Application of electromagnetic induction for impact load measurement

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Abstract. In this paper, a small impact testing machine was developed as an application of the method for measuring impact load based on electromagnetic induction phenomena. The experimental results were shown to determine the effectiveness of the method. The electromotive forces generated in two coils near a specimen were measured when a small impactor containing a neodymium magnet, having a mass of 0.36 g, was dropped freely onto a 1.2-mm-thick glass plate. The histories of the impact load and the relation between the impact load and specimen deflection were evaluated from the measured electromotive forces because the electromotive force per impactor velocity is dependent on only the position of the impactor. The method and developed machine with the measurement system were determined to be effective by considering the experimental impact test results for the glass plates.

1. Introduction
Impact load [1] is very important to evaluate the dynamic strength and stiffness of a material or structure. Generally, the impact load cannot be easily measured, especially when a small impactor collides with a structure or specimen. There are mainly two reasons for this difficulty: attaching an impact load sensor to the impactor, and balancing impact load and reaction force. First, the sensor, such as a load cell, a strain gage, or an accelerometer, cannot be attached to the impactor due to lack of space. Even if the sensor could be attached, the motion of the impactor is disturbed by the cable from the sensor to a measuring instrument. Second, because the inertia of the specimen or structure is generated under dynamic loading, the impact load often does not coincide with the reaction force at supporting positions. Namely, dynamic equilibrium is not always satisfied. Therefore, in previous studies, impact test results were estimated using the impact velocity or kinetic energy of the impactor, which was determined from the impactor behavior before the tests. [2–8].

In our previous works [9-11], impact load and specimen deflection were evaluated accurately from the measured electromotive force induced in coils near a specimen when a small impactor containing a magnet collided with the specimen. In the present work, the principle and method for measuring impact load were explained and a small impact testing machine with the measurement system was developed.

2. Measurement principle
We have suggested a novel method based on electromagnetic induction phenomena [12] to measure impact load when a small impactor collides with a structure or specimen [9-11]. The measurement principle is explained as follows.

Electromotive force is generated in a coil when an impactor containing a magnet passes through the coil with \(N\) turns (Fig. 1(a)). The electromotive force \(V\) is evaluated by Faraday’s law of induction [12].

\[
V(t) = -N \frac{d\Phi(t)}{dt} \tag{1}
\]

where \(\Phi\) and \(t\) are the magnetic flux in the area surrounded by the coil and time, respectively. The induced electromotive force is proportional to the turns of the coil and the time derivative of \(\Phi\), namely the velocity of the impactor. The electromotive force becomes zero when the magnet arrives at the coil. The electromotive force per impactor velocity relation (Fig. 1(b)) is dependent on only the magnet position regardless of impactor velocity. Impact load and displacement of the impactor can be evaluated on the basis of the impactor’s initial position and velocity.

Figure 1. Electromagnetic induction phenomena.

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Two groups of coils are used to measure the impact load and displacement of the impactor as shown in Fig. 2(a). The first group is composed of Coils No. 1 and 2 that obtain the initial position and velocity of the impactor as the initial condition in the impact load analysis. Typical electromotive forces generated in Coils No. 1 and 2 are shown in Fig. 2(b). The impactor position coincides with the positions of Coils No. 1 and 2, \(x_1\) and \(x_2\), at time, \(t_1\) and \(t_2\), when the electromotive forces of the coils become zero. The initial velocity of the impactor \(v_0\) can be calculated as follows:

\[
v_0 = \frac{x_2 - x_1}{t_2 - t_1} \tag{2}
\]

The second coil group is composed of a single coil or multiple coils connected in series. Multiple coils are used to extend the measurable region [9]. Because the electromotive force is proportional to the impactor velocity, the velocity can be evaluated as (Fig. 2(c))
\[ v(t) = \frac{V(t)}{e(x)} \quad x = x(t) \]  

Figure 2. Principle of measuring impact load.

\[ v(t) = v(t) \quad x = x(t) \]  

where \( e \), \( V \), and \( x \) denote the electromotive force per impactor velocity (reference data), the electromotive force in the impact test, and the impactor position, respectively.

The impactor position can be determined by integrating Eq. (3) with the initial conditions.

\[ x(t) = x_i + \int_{t_i}^{t} v(\tau) d\tau \quad i = 1 \text{ or } 2 \]  

The impactor acceleration \( \alpha \) can be determined by differentiating Eq. (1).
\[ \alpha(t) = \frac{dv(t)}{dt} \]  \hspace{1cm} (5)

The impact force \( F \) can be evaluated by multiplying Eq. (5) by the mass of the impactor \( m \) on the assumption that the impactor is a mass point. This assumption is valid when the natural frequency of the impactor is much higher than that of the specimen.

\[ F(t) = ma(t) \]  \hspace{1cm} (6)

The impactor displacement \( x \) can be regarded as the deformation of the specimen because the impactor is in contact with the specimen during the impact loading.

3. Application to small impact testing machine

3.1. Impact testing machine

We developed the impact testing machines for penetration testing of rubber sheets [9-11]. In this paper, a novel impact testing machine developed for a small impactor is denoted. The machine and impactor are illustrated in Fig. 3. The machine was designed and manufactured on the basis of a drop weight testing machine (Fig. 3(a)).

![Small drop weight testing machine](image1)

![Impactor (Cross section)](image2)

**Figure 3.** System of small impact testing machine.

The impactor (Fig. 3(b)) contained a cylindrical neodymium magnet with 2 mm in diameter and 10 mm in length. The tip of the impactor was an aluminum oxide ball on the aluminum-alloy cylinder having 2.0 mm in diameter and 5.0 mm in length, and the sides of the cylinder and magnet were covered by a polycarbonate pipe. The impactor mass was 0.36 g.

The impactor was dropped inside a glass pipe with inner and outer diameters of 3.4 mm and 6.0 mm respectively and collided with a specimen clamped between two thick polyvinyl chloride plates having holes with a diameter of 30 mm. Two coils, A and B, were placed in front of the specimen. A
0.5-mm polyurethane-covered copper wire (2UEW-0.16, JIS C3202) was wrapped around the external area of the circular pipe to prepare both coils. Coil A had 50 turns with an outer diameter of 13 mm and a width of 1 mm, and Coil B had 250 turns with an outer diameter of 23 mm and a width of 2 mm. Coils A and B (first group) were used to determine the initial conditions and Coil B (second group) was also used to measure the impact load and specimen deformation. In contact with the specimen during the impact loading.

3.2. Experimental results
The impactor was dropped freely from a height of 250 mm and collided with the glass plate specimen. The glass plate was 1.2 mm thick, 26 mm wide, and 76 mm long. No damage was observed in the plate after the impact test.

![Graphs showing experimental results](image)

(a) Histories of electromotive forces in the impact test.

(b) History of impact load.

(c) Impact load-specimen deflection curve.

**Figure 4.** Experimental results.
Figure 4 shows the history of the measured electromotive forces in the impact test. The time of the horizontal axis in Fig. 4 is relative. The impactor collided with the specimen at about 10 ms when the electromotive force of Coil No. B decreased drastically.

The impact load and specimen deflection were evaluated from the histories of the electromotive forces in Fig. 4(a) with Eqs. (2)-(6) and the reference data measured before the impact test. The history of the impact load is shown in Fig. 4(b). Because the specimen was not penetrated, the impact load increased and decreased linearly after the maximum load of 37 N. The duration of the impact load was approximate 50 μs. The minor fluctuation after 50 μs was caused by the natural vibration of the impactor. The impact load-specimen deflection curve was determined by evaluating the deflection. The curve is shown in Fig. 4(c). The curve after the collision was linear to the deflection until the maximum value, and the curve decreased drastically after the maximum value.

The momentum variation of the impactor due to the collision was evaluated as 0.93 gm/s from the velocities before and after the impactor collision of 1.99 and −0.58 m/s. The impulse of the impact load in Fig. 4(b) was also calculated as 0.93 mNs. The validity of the analysis for the impact load and specimen deflection was confirmed by the agreement of the momentum and impulse.

The impact load and specimen deflection were determined on the basis of the electromagnetic induction even though an impactor weighting less than 1 g collided with the specimen.

4. Conclusion
In this paper, the principle and system for measuring impact load and specimen deformation based on the electromagnetic induction phenomena was explained, and a small impact testing machine was developed as an application of the method. The impact load and specimen deflection, which were difficult to measure with conventional methods, were determined when a small impactor with a mass of less than 1 g collided with a 1.2-mm-thick glass plate. The method and developed machine with the measurement system were determined to be effective by considering the experimental impact test results for the glass plates.

References
[1] Adachi T and Ishii Y 2017 J. Jpn. Soc. Exper. Mech. 17 167 (in Japanese).
[2] Abrate S 1998 Impact on Composite Structures (Cambridge: Cambridge University Press)
[3] Zukas J A, Nicholas T, Swift H F, Greszczuk L B and Curran D R 1982 Impact Dynamics (New York: John Wiley & Sons).
[4] Walker J D 2001 Int. J. Impact Eng. 26 809
[5] Bourne N K 2012 Exp. Mech. 52 153
[6] Warren T L 2016 Int. J. Impact Eng. 91 6
[7] Antonucci V, Caputo F, Ferraro P, Langella A, Lopresto V, Pagliarulo V, Ricciardi M R, Riccio A and Toscano C 2016 Prog. Aerosp. Sci. 81 26
[8] Omidvar M, Iskander M and Bless S 2014 Int. J. Impact Eng. 66 60
[9] Adachi T, Matsukawa N, Takamizo C and Ishii Y 2017 J. Jpn. Soc. Exper. Mech. 17 231 (in Japanese).
[10] Adachi T, Matsukawa N, Takamizo C and Ishii Y 2018 Int. J. Impact Eng. 121 172
[11] Adachi T, Mochizuki Y and Ishii Y 2019 Measurement system of impact force and specimen deflection based on electromagnetic induction phenomena. Dynamics and Control of Advanced Structures and Machines ed V. P. Matveenko V P, Krommer M, Belyaev A and Irschik H (Wien: Springer) Chapter 1 pp 1-9, Springer.
[12] Ida K 2015 Engineering electromagnetics 3rd ed (New York: Springer) p 515