Research on High-Velocity Impact Damage Monitoring Method of CFRP Based on Guided Wave

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Abstract: Carbon fiber-reinforced polymer (CFRP) is widely used in aerospace applications. This kind of material may face the threat of high-velocity impact in the process of dedicated service, and the relevant research mainly considers the impact resistance of the material, and lacks the high-velocity impact damage monitoring research of CFRP. To solve this problem, a real high-velocity impact damage experiment and structural health monitoring (SHM) method of CFRP plate based on piezoelectric guided wave is proposed. The results show that CFRP has obvious perforation damage and fiber breakage when high-velocity impact occurs. It is also proved that guided wave SHM technology can be effectively used in the monitoring of such damage, and the damage can be reflected by quantifying the signal changes and damage index (DI). It provides a reference for further research on guided wave structure monitoring of high/hyper-velocity impact damage of CFRP.

Key words: guided waves; structural health monitoring (SHM); carbon fiber reinforced polymer (CFRP); high-velocity impact

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0 Introduction

The structure of aircraft is related to flight safety and needs regular inspection and maintenance. The structural health monitoring (SHM) technology is derived from the concept of intelligent structure, which can collect, diagnose and feedback the structural status information by using pre-integrate advanced sensors during the aircraft service. It can provide the basis for situational inspection and effectively reduce the service maintenance cost. Therefore, this technology has attracted more and more attention[1].

There are many sensing methods available for SHM, such as fiber Bragg sensing methods[2], strain sensors, etc. Among them, the SHM based on piezoelectric guided wave method, most time whose sensor is PZT, has the advantages of wide monitoring range, excellent sensing sensitivity, high reliability, and both online and offline monitoring.

So SHM based on piezoelectric guided wave has a broad engineering application prospect, especially useful to large-area plate structure etc[3]. And by preparing the PZT sensors network for smart skin[4], the sensors can be better integrated on curved structures such as aircraft skin.

Compared with traditional metal materials, composite materials have the advantages of preeminent specific stiffness, light weight, excellent vibration damping performance and low expansion coefficient. It is an important development direction of modern aerospace vehicles to use high-performance composite materials and put them into main bearing structures[5]. For example, since the 1960s, composite materials have been gradually applied to the

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non-bearing and bearing structures of the airframe, and the proportion of composite materials used in modern military helicopter structures even exceeds 80%. In the advanced civil aircraft Boeing B-787/ Airbus A-350, composite material mass accounted for more than 50% of the total weight[6].

In addition to being used in load-bearing structures in aerospace, composite materials also have the research prospect of replacing traditional metal aircraft engine fan blades due to their excellent properties[7]. For example, GE's GEnx turbofan engine uses carbon fiber two-dimensional triaxial fabric as reinforcement material and is prepared into fan-containing casing through resin transfer molding (RTM) process, which improves energy efficiency by 30%. And the overall weight of the engine is reduced by 160 kg.

However, during the service of composite load-bearing structural parts, they will be threatened by various foreign objects, such as high-velocity impact of tire debris, gravel or hail, which seriously affects the structure and flight safety[8]. The engine blade structure may also be damaged by unexpected impact during service, which will seriously threaten the engine structure.

At present, there are some high-velocity impact studies of composite materials, but these studies mainly consider the impact resistance and mechanical properties of materials, and the relevant high-velocity impact of composite materials monitoring methods are scarce. Therefore, in this paper, T700 carbon fiber/resin matrix composite laminate, which is commonly used in the aviation field, is used as the test object, the guided wave monitoring method is adopted, and high-velocity impact actual damage is generated based on a light gas gun. The main work of this paper includes:

(1) The light gas gun and spherical projectile are used to produce two bullet impact damage at high-velocity (above 450 m/s), and the additional guided wave SHM test system is established. The macroscopic characteristics and nondestructive inspection results of these materials subjected to high-velocity impact penetration damage are demonstrated.

(2) Based on the comparison of guided wave signals and characteristic parameters before and after high-velocity impact damage and the reflection of damage degree, the guided wave propagation characteristics and damage influence rule of CFRP sheets under high-velocity impact damage (450 m/s) are analyzed. Damage index(DI) and design thresholds are used to warn when the damage occurs. The applicability of guided wave monitoring method to high-velocity impact damage monitoring is verified.

1 Principle of Guided Wave Structure Health Monitoring

The guided wave is a kind of mechanical stress wave that can propagate in solid structures. The most common guided wave between plates is Lamb wave, which is a special form of stress wave in thin plates by coupling P-waves and S-waves. When the guided wave propagates in the structure, various damages inside the structure will cause stress concentration and crack propagation, and these damages or the surrounding boundaries will cause the scattering of guided wave signals propagating in the structure and the absorption of energy. It is based on this phenomenon that guided waves can be used to monitor the damage in the structure[9].

Guided wave signals can be generated by placing an integrated piezoelectric sensor network on the surface of CFRP plate and utilizing its piezoelectric effect in the structure. Damage to the structure will affect the propagation and characteristics of guided wave, and monitoring the generation, expansion and degree of damage can be realized by analyzing the guided wave response signals with specific damage monitoring methods. The principle of SHM based on piezoelectric guided wave is shown in Fig.1.

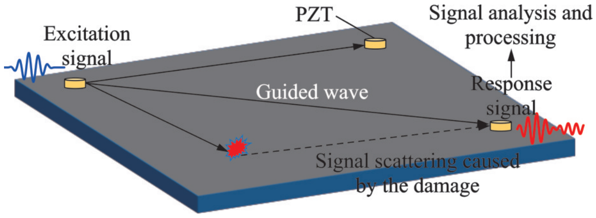


Fig.1 Principle schematic of guided wave structure health monitoring

2 Experiment and Method of High-Velocity Impact Guided Wave Monitoring for CFRP Plate

2.1 Overall framework of experiment

The overall structure of CFRP-T700 high-velocity impact monitoring test method is shown in Fig.2. It includes: (1) basic experiment design, including test material selection and material properties and characteristics; (2) high-velocity impact test and data recording in the process: test and adjust the launch speed to about 450 m/s, and record the speed accurately through the test device; (3) experiment guided wave signal acquisition, including guided wave data acquisition before and after specimen damage; (4) material characteristics after impact, including macroscopic damage conditions and non-destructive testing methods using ultrasonic C-scan; (5) test guided wave signal analysis: after the completion of the test, the guided wave signs before and after the damage are extracted for analysis.

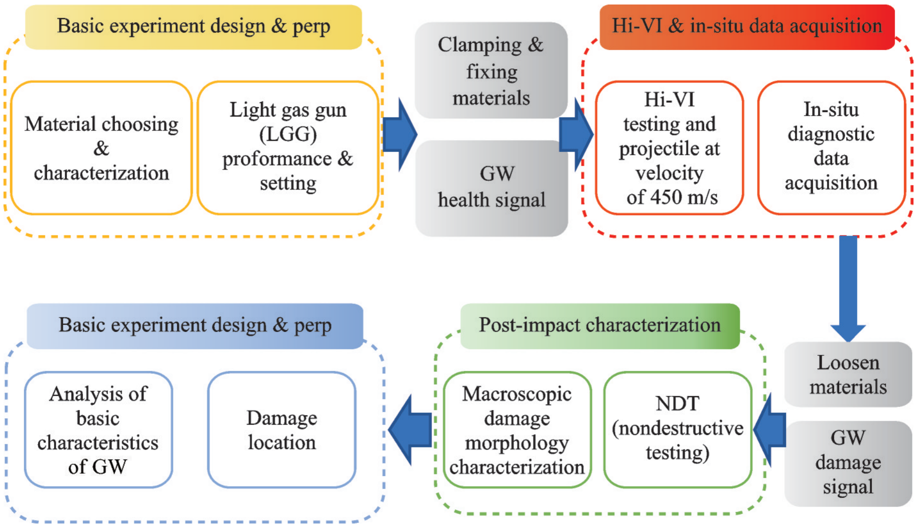


Fig.2 Overall architecture of CFRP-T700 high-velocity impact monitoring test method

2.2 Experiment object and performance

In this paper, a T700-grade epoxy resin-based carbon fiber laminate with a size of 300 mm×300 mm×2 mm and symmetrical layup of 0/90/45/—45 is selected by Jiangsu Bo-Shi Carbon Fiber Technology Co., Ltd. as the test object. Its schematic diagram and physical diagram are shown in Fig.3, and its basic structural performance parameters are shown in Table 1.

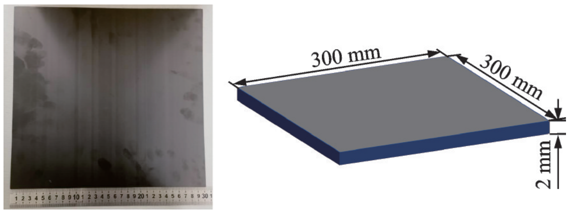


Fig.3 CFRP-T700 physical drawing and size drawing

Table 1 Basic material properties of T700

Mechanical property	Value
Density/(g•cm^{-3})	1.7—1.8
Poisson's ratio	0.37
Transverse tensile strength/MPa	42.0
Longitudinal tensile strength/MPa	2 197
Vertical and horizontal shear modulus/GPa	119
Bending strength/MPa	1 862
Bending modulus/GPa	129

2.3 Experimental platform and equipment

According to the classification of impact events by impact speed, generally low- and medium-speed impact occurs below 50 m/s, high-velocity impact speed ranges from 50 m/s to 1 000 m/s, and hyper-velocity impact speed is usually 1 km /s or above[8]. The essential thing to be solved in relevant tests is how to generate high-velocity impact on the ground.

Common methods include light gas gun technology, plasma driven acceleration technology, electromagnetic acceleration technology and laser driven flying vane technology[10]. Among them, the maximum of the one-stage light gas gun can theoretically reach below 1 km/s. According to the situation and needs of this paper, the selection of the one-stage light gas gun could fit the high-velocity speed requirements.

In this paper, a one-stage light gas gun using gas compression propulsion is selected for test. The device can launch projectiles below 12.7 mm and the maximum launching speed is 600 m/s. A ball-bearing steel with a diameter of 8 mm is selected as the launching projectile, whose projectile body and supporting projectile support are shown in Fig.4, with a mass of 2.01 g. The expected impact speed is 450 m/s and the expected impact angle is vertical plate surface, just meaning the normal of the plate surface is 0°. The launch impact is on the surface without an attached sensor, while the surface attached with PZT sensor is the impact back. The key design parameters of the test are shown in Table 2.

Fig.4 Projectile and its cartridge

Table 2 Experimental setup

Key parameter	Value(No.1/No.2)
Driving mode	Gas
Actual impact velocity/(m•s^{-1})	455/411
Firing projectile diameter/mm	8
Projectile material	Steel
Projectile mass/g	2.01
Impact kinetic energy/J	204.4/169.7

In addition, the ground experiment also needs to solve how to accurately measure the test impact velocity. Commonly used measurement methods include electric probe method, magnetic induction method, ultra-high speed photography method, laser beam occlusion method, X-ray shooting method, etc[11]. In this paper, the laser velocity measurement method is used to calculate the time difference of the laser beam being blocked. The final measured impact velocity is: Position No.1—451 m/s, position No.2—411 m/s.

To sum up, the overall test equipment and connection are shown in Fig.5.

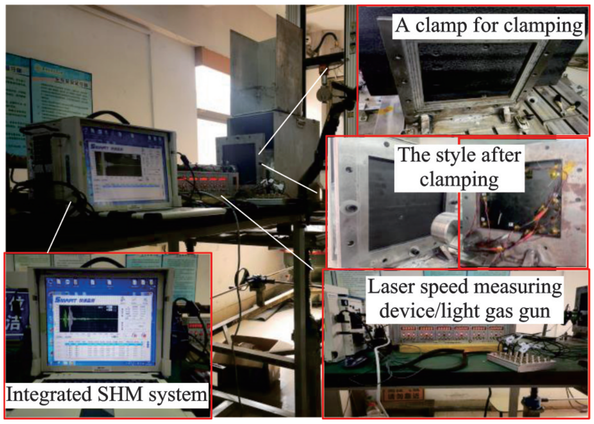


Fig.5 Experimental equipment

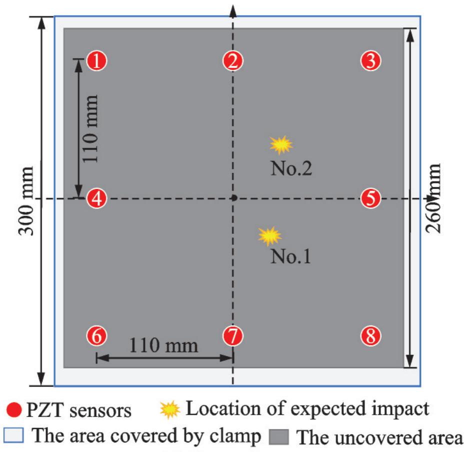
2.4 Guided wave signal acquisition

The application of guided wave SHM needs to be based on guided wave excitation-sensing systems. It should include the ability to excite PZT to generate guided wave signals, to sample and amplify weak response signals from other PZTs, and to filter them. Therefore, the SHM based on guided wave system (lower left of Fig.5) independently developed by the Structural Health Monitoring and Prediction Research Center of NUAA is selected as the main acquisition and processing system in this experiment.

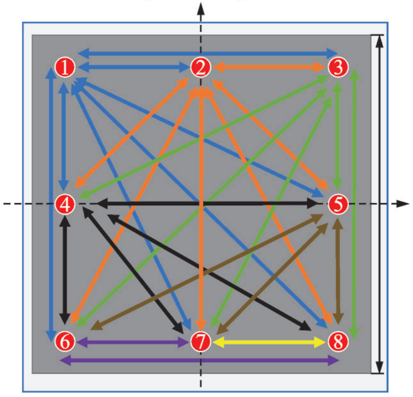
The 5-wave narrow-band sinusoidal modulation signal, which is more stable in frequency domain, is selected as the guided wave excitation signal in the system. In order to investigate the propagation of guided waves at different frequencies and select appropriate frequencies for subsequent signal analysis, the frequency sweep method with equal intervals is adopted. The sweep frequency range is 50—250 kHz, and the step is 10 kHz. According to Nyquist sampling theorem, in order to make the sampled digital signal as complete as possible to reflect the original signal waveform, the sampling frequency is set to 10 MHz.

The layout of piezoelectric PZT sensor will directly affect guided wave acquisition, damage monitoring performance and monitoring results. Considering that the fixture itself needs to squeeze and block part of the specimen, and PZT should not be too close to the fixture, this paper starts from the perspectives of sensor layout spacing, reduces boundary reflection, weakens mode aliasing, and more clearly understands the propagation characteristics of guided waves in T700 CFRP plates. The layout of PZT points and the guided wave sensor network is shown in Fig.6. The sensors are all pre-integrate on the back of the impact surface of structural parts. The number of each sensor is PZT1-8, the size of the theoretical monitoring area is 220 mm×220 mm, and the number of sensor network paths reaches 56.

After the layout of the sensor and the sensor network are designed, the epoxy resin AB adhesive is used to bond the sensor and the structural part. Meanwhile, in order to reduce the difficulty of signal analysis caused by the boundary reflection of the guided wave, this paper applies wave-absorbing gum around the test part to effectively reduce the boundary reflection of the guided wave. The actual picture of the test piece after finishing integrating the sensor and absorbing gum is shown in Fig.7.



(a) Sensor layout



(b) PZT sensor network

Fig.6 Sensor layout and PZT sensor network

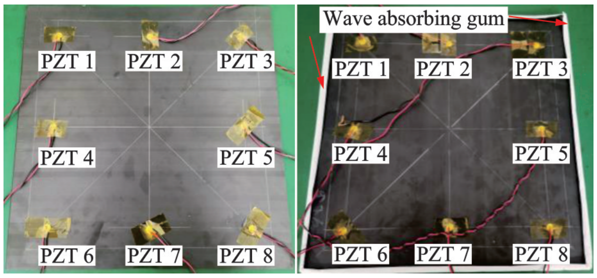


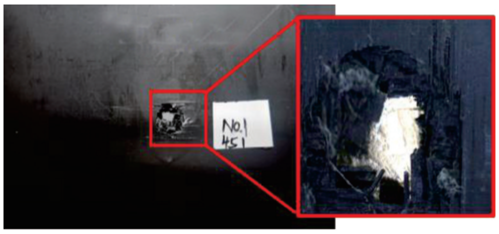
Fig.7 Actual picture of sensor paste and its absorbing gum

2.5 Results of high-velocity impact damage of CFRP

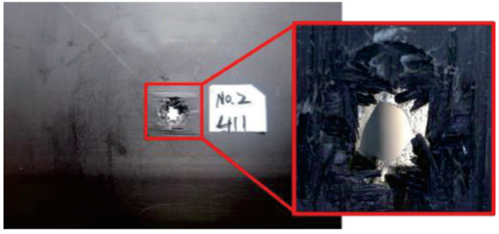
After the impact of two high-velocity projectiles, it can be seen from the impact results that a complete perforation has been formed, the fiber is pulled out at the perforation, and a certain damage area is still formed near the direct perforation on the front of the impact. In this area, the surface resin matrix is damaged and the broken fiber is exposed to the outer surface. The longest matrix cracking length is greater than 13 mm. At the same time, it can be seen that the area around the perforation is nearly circular, and the center full penetration aperture measured by vernier caliper is about 8.27 mm, which is slightly larger than the projectile aperture.

In the process of penetration of projectile into the composite laminates at high velocity, the transverse shear stress is usually generated due to the discontinuity of in-plane stiffness. Due to the low strength of the composite matrix, the transverse shear stress perpendicular to the direction of the fiber will cause the fracture of the interfiber matrix. During the impact, the matrix of the back is damaged by the strong bending action to the critical value, resulting in the matrix fracture along the direction of the fiber. Therefore, the matrix cracking and material spalling on the back of composite laminates are more serious than those on the front. After the measurement, the longest fracture of the fiber is more than 110 mm, and the back damaged area is much larger than that of the front.

Optical images of two damages are taken, as shown in Figs.8 and 9, and non-destructive testing images are obtained by portable ultrasonic C-scan, as shown in Fig.10.

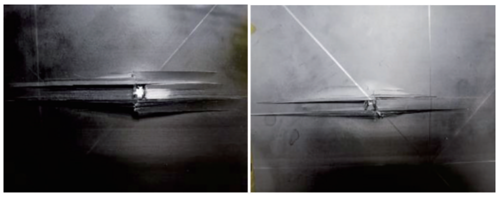


(a) No.1



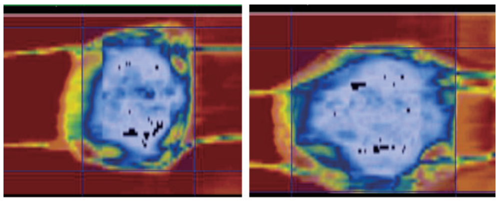
(b) No.2

Fig.8 Frontal damage optical image recording



(a) No.1 (b) No.2

Fig.9 Back damage optical image recording



(a) No.1 (b) No.2

Fig.10 Ultrasonic C-scan image of damage

The high-velocity impact projectile may impact on PZTs, and then affect the guided wave signal. Taking the excitation guided wave generation as an example, the possible problems are as follows: (1) PZT cannot excite the guided wave signal; (2) the waveform distortion of PZT excited guided wave signal does not accord with the pre-setup.

It can be seen from the guided wave data before and after the experiment, the high-velocity projectile does not damage PZTs and the transmission circuit. PZTs can excite the guided wave, and the guided wave signal waveform is in line with the per-setup, and then the guided wave signal does not have macroscopic changes in waveform before and after the damage. For example, it can be seen from Fig.11 that there are PZT1-3 guided wave signals before and after the damage of No.1, and the signal waveform is not distorted.

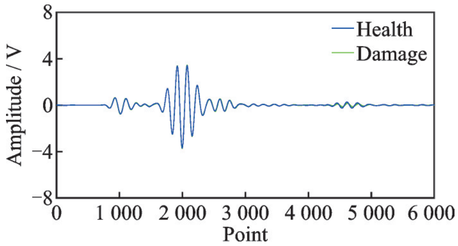


Fig.11 No.1 typical health/damage signal of PZT1-3

3 Analysis and Processing of Guided Wave Signal

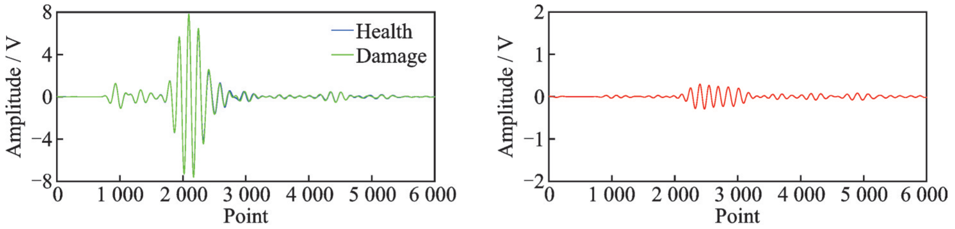
3.1 Guided wave signal before and after damage

The following is a simple analysis of the guided wave propagation of the 2 mm-thick T700 CFRP plate in this paper, and the signal under the excitation frequency of 70 kHz is selected as the analysis object. It can be seen from the signal diagram that the guided wave can be stimulated and responded normally, and the boundary reflection of the guided wave can be effectively suppressed after the absorbing glue is used.

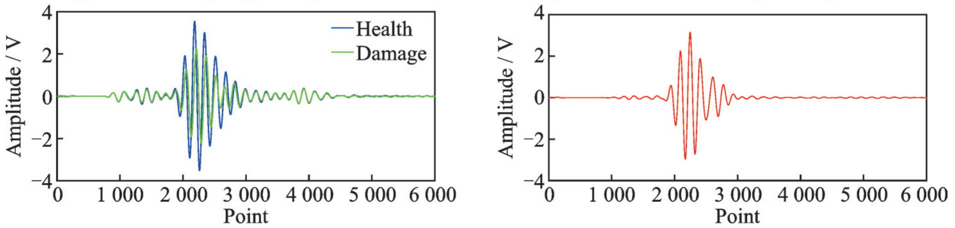
It can be seen from Fig.12 that the sensor can well form the expected guided wave signal, the guided wave signal waveform is good, and the signal propagation is normal. By observing the characteristics before and after the signal, it can be seen that the impact damage will cause the amplitude, phase and waveform of the signal to change in different degrees.

The amplitude and phase of the guided wave signal of the over-damaged channel are more significantly affected, and the damaged scattering signal of the over-damaged channel is obviously greater than that of the non-damaged channel, indicating the effectiveness of the guided wave structure monitoring method in such damage monitoring.

It can be seen from Fig.13 that No.2 damage also presents the same pattern. It is shown that the guided wave structure health monitoring method is universal in the structure and damage.

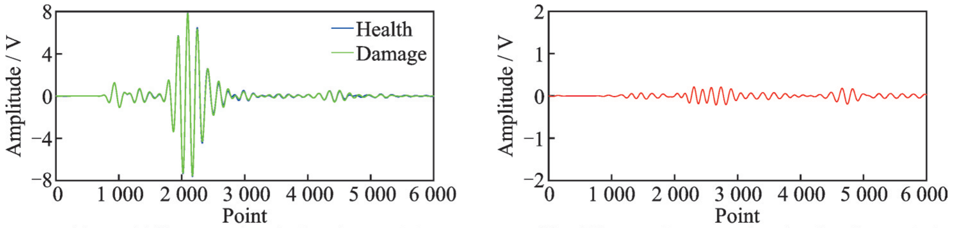


(a) Health/damage signal of path PZT 3-8 (b) Difference between signals of path PZT 3-8

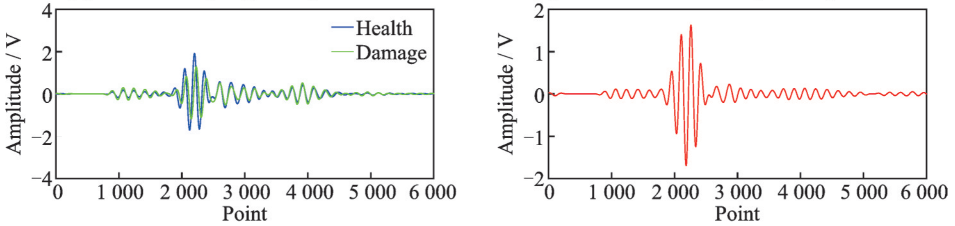


(c) Health/damage signal of path PZT 5-6 (d) Difference between signals of path PZT 5-6

Fig.12 No.1 typical health/damage signals and their difference



(a) Health/damage signal of path PZT 3-8 (b) Difference between signals of path PZT 3-8



(c) Health/damage signal of path PZT 1-5 (d) Difference between signals of path PZT 1-5

Fig.13 No.2 typical health/damage signals and their difference

3.2 Characterization of guided wave damage based on damage index

DI is a data processing method that correlates the damage degree with certain signal characteristics of guided wave monitoring signals. It can effectively quantify the response of guided wave to damage and the monitoring rule, so as to better abstract the relationship between damage characteristics and guided wave. Since the DI is a clear expression, it can make a relatively quick judgment without a lot of prior knowledge and complex signal processing. The essence of DI is to compare the characteristic difference between the two signals for calculation. So it is more stable than just only using the characteristic of guided wave signal itself[12-13].

There are three kinds of DI used in this paper, including the spectrum amplitude difference of the signal, the spectrum difference of the signal, and the amplitude damage factor of the difference signal, which correspond to DI-1, DI-2, and DI-3, respectively.

The DI-1 about spectrum amplitude difference mainly measures the difference in signal frequency response amplitude based on the amplitude of signal, which can be calculated by

$$\mathrm{DI\text{-}1}=\sqrt{\frac{\int_{\omega_1}^{\omega_N}(|H(\omega)-D(\omega)|)^2\mathrm{d}\omega}{\int_{\omega_1}^{\omega_N}|H(\omega)|^2\mathrm{d}\omega}} \tag{1}$$

where $H(\omega)$ and $D(\omega)$ are the signal spectrum after Fourier transform of reference signal and damage signal, respectively.

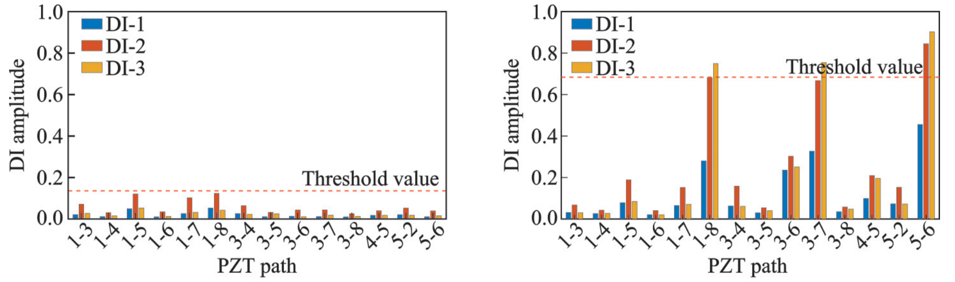
The DI-2 about the spectrum difference of the signal just cares about difference of spectrum, which can be calculated by

$$\mathrm{DI\text{-}2}=\frac{\int_{\omega_1}^{\omega_N}|H(\omega)-D(\omega)|\mathrm{d}\omega}{\int_{\omega_1}^{\omega_N}|H(\omega)|\mathrm{d}\omega} \tag{2}$$

The DI-3 pays attention to the transformation of the difference before and after damage the signal, which can be calculated by

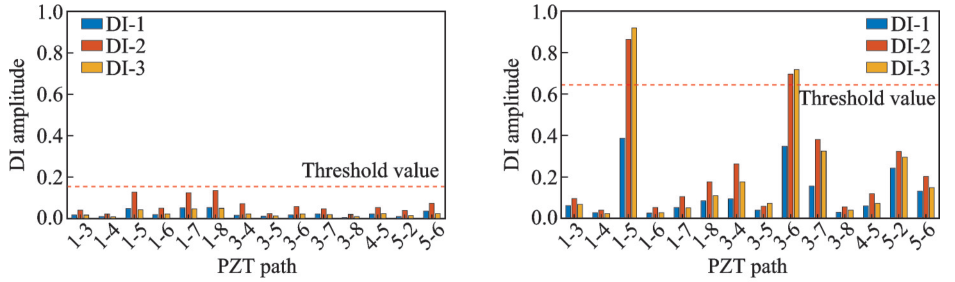
$$\mathrm{DI\text{-}3}=\frac{\max(\mathrm{d}f(t))}{\max(H(t))} \tag{3}$$

Taking No.1 damage as an example, the DI of healthy state is calculated by health signal collected at different time under the healthy state respectively. The DI of damaged state is calculated by health and damage signals. The graph drawn is shown in Fig.14, which indicates the applicability of the damage index method in the diagnosis of high-velocity impact damage of CFRP. In addition, it can be seen from the corresponding channels of DI that the closer the excitation-sensing channel is to the damage, the greater the impact of damage and the greater the amplitude of DI is. As shown in Fig.15, No.2 damage also shows the same pattern.



(a) Healthy state (b) Damaged state

Fig.14 No.1-DI in healthy state and damaged state



(a) Healthy state (b) Damaged state

Fig.15 No.2-DI in healthy state and damaged state

A threshold is designed as the alarm limit of damage, and the threshold is defined as the sum of the mean, standard deviation and median of each DI.

Using this threshold to calculate DI-2 of each damage, it can be found that when the structure is damaged, it can accurately alarm and explain the damage of the structure through a certain DI and the threshold, and will not exceed the threshold and false alarm when there is no damage. Due to the more obvious damage caused by high-velocity impact, so more propagation path needs to go directly through the fiber fracture. It can also be seen that the DI value through the fiber fracture channel is significantly higher than that of through other channels, and more channels are affected. Therefore, this is one of the DI's difference between the high-velocity impact and routine velocity impact on CFRP.

4 Conclusions

Aiming at T700 CFRP, this paper uses a one-stage light gas gun to carry out high-velocity impact damage inflicting tests above 450 m/s, and initially proposes and verifies solutions for high-velocity impact real damage inflicting, excitation and response of guided wave, damage measurement, guided wave signal characteristic expression and other problems. The following conclusions can be drawn from the analysis:

(1) High-velocity (450 m/s) impact will cause obvious perforation damage to CFRP plates, accompanied by fiber breakage, pulling out, material spalling and other damages. At the same time, the damage shape of the front side of the impact surface is approximately circular, and the damage size is slightly larger than the diameter of the projectile, while the damage and destruction of the back side are obviously greater.

(2) The SHM based on piezoelectric guided wave can be used in this type of structure, and the guided wave signal propagates well. After the high-velocity impact damage occurs, the amplitude and phase of the guided wave signal of the cross-damaged paths are more significantly affected, which indicates the effectiveness of the guided wave structure monitoring method in such damage monitoring.

(3) It indicates that DI can be explained, and a threshold value composed of mean value, standard deviation and median is proposed to be used as the alarm description of DI. When the structure is damaged, the threshold value can be used to accurately explain the damage of the structure, and the health state will not give false alarm.

This provides support for further research on high-velocity/hyper-velocity impact damage SHM methods of advanced composite materials such as CFRP, C/C in the future.

References

[1] STASZEWSKI W J, TOMLINSON G, BOLLER C, et al. Health monitoring of aerospace structures[M]. Chichester: Wiley, 2004.

[2] RAMLY R, KUNTJORO W, RAHMAN M K, et al. Using embedded fiber Bragg grating sensors in smart aircraft structure materials[J]. Procedia Engineering, 2012, 41: 600-606.

[3] QIU L, LIU M, QING X, et al. A quantitative multi-damage monitoring method for large-scale complex composite[J]. Structural Health Monitoring, 2013, 12(3): 183-196.

[4] WANG Y, QIU L, LUO Y, et al. A stretchable and large-scale guided wave sensor network for aircraft smart skin of structural health monitoring[J]. Structural Health Monitoring, 2021, 20(3): 861-876.

[5] SOUTIS C, IRVING P. Polymer composites in the aerospace industry[M]. Amsterdam: Elsevier, 2014.

[6] QING Xinlin, WANG Yishou, ZHAO Lin. Structural health monitoring technology and its application in aeronautics and astronautics[J]. Journal of Experimental Mechanics,2012, 27(5): 517-526. (in Chinese)

[7] GU Shanqun, ZHANG Daijun, FU Shanlong, et al. Anti-high speed impact properties of carbon fiber/bismaleimide resin composites[J]. Journal of Materials Engineering, 2021,49(11): 73-82. (in Chinese)

[8] SAFRI S, SULTAN M, YIDRIS N, et al. Low velocity and high velocity impact test on composite materials—A review[J]. International Journal of Engineering and Sciecce, 2014, 3(9): 50-60.

[9] CHEN J, YUAN S F, JIN X. On-line prognosis of fatigue cracking via a regularized particle filter and guided wave monitoring[J]. Mechanical Systems and Signal Processing, 2019, 131: 1-17.

[10] ZHANG H, YIN C, HUANG X, et al. Design of hypervelocity-impact damage assessment technique based on variational Bayesian[J]. IFAC—Papers OnLine, 2020, 53(2): 814-819.

[11] ZHANG Tingting. Impact effects of stratified structures in space debris environment[D]. Tianjin: Tianjin University, 2018. (in Chinese)

[12] QIU L, YUAN S F, CHANG F K, et al. On-line updating Gaussian mixture model for aircraft wing spar damage evaluation under time-varying boundary condition[J]. Smart Materials and Structures, 2014, 23(12): 125001.

[13] LIAO Y, QING X, WANG Y, et al. Damage localization for composite structure using guided wave signals with Gramian angular field image coding and convolutional neural networks[J]. Composite Structures, 2023, 312: 116871.

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基于导波的CFRP板高速冲击损伤监测方法研究

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摘要：碳纤维增强环氧树脂复合材料(Carbon fiber reinforced polymer, CFRP)广泛应用于航空航天领域。该类材料结构在服役过程中可能面临高速冲击的威胁，相关研究主要考虑材料的抗冲击性能，较少进行CFRP高速冲击损伤的监测研究。因此，本文进行了一种基于压电导波结构健康方法的CFRP板高速冲击损伤监测实验。结果表明，CFRP在高速冲击下具有明显的穿孔损伤和纤维断裂现象。同时也表明了导波结构健康监测方法可以有效地应用于此类结构损伤的监测，并且可以通过量化导波信号变化和损伤因子来反映损伤。该研究为CFRP的高/超高速冲击损伤导波结构健康监测的进一步研究提供了参考。

关键词：导波；结构健康监测；碳纤维增强环氧树脂复合材料；高速冲击