characteristics of force transducers [4] and torque transducers [5], and for measuring mass under microgravity conditions in the ISS (International Space Station) [6,7]. In the method for evaluating the impulse response of force transducers [4], a mass is made to collide with the force transducer under test, and the impulse is measured as the momentum change of the mass. To realize linear motion with sufficiently small friction acting on the mass, a pneumatic linear bearing was used [8]. Recently, the author proposed a crash testing method for determining the instantaneous value of the impact force [9]. In this study, by modifying the above methods based on the law of conservation of momentum, a method for determining the impact response of force transducers is proposed.

2 EXPERIMENT

Fig. 1 shows a schematic of the experimental setup to evaluate the impact response of force transducers. A semiconductor strain gauge force transducer (full scale: 9.8N, manufactured by Showa Co., Ltd., Japan) is attached to the base, and a moving part of approximately $\boldsymbol{M}$ =3.91 kg, is made to collide with the transducer. The sponge damper moderates and adjusts the width and the intensity of the impact. The output signal of the force transducer is recorded on a computer through an analog-to-digital converter with a sampling interval of 0.5 ms or 0.1 ms..

A pneumatic linear bearing, “Air-Slide TAAG10A-02” (NTN Co., Ltd., Japan), is attached to a tilting stage whose tilt angle is measured using an autocollimator. The maximum weight of the moving part is approximately 30 kg, the thickness of the air film is approximately 8 µm, the stiffness of the air film is more than 70 N/µm, and the straightness of the guideway is better than 0.3 µm/100 mm. The angle of the tilting stage is set so that the moving part is at a standstill at the contact position of the transducer.

The moving part of the linear bearing is made to collide with the transducer under test with a velocity $\boldsymbol{v}_1$ (m/s). It accelerates by the reaction force of the transducer; it finally separates from the transducer with a velocity $\boldsymbol{v}_2$ (m/s). The velocity of the moving part, $\boldsymbol{v}$ m/s, is measured as the Doppler shift frequency of the signal beam of a laser interferometer, $\boldsymbol{f}_{\mathbf{Doppler}}$ (Hz), and the frequency is measured using an electric frequency counter (model: R5363, manufactured by Advantest Corp., Japan). 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, $\boldsymbol{f}_{\mathbf{beat}}$, is measured as an interference fringe which appears at the output port of the interferometer; it varied around $\boldsymbol{f}_{\mathbf{rest}}$, approximately 2.6 MHz, depending on the velocity of movement. The counter continuously measures the beat frequency, $\boldsymbol{f}_{\mathbf{beat}}$ (Hz), 14000 times with a sampling interval of about $\boldsymbol{T}$=4 00/ $\boldsymbol{f}_{\mathbf{beat}}$ (s), and stores the values in memory. The sampling period of the counter is approximately 0.15 ms around the frequency of 2.6 MHz. The acceleration, a (m/s^2), and the position, $\boldsymbol{x}$ (m), are calculated by differentiating $\boldsymbol{v}$ and integrating $\boldsymbol{v}$, respectively. The velocity of the moving part, $\boldsymbol{v}$, is expressed as:

$$\boldsymbol{v} = l_{\mathbf{air}} (\boldsymbol{f}_{\mathbf{Doppler}})/2 ,$$
$$\boldsymbol{f}_{\mathbf{Doppler}} = \boldsymbol{f}_{\mathbf{beat}} - \boldsymbol{f}_{\mathbf{rest}},$$

where $l_{\mathbf{air}}$ is the wavelength of the signal beam under the experimental conditions.

The reaction force acting on the moving part from the transducer at the time of crashing, $\boldsymbol{F}$ (N), and the inertia force of the moving part, $\boldsymbol{M}a$ (kgm/s^2), are equal according to the law of conservation of momentum if other forces, such as the frictional force inside the bearing or the inertial force of the sponge damper, can be ignored, and can be expressed as

$$\boldsymbol{F} = \boldsymbol{M}a.$$

If the acceleration distribution of the moving part cannot be ignored, the right-hand side of the equation must be calculated as the space integration of ra, where r is the density.
The following expression in integral form is also derived,

$$\boldsymbol{F}\,\mathrm{dt} = \boldsymbol{M}(\boldsymbol{v}_1 - \boldsymbol{v}_2).$$

This integral form may be useful for macroscopic evaluation of the uncertainty in applying the other dynamic calibration method for impact detection.

3 RESULTS

Fig. 2 shows the change in the beat frequency, $\boldsymbol{f}_{\mathbf{beat}}$, during impact acting on the force transducer. The moving average for every 10 measurements is adopted; thus the averaging period is approximately 1.5 ms. The beat frequency changes according to the velocity change of the moving part.

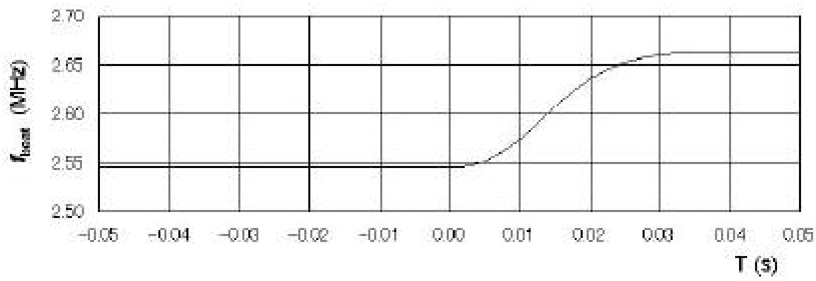

Figure 2. Change in the beat frequency $\boldsymbol{f}_{\mathbf{beat}}$

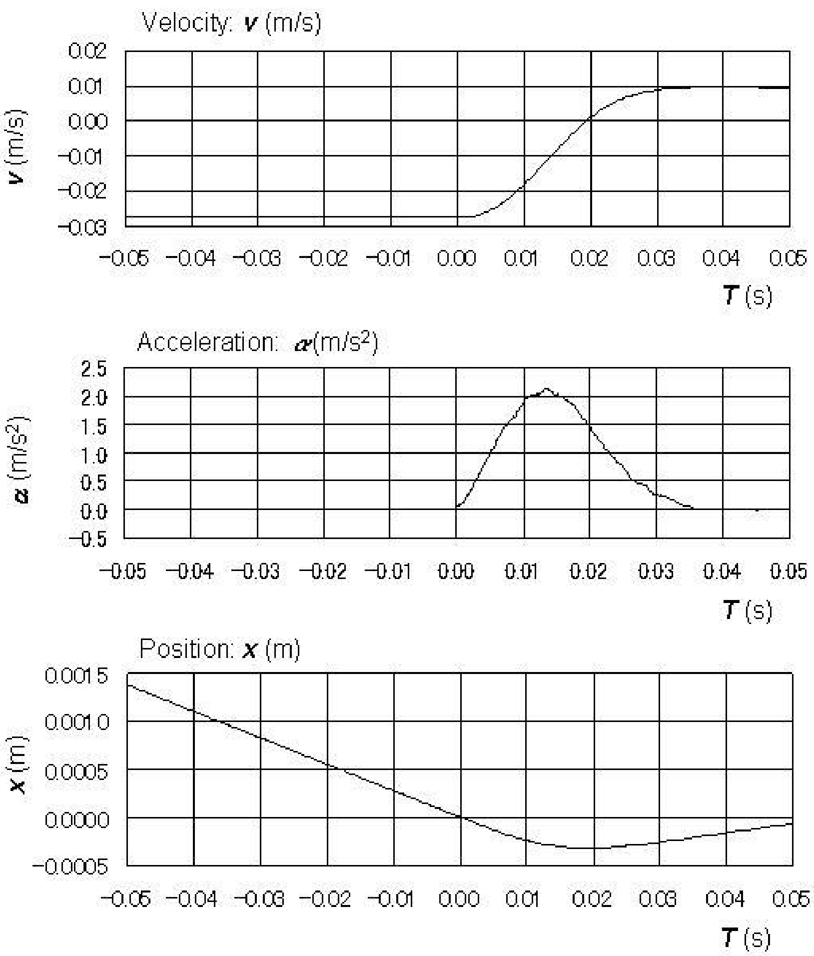

Figure 3. Change in velocity, acceleration and position

Fig. 3 shows the velocity, $\boldsymbol{v}$, the acceleration, a, and the position, $\boldsymbol{x}$, of the moving part, calculated from the beat frequency shown in Fig. 2. The time, $\boldsymbol{t}$, and the position, $\boldsymbol{x}$, are set to be zero at the beginning of contact with the transducer. The velocity, $\boldsymbol{v}$, changes from the initial velocity, $\boldsymbol{v}_1$= -2.7 cm/s, to the final velocity, $\boldsymbol{v}_2$= 1.0 cm/s, during the impact period of about 0.035 s. The acceleration, a, has a positive value during the impact. The sponge is pushed to the position of approximately -0.3 mm.

Fig. 4 shows the output signal of the force transducer compared with the value measured by the proposed method, $\boldsymbol{F} = \boldsymbol{M}\, a$ (N). These two signals coincide well on impact with the half value width of approximately 0.02 s.

Fig. 5 shows the response for a steeper impact with the half value width of approximately 0.006 s. In this case, the impact force measured by the proposed method vibrates with the amplitude of about 0.2 N after the impact. Except for the vibration, these two signals coincide well.

4 DISCUSSION

The impact response of the semiconductor strain gauge force transducer tested here is so quick and accurate that the proposed method cannot determine the error. In other words, the transducer is guaranteed to be sufficiently accurate as determined by the proposed method.

The vibration in Fig.5 is thought to be caused by the vibration of the optics of the interferometer, which is constructed on the same base as the transducer using the conventional magnetic holder used for optics. The vibration of the interferometer will be considerably reduced if the interferometer is constructed on the isolated base.

The accuracy and the time resolution of the frequency measurement in the proposed method will be considerably improved by introducing a better electric counter, by using multiple counters, or by memorizing the waveform using a wave memorizer.

The frictional characteristics of the air bearing, especially when the impact force acts on the moving part, must be carefully considered. Realization of linear motion with sufficiently small friction or sufficiently well-known friction is a key requirement.

Although the proposed method is currently under development, this method has the potential of playing an important role in the field of force measurement.

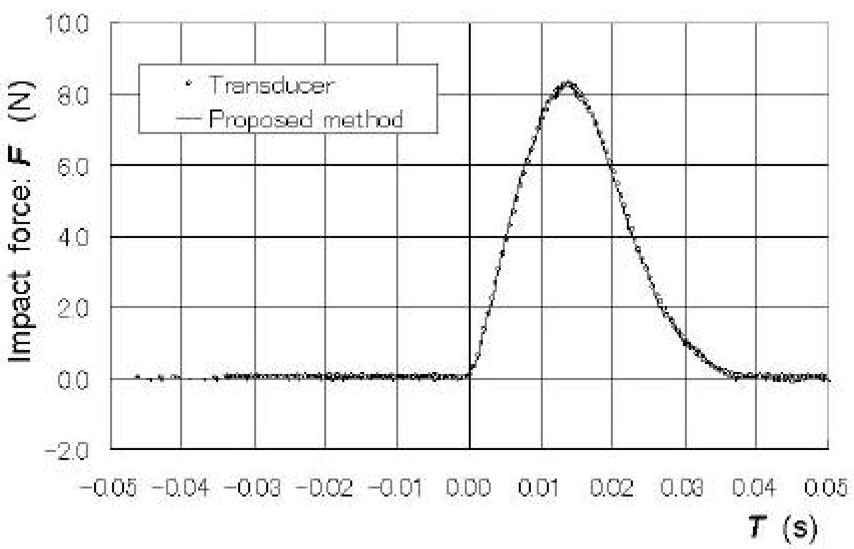

Figure 4. Impact force measured by the force transducer and the proposed method

5 UNCERTAINTY EVALUATION

The uncertainty components in determining the instantaneous value of the impact force are as follows.

A. Electric counter (R5363):

A-1) Frequency measurement: the standard uncertainty in measuring the instantaneous value of the frequency with the sampling period of approximately 0.15 ms and with the moving averaging period of approximately 1.5 ms is estimated to be 32 Hz.

A-2) Time measurement: the standard uncertainty in the time measurement for each frequency measurement is estimated to be 6 μs.

The above uncertainty originating from the electric counter results in the standard uncertainty in measuring the instantaneous value of the impact force of approximately 0.036 N.

B. Force inside the air bearing: The frictional characteristics of the air bearing are determined using the method under development [4].

B-1) Dynamic friction: the dynamic frictional force acting on the moving part, $\boldsymbol{F}_{\mathbf{fd}}$, is estimated to be 0.2 mN at $\boldsymbol{v}$ = 3 cm/s.

B-2) Static force: the static force inside the air bearing, due to the asymmetry of the air flow, $\boldsymbol{F}_{\mathbf{fs}}$, is estimated to be less than 0.2 mN at the deepest point, $\boldsymbol{x}$ = -0.3 mm.

C. Optical interferometer:

C-1) Laser: the uncertainty of the frequency difference of the laser is estimated to be 10 Hz.

C-2) Alignment: the major uncertainty source concerning optical alignment is the inclination of the signal beam of 1mrad, and it results in the relative uncertainty in the force measurement of 5×10^{-7}.

C-3) Vibration of the interferometer: this is not observed and is less than 0.1 N in the impact in Fig.4; however this appears to be 0.2 N in the impact in Fig.5.

Therefore, the combined standard uncertainty in measuring the instantaneous value of the impact force, with the sampling period of approximately 0.15 ms and with the moving averaging period of approximately 1.5 ms, is approximately 0.05 N, which is approximately 0.5×10^{-2} (0.5 %) of the full scale of the transducer, under the condition that the vibration of the interferometer which occurs after the impact corresponds to the force vibration of less than 0.1 N.

If the vibration of the interferometer occurs, the uncertainty will be much larger.

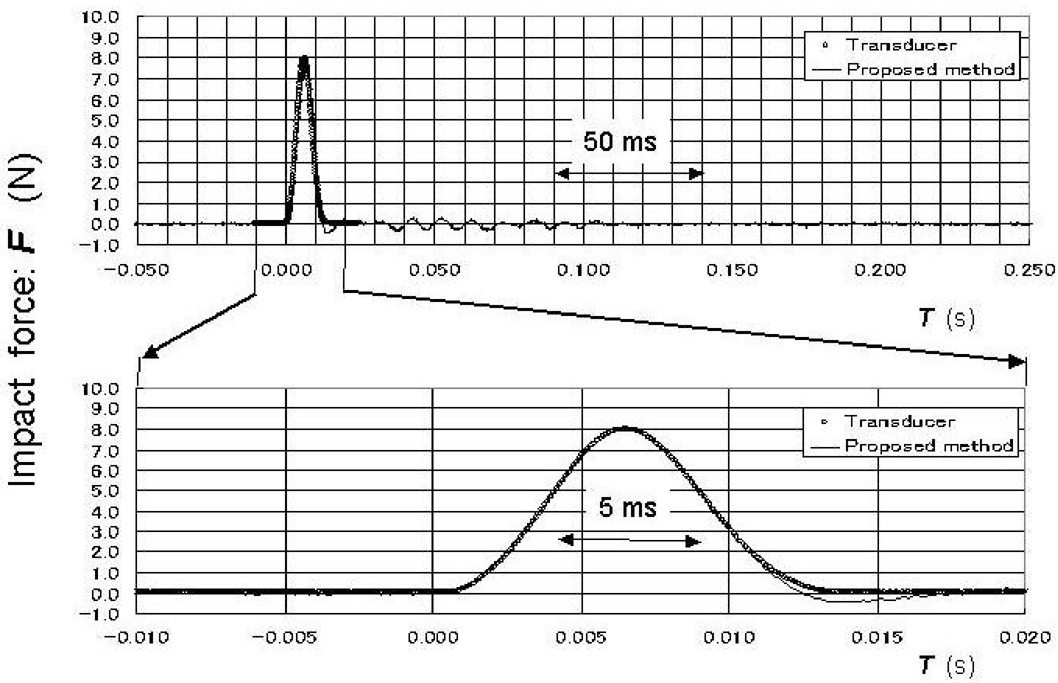

Figure 5. Response for a steeper impact

6 CONCLUSION

A method for measuring the impact response of force transducers is proposed. In this method, a mass is made to collide with a force transducer, and the instantaneous value of the force acting on the sensing point of the transducers is determined by measuring the instantaneous value of the acceleration of the inertial mass. An impact force with half value width of approximately 5ms to 20ms is applied to a semiconductor strain gauge force transducer, and the values measured by the transducer and by this method are compared. The standard uncertainty in determining the instantaneous force in an impact is estimated to be 0.05 N, which is approximately 0.5×10^{-2} (0.5 %) of the full scale of the transducer, under the condition that the vibration of the interferometer which occurs after the impact corresponds to the force vibration of less than 0.1 N.

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