A new approach for health monitoring of composite structures through identification of impact force

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In this paper, for composite structures, an identification method of impact force is proposed. Based on the finite element method (FEM), the relation between force histories and strain responses is first formulated. From this relation, an error vector indicating the force location is defined and used for the force location identification. Next, the identification of force history is performed with the modified least-squares method that imposes the penalty on the first derivative of the force history. The validity of the present method has been verified through the impact experiment of CFRP laminated plates embedded with PZT piezoelectric sensors. Based on a FEM model, the possibility of employment of the obtained impact force history and impact force location for the prediction of material internal damages is discussed, which illustrates that this method can be used for the real-time health monitoring of composite structures.

Keywords : Impact force, Identification, Composites, Damage prediction

I. INTRODUCTION

The mechanical properties of composite structures may degrade severely after external impact events. Modern techniques of structural health monitoring are a possible resort to insure the safety of composite structures. In recent years, a lot of structural health-monitoring studies¹⁻² have been reported. In addition, the identification of the external impact forces has been investigated by many researchers.³⁻⁶ For instance, Wu et al.³ described the relation between the impact force and the strain response by Green's function and reported the experimental results of impact forces on various plates. Seydel and Chang⁴⁻⁵ identified the location and the history of the impact force applied to stiffened composite panels. However, the stable identification system of impact force for practical structures in real time has not been

fully established yet and further investigation is still required.

In this paper, a technique to identify the location and history of impact force acting on CFRP laminated plates is proposed. First, the relation between force histories and strain responses in CFRP laminated plates is formulated based on the FEM. Then the dynamic strain response is formulated when using the output charge of thin piezoelectric sensors embedded in the plates. Next, a reliable identification method of force history and force location is studied. This technique is realized using an identification system consisting of a measurement part and several signal conditioners. This study shows that it is possible to use the present method for the real-time health monitoring of composite structures.

II. FORMULATION OF FORWARD PROBLEM

II-A. Strain response induced by impact force

In the low-velocity impact event, a CFRP plate excited by a force in the out-of-plane direction is considered. The governing equation of undamped vibration of the plate is described as follows:

$$[M]\{\ddot{u}(t)\} + [K]\{u(t)\} = \{r_f\} f(t) \quad (1)$$

where $[M]$ and $[K]$ are the mass matrix and the stiffness matrix, respectively, $\{u(t)\}$ is the nodal displacement vector, and $(\cdot)$ denotes a derivative with respect to time t . The force location $\{r_f\}$ and the history $f(t)$ describe the impact force. The above differential equation can be solved by means of Duhamel's integral after the governing equation is transformed into the modal coordinates.

Then the relation between the impact force history acting at the location (x_f, y_f) and the strain response observed at the location (x_o, y_o, z_o) can be expressed in the following algebraic equation:

$$\{\tilde{\varepsilon}_\zeta\} = [G_\zeta(x_f, y_f, x_o, y_o, z_o)] \{\tilde{f}\} \quad (2)$$

where

$$\begin{aligned} \{\tilde{\varepsilon}_\zeta\} &= [\varepsilon(0) \quad \varepsilon(\Delta t) \quad \cdots \quad \varepsilon(k\Delta t)]^T \\ \{\tilde{f}\} &= [f(0) \quad f(\Delta t) \quad \cdots \quad f(k\Delta t)]^T \end{aligned} \quad (3)$$

and the strain and force history can be expressed at discrete time points. In Eq.(2), ζ represents x or y , and $[G_\zeta(x_f, y_f, x_o, y_o, z_o)]$ is a transform matrix composed of the Green's function at each time, which is a lower triangular matrix.³⁻⁶ This matrix is determined by the force location and the observation point of strain only, and is not influenced by the force history.

In this paper, we use PZT piezoelectric sensors as strain sensors. Consider a thin circular PZT element attached on or embedded in structures. Assuming the in-plane elasticity of the piezoelectric element is isotropic and the element is polarized in the out-of-plane direction, the out-of-plane electric displacement D_3 can be written as follows:

$$D_3(t) = d_{31} \frac{E_1}{1 - \nu_{12}} \{\varepsilon_x(t) + \varepsilon_y(t)\} \quad (4)$$

where d_{31} is the piezoelectric constant, E_1 and ν_{12} are the Young's modulus and Poisson's ratio, and ε_x and ε_y are in-plane strains. The above equation yields

$$V_{PZT}(t) = G_{PZT} \{\varepsilon_x(t) + \varepsilon_y(t)\} \quad (5)$$

where V_{PZT} and G_{PZT} are the output voltage and the sensitivity of PZT element as a strain sensor. The above equation states that the output voltage is proportional to the summation of in-plane strains. The sensitivity of PZT sensors is calibrated through an impact test.

III. FORCE IDENTIFICATION

III-A. Force history identification

The identification of impact force is discussed in this section, which includes detection of the force location and identification of the force history. First, an identification technique of force history is set up by solving an inverse problem. When the strain responses are acquired by using the multi-point measurement of PZT sensors, the force history can be obtained by employing the least-squares method in the case of that the force location is known. In a practical system, however, the identified force history has a very large oscillation due to the influence of measurement noise, the FEM modeling error and other factors. Consequently, a technique imposing the penalty on the derivative of the force history is proposed to improve the numerical stability. By applying this technique, the force history can be identified using a minimization problem as:

$$\begin{aligned} \underset{\{\tilde{f}\}}{\text{Minimize}} \quad F &= \sum_{i=1}^m \|\{\tilde{\varepsilon}_i\} - [G_i]\{\tilde{f}\}\|^2 + \alpha \|\{\Delta \tilde{f}\}\|^2 \\ \text{subject to} \quad \{\tilde{f}\} &\geq 0 \end{aligned} \quad (6)$$

where $\{\tilde{\varepsilon}_i\}$ is the strain response measured by the i th sensor located at (x_{oi}, y_{oi}, z_{oi}) , $[G_i]$ is the transform matrix relating $\{\tilde{\varepsilon}_i\}$ to $\{\tilde{f}\}$, m is the number of sensors, α is the regularization parameter for the derivative of the force history, $\{\Delta \tilde{f}\} = L \tilde{f}$ is the finite difference approximation

It is important to select a proper regularization parameter α . When the regularization parameter is too small, the identified force history has a very large oscillation. On the contrary, when the regularization parameter is too large, the force history is identified excessively smoothly, and the identified maximum impact force is usually lower than the true one. In this paper, the optimal regularization parameter is determined as a solution of the following maximization problem:

$$\begin{aligned} J &= \max_{\alpha} \lambda_{\min}([A(\alpha)]) \\ \text{subject to } \lambda_{\max} &\leq a \lambda_{\max}([A_{\alpha=0}]) \end{aligned} \quad (7)$$

where

$$[A] \equiv \sum_{i=1}^m [G_i]^T [G_i] + \alpha [L]^T [L] \quad (8)$$

In Eq.(7), $\lambda_{\min}([A(\alpha)])$ and $\lambda_{\max}([A_{\alpha=0}])$ denote, respectively, the minimum eigenvalue of the matrix A for any α and the maximum eigenvalue of A for $\alpha=0$. A solution of Eq.(7) gives the stable solution without excessive change of the matrix A . In Eq.(7), the small value of $a=1.01$ in this paper is used to avoid excessive smoothing, which leads to the lower maximum impact force compared with the experimental one.

III-B. Force location identification

Another issue is the determination of the force location. In the force history identification with the assumed location, we can have a force history denoted by $\{\mathcal{F}_e\}$. Then an error vector, which indicates the deviation between the calculated strains and measured strains, can be defined. The force location is determined by solving a minimization problem as follows:

$$\underset{x_c, y_c}{\text{minimize}} \quad E = \sum_{i=1}^m \frac{\| [G_i] \{ \tilde{f}_c \} - \{ \tilde{\epsilon}_i \} \|^2}{\| \{ \tilde{\epsilon}_i \} \|^2}. \quad (9)$$

Eq.(9) is solved by a nonlinear programming method.⁷ In the minimization process, the force history $\{\tilde{f}_e\}$ is updated using Eq.(6) for each force location.

IV. IDENTIFICATION RESULTS

IV-A. Experimental identification system

To verify the formulations stated in the previous sections, the impact test for CFRP rectangular laminated plates has been performed. The impact test system and the specimen utilized in this study are shown in Fig. 1 and 2, respectively. The impact test system consists of a measurement part and identification codes as shown in Fig. 1. The former part consists of a sensor network and several signal conditioners. The present study utilizes the SMART Layer¹ developed in Stanford University as a sensor network as shown in Fig. 2, which can be easily embedded in structures. The specimen is cantilevered and impacted by an impulse hammer. The strain response is measured by four PZT sensors.

Fig.1. Impact test system.

Fig.2. CFRP specimen.

The identification task is carried out intermittently. When the impact force is applied and the strain responses are induced, a trigger signal is sent to the computer from the oscilloscope. After receiving the trigger signal, the computer imports the strain responses from the oscilloscope, then identify the impact force, and monitor the strain responses again. In this test, the measurement time and the sampling time are 10.0×10^{-3} second and 1.0×10^{-4} second, respectively. The force history is also directly measured from the output of impulse hammer. The finite element model is used in the numerical analysis.

The material properties of the specimen are shown in Table 1. In order to determine the sensitivity of the PZT sensors, the calibration is performed by comparing the output voltage of the PZT sensor with the output of the biaxial strain gauge located at the same point. The sensitivity G_{PZT} in Eq.(5) was determined by comparing the maximum and minimum peaks of the output voltages. The calibration result is shown in Fig. 3.

Table 1. Material properties of CFRP specimen.

Stacking sequence	Material properties of unidirectional lamina
$[45_2/-45_4/45_2]_s$ (CFRP1)	$E_1=114$ GPa
$[0_2/45_2/-45_2/90_2]_s$ (CFRP2)	$E_2=9.20$ GPa
	$G_{12}=5.49$ GPa
	$\nu_{12}=0.30$
	$\rho=1550$ kg/m ³

Fig.3. Calibration of PZT sensors.

IV-B. Effect of α on the identified force history

First, we examine the effect of the regularization parameter α in Eq.(6) on the identification results of the force history through numerical simulations. When the force location is specified, the optimal regularization parameter is determined using Eq.(7). Fig. 4 shows the identified force histories for the optimal value of α and for the value of $\alpha = 0$, comparing with the true force history. It is shown that the identified force history has a very large oscillation when the regularization parameter is too small. For the optimal regularization parameter, the identified force history agrees well with the true one.

Fig.4. Relation between regularization parameter and force history.

IV-C. Identification results of force location

The impact force is identified using the output of

four PZT sensors embedded in CFRP laminates. The force location is determined by Eq.(9). Fig. 5(a) and 5(b) show the identification results for $[45_2/-45_4/45_2]_s$ laminate (CFRP1) and $[0_2/45_2/-45_2/90_2]_s$ laminate (CFRP2), respectively. Each circle involves the true and identified force locations. The average errors of the force location were 8.5 mm for CFRP1 and 4.1 mm for CFRP 2, respectively. The location error is large near the clamped edge or near the free edge while the error is small in the locations apart from the edge of the plate. The main reason of the location error may be due to the error of FEM modeling.

(a) $[45_2/-45_4/45_2]_s$ laminate

(b) $[0_2/45_2/-45_2/90_2]_s$ laminate

Fig.5. Identified force location.

IV-D. Identification results of force history

Fig. 6(a) and 6(b) show the identified force histories in the case of point A for CFRP1 and the point B for CFRP2, respectively. In these cases, the force locations are identified near the true ones, and therefore the identified force histories agree well

with the true ones. Fig. 7 shows the identified force history when the identified force location is not accurate, as an example, in the case of point C for CFRP1. In this case, the identified force history is much different from the true one. If the true force location can be identified, the identification result of the force history is improved as shown in Fig. 7.

(a) $[45_2/-45_4/45_2]_s$ laminate (point A)

(b) $[0_2/45_2/-45_2/90_2]_s$ laminate (point B)

Fig.6. Identified force history.

Fig.7. Identified force history ($[45_2/-45_4/45_2]_s$ laminate, point C).

In the present force identification, it takes a few seconds to identify the location and the history for each case. Most of the identification time is required in the force location identification. The force history identification is very fast for a specified force location. When we use other methods such as the neural network in place of a nonlinear programming method, we can further shorten the identification time considerably. This kind of methods can be adopted in the future practical applications.

V. HEALTH MONITORING

Structural health monitoring is important to insure the safety of composite structures. Especially real-time monitoring of the impact events is one of the most important health monitoring. The present method of the force identification gives the location and history of the impact force acting on composite structures. Also, we can get the information of impact events in real time since it takes only a few seconds to identify impact events. When we know the location and history of the impact force, we can estimate the damage state in composite structures such as delamination, matrix cracking and fiber breakage.⁸⁻⁹

In the present identification method, we assume that there is no damage in structures, and we use a FEM model of a healthy structure. When impact events cause severe damage in the structures, we need develop the impact force identification method based on the damage growth model. On the contrary, when impact damage is not so severe and the damage extent is not so large, we can use a FEM model of a healthy structure in the force identification, and therefore real-time health monitoring of composite structures is possible based on the information of the identified force.

After obtaining the impact force history, we need to build up a numerical model to predict the possible damages in materials caused by the impact force. Here, for the problem of CFRP laminates under the impact of a rigid ball, by considering the contact between the rigid ball and laminates, and various damages patterns (e.g. fiber breakage, matrix

cracking and delaminations), a finite element model is employed.⁸⁻⁹ When considering a square CFRP cross ply laminates $[0_4/90_2/0_4]$ with length of 0.2 m under the impact of 26.8 g rigid ball, the relationship between the impact velocity and impact force history is shown in Fig. 8. With the increase of impact velocity, the increase of maximum impact force can be identified.

Next, the relationship between the maximum impact force and the size of delamination is shown in Fig. 9. From this figure, it can be found that the size of delamination is tightly connected to the maximum impact force. In Fig. 10, the impact force history and delamination in the laminates are shown for the impact velocity of 13 m/s. It was found that the delamination size reaches its final shape at around the peak of the impact force. It almost does not propagate after the maximum impact force. In this figure, the impact force history using a model without consideration of damage formations, i.e., 'intact model', is also shown. From this figure, it can be found that there is no obvious difference between the result considering the damages and the result without consideration of damages. Furthermore, for the impact velocity of 19 m/s, from Fig. 11, it can be found that there is no obvious difference between the results of intact model and damaged model. Also, compared with that of 13 m/s, the delamination size increases.

The impact damages in CFRP, which cannot be observed by eyes, are of the similar extents of size as shown in Fig. 10 and 11. It is important to identify

Fig.8. Impact force history due to rigid-ball impact.

these kinds of damages. In this research, by using the identification method of impact force based on the non-damaged model, it is possible to estimate the internal damages using the identified location and history of impact force and an effective FEM model.

Fig.9. Relation between maximum impact force and delamination size.

(a) Impact force history at rigid-ball impact with 13m/s

(b) Delamination

Fig.10. Impact force and damage at rigid ball impact with 13 m/s.

(a) Impact force history at rigid-ball impact with 19m/s

(b) Delamination

Fig.11. Impact force and damage at rigid ball impact with 19m/s.

VI. CONCLUSIONS

In this paper, the method to identify the impact force location and force history is developed. PZT piezoelectric sensors embedded in composite structures are used as a strain sensor. The identification tests have been demonstrated for cantilevered CFRP laminated plates. The knowledge from these results are summarized as follows:

- (1) The accurate force location can be identified using the developed identification method.
- (2) The force history can be identified accurately by imposing the penalty on the derivative of the force history and by selecting a proper regularization parameter.

Furthermore, a FEM model based on the identified force is developed to estimate the possible internal various damages caused by the impact force. Therefore, the real-time health monitoring of composite structures is possible based on the information of identified forces.

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