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Developing Impulse Generator Based on the Law of Conservation of Momentum

Part-1: Impulse Response Measurements of Force Transducers

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Abstract

In this paper, present status of the developing impulse generator based on the law of conservation of momentum is reviewed. Impulse responses of two commercial force transducers are evaluated by means of this method. In the experiment, an object levitated with sufficiently small friction using a pneumatic linear bearing is collided with a force transducer. The inertial force acting on the object is measured as the product of the mass and the acceleration. Approximately 160 sets of collision experiments, whose impulses with the maximum value of approximately 20 to 230 N with the half value width of approximately 10 ms to 40 ms, have been conducted using two commercial force transducers and two dampers. The instantaneous value of inertial force is measured with the sampling period of approximately 0.15 ms. its standard uncertainty is approximately 0.9 N, which corresponds to approximately 0.4 % of the maximum applied impulse.

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. However, there are no working methods for evaluating the dynamic response of force transducers, at present. In other words, it is impossible to accurately and properly determine the uncertainty of measured values of dynamic force.

Force is defined as the product of mass and acceleration,

$$\boldsymbol{F} = \boldsymbol{M}\,\boldsymbol{\alpha},$$

where $\boldsymbol{F}$ is the force acting on a rigid object, $\boldsymbol{M}$ is the mass of the object, and $\boldsymbol{\alpha}$ is the acceleration acting on the center of gravity of the object. The acceleration must be accurately measured to calibrate force transducers in the dynamic conditions based on the above principle.

Acceleration due to gravity, $\boldsymbol{g}$, is convenient and usually used for generating and/or measuring constant force. This constant force can be accurately compared using a conventional balance with a knife-edge or hinge. To generate and/or measure dynamic force, dynamic acceleration is required under the condition where the external force acting on the mass is sufficiently small.

A few methods have been proposed for this purpose. One method [1,2] uses the inertial force of the attached mass generated by a shaker. In this method, a shaker shakes the mass and the force transducer being tested continuously, and the 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 the calibration is conducted, such as the condition of continuous vibration with a single frequency. However, it 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 [3-7]. This method was first proposed [3] 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 is used, and the velocity of the mass, the moving part of the bearing, is measured using an optical interferometer. Subsequently, this method was improved [4] as a method for determining the impact force in crash testing. In this case, the instantaneous value of the impact force is measured as the inertial force acting on the mass, by means of measuring the instantaneous acceleration of the mass. This method is then improved as a method for determining the impulse response of force transducers [5]. The method is then improved in accuracy and efficiency, and the impulse response of commercial force transducers are evaluated in detail [6].

The author has shown, in general, the possible contributions and importance of this method to force measurement [7].

In this paper, impulse responses of two force transducers are evaluated in detail by means of the developing method shown in reference-6 [6].

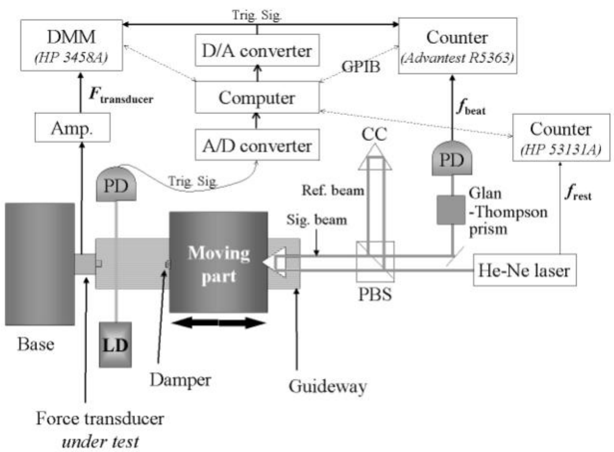

Fig. 1 Experimental setup

2. Experimental Set-Up and Measurement Procedure

Fig. 1 schematically shows the experimental set-up. Impulse is generated and applied to the transducer by colliding the moving part of the pneumatic linear bearing to the transducer. The moving part of the linear bearing is made to collide with the transducer with a velocity $\boldsymbol{v_1}$ (m/s). It accelerates due to the reaction force of the transducer, and then finally separates from the transducer with velocity $\boldsymbol{v_2}$ (m/s). The initial velocity, $\boldsymbol{v_1}$, is given to the moving part by hand, in other words, manually. The width and the intensity of the impulse are adjusted by changing the damper and the initial speed of the moving part.

The output signal of the force transducer is measured by means of a digital multi-meter with memory (model HP3458A, manufactured by Agilent Technologies Corp., U.S.A.) with a sampling interval of 0.1ms.

On the other hand, the inertial force acting on the moving part is measured as the product of mass and acceleration, α (m/s^2). The acceleration is calculated by differentiating the velocity, $\boldsymbol{v}$ (m/s), with respect to time. The velocity is measured as the Doppler shift frequency of the signal beam of a laser interferometer, $f_{\mathbf{Doppler}}$, which can be expressed as

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

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

where $\lambda_{\mathbf{air}}$ is the wavelength of the signal beam under the experimental conditions, $f_{\mathbf{beat}}$ is the beat frequency which is the frequency difference between the signal beam and the reference beam, $f_{\mathbf{rest}}$ is the rest frequency which is the value of $f_{\mathbf{beat}}$ when the moving part is at standstill, and the direction of the coordinate system for the velocity, the acceleration and the force acting on the moving part is set to be 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, $f_{\mathbf{beat}}$, is measured from an interference fringe which appears at the output port of the interferometer; it varied around $f_{\mathbf{rest}}$, approximately 2.6 MHz, depending on the velocity of movement. An electric frequency counter (model: R5363; manufactured by Advantest Corp., Japan) continuously measures and memorized the beat frequency, $f_{\mathbf{beat}}$ (Hz), 14000 times with a sampling interval of $\boldsymbol{T}$=400/ $f_{\mathbf{beat}}$ (s), and stores the values in memory. This counter continuously measures the 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 (model HP53131A, manufactured by Agilent Technologies Corp., U.S.A.) is measured the rest frequency, f_{rest} (Hz), using an electric signal supplied by a photo diode embedded inside the He-Ne laser.

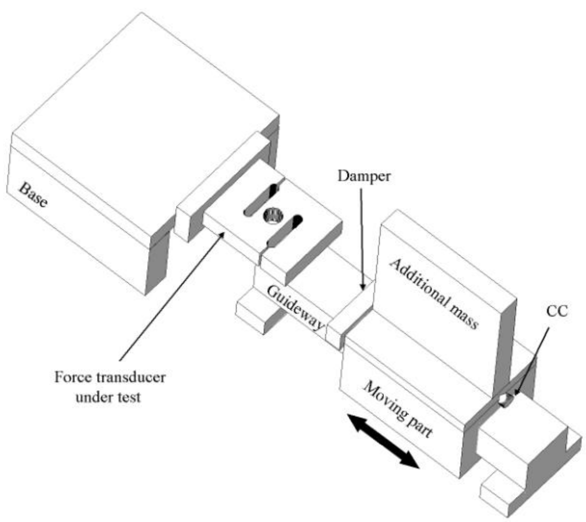

Fig. 2. Solid figure around the test section

Fig. 2 shows a solid figure around the test section of the experimental setup. The height of the collision point and the height of the center of gravity of the moving part are set to be the same. This is carried out in order to avoid a change in the shape of the air film between the moving part and the guide way caused by attitude change of the moving part, which occurs due to the moment generated by the collision. In order to set the height of the center of gravity of the moving part at a convenient position, an additional mass is attached to the moving part. The total mass of the moving part, including the additional mass and the cube corner prism, is approximately 4.1182 kg or 4.5002 kg.

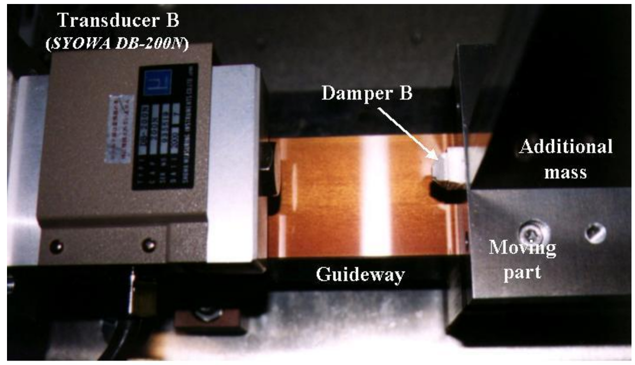

Fig. 3. Photograph around the test section

Fig.3 shows the photograph around the test section. The pneumatic linear bearing (model Air-Slide TAAG10A-02, manufactured by 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 guide way is better than 0.3 μm/100 mm. The frictional characteristics are determined by means of the developed method [8]. The angle of the tilting stage is set so that the moving part is at a standstill at the position of contact with the transducer. In order to reduce the vibrations appeared in the optics of the interferometer, the force transducer is independently attached to a cast iron base, 1500 kg in mass.

Fig. 4 shows the two different types of force transducers prepared for the measurement, Transducer A (model RC10K9807, manufactured by Syowa Electronic Instruments Co., Ltd., Japan) and Transducer B (model DB-200N, manufactured by Syowa Electronic Instruments Co., Ltd., Japan).

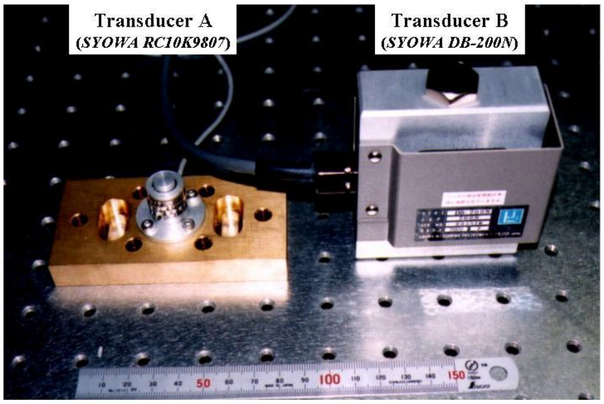

Fig. 4. Photograph of the force transducers under test, Transducer A and Transducer B

Transducer A was specially made for high-speed measurement with high resonance frequency. An aluminium block is used as the elastic body, and semiconductor strain gauges are used. Transducer B is a conventional S-shaped transducer used for accurate measurements. The nominal forces of Transducer A and Transducer B are 100N and 200N, respectively. Transducer A and Transducer B were statically calibrated with the standard uncertainties of approximately 1% and 0.1%, respectively.

The impulse responses of force transducers are determined by comparing the output signal of the transducer, $\boldsymbol{F}_{\mathbf{transducer}}$, with the inertial force acting on the moving part, $\boldsymbol{F}_{\mathbf{inertial}}$, measured as the product of the mass and the acceleration.

Two dampers are also prepared for the evaluation, Damper A and Damper B. Damper A is softer than Damper B. Approximately 30 or 50 sets of measurements are conducted for every combination of the transducer and the damper. In each measurement, the maximum values of the impact force measured by this method and by the transducer, the half value width of the impact force measured by this method, the time integrations of the impact forces measured by this method and by the transducer are calculated.

3. Results

Fig. 5 shows the measurement procedure of the inertial force acting on the moving part. During the collision, the beat frequency, $\boldsymbol{f}_{\mathbf{beat}}$, is measured using the electric counter (R5363). The velocity, $\boldsymbol{v}$, the acceleration, $\boldsymbol{\alpha}$, and the force, $\boldsymbol{F}$, are calculated from the beat frequency, $\boldsymbol{f}_{\mathbf{beat}}$. The impact force in Fig. 5 has a maximum value of approximately 102.1 N, the half value width of approximately 18 ms and the impulse, i.e., the time integration of the impact force, of approximately 1.976 Ns.

Fig. 6 shows the responses of Transducer A, with Damper A or Damper B. For the combination of Transducer A and Damper A in Fig.6, the maximum values of the impact force measured by this method, $\boldsymbol{F}_{\mathbf{inertial,\ max}}$, and by the transducer, $\boldsymbol{F}_{\mathbf{transducer,\ max}}$, are approximately 102.1 N and 101.0 N, respectively.

For the combination of Transducer A and Damper B in Fig.6, the maximum values of the impact force measured by this method, $\boldsymbol{F}_{\mathbf{inertial,\ max}}$, and by the transducer, $\boldsymbol{F}_{\mathbf{transducer,\ max}}$, are N, respectively.

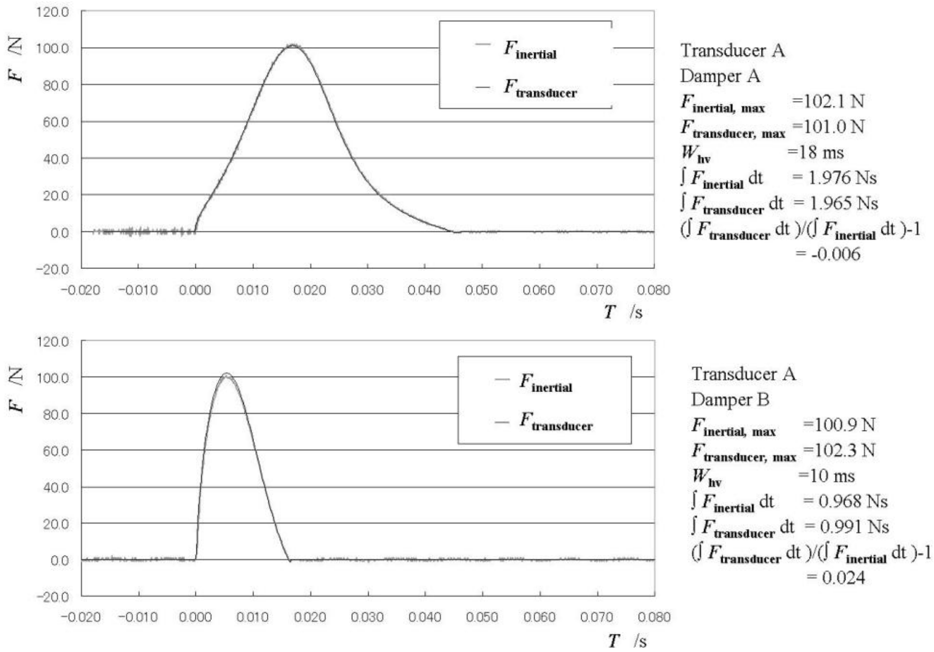

Fig.6. Impulse responses of Transducer A with Damper A and Damper B

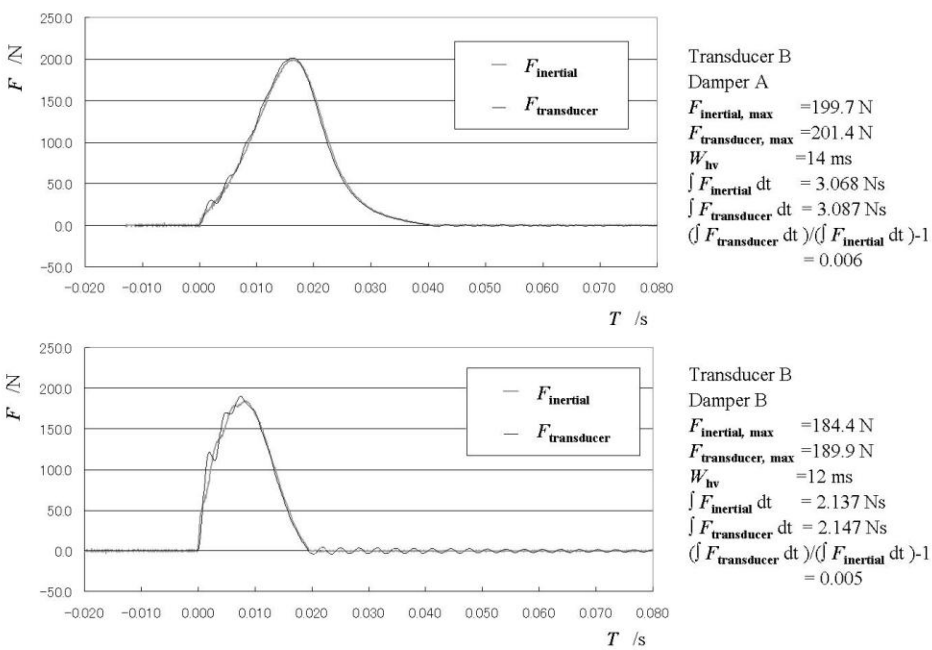

Fig.7. Impulse responses of Transducer B with Damper A and Damper B

The half value width of the impact force measured by this method, $\boldsymbol{W}_{\mathbf{hv}}$, is approximately 10 ms. The impulses measured by this method, $\int \boldsymbol{F}_{\mathbf{inertial}}\, dt$, and by the transducer, $\int \boldsymbol{F}_{\mathbf{transducer}}\, dt$, are approximately 0.968 Ns and 0.991 Ns, respectively. The relative difference between them, $(\int \boldsymbol{F}_{\mathbf{transducer}}\, dt) / (\int \boldsymbol{F}_{\mathbf{inertial}}\, dt) - 1$, is approximately 0.024.

Fig. 7 shows the responses of Transducer B with Damper A and Damper B.

approximately 100.9 N and 102.3

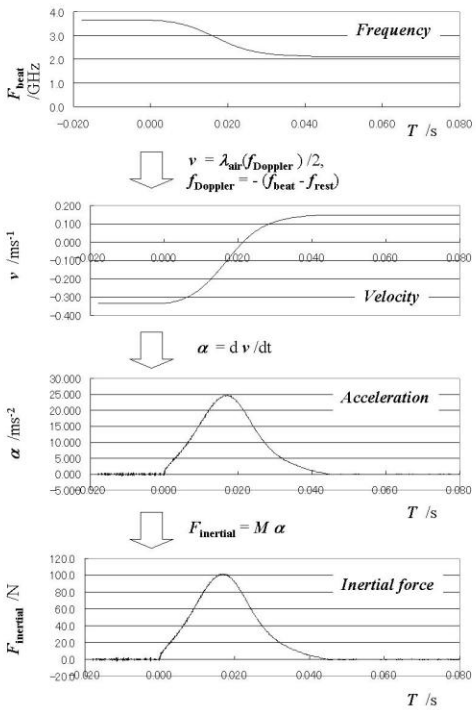

Fig. 5. Change in frequency, velocity, acceleration and force in a single collision experiment

For the combination of Transducer B and Damper A in Fig.7, the maximum values of the impact force measured by this method, $\boldsymbol{F}_{\mathbf{inertial, max}}$, and by the transducer, $\boldsymbol{F}_{\mathbf{transducer, max}}$, are approximately 199.7 N and 201.4 N, respectively. The half value width of the impact force measured by this method, $\boldsymbol{W}_{\mathbf{hv}}$, is approximately 14 ms. The impulses measured by this method, ∫ $\boldsymbol{F}_{\mathbf{inertial}}$ dt, and by the transducer, ∫ $\boldsymbol{F}_{\mathbf{transducer}}$ dt, are approximately 3.068 Ns and 3.087 Ns, respectively. The relative difference between them, (∫ $\boldsymbol{F}_{\mathbf{transducer}}$ dt) / (∫ $\boldsymbol{F}_{\mathbf{inertial}}$ dt)-1, is approximately 0.006. In this case, the output signal of Transducer B, $\boldsymbol{F}_{\mathbf{transducer}}$, vibrates at its characteristic frequency. The vibration initiated at the beginning of the impulse and damped rapidly during the first half of the impulse.

For the combination of Transducer B and Damper B in Fig.7, the maximum values of the impact force measured by this method, $\boldsymbol{F}_{\mathbf{inertial, max}}$, and by the transducer, $\boldsymbol{F}_{\mathbf{transducer, max}}$, are approximately 184.4 N and 189.9 N, respectively. The half value width of the impact force measured by this method, $\boldsymbol{W}_{\mathbf{hv}}$, is approximately 12 ms. The impulses measured by this method, ∫ $\boldsymbol{F}_{\mathbf{inertial}}$ dt, and by the transducer, ∫ $\boldsymbol{F}_{\mathbf{transducer}}$ dt, are approximately 2.137 Ns and 2.147 Ns, respectively. The relative difference between them, (∫ $\boldsymbol{F}_{\mathbf{transducer}}$ dt) / (∫ $\boldsymbol{F}_{\mathbf{inertial}}$ dt)-1, is approximately 0.005. In this case, the vibration appeared in the output signal of Transducer B, $\boldsymbol{F}_{\mathbf{transducer}}$, is larger after applying the impulse, in comparison with the previous case.

Fig.8 shows the half value width of the impact force measured by this method, $\boldsymbol{W}_{\mathbf{hv}}$, against the maximum value of the impact force measured by this method, $\boldsymbol{F}_{\mathbf{inertial, max}}$. The relationship between $\boldsymbol{W}_{\mathbf{hv}}$ and $\boldsymbol{F}_{\mathbf{inertial, max}}$ mainly comes form the mechanical properties, such as elasticity and viscosity, of the damper and the transducer. As known form the figure, Transducer B is more elastic than Transducer A.

Fig.9 shows the relative difference between the impulses measured by this method and by the transducer, (∫ $\boldsymbol{F}_{\mathbf{transducer}}$ dt) / (∫ $\boldsymbol{F}_{\mathbf{inertial}}$ dt)-1, against the maximum value of the impact the impact force measured by this method, $\boldsymbol{F}_{\mathbf{inertial,\ max}}$. Although the vibration appears in the output signal of Transducer B, the impulse measured by Transducer B is much more stable than that measured by Transducer A.

4. Uncertainty Evaluation and Discussion

The major uncertainty components in the determination of the instantaneous value of the impulse force are as follows.

(1) Electric counter (R5363)

The standard uncertainty in measuring the instantaneous value of the frequency with the sampling period of approximately 0.15 ms is estimated to be 100 Hz. This corresponds to 0.85 N in force determination.

(2) Force inside the air bearing

The frictional characteristics of the air bearing are determined using the developed method [7]. The dynamic frictional force acting on the moving part, $\boldsymbol{F}_{\mathbf{fd}}$, is estimated to be less than 0.02 N at $\boldsymbol{v}$ = 0.3 m/s. The static force inside the air bearing, due to the asymmetry of the airflow, $\boldsymbol{F}_{\mathbf{fs}}$, is estimated to be less than 0.002 N.

(3) Optical interferometer

The uncertainty of the frequency difference of the laser is estimated to be 10 Hz. The major uncertainty source concerning optical alignment is the inclination of the signal beam of 1 mrad, and it results in the relative uncertainty in the force measurement of 5×10^{-7}.

Therefore, the combined standard uncertainty in measuring the instantaneous value of the impact force, with the sampling period of approximately 0.15 ms, is approximately 0.85 N. This uncertainty corresponds to approximately 0.4 % of the maximum value of the experiments.

In the above evaluation, the uncertainty of the electric counter is dominant. This uncertainty will be considerably reduced if the beat frequency is recorded using a data logger and then analysed.

In integral form, the measurement uncertainty will be considerably reduced, because the dominant uncertainty component shown above comes form the electric counter (R5363). The impulse will be useful for macroscopic evaluation of the uncertainty in applying the other dynamic calibration method for impact detection.

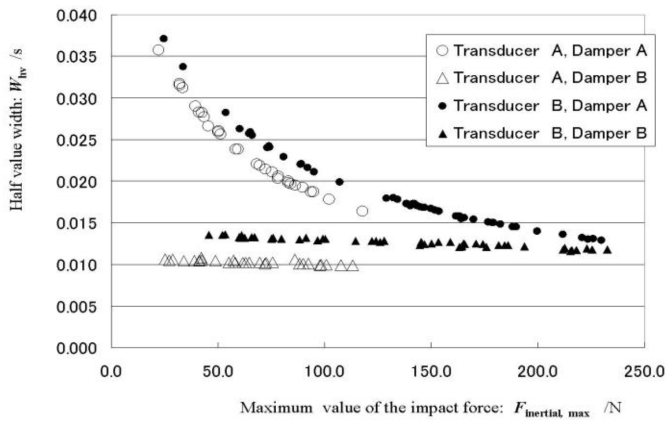

Fig. 8. The half value width against the maximum value of the impact force

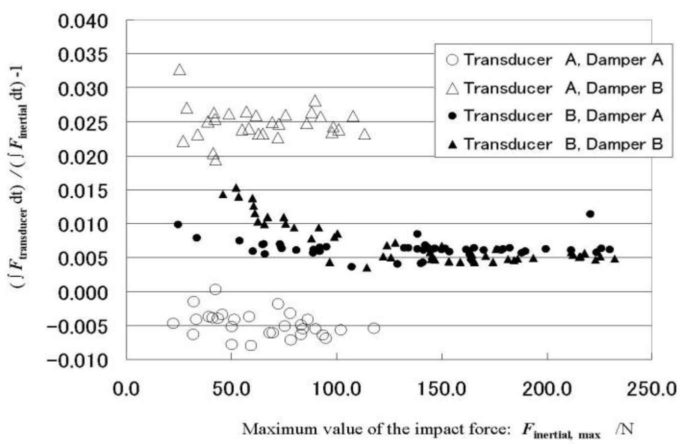

Fig. 9. Relative difference between the impulses measured by the transducers and the proposed method against the maximum value of the impact force

The points to be considered at present for improving the accuracy and efficiency in generation and/or measurement of impact force are as follows:

(1) Sufficiently small external force acting on the mass:

When the height of the collision point and the height of the center of gravity of the moving part were set to be much different, more than 20 mm, a large vibration of acceleration of the measurement point, the optical center of the cube corner prism attached to the moving part, was observed during and after applying the impulse. This might come from the break of the air film between the moving part and the guide way and change in friction. For improving this method, the frictional characteristics of the pneumatic linear bearing must be carefully elucidated. Particularly, friction under dynamic conditions, such as the time of collision, must be investigated.

(2) Validity of the presumption that the mass is rigid:

In the experiment shown in this paper, the vibration appeared in $\boldsymbol{F}_{\mathbf{inertial}}$ during and after applying the impulse is the same level as it before applying the impulse. This is a supporting-evidence that the presumption is valid in the experiment shown in this paper. However, for more accurate measurement for steeper and larger impulse, the validity of this assumption must be carefully considered. Under the conditions in which the presumption that the mass is rigid is not valid, the distributions of both density and acceleration must be considered. The finite element method (FEM) analysis will be effective for this purpose.

(3) Arbitrary setting of the force acting on the mass:

At present, the initial momentum of the object is provided manually, so its arbitrary setting is difficult. Moreover, the arbitrary setting of the time series of the instantaneous value of force is currently impossible. The shape of the impulse could be adjusted by means of changing the structure and the material of the damper. Incorporation of an actuator such as a piezoelectric transducer (PZT) to the damper might be effective for adjusting the shape of the impulse.

5. Conclusions

In this paper, present status of the developing impulse generator based on the law of conservation of momentum is reviewed. Impulse responses of two commercial force transducers are evaluated by means of this method. In the experiment, an object levitated with sufficiently small friction using a pneumatic linear bearing is collided with a force transducer. The inertial force acting on the object is measured as the product of the mass and the acceleration. Approximately 160 sets of collision experiments, whose impulses with the maximum value of approximately 20 to 230 N with the half value width of approximately 10 ms to 40 ms, have been conducted using two commercial force transducers and two dampers. The instantaneous value of inertial force is measured with the sampling period of approximately 0.15 ms. Its standard uncertainty is approximately 0.9 N, which corresponds to approximately 0.4 % of the maximum applied impulse.

6. References

[1]. Kumme R., *Investigation of the comparison method for dynamic calibration of force transducers*, Measurement, 1998, Vol.23 239-245.

[2]. Kumme R., Dixon M., *The results of comparisons between two different dynamic force measurement systems*, Measurement, 1992, Vol. 10, 140-144.

[3]. Fujii Y., Fujimoto H., *Proposal for an impulse response evaluation method for force transducers*, Meas. Sci. Technol., 1999, Vol. 10 No.4, N31-N33

[4]. Fujii Y., Isobe D., Saito S., Fujimoto H., Miki Y., *A method for determining the impact force in crash testing*, Mechanical Systems and Signal Processing, 2000, Vol.14 No.6, 959-965.

[5]. Fujii Y., *Measurement of impulse response of force transducers*, Rev. Sci. Instrum., 2001, Vol.72, No.7 (in press).

[6]. Fujii Y., *Evaluation of impulse responses of commercial force transducers*, Measurement, (revised manuscript of IMEKO2000 World Congress paper, under reviewing process)

[7]. Fujii Y., Fujii, *Possible application of mass levitation to force measurement*, Metrologia, 2001, Vol.38, No.1, 83-84.

[8]. Fujii Y., Fujimoto H., *Frictional characteristics measurements of a pneumatic linear bearing*, Meas. Sci. Technol., 1999, Vol.**10** No.5, 362-366.

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