Impact Force Magnitude and Location Recognition of Composite Materials

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Abstract: In order to identify the location and magnitude of the impact force accurately, determine the damage range of the structure and accelerate the health monitoring of key components of the composite, this paper studies the location and magnitude of the impact force of composite plates by an inverse method. Firstly, a PZT sensor mounted on the material plate is used to collect the response signal generated by the impact force, which is from several impact locations, and establish transfer functions between the impact location and the PZT sensor. Secondly, this paper applies several forces to any location on the material plate, and collects the corresponding response signals, and reconstructs the impact force of several locations in turn. Finally, according to the reconstruction result of each location, the correct impact location is identified. Then, an improved regularization method is used to optimize the reconstructed impact force and accurate the magnitude of the impact force. The comparison experiments prove that the recognition error of this method is smaller.

Keywords: Impact force identification, transfer function, regularization.

1 Introduction

Structural health monitoring (SHM) technology is a technology for detecting structural performance and damage. It uses sensor technology and advanced signal processing methods to monitor the response of the detected structure and system characteristics in real time in the early stage of structural damage, and then identify damage in the structure timely and accurately [Sun and Gu (2017); Sun, Zhang, Qian et al. (2013); Gao, Dai, Liu et al. (2016)]. With the continuous development of aviation and aerospace technology, the structural design of aircraft is ever-changing, and the application requirements of aircraft materials with light weight and high efficiency are also sharply enhanced.

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Therefore, composite materials with light and high strength characteristics are widely used in aviation and aerospace fields. However, in the molding process of composite materials, defects such as cracks, doping, and bubbles greatly affect the properties of the materials due to differences in manufacturing processes and various human factors. In order to ensure the safety of composite products, the use of efficient structural monitoring technology is crucial [Yuan, Ren, Qiu et al. (2016)].

For the composite structure, the undetectable damage caused by the impact force is the biggest threat and hidden danger of structural safety. Therefore, timely and accurately identifying the impact force of the external action on the composite material is important to determine whether there is damage and damage in the composite structure, and estimate the residual strength of the composite material [Qiu, Yuan, Mei et al. (2016)]. Composite structure impact force identification includes two aspects: impact location identification and impact force reconstruction. Accurate identification of the impact location helps to determine the location of the injury and accelerate the detection of key locations [Alamdar, Li and Samali (2014); Boukria, Perrotin, Bennaniet et al. (2012); De Stefano, Gherlone, Mattone et al. (2015)] introduced genetic algorithm into the recognition of impact location, and proposed a “smart triangulation” positioning method; Kalhori et al. used minimized convolution integral that the method identifies multiple impact locations in the composite [Kalhori, Ye and Mustapha (2017); Kalhori, Ye, Mustapha et al. (2016)]. The time course of reconstructing the impact force is of great significance for determining the impact force and then determining the damage degree and damage mode by means of experiments and calculations. Lourens et al. [Lourens, Reynders, De Roeck et al. (2012)] used extended Kalman filtering techniques to identify forces. Ding et al. [Ding, Law, Wu et al (2013)] proposed the state force recognition technology of the average acceleration discrete algorithm, and achieved good recognition results. Zhao et al. [Zhao, Wu, Zhang et al. (2018)] proposed a motor fault diagnosis method based on superposition denoising automatic encoder.

In SHM, the identification of composite impact force belongs to the category of passive monitoring. It only needs to use sensors to sense and analyze the structural response caused by impact force. This method Combines signal processing and force identification method to determine the impact force, without in the structure. And it proactively motivates the diagnostic signal. In mathematics, load recognition is an inverse problem.

The identification problem of impact force is to establish a system model, which is based on the impulse response function of the reference impact force, and find out the impact force, and realize the comprehensive understanding of the impact force by identifying its location, direction and size. However, the solution to the inverse problem will lead to unstable results, and generally obtain stable and accurate results through regularization methods. At present, the regularization technology has been widely used in inverse problems [Rezghi and Hosseini (2009); Wang, Cao and Xie (2015)]. Continuously improved and optimized on the basis of the classical Tikhonov regularization algorithm for ill-conditioned problems [Rezghi and Hosseini (2009); Wang, Cao and Xie (2015)]. Ma et al. [Ma and Hua (2015)] introduced a stable function to improve the regularization method and realized the identification of state space payloads. Liu et al. [Liu, Law, Zhu et al. (2014)] used the combination of regularization technique and traditional least squares method to invert the force, and the recognition result was also ideal.

In this paper, the inversion method is used to identify the location and size of the impact force of the composite plate. The second chapter introduces the principle of the inversion method and the principle of the improved regularization method; the third section introduces the experimental equipment; the fourth chapter verifies the feasibility and accuracy of the method, and compares the results with error analysis.

2 Experimental principle

2.1 Deconvolution

In the vibration response of the linear system, for example, the dynamic strain ε recorded at the point α caused by the impact force f applied at the location β can be expressed by the convolution integral as:

$$\varepsilon(\beta,t)=\int_0^t k(\alpha,\beta,t-\tau)f(\alpha,\tau)d\tau \tag{1}$$

where, the transfer function $\mathrm{k}(\alpha,\beta,\mathrm{t}-\tau)$ is defined as an impulse response function at a point β at which the impact force is applied at the point α at time. The discrete form of convolution integral ($\mathrm{t}_i=i.\Delta t; i=1,...,p$, where p is the number of samples) can be represented by a Riemann approximation and written as a system of algebraic equations such as:

$$\mathrm{kf}=\varepsilon, k\in R^{m\times n}, f\in R^n, \varepsilon\in R^m \tag{2}$$

where, in the case of n=m, the transfer function k is a lower triangular matrix, and $R^{\mathrm{m}\times n}$ represents a space having m rows and n columns.

In order to obtain f, Eq. (2) should be solved in contrast to the established transfer function k and the known response. The solution Eq. (2) for f is often referred to as deconvolution.

In general, a simple method such as a standard inversion method, that is, a solution of $\mathrm{f}=(k^t k)^{-1}k^t\varepsilon$ does not exist or if there is a result that may cause instability. Usually Tikhonov regularization is expressed as:

$$\min\left\{\|kf-\varepsilon\|^2+\varphi\|f\|^2\right\} \tag{3}$$

2.2 Establish transfer function

In order to solve Eq. (2), it is necessary to pre-establish the transfer function K of the system using the reference impact force and the corresponding recorded response. Eq. (2) can be rewritten as:

$$fK=\varepsilon, f\in R^{mxn}, K\in R^n, \varepsilon\in R^m \tag{4}$$

To create a more accurate transfer function, up to N impacted reference effects can be performed in one location. If p is the number of samples, then m=p×N, n=p, and f, K and ε are expressed as:

$$\varepsilon=\begin{bmatrix}\varepsilon_1^{(1)}\\ \varepsilon_2^{(1)}\\ \vdots\\ \varepsilon_p^{(1)}\\ \vdots\\ \varepsilon_1^{(N)}\\ \varepsilon_2^{(N)}\\ \vdots\\ \varepsilon_p^{(N)}\end{bmatrix},f=\begin{bmatrix}f_1^{(1)} & 0 & \cdots & 0\\ f_2^{(1)} & f_1^{(1)} & \ddots & \vdots\\ \vdots & \vdots & \ddots & 0\\ f_p^{(1)} & f_{p-1}^{(1)} & \cdots & f_1^{(1)}\\ \vdots & \vdots & \vdots & \vdots\\ f_1^{(N)} & 0 & \cdots & 0\\ f_2^{(N)} & f_1^{(N)} & \ddots & 0\\ \vdots & \vdots & \ddots & 0\\ f_p^{(N)} & f_{p-1}^{(N)} & \cdots & f_1^{(N)}\end{bmatrix},K=\begin{bmatrix}K_1\\ K_2\\ \vdots\\ K_p\end{bmatrix} \tag{5}$$

where $f_i^{(j)}$ and $\varepsilon_i^{(j)}$ are the forces of the impact of j^{th} on $t_i=i.\Delta t$ and the corresponding responses, respectively. Now the problem is to solve the K in Eq. (4), which is another ill-posed inverse problem that needs to be solved by regularization [Kalhori, Li, Li et al. (2017)].

2.3 Improve the regularization method to regulate ill-conditioned problems

(1) Traditional Tikhonov regularization method

The currently widely used and quite effective regularization method is the Tikhonov regularization method.

$$\min(\|Kf-\varepsilon\|^2+\varphi\|If\|^2) \tag{6}$$

where I is the identity matrix and φ is the regularization parameter. Its regular solution is:

$$f_\varphi=(K^*K+\varphi I)^{-1}K^*\varepsilon \tag{7}$$

The part of the coefficient matrix at the right end of Eq. (7) adds the φI term, because this can play a role in overcoming the ill-conditioned matrix of the equation coefficient, so a stable solution can be obtained. Since the regularization solution in Eq. (7) is related to the parameter φ, the value of φ is different, and the solution is different. Therefore, how to choose the appropriate parameter φ is the key to obtain a stable solution. This paper uses the GCV method to determine the regularization parameters.

(2) Optimization method

Introduce a stable functional:

$$\phi_\lambda(f)=(1-\lambda)\|Kf-\varepsilon\|^2+\lambda\|f\|^2 \tag{8}$$

where λ is a regularization parameter that satisfies the condition: $0<\lambda<1$.

The regular solution f is the minimum point of the functional $\phi_\lambda(f)$. Let Eq. (8) be derived and let its derivative equal zero.

$$(1-\lambda)K^*(Kf-\varepsilon)+\lambda f=0 \tag{9}$$

Solve the above formula (9):

$$f_\lambda=[(1-\lambda)K^*K+\lambda I]^{-1}(1-\lambda)K^*\varepsilon \tag{10}$$

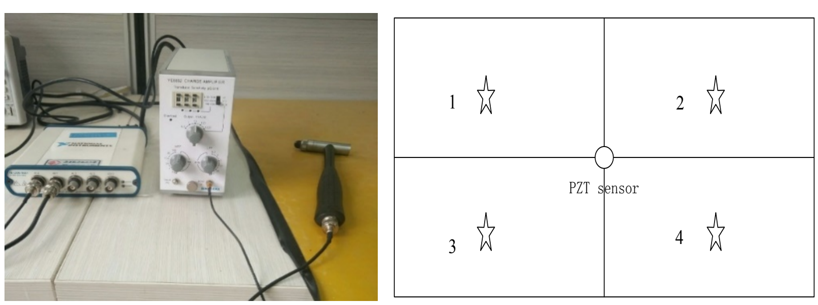
Eq. (10) is a regular solution to improve the regularization method. For the determination of the regularization parameter λ in Eq. (10), this paper uses the following formula:

$$\lambda(N)=\frac{1}{1+e^{-\beta(N_0-N)}} \tag{11}$$

where N is the number of iteration steps, N_0 is the initial value selection parameter (generally an integer between 0 and 5), β is the rate of decline parameter (generally recommended to take around 0.5), and $\lambda(N)$ is the regularization at step N. Parameter value. This article N_0=0, β=0.5 [Ma and Hua (2015)].

3 Experimental device

In this paper, epoxy composite plate is used for impact test. The impact hammer model is LC-01. The experimental device of this paper is shown in Fig. 1(a). The arrangement of four impact points and PZT sensor is shown in Fig. 1(b) (the five-pointed star represents the impact point. The circle indicates the PZT sensor placement point). This experiment uses the impact hammer to tap the assumed four impact locations in sequence, uses the USB-4431 data acquisition card to collect the impact force signal for each hammer and the response signal of the composite plate vibration caused by hammering, and the charge amplifier (model YE5852) for the response signal. Next step is to establish the transfer function between the four impact points and the sensor in turn; perform more precise transfer functions. The final steps are to tap the board at any point (assuming the impact force is unknown) and collect the resulting response signal. Then the impact can be reconstructed and located using inverse problem.



(a) (b)

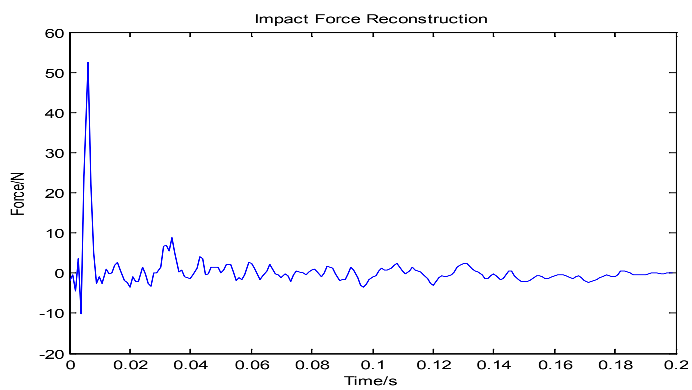
Figure 1: Experimental set-up including the impact hammer, data acquisition card and charge amplifier (a), impact location and PZT sensor arrangement (b)

In order to reduce the influence of stress wave delay on the impact force identification, the strain gauge is installed at a location of 1 cm from the collision surface of the upper and lower modes to collect the strain response signal. The impact force signal is collected by the impact mode hammer, and the sampling frequency is 1000 Hz.

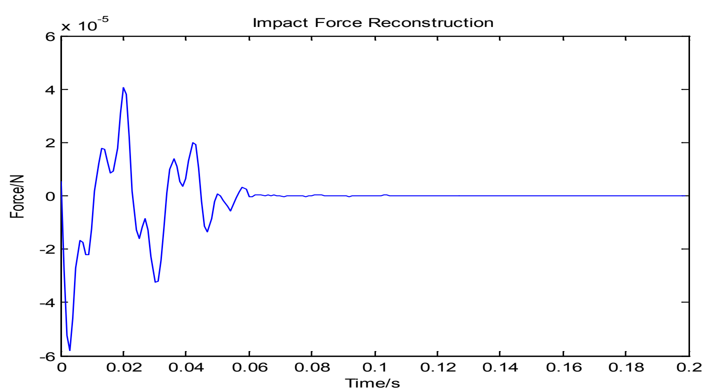
4 Experimental verification

4.1 Identify the impact location

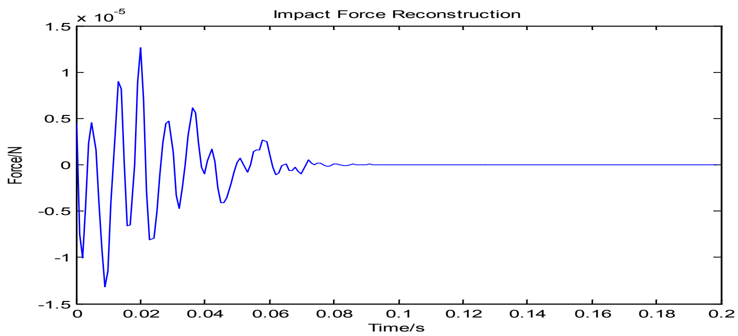
In order to verify the validity and applicability of the proposed method, an experimental system as shown in Fig. 1 was established to conduct an experimental study on a composite sandwich structure. Firstly, the impact location is determined, and the reconstruction force of each impact location is shown in Fig. 2.



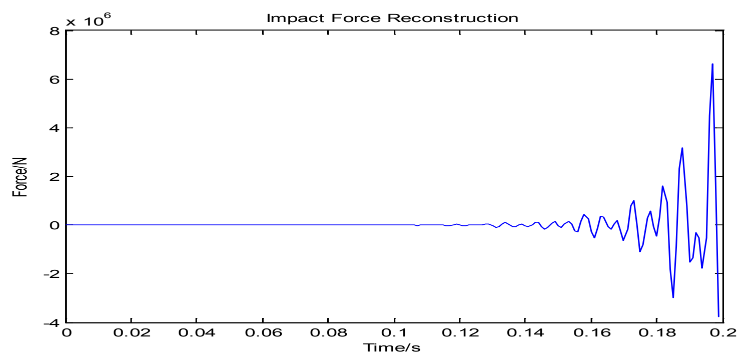
(a)



(b)



(c)



(d)

Figure 2: Reconstructed impact forces at (a) location 1, (b) location 2, (c) location 3 and (d) location 4

A typical impact force waveform has a high peak value greater than zero, and some aftershock peaks that are very low near zero. Fig. 3 shows the reconstructed impact force at four potential impact locations when the actual impact is applied at location 1. As can be seen from (b)-(d) in Fig. 2, the reconstructed impact forces at locations 2-4 are not like nominal impact forces. The reconstruction force at location 1 looks like the impact of a normal temple shape, and the reconstruction force at location 1 is similar to the nominal impact force with multiple peaks, where the first peak is much higher than the other peaks. Therefore, it can be confirmed that the impact at location 1 is likely to be the actual location.

4.2 Accurate the magnitude of impact force

In summary, location 1 is the impact point. However, compared with the actual impact force and the waveform, the error is large. Therefore, the Tikhonov regularization parameters are optimized and the exact force is reconstructed. The reconstruction result is shown in Fig. 3.

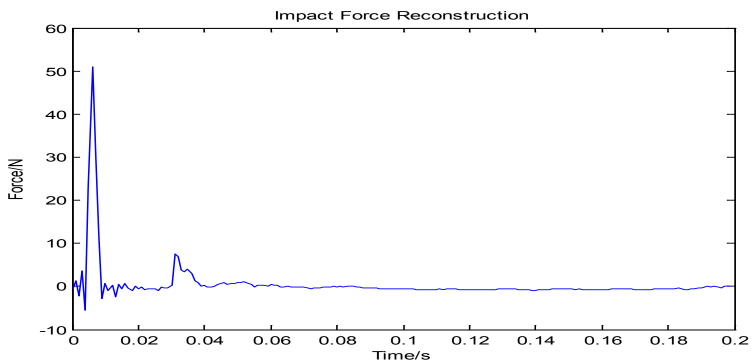


Figure 3: Impact of the reconstructed location 1 after improvement

The comparison between the impact force of the improved reconstruction and the impact force of the original reconstruction and the original impact force is shown in Fig. 4. As can be seen from the figure, the improved impact force eliminates the noise interference and is more stable. As shown in Fig. 4, it can be seen from the figure that the reconstruction force after the improvement is almost the same as the original signal.

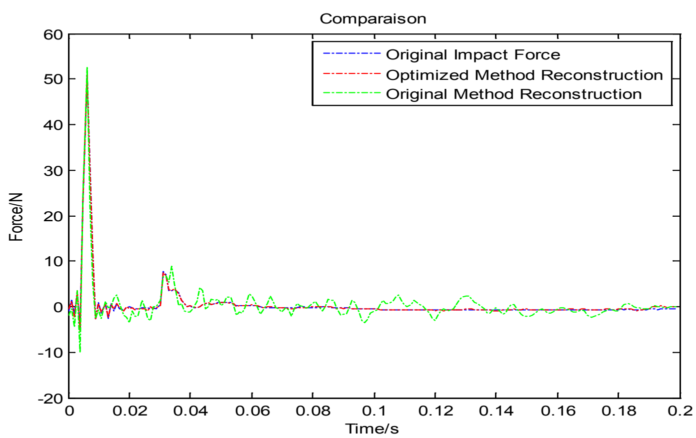


Figure 4: Comparison of the two reconstruction methods with the original impact force

4.3 Error analysis

In order to compare the effectiveness of the improved reconstruction method more clearly, two error methods are used to compare the reconstruction errors: absolute error δ and relative error Δ. And they are calculated separately:

$$\delta = \left| f_1 - f \right| \tag{12}$$

$$\Delta = \frac{\left| f_1 - f \right|}{f} \times 100\% \tag{13}$$

Among them, f1 is the impact force of reconstruction, and f is the original impact force. Tab. 1 shows the error comparison of the two reconstruction methods. Obviously, after the improvement, both errors are much smaller than the original.

Table 1: Comparison of error between the two methods

	Absolute error	Relative error
Optimization method	0.9774	0.0146
Original method	8.9543	0.1336

5 Conclusion

This paper focuses on the impact force identification of composite structures, which is of great significance for determining the location of structural damage and studying the degree of structural damage. Through the inversion method and its improvement and optimization, the location and size of the impact of the composite plate are identified. First of all, the PZT sensor mounted on the material plate is used to capture the response signal generated by the impact force from several assumed impact locations, and establish a transfer function between the impact location and the PZT sensor. Secondly, this paper applies several forces at any place, collects the corresponding response signals, and reconstructs the impact force of several locations in turn. Finally, according to the reconstruction result of each location, the correct impact location is identified. Then, the improved regularization method is used to optimize the reconstructed impact force, which is the magnitude of the impact force. Experiments show that the inversion method can accurately identify the impact location, and the optimized reconstruction impact force is more accurate and the error is smaller. According to the existing research, there are two points in the future research direction: (1): Dividing more impact points, precise and specific impact location; and (2): Simultaneously identifying two or more impact locations and impact forces.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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