

A coin-tap method of composite materials non-destructive testing based on improved grey clustering

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Abstract: Aiming at the problems of low reliability and complex operation of traditional coin-tap test of composite material, this paper introduces the grey system theory and achieves better performance. The response signals of coin-tap are classified through the grey clustering based on relation analysis, and corresponding improvements are made to the calculation method of the relation degree of nearness. First, the time history of acceleration is taken as the system behavior sequence. The improved correlation calculation method is used to solve the relation degree of nearness between the sequences, and the matrix of degree of grey relation is constructed based on this. Then, the sequence groups are summarized through the matrix, and the response signals of coin-tap are qualitatively classified according to the location of the reference sequence. Finally, the defect detection of composite materials is completed without pre-testing. The test results show that the accuracy of the coin-tap test based on improved grey clustering reaches 100%, which simplifies the operation steps while ensuring the reliability of the coin-tap test results.

Key words: non-destructive testing; coin-tap test; grey clustering based on relation analysis; composite material

0 Introduction

Composite materials are widely used in aviation, aerospace and other industrial fields, and the installed capacity of composite materials can reach 50% of aircraft structural weight^[1]. Due to process limitations, composite materials may have defects or damages during the forming process, which will affect the original structures and functions of composite materials, and cause serious accidents in severe cases. Therefore, non-destructive testing technology for composite materials is very important.

As one of the oldest non-destructive testing methods, coin-tap test is widely used due to its cheap and fast advantages. Initially, the operator held a small hammer or coin to tap on the surface of the material, and the sound of the tap was used to judge the integrity of the structure. However, the detection effect was often limited by the experience of the operator. In order to improve the reliability of coin-tap test, scholars have conducted a lot of research and made corresponding progress. Cawley et al. established a physical model of coin-tap test,

which provides a theoretical basis for coin-tap test technology. They used the duration of impact force to judge the defects, free from the constraints of subjective experience. At the same time, they pointed out that when the material vibration causes the pulse to produce a “tail”, the impact duration will become difficult to measure^[2-3]. Kim used finite element modeling (FEM) software to conduct a simulation analysis of spring-mass model, and concluded that the maximum impact force change is related to the decrease in stiffness. He carried out the numerical simulation of the tap test, which perfected the physical basis of the tap detection method^[4-5]. Esola et al. analyzed the percussive sound, and confirmed that larger defects can be detected by frequency content analysis, and discussed the limitations of the method^[6]. Erik used neural network to analyze the acceleration signal of tapping response, and proposed a defect evaluation procedure^[7].

In practical applications, the accuracy of using the maximum impact force for defect identification is relatively low, therefore it is rarely used. Since the

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working environment of coin-tap test is prone to noise interference, the usage of sound frequencies for defect analysis is not reliable. The test based on impact duration is the most widely used. However, as pre-tests for the suitable voltage is essential for the method, it is pretty hard to accurately measure the duration of the impulse force. Whether it is to inspect defects directly through the duration of impact force or use neural networks for data analysis, a large amount of sample data and pre-tests are required, which makes the coin-tap test very complicated. Therefore, it is particularly important to find a simple and accurate identification algorithm for coin-tap test.

Grey system theory is used to study systems with some information known and some information unknown. It has no requirements on the number of samples and small amount of calculation. It has been applied in the field of fault diagnosis^[8-9]. There is a grey relationship between the internal defects of the material and the coin-tap response signal, which can be analyzed as a grey system. According to the related literature, this is the first study of grey system for coin-tap test. In this paper, the grey system theory into the coin-tap test of composite materials is introduced, and the response signals of coin-tap are clustered through the grey clustering based on relation analysis to realize the classification of the defect response signal and the nondestructive response signal. The defect identification work is completed by using small sample data without the need for pre-tests. And the reliability of the coin-tap test is ensured while simplifying the working steps.

1 Problem description

Based on the principle of coin-tap test, Cawley established a spring-mass model, modeling the internal defects of the material as a spring with a certain stiffness, whose stiffness is that of the layer (s) above the defect^[3]. The vibration model is shown in Fig. 1.

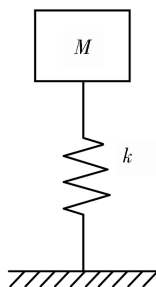


Fig. 1 Vibration model of the system in Ref. [2]

Assuming that the stiffness of the material defect is k and the mass of the hammer is M , the kinematic equation based on the model is established as

$$M\ddot{x} + kx = 0. \quad (1)$$

The general solution is

$$x(t) = C_1 \cos \sqrt{\frac{k}{M}}t + C_2 \sin \sqrt{\frac{k}{M}}t \quad (2)$$

or expressed as

$$x = A \sin \left(\sqrt{\frac{k}{M}}t + \alpha \right), \quad (3)$$

where t is the time, A represents the amplitude of system vibration, and α represents the initial phase. The values of these parameters are determined by the initial conditions. The relationship between the parameters can be expressed as

$$A = \sqrt{C_1^2 + C_2^2}, \quad (4)$$

$$\alpha = \arctan \frac{C_1}{C_2}. \quad (5)$$

Eq. (3) shows that when the mass of the hammer is constant, the vibration characteristics of the system such as the period of vibration and the circular frequency depend on the stiffness of the defect model. Previous studies have shown that the size and location of material defects will change the stiffness value of the defect model, which leads to the difference in the coin-test response signal. At present, the duration of the impact force is often used as the basis for identification of defects. The longer the duration of the impact force, the higher the degree of defects. In the actual test, the comparison results of the coin-tap response signal of the sound area and the defective area are shown in Fig. 2.

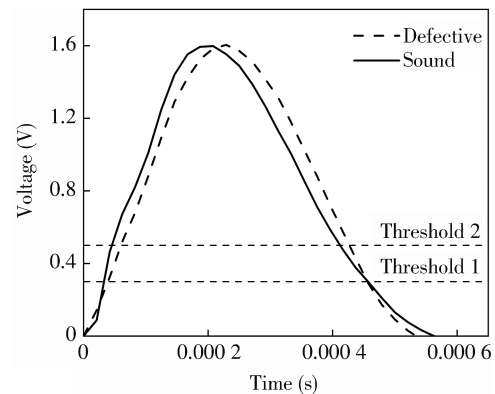


Fig. 2 Pulse widths under different thresholds

Cawley pointed out that the vibration of the tested material will lead to the generation of the “tail” of

the impact force. As shown in Fig. 2, the “tail” of the impact force extends the pulse width and makes the exact impact duration difficult to measure. In order to eliminate the interference caused by the “tail”, it is often necessary to set the voltage threshold in the measurement and take the time when the voltage waveform exceeds the threshold as the characteristic value^[10]. If the set voltage thresholds are different, the obtained characteristic values will be different, and the wrong threshold may lead to erroneous detection results. However, selecting an appropriate voltage threshold requires a lot of pre-tests, which will increase the complexity of coin-tap test.

According to the principle of the grey system, there are information differences between the coin-tap response signals in different areas. How to find the information difference between the coin-tap response signals based on the limited information space is the key of solving the defect identification problem.

2 Improvement of grey clustering model

2.1 Grey relational analysis

To analyze a system, a data sequence needs to be selected firstly to reflect the behavior of the system. The basic idea of grey relational analysis is to judge whether the connection is close according to the similarity of the geometric shapes of the sequence curves. The closer the curves are, the greater the correlation between the corresponding sequences will be^[11].

Supposing X_i is the system factor and its observation data on serial number k is $x_i(k)$, where $i=1,2,\dots,m$, $k=1,2,\dots,n$, the behavior sequence of factor X_i can be expressed as

$$X_i = (x_i(1), x_i(2), \dots, x_i(n)), \quad (6)$$

where i and k represent the serial numbers of system factors and observation data, respectively.

Assuming that X_i and X_j have the same length, let

$$S_i - S_j = \int_1^n (X_i - X_j) dt, \quad (7)$$

then the degree of grey relation of X_i and X_j based on the proximity perspective can be expressed as

$$\rho_{ij} = \frac{1}{1 + |S_i - S_j|}. \quad (8)$$

The closer the X_i is to X_j , the greater the degree of grey relation will be.

2.2 Improved calculation method of degree of grey relation

The traditional calculation method of degree of grey relation has the following characteristics:

When X_i and X_j coincide, or X_i swings around X_j , and the area of X_i above X_j is equal to the area of X_i below X_j (see Fig. 3), we can obtain $\rho_{ij} = 1$.

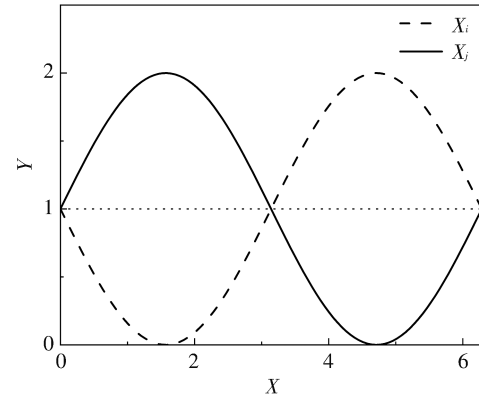


Fig. 3 Two different curves with $\rho_{ij} = 1$

In Fig. 3, the “positive difference” and “negative difference” between the two sequences will offset each other out in the calculation of the degree of grey relation, which will produce the least desirable calculation results for the research.

In order to make the algorithm more pertinent, we take the overall difference of the sequences into account and improve the calculation method of the degree of grey relation.

Let

$$S_i - S_j = \int_1^n |X_i - X_j| dt, \quad (9)$$

then the degree of grey relation of X_i and X_j based on the proximity perspective can be expressed as

$$\rho_{ij} = \frac{1}{1 + \frac{S_i - S_j}{10}}. \quad (10)$$

The improved calculation method fully considers the possible influence of the difference between the curve shapes. Therefore, the degree of grey relation calculated by this method can describe the closeness of the curve in space more accurately.

2.3 Grey relational clustering method

Gray correlation clustering is a method of classifying observation objects according to grey correlation matrix. A cluster can be regarded as a collection of observation objects that belong to the same type.

Assuming that there are n observation objects and each object contains m data features, the sequences obtained are as follows:

$$\begin{aligned} X_1 &= (x_1(1), x_1(2), \dots, x_1(n)), \\ X_2 &= (x_2(1), x_2(2), \dots, x_2(n)), \\ &\vdots \\ X_m &= (x_m(1), x_m(2), \dots, x_m(n)). \end{aligned} \quad (11)$$

For all $i \leq j (i, j = 1, 2, \dots, m)$, the degrees of grey relation between X_i and X_j are calculated, and the matrix of degrees of grey relation can be formed as

$$A = \begin{bmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_{1n} \\ & & \ddots & \rho_{2n} \\ & & & \vdots \\ & & & \rho_{nn} \end{bmatrix}. \quad (12)$$

Taking the critical value $r \in [0, 1]$, when $\rho_{ij} \geq r$ ($i \neq j$), X_i and X_j can be regarded as the same category^[12].

3 Design of coin-tap test

The composite laminate with pre-defects is used as the test object. The test piece is shown in Fig. 4. The tapping response signal collected in the experiment is an acceleration curve that changes with time, which is a description of the impact force characteristics during the tapping process. In coin-tap test, it is the existence of internal defects that changes the impact characteristics, which makes the difference between the sound of the sound area and the one of the defective area^[13]. Therefore, clustering analysis on the acceleration curves of the response signals in different regions makes it possible to detect whether the regions corresponding to each group of response signals have defects or damages.

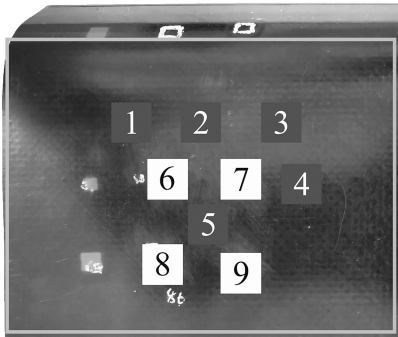


Fig. 4 Composite laminate with preset defects

As shown in Fig. 4, nine points are selected and marked on the surface of the material. Among them, the points labeled 1 to 5 are in the sound area, and the points labeled 6 to 9 are in the defective area. A

percussion hammer with a built-in piezoelectric acceleration sensor is used to strike the nine marked points respectively. The acceleration signal is collected through the data acquisition card USB-6009 with the signal sampling frequency of 48 kHz. In the process of data collection, the sampling frequency and sampling duration are remained constant, and nine sets of curves with equal time interval, length and dimension are obtained, as shown in Fig. 5.

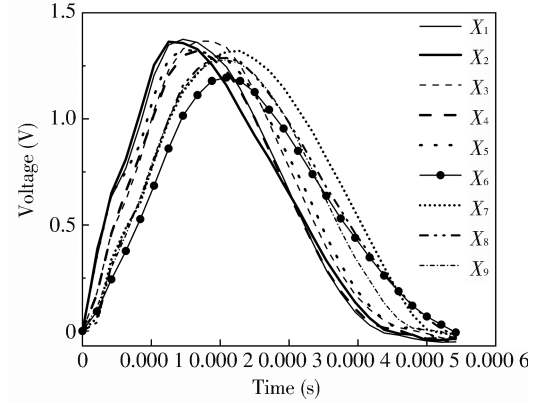


Fig. 5 Data sequences of coin-tap response signals

As shown in Fig. 5, nine observation objects are set in the experiment, each of which contains 27 data features, corresponding to the voltage values observed at different times. Among them, X_1 is a known behavior data sequence of the sound area, which is set as a standard sequence for later classification reference and this data can be collected by tapping a complete test template in practical applications.

4 Data analysis

4.1 Clustering analysis based on traditional degree of grey relation

According to Eq. (6), the degree of grey relation of X_i and X_j is calculated. Meanwhile, the matrix of degree of grey relation is obtained, as shown in Table 1.

In the test, when the stiffness of a certain area of the material is reduced by more than 20%, this part is defined as the damage site. Therefore, without loss of generality, let $r=0.8$.

According to the principle of grey relational clustering, the sequence group with degree of grey relation greater than or equal to 0.8 is selected. Then the data are obtained as

$$\begin{aligned} &\{X_{12}, X_{16}\}, \\ &\{X_{26}\}. \end{aligned} \quad (13)$$

In the above data, the same set of sequences are regarded as the same category. The repetitive sequence group is summarized and merged to obtain the final sequence group as

$$\{X_1, X_2, X_6\}. \quad (14)$$

Since sequence X_1 is contained in the sequence group, it is considered that X_1, X_2 and X_6 are the

response sequences of the sound area, and X_3, X_4, X_5, X_7, X_8 and X_9 are the response sequences of the defective area.

In the actual situation, the points labeled 1 to 5 located in the sound area, and the points labeled 6 to 9 are situated in the defective area. It can be seen that the sound area and the defective area cannot be effectively distinguished.

Table 1 Matrix of degrees of grey relation

	ρ_{ij}								
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
X_1	1	0.971	0.736	0.491	0.466	0.936	0.285	0.396	0.614
X_2		1	0.721	0.498	0.459	0.911	0.283	0.391	0.603
X_3			1	0.418	0.559	0.776	0.318	0.461	0.787
X_4				1	0.314	0.475	0.220	0.281	0.375
X_5					1	0.481	0.424	0.725	0.658
X_6						1	0.291	0.407	0.641
X_7							1	0.505	0.347
X_8								1	0.527
X_9									1

4.2 Clustering analysis

The clustering analysis is performed. According to

Eq. (8), the degrees of grey relation of X_i and X_j are calculated, and the matrix of degrees of grey relation is obtained, as shown in Table 2.

Table 2 Matrix of degrees of grey relation

	ρ_{ij}								
	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
X_1	1	0.913	0.805	0.883	0.836	0.597	0.573	0.609	0.645
X_2		1	0.786	0.851	0.821	0.597	0.567	0.602	0.639
X_3			1	0.866	0.886	0.677	0.658	0.703	0.751
X_4				1	0.817	0.644	0.615	0.656	0.698
X_5					1	0.669	0.645	0.690	0.736
X_6						1	0.780	0.859	0.827
X_7							1	0.877	0.823
X_8								1	0.898
X_9									1

According to the principle of grey relational clustering, the sequence group with degree of grey relation greater than or equal to 0.8 is selected, and the data are obtained as

$$\{X_{12}, X_{13}, X_{14}, X_{15}\},$$

$$\{X_{24}, X_{25}\},$$

$$\{X_{34}, X_{35}\},$$

$$\{X_{45}\},$$

$$\{X_{68}, X_{69}\},$$

$$\{X_{78}, X_{79}\},$$

$$\{X_{89}\}.$$

(15)

In the above data, the same set of sequences are regarded as the same category. The repetitive sequence group is summarized and merged to obtain the final sequence group as

$$\{X_1, X_2, X_3, X_4, X_5\}, \\ \{X_6, X_7, X_8, X_9\}. \quad (16)$$

The nine groups of sequences are finally divided into two categories, where X_1, X_2, X_3, X_4 and X_5 are classified into one category, and X_6, X_7, X_8 and X_9 are classified into the other category. Since X_1 is the standard reference sequence of the known lossless area, it is considered that X_1, X_2, X_3, X_4 and X_5 are the response sequences of the sound area, and X_6, X_7, X_8 and X_9 are the response sequences of the defective area.

In the actual situation, the points labeled 1 to 5 are located in the sound area, therefore the points labeled 6 to 9 are situated in the defective area, so the classification result is completely consistent with the actual situation, and the defect detection rate reaches 100%.

By comparing the results obtained by the two algorithms, it can be seen that, compared with the traditional grey correlation clustering method, the improved grey correlation clustering method greatly improves the detection accuracy, and it is more suitable for the classification of coin-tap response signals.

5 Conclusions

In this study, a coin-tap method of composite materials non-destructive testing based on improved grey correlation clustering method is proposed. The improved calculation method of degree of grey relation is constructed to perform clustering analysis on the coin-tap response signal and eliminate the influence of subjective factors. A small sample of data are used to complete the defect detection work and simplify the operation steps. The test results reveal the lack of the reliability of clustering analysis based on traditional degree of grey relation. After improving the calculation method of degree of grey relation, the defect detection rate reaches 100%, which can accurately classify the coin-tap response signals of the sound area and the defective area. At the same time, although the “tail” of the pulse generated by the vibration of the material has a great

impact on the pulse width of the coin-tap response signal, it has a relatively low impact on the amplitude. Since the improved calculation method of degree of grey relation focuses on the closeness of sequence curves in space, the interference caused by the “tail” of the pulse is almost negligible in the grey correlation analysis, which can improve the reliability of the coin-tap method of composite material.

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基于改进灰色聚类的复合材料无损敲击检测方法

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摘 要: 针对传统复合材料敲击检测方法可靠性低、操作复杂的问题, 引入了灰色系统理论, 基于灰色关联聚类方法对敲击响应信号进行分类, 并对接近关联度的计算方法进行了相应的改进。首先以加速度的时间历程作为系统行为序列, 利用改进的计算方法对各序列间的接近关联度进行求解并构建灰色关联矩阵。然后通过灰色关联矩阵对序列组进行归纳合并, 根据参考序列所在位置对敲击响应信号进行定性分类, 最终在无需预先试验的情况下, 完成了复合材料的缺陷检测工作。试验结果表明, 基于改进灰色聚类的敲击检测方法准确率达到 100%, 在简化操作步骤的同时保证了敲击检测结果的可靠性。

关键词: 无损检测; 敲击检测; 灰色关联聚类分析; 复合材料

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