Linear and Nonlinear Ultrasonic Detections of Impact Damage in Composite Laminate

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Abstract: The appearance and accumulation of internal impact damage seriously influence overall performance of carbon fiber reinforced plastic (CFRP). Thus, this study evaluates the change in impact damage number by using linear and nonlinear ultrasonic Lamb wave detection methods, and compares these two detection results. An ultrasonic wave simulation model for composite structure with impact damage is established using the finite element method, and the interaction between impact damage and the ultrasonic wave is simulated. Simulation results demonstrate that the ultrasonic amplitude linearly decreases, and the relative nonlinear parameter linearly increases in proportion to the impact number, respectively. The linear-fitting slope of nonlinear parameter is 0.38 per impact number at an input frequency of 1.0 MHz. It is far higher than that of the linear ultrasonic amplitude, which is only −0.12. However, with the increase of impact damage, the linear growth of nonlinear parameters mainly depends on the decrease in ultrasonic amplitude rather than the accumulation of second harmonic amplitude. In the linear ultrasonic amplitude detection, the linear fitting slope at 1.1 MHz is −0.14, which is lower than those at 0.9 MHz and 1.0 MHz. Meanwhile, in the nonlinear ultrasonic parameter detection, the linear fitting slope at 1.1 MHz is 0.92, which is higher than those at 0.9 MHz and 1.0 MHz. The results show that higher frequencies lead to greater attenuation of ultrasonic amplitude and a larger increase in nonlinear parameters, which can enhance the sensitivity of both linear and nonlinear ultrasonic detections. The accuracy of simulation results is demonstrated through the low-velocity impact and ultrasonic experiments. The results show that compared with nonlinear ultrasonic technology, the linear ultrasonic technology is more suitable for impact damage assessment of carbon fiber reinforced plastic because of its simpler detection process and higher sensitivity.

Key words: carbon fiber reinforced plastic (CFRP); nonlinear ultrasonic; Lamb wave; impact damage; nondestructive testing

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0 Introduction

Composite material, especially carbon fiber reinforced plastic (CFRP), is widely used in aviation due to its advantage of high specific strength and light weight[1-2]. However, CFRP materials always suffer low-velocity impacts caused by bird strikes and foreign object debris, resulting in superimposed damage[3]. Due to the low shear strength, the CFRP material easily produces the micro crack and delamination, reducing its load-bearing and mechanical properties[4-5]. Therefore, it is necessary to detect impact damage of CFRP to ensure safe operation and improve the performance of aircraft.

In recent years, the ultrasonic detection has become the main effective nondestructive testing (NDT) of composite materials because of its flexibility, wide detection range, and high accuracy. Ac-

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cording to detection principles, it can be divided into linear and nonlinear ultrasonic detections. Both technologies have been studied to evaluate impact damage by analyzing the Lamb wave propagating in a composite laminate. In the case of linear detection, Burkov et al.[6] presented a Lamb wave based technique for impact damage detection via analyzing parameters of the amplitude, energy, and cross-correlation of signals in baseline and damaged states. Ochôa et al.[7] evaluated the applicability of two zero-order ultrasonic wave modes by detecting impact damage of composite materials, and analyzed the effects of different impact energies on linear parameters including ultrasonic amplitude, waveform, and frequency.

Nonlinear ultrasonic techniques consist of three major categories, including wave modulation, frequency shift, and higher harmonic generation[8]. Among all of the nonlinear ultrasonics, high harmonic generation has become one of the most common methods for micro damage detection owing to its simple setup and high sensitivity[9]. For example, Router et al.[10] demonstrated that the acoustic nonlinearity increased with the growth of impact density, and was more sensitive than that of group velocity. Tie et al.[11] detected the low-velocity impact damage of CFRP laminate by nonlinear ultrasonic simulation and experiment, and found that the harmonic wave and nonlinear parameter both increased with the growth of impact energy and delamination area. Although there has been considerable research on impact damage detection in composite materials, most studies primarily focus on changes in impact energy. In practical applications, these composite structures are often susceptible to multi-point impacts and varying impact energies. The paper primary investigates the effects of random impacts occurring at various locations. Regarding ultrasonic detection, the limitations of both linear and nonlinear methods are not well-defined, making it challenging to select an appropriate method for damage detection. Therefore, this paper comprehensively analyzes the characteristics of these two technologies, focusing on detection sensitivity, data processing methods, and equipment requirements to identify a more suitable method for impact damage detection of CFRP. In summary, this study evaluates changes in impact number using linear and nonlinear ultrasonic methods and provides a comprehensive comparison of both technologies, distinguishing it from the existing research.

The objective of this study is to evaluate the number of impact damage in CFRP by detecting Lamb wave signals via simulation and experiments, as well as to compare results of linear and nonlinear ultrasonic detections. After the Introduction, Section 1 explains the principles and parameters of linear and nonlinear ultrasonic detections. A finite element model of CFRP laminate is introduced in Section 2. Section 3 introduces linear and nonlinear ultrasonic experiments to validate simulation results. Finally, conclusions are delivered in Section 4.

1 Theory

1.1 Linear ultrasonic detection

The matrix crack and delamination damage caused by low-velocity impact in CFRP laminate leads to discontinuity and acoustic impedance inconsistency. Lamb waves will be reflected at the interface of damage, resulting in changes of amplitude[12]. Based on the classical linear elastodynamic theory[13], linear ultrasonic detection can assess impact damage by detecting the linear signal features of Lamb wave. Thus, in this research, the ultrasonic amplitude is selected as the damage index for linear ultrasonic detection.

1.2 Nonlinear ultrasonic detection

When the CFRP material is in an intact state, geometric nonlinearity β_G and material nonlinearity β_M exist. Geometrical nonlinearity is considerably less than the material nonlinearity. When the material is subject to low-velocity impact, contact acoustic nonlinearity (CAN) β_{CAN} is considered as the primary nonlinearity caused by the crack-wave interaction. Different layup and fiber orientations of composite materials primarily causes variations in the Young's modulus, which in turn alter the group velocity of ultrasonic guided waves. Changes in group velocity can affect the input frequency required to satisfy the material's nonlinear accumulation requirements. However, this change in group velocity does not impact the primary nonlinear effects generated by matrix crack and delamination. The total nonlinearity β in materials can be described as

$$\beta = \beta_{G} + \beta_{M} + \beta_{CAN} \tag{1}$$

To accumulate weak second harmonic wave induced by the material nonlinearity in a plate-like structure, two conditions of non-zero power flow and synchronism should be satisfied[14] in this study. The conditions indicate that the fundamental and second harmonic modes should be symmetric and have the same group velocity and phase velocity. According to the calculation of dispersion curves, the fundamental frequency of 1.0 MHz and harmonic frequency of 2.0 MHz meet the conditions when the CFRP laminate has a thickness of 1.6 mm. Therefore, Lamb wave with a central frequency of 1.0 MHz is selected to be the primary input signal. Moreover, the input frequencies of 0.9, 1.0 and 1.1 MHz are all simulated to analyze the influence on the sensitivity of linear and nonlinear ultrasonic detections.

When the ultrasonic wave propagates in the CFRP materials with impact damage, the one-dimensional longitudinal wave equation is expressed as[15]

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma}{\partial x} \tag{2}$$

where u is the particle displacement, ρ the density, σ stress tensor, t the propagation time, and x the propagation distance. Through theoretical theory[16], the expression of longitudinal wave can be obtained as

$$u(x,t) = A_1 \sin(kx - \omega t) - \frac{\beta}{8} A_1^2 k^2 x \cos[2(kx - \omega t)] \tag{3}$$

where ω is the radial frequency of the wave, A_1 and A_2 are the amplitudes of the fundamental wave and second-order harmonic wave, respectively. β denotes the nonlinear parameter[17]

$$\beta = \frac{8}{k^2 x} \frac{A_2}{A_1^2} \tag{4}$$

The nonlinear parameter is determined by measuring the amplitudes of the fundamental and second harmonic signals. However, Eq.(4) cannot be directly used to calculate the nonlinear parameter of the Lamb wave. It is influenced by a partial vector, angle, and high-order elastic constant[18]. Therefore, to facilitate the data analysis, the change in ultrasonic nonlinearity is characterized by introducing the relative nonlinear parameter β', which is shown as

$$\beta' = \frac{A_2}{A_1^2} \tag{5}$$

2 Finite Element Simulation

2.1 Establishment of model

The finite element model of CFRP laminate is used to simulate the interaction between impact damage and ultrasonic wave. The size of the model ($L \times W \times H = 220$ mm$\times 60$ mm$\times 1.6$ mm) could be different from the actual plate size, as long as the same effective area is consistent in the model and the following experimental specimen. The CFRP model exhibits a layup structure of $[0/90]_{2s}$. The material parameters for the unidirectional CFRP prepreg are presented in Table 1, defined under the keyword "orthotropic_elastic" in LS-DYNA software. The sampling frequency and the time step are set to 10 MHz and 1e−4 s, respectively. The in-plane and thickness direction elements are sized at 0.2 mm to ensure at least 10 elements per wavelength for the second harmonic wave. In the intact state, the total number of nodes is 1 220 227, and the element number is 1 075 200.

Table 1 Material parameters of CFRP

Elastic modulus/GPa			Shear modulus/GPa			Passion ratio		
E_{11}	E_{22}	E_{33}	G_{12}	G_{13}	G_{23}	ν_{12}	ν_{13}	ν_{23}
130	8	8	4.8	4.8	2.7	0.3	0.3	0.48

According to actual damage size of the impact experiment, the node separation method is carried out to simulate the matrix crack and delamination. Single surface contact with an initial value of 0 is set to make the crack and delamination work correctly.

The shape of impact damage in the model is shown in Fig.1. The matrix crack is generated around the impact area, and the delamination damage is at the bottom of the 90° layer. The simulation model with different numbers of impact damage is introduced in the research.

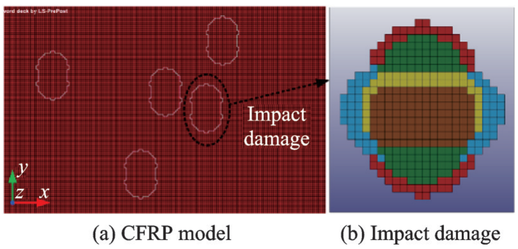


Fig.1 CFRP laminate model with impact damage in LS-DYNA software

A sinusoidal tone-burst force modulated by a 10-cycle hamming window is acted on surface nodes as an excitation source. The magnitude of the force is 10 N. The boundary of the model is set as a non-reflecting condition at the periphery of the plate; thus, no ultrasonic wave could reflect from the plate boundary.

2.2 Simulation results

Fig.2 illustrates the X-axis stress while the ultrasonic wave propagates through the impact damage. Fig.2(a) shows that the ultrasonic wave is approaching the matrix crack. The impact damage surfaces are opened and the ultrasonic wave is blocked as shown in Figs. 2(b) and 2(c). When the wave passes through the impact damage, the impact damage is closed again in Fig.2(d). The breathing-crack motion causes the distortion of the ultrasonic wave, generating higher harmonic wave. Moreover, the ultrasonic energy is obviously reduced when the ultrasonic wave propagates through the impact damage.

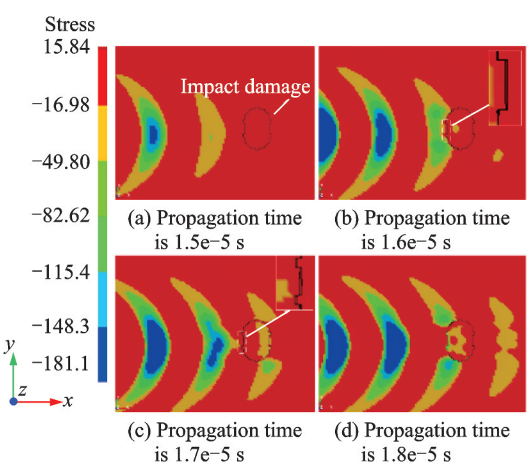


Fig.2 Process of ultrasonic wave traversing impact damage

A 10-cycle Hamming-windowed sinusoidal tone-burst signal with a central frequency of 1.0 MHz is used to generate an ultrasonic wave in the CFRP laminate. Fig.3(a) shows typical ultrasonic waveform in the time domain while the model has 1 impact. To extract the effective fundament and second harmonic amplitudes, wavelet transform with mother wavelet "cmor 2-2.5" is utilized[19], as shown in Fig.3(b). It has a bandwidth parameter of 2 and a central frequency parameter of 2.5. It has strong frequency characteristics and excellent capabilities in signal processing, making it especially suitable for frequency domain analysis and time-frequency analysis. The signal exhibits its energy concentrated at approximately 1.0 MHz, corresponding to the middle frequency of the input signal. The signal also shows a clear harmonic component at 2.0 MHz albeit with a low amplitude. The amplitude envelopes at both fundamental and second harmonics marked by the gray dashed line in Fig.3(b) are extracted and smoothed. Fig.3(c) shows envelopes of the harmonic wave (red line) and the fundamental wave (black line). The first peak values of envelopes are set as the fundamental and second harmonic amplitudes, noted as A_1 and A_2, respectively. Then, the relative nonlinear parameter β' can be calculated according

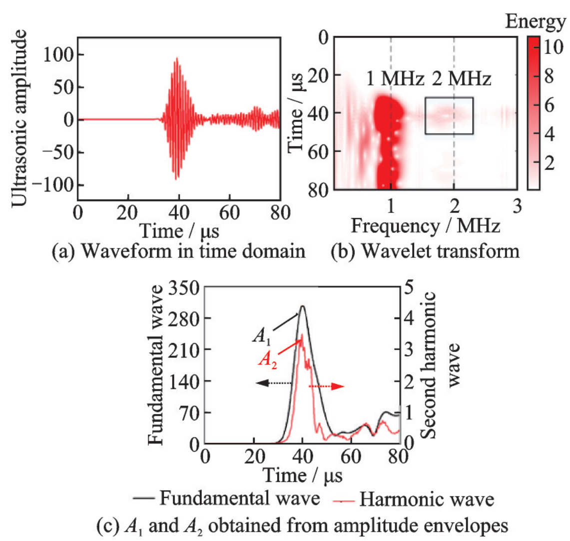


Fig.3 Typical simulated ultrasonic signal

to Eq.(5).

The amplitude A_1 extracted from the wavelet transform is set as the damage index for linear ultrasonic detection. Fig.4 displays the normalized amplitude of the fundamental wave at different numbers of impact damage in case of different frequencies. More part of the ultrasonic wave is reflected increasingly with an increase in the number of impact damage, resulting in the decrease in fundamental amplitude A_1. The linear slopes at input frequencies of 0.9, 1.0 and 1.1 MHz are −0.119, −0.126, and −0.141, respectively, indicating that the amplitude of higher-frequency waves has higher sensitivity. The reason may be that the higher frequency ultrasonic wave has a shorter wavelength and can be easily reflected at the impact damage interface.

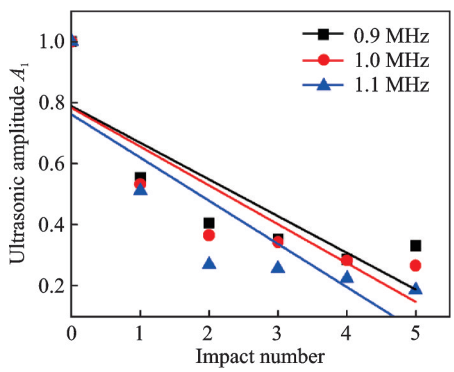


Fig.4 Ultrasonic amplitude versus impact number at different input frequencies in simulation

Fig.5 shows the normalized amplitude of β' at different numbers of impact damage. The linear slopes at different input frequencies are 0.255, 0.385, and 0.92, respectively. It can be seen that β' linearly increases with an increase in the number of impact damage. Although 1.0 MHz is selected as the input frequency for obtaining better accumulative material nonlinearity, the higher frequency of 1.1 MHz has a higher sensitivity in simulation. The reason may be that the nonlinearity of CAN is much larger than that of the material[20-21]. Therefore, the selection of input signal frequency does not need to meet conditions of non-zero power flow and synchronism.

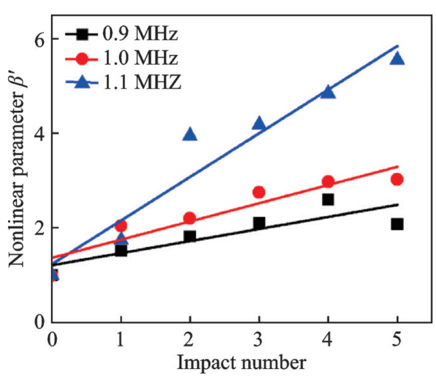


Fig.5 β' versus impact number at different input frequencies in simulation

3 Experiment

3.1 Acousto-ultrasonic detection

A cross-ply CFRP laminate with a dimension of 200 mm× 200 mm× 1.6 mm is used in the ultrasonic experiment. It is manufactured by unidirectional prepreg (Shanghai Guangwei, T700SC-12K-50C) with a resin volume fraction of 33%. A schematic of the ultrasonic experiment setup is presented in Fig.6. The effective simulation area is marked by a blue dash line, and the impact area is marked by a red line with a diameter of 40 mm. The CFRP laminate is in an intact state with no initial damage after manufacturing. For the experiments, two lead zirconate titanate (PZT) transducers (AE-900M, NF) with a diameter of 5 mm and a thickness of 2 mm are used as an exciter and a sensor, respectively. It is glued 200 mm apart on the CFRP laminate using a cyanoacrylate adhesive. To ensure proper bonding, the PZT sensors are pressed for at least 2 min until the cyanoacrylate adhesive fully cures. This process allows the adhesive to become thinner, ensuring a tight fit between the sensor and the

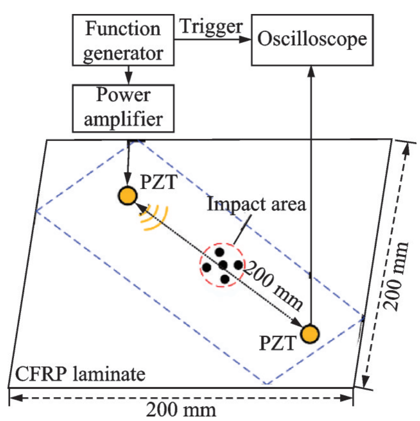


Fig.6 Schematic of the acousto-ultrasonic experiment setup

CFRP, which enhances the bonding strength. Moreover, the reduced thickness of the adhesive has minimal effect on ultrasonic wave propagation. The function generator (Aglient, 33521A) provides an excitation signal with a peak-to-peak amplitude of 20 V. Then, the signal is amplified to 80 V using a power amplifier (Aigtek, ATA-43151) and input into the PZT exciter. The oscilloscope (Keysight, DSOX2004A) converts the output voltage from the PZT sensor to a digital waveform with a sampling frequency of 10 MHz. The data is recorded after it averages 4 096 times for noise reduction.

3.2 Impact testing

An impact testing machine (INSTRON, CEAST9340) is used to generate the impact damage in the CFRP specimen, as shown in Fig.7. A hemispherical punch with a diameter of 12.7 mm is released at a designed height. The specimen is impacted at a low velocity with an energy of 3 J. Overall, the specimen is subject to five impacts, randomly distributed within a range of 40 mm.

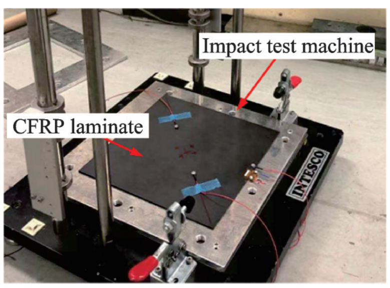
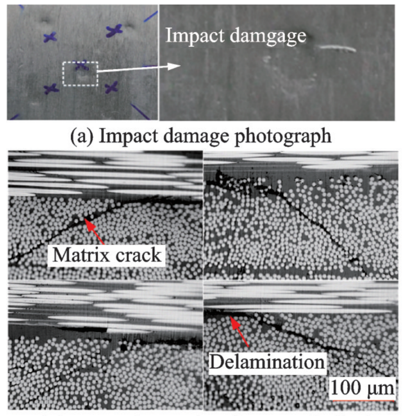


Fig.7 Impact test platform of CFRP specimen

The impact damage photograph of the specimen is shown in Fig.8(a). It can be found from Fig.8(a) that the damage is elliptical concave with a diameter of about 6 mm. The impact damage observed on the cross-section of the specimen via an optical microscope is displayed in Fig.8(b). The impact damage is composed of matrix cracks and delamination. The delamination is distributed beneath the impact location and extended into the deeper interfaces of the plies. The average width of delamination damage is approximately 5 μm at the 0°/90° interface. The matrix crack has an average width of 3 μm and is located near the delamination. The overall shape of impact damage is superimposed and has



(b) Impact damage observed under an optical microscope

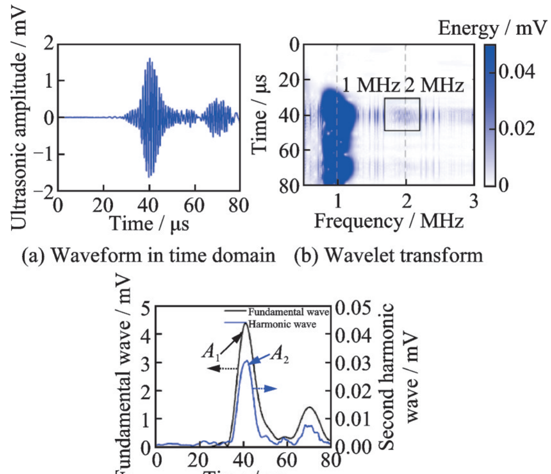
Fig.8 The impact damage in impact testing

the shape of a peanut[22].

3.3 Experiment results

Although actual CFRP laminate and the shape of impact damage are simplified, the minor electrical nonlinearity and noise induced by the ultrasonic experimental system are ignored in simulation. This study primarily focuses on detecting changes in ultrasonic amplitude and nonlinear parameters as the number of impacts increases. Therefore, these differences between the experimental and simulation setups will not affect the final analysis of detection results.

The detected ultrasonic waveform of experiments is shown in Fig.9(a), which is similar to simulation results. Fig.9(b) displays the wavelet transform results of the signal, existing second harmonic components at a high-order harmonic frequency of



(c) A_1 and A_2 obtained from the amplitude envelopes

Fig.9 Typical experimental ultrasonic signal

2.0 MHz. The fundamental and second harmonic amplitude envelopes are shown in Fig.9(c). The data process method used to obtain β' is the same as that used in the simulation in Section 2.2.

Fig.10 shows the linear fit of ultrasonic amplitude A_1 at different frequencies in the experiment. The linear slopes for center frequencies of 0.9, 1.0, and 1.1 MHz are −0.07, −0.19 and −0.2, respectively. The input frequency of 1.1 MHz seems to be the best choice for linear ultrasonic detection, which is also in agreement with simulation results.

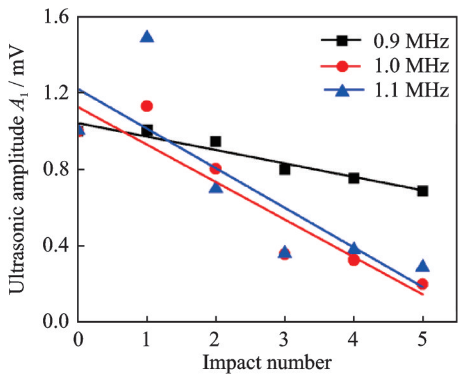


Fig.10 A_1 versus impact number at different input frequencies in experiment

This study involves conducting a single analysis and performing all ultrasonic experiments within a single day. The maximum temperature variation is approximately 3 ℃. The changes in ultrasonic amplitude are about 1.5%, which is significantly smaller than changes associated with impact damage. Furthermore, utilizing a sampling rate that complies with the Nyquist theorem and applying a Hamming window, aliasing and leakage phenomena can be effectively eliminated.

Fig.11 shows the increase of β' with an increase in the number of impact damage at different frequencies. The linear slopes at input frequencies of 0.9, 1.0, and 1.1 MHz are 0.299, 0.661 and 0.87, respectively. All experiment results are consistent with the ultrasonic theory and simulation results, concluding that the experiment data exhibit good coherence.

The experimental data presented in Figs.10 and 11 indicate that the ultrasonic amplitude decreases while the nonlinear parameter increases as the

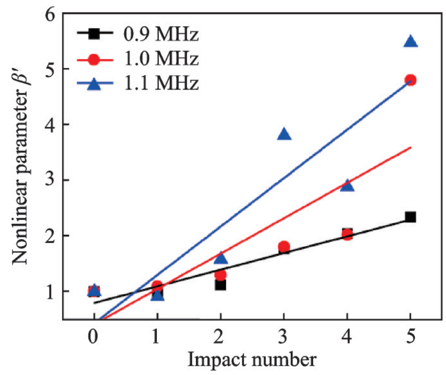


Fig.11 β' versus impact number at different input frequencies in experiment

number of impacts grows. Furthermore, compared with the linear fit slopes at input frequency of 0.9 and 1.0 MHz, that at 1.1 MHz exhibits the highest absolute slope value of −0.2 for linear ultrasonic amplitude and the highest slope value of 0.87 for the relative nonlinear parameter β' with respect to the number of impacts. This indicates that increasing the input frequency enhances the sensitivity of both ultrasonic detection techniques. The linear fit slopes for β' at frequencies of 0.9, 1.0 and 1.1 MHz are 0.29, 0.66, and 0.87, respectively. They are significantly higher than the corresponding slopes for ultrasonic amplitude, which are −0.07, −0.19, and −0.2, as shown in Fig.10.

Table 1 summarizes the linear fit slope and standard error σ of linear parameter A_1 and nonlinear parameter β' for the signal detected by the linear and nonlinear ultrasonic detection. In the simulation, the standard error σ of linear fit curve for A_1 is 0.16, 0.16, and 0.18 at input frequencies of 0.9, 1.0, and 1.1 MHz, which is smaller than corresponding σ values of 0.30, 0.29, and 0.52 for β'. This indicates that linear ultrasonic detection has a better degree of linear fitting due to the smaller value of σ. The linear fit slopes of β' are 0.25, 0.38, 0.92 for input frequencies of 0.9, 1.0 and 1.1 MHz, respectively, which are larger than the slopes of A_1. However, since β' is calculated by A_2/A_1^2, it was found that the increase rate of $1/A_1^2$ induced by the ultrasonic amplitude is greater than that of β'. Consequently, the increase in β' is primary attributed to the decrease in A_1, indicating that the linear ultrasonic sensitivity is higher than nonlinear ultrasonic sensitivity. Experimental results of CFRP laminate are consistent with simulation results presented in Table 2. The phenomenon differs from the published results[23]. The reason may be that the dimension of matrix crack and delamination exceeds the sensitive range of nonlinear ultrasonic detection. The larger size of impact damage makes the ultrasonic wave mainly reflect rather than distort when it propagates through the damaged surface. Furthermore, CFRP laminate has a large number of interfaces and intensifiers, and second harmonic wave with longer short wavelength is more susceptible to be reflected by the interface and intensifiers, making it difficult to accumulate.

Table 2 Linear-fit slope and standard error of ultrasonic detection at different input frequencies

Input frequency/MHz		Simulation		Experiment	
		A_1	β'	A_1	β'
0.9	Slope	−0.11	0.25	−0.07	0.29
	σ	0.16	0.30	0.03	0.18
1.0	Slope	−0.12	0.38	−0.19	0.66
	σ	0.16	0.29	0.15	0.88
1.1	Slope	−0.14	0.92	−0.20	0.87
	σ	0.18	0.52	0.29	1.00

Compared with linear ultrasonic, nonlinear ultrasonic needs more complex data processing. In terms of bandwidth, nonlinear ultrasonic needs to detect higher harmonics, indicating that a higher bandwidth is required for ultrasonic sensors and instruments. Furthermore, the fundamental wave is over 100 times greater than the second harmonic wave in terms of amplitude, as shown in Figs.3(c) and 9(c). Thus in this research, the linear ultrasonic detection is generally superior to the nonlinear alternative for the detection of impact damage in a cross-ply CFRP.

4 Conclusions

A finite element model of CFRP laminate is constructed to assess the impact damage by analyzing linear and nonlinear ultrasonic parameters. All the simulation results are solidly validated via experiments. The main finding of this research can be summarized as follows:

(1) The number of impact damage can be effectively evaluated using linear and nonlinear ultrasonic detections.

(2) The fundamental amplitude of ultrasonic wave decreases linearly, whereas the nonlinear parameter increases with the growth number of impact damage.

(3) The increase in input frequency of ultrasonic waves can improve both the linear and nonlinear ultrasonic sensitivities.

(4) Compared with the nonlinear ultrasonic, the linear ultrasonic technique is more suitable to assess the number of impact damage in a CFRP laminate because of its advantages with respect to the linear-fit slope, complexity of data processing, and requirement of the instrument.

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复合材料板冲击损伤的线性与非线性超声检测

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摘要:碳纤维增强复合材料(Carbon fiber reinforced plastic, CFRP)内部冲击损伤的出现和扩展严重影响结构的整体性能。因此,提出采用线性与非线性超声Lamb波检测方法,评估复合材料的冲击损伤次数变化,并对两种检测结果进行比较。通过有限元法建立了复合材料平板结构在产生冲击损伤后的超声波仿真模型,并模拟了冲击损伤与超声波之间的相互作用过程。仿真结果表明,复合材料结构中冲击损伤次数与超声幅值呈线性递减关系,而与非线性参数呈线性增长关系。当超声信号的输入频率为1.0 MHz时,非线性参数的线性拟合斜率为0.38,远高于线性超声幅值的拟合斜率,仅为−0.12。然而,随着冲击损伤的增加,非线性参数的线性增长主要依赖于超声基波幅值的减少,而不是二次谐波的累积。在线性超声幅值检测中,输入信号频率为1.1 MHz时线性拟合斜率为−0.14,低于0.9 MHz和1.0 MHz对应的线性拟合斜率。而在非线性超声参数检测中,1.1 MHz的线性拟合斜率为0.92,高于0.9 MHz和1.0 MHz对应的斜率。结果表明,随着冲击损伤次数的增加,采用更高输入信号频率会导致超声幅值减小幅度增大,非线性参数增长幅度也增大。这表明增加输入信号频率可以提高线性和非线性超声检测的灵敏度。本研究还通过低速冲击和超声实验验证了仿真结果的准确性。研究表明,与非线性超声技术相比,线性超声技术因其检测过程更简单且灵敏度更高,更适用于碳纤维增强复合材料的冲击损伤评估。

关键词:碳纤维增强复合材料;非线性超声;Lamb波;冲击损伤;无损检测