Detection of Acoustic Emission Signal Due to Impact Damage of Composite Materials Based EMD

Qingwen You, Zhefeng Yu and Jicheng Fang

Abstract Drop-weight impact test and small-mass impact test were carried out on composite laminates. The contact force and AE signal were measured during the tests, and the correspondence between AE signals and damage were analyzed respectively. For the drop-weight impact test, the contact force dropped and the frequency of the AE signal increased suddenly when the delamination appeared. Then the AE signal was decomposed using empirical mode decomposition (EMD). The amplitude anomaly were found in the first several intrinsic mode functions (IMFs), which could be used as a signal to characterize damage.; In the small-mass impact test, the contact force and AE signal were investigated in the same way. Additionally, Fourier transform (FFT) was used to find whether there is delamination. Results reveal that when laminates suffers the drop-weight impact, AE signals, combined with EMD, can be used for real-time health monitoring, For the plates impacted by small-mass objects, AE signal, EMD and Fourier transform can be used to determine whether there is delamination in the laminate.

Keywords Acoustic emission · Composite laminates · Drop-weight test · Small-mass impact test · Health monitor

1 Introduction

1.1 Background

Due to high strength ratio and high stiffness ratio, composite materials are widely used in many fields such as aircraft and ships. On the other hand, composite materials, such

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as Carbon Fiber Reinforced Plastic (CFRP), are prone to delaminate after impact, and the compressive strength can be significantly reduced. And the delamination is hardly observed by naked eyes. Therefore, it is important to find a method which can detect the signal of damage. Acoustic emission (AE) is a technique for detecting and analyzing damage by detecting AE signals. Since the composite material generates elastic waves when damage appears, the abnormal signal can be detected non-destructively. Then we can find whether there is delamination or not.

When the composite material is impacted by foreign objects, the response mode of the plate is divided into two types: large mass impact and small-mass impact according to the mass ratio of the foreign object and the composite material. When the mass ratio is greater than 2, the plate is dominated by a quasi-static response. In this case, the impact history is long and the propagation of the bending wave is affected by the boundary. The contact force and displacement change synchronously [1, 2]. While if the mass ratio is less than 0.23, a small-mass impact yields. In this situation, the plate has a wave control response, and the bending wave propagation is not affected by the boundary. The contact force and the displacement of the plate are not synchronized. When the airplane takes off and lands, the skin of its structure is extremely vulnerable to impact by stones, other debris and so on. These are small-mass impact problem. Therefore, it is of great practical significance to study the small-mass impact of composite laminates. Ye Wenxun [3] measured the contact force of small-mass impact by a "mouse-trap" hammer machine. It was also found that when the force gradually rises to a certain value, the laminate would delaminate and then the delamination expands rapidly. The force at this time is called the delamination threshold load (DTL). Therefore, the sudden drop of contact force can be a characteristic of the delamination.

When the laminate is impacted by a foreign object, it may undergo various damages such as matrix cracking, delamination, fiber breakage, etc. And the AE signals corresponding to these failure modes have different frequencies [4]. The methods used for detecting these damage include C-scan, X-ray, acoustic-ultrasonic detection, and AE detection. AE detection is an effective dynamic health monitoring technology. Analysis of AE signals can be used to distinguish matrix cracking, delamination, and fiber breakage. The whole process of the damage evolution can be characterized through the parameters of the AE signal. Chen Hao [5] studied AE signal due to an impact on resin-based laminates with a low speed, and summarized the parameters of different damage models by studying the distribution rules of high-energy damage points. Ajit Mal [6] studied the influence of the position of the AE sensor when composite materials is impacted with a low speed. Mikael Johnson [7] compared the experimental results and numerical simulation results of the matrix damage evolution of composite materials, and found that the simulation results are quite different due to the complex damage. Tao Fu [8] and José Martínez-Jequier [9] conducted a three-point bending experiment on the composite material and analyzed the AE signal. They believed that the AE signal can be used for real-time health monitoring of delamination. Efe Selman [10] conducted fatigue tests on composite cement beams and found that the AE signal is in good agreement with the Sentry Function. Through the buckling experiment, John P. McCrory [11] classify the types of damage in the composite according to the AE signal. YANG Yu [12] made a compression test on the damaged composite panel after impact and analyzed the AE signal. It is believed that the main form of damage is fiber fracture rather than delamination.

The abnormal signals can be identified by wavelet decomposition [13] and empirical mode decomposition(EMD). Sun Liying found that the intrinsic mode function (IMF) decomposed by EMD technology can be used to find the position of leaked on the pipeline precisely according to the occurrence time of the abnormal signal [14]. By combining EMD technology and wavelet decomposition technology, Zhao Lifeng [15] determined the local damage on the bearing effectively.

From the above research, it can be found that current researches on AE signal of composite materials mainly focus on the static experiments of composite materials, while the impact experiments are relatively less. The AE studies of small-mass high-speed impact are even few. In this paper, composite plates were undergone drop-weight impacts and the small-mass impacts. The EMD technique was used to analyze the AE signal to find the time when composite damage occurs. Finally, the AE signal was compared with the contact force under different impact energies to achieve real-time monitoring of composite damage.

1.2 EMD Technology

EMD is proposed by Huang, N.E [16], in which it is believed that signals can be decomposed into several IMFs and a residual. Different orders of IMF represent the dynamic characteristics of the signal, while the residual reflects the offset of the signal. EMD technology is adaptive, and IMF can be automatically selected by analyzing the signal itself. Therefore, EMD technology is widely used.

The specific steps of EMD technology are as follows:

(1) Assuming that the original signal is $x(t)$, connect all the maxima and minimum points of $x(t)$ by cubic spline to form the upper and lower envelop. The mean of the upper and lower envelopes is defined as $m_1(t)$, and $h_1^1(t)$ is defined as:

$$h_l^1(t) = x(t) - m_1(t) \tag{1}$$

$h_1^1(t)$ is an IMF if it satisfies the following two conditions:

(1) The number of extreme points is equal to the times that the $h_1^1(t)$ across zero axis or the difference of them is equal to 1.
(2) The upper and lower envelopes at any point equal 0.

If $h_1^1(t)$ is the first order IMF $\mathrm{imf}_1(t)$, the calculation goes to step (2). Otherwise $h_1^1(t)$ is treated as $x(t)$, then the above process will be repeated.

(3) Repeat the above steps using the difference between $h_1^1(t)$ and $\mathrm{imf}_1(t)$ as the new signal until the Nth order IMF or the residual is less than pre-set value, or is monotonic. Then can be represented as follows:

$$x(t) = \sum_{i=1}^{n} \mathrm{imf}_i(t) + r_n(t) \tag{2}$$

where $\mathrm{imf}_n(t)$ is the Nth order IMF, $r_n(t)$ is the residual.

2 Impact Experiment

2.1 Drop-Weight Impact Test

The CFRP specimen for drop-weight impact test has a size of 150 × 100 × 3 mm. The impact device is the INATRON CEAST-9350 drop hammer impact tester. The diameter of the hammer is equal to 16 mm, and the weight is 5.3 kg. The impact energy can be changed by adjusting the dropping height of hammer.

The specimen is installed on the support bracket and fixed with clamps. The AE sensor is mounted 5 mm from the impact point, as shown in Fig. 1. Special coupling agent is scribbled between the sensor and plate, and the sensor is fixed by tape to make them contacted tightly. The signal collected by the AE sensor is amplified and recorded at the frequency of 1 MHz. The contact force and AE signals were collected when the impact energy equals 1.1, 1.6, 4, 6, 8, 12, and 15 J respectively.

2.2 Small-Mass Impact Test

The specimen for small-mass impact has a dimension of 240 × 240 × 1.5 mm, and the impact point is located at the center of the plate. The impact equipment is

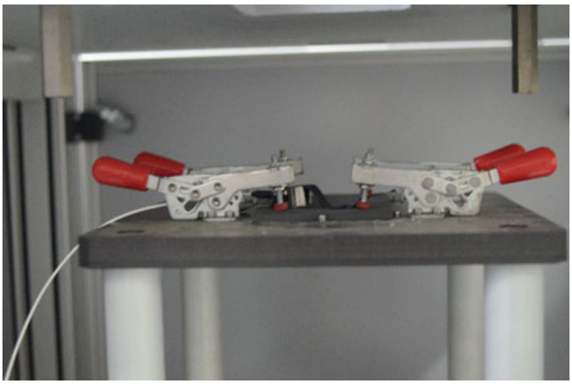


Fig. 1 The composite plate and AE sensor

a multi-angle "mouse-clip" hammer machine and the hammer weights 20 g. It can simulate the case when a small-mass hammer impact a plate freely in a high speed. During the experiment, the rocker arm is wrenched to drive the spring to twist. When the rocker arm is released, the rocker arm accelerates under the driving of the spring. When the rocker arm swings to the horizontal position, it is blocked by the bump, and the rocker arm stops moving. The hammer and the rocker arm are connected by a thin steel wire. The hammer continues to move downward due to inertia, and then impacts the laminate. Different energy can be stored in the spring when the angles of spring change. When the hammer is released, different impact speeds can be achieved, and then the corresponding impact energy can be calculated (Fig. 2).

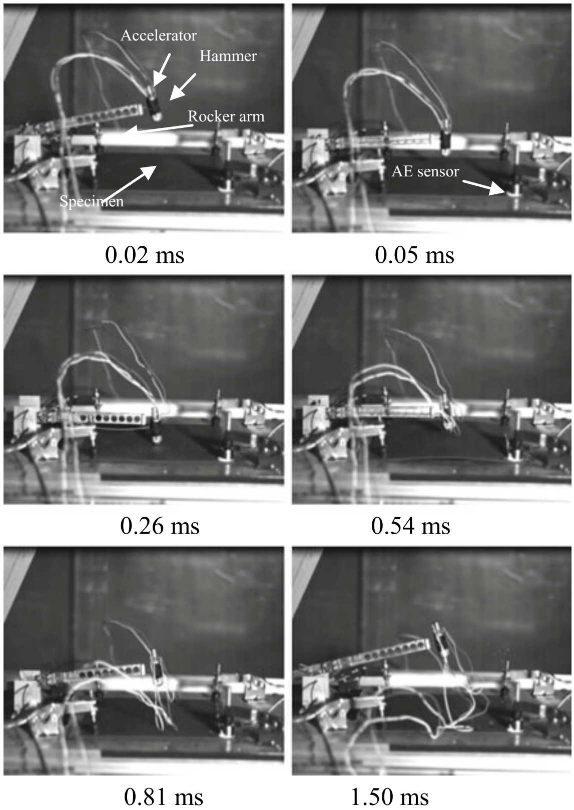


Fig. 2 Small-mass impact at various stages

3 Results

3.1 Drop-Weight Impact Test

The contact force and the AE signal obtained by the drop-weight impact test are shown in Figs. 3, 4, 5, 6, 7, 8 and 9.

After the impact, the specimen was non-destructive inspected with ultrasonic scanning. It was found that when the impact energy equals 1.1 J, the specimen didn't delaminate. When the impact energy equals 1.6 J, the delamination occurred, but the damage area was small, while other specimens delaminates obviously. It can be seen from Fig. 3 that when the impact energy equals 1.1 J, the contact force is smoother except for slight fluctuations at the beginning. However, we can find that, in Fig. 4, when the impact energy equals 1.6 J, a sudden drop occurs when the contact force reaches the maximum at 3 ms. The corresponding force is about 2600 N, which is the delamination threshold load. The sudden drop in contact force is caused by rapid decrease of the stiffness of the laminate after delamination.

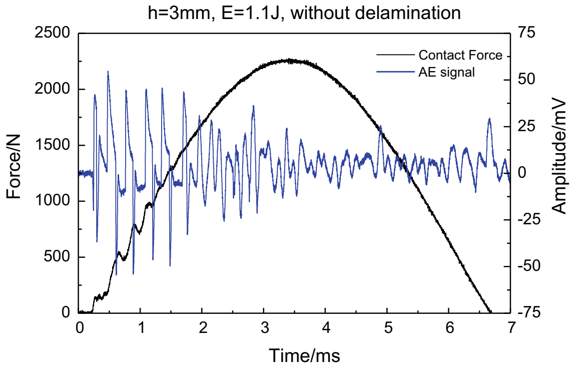


Fig. 3 Force and AE signal (E = 1.1 J)

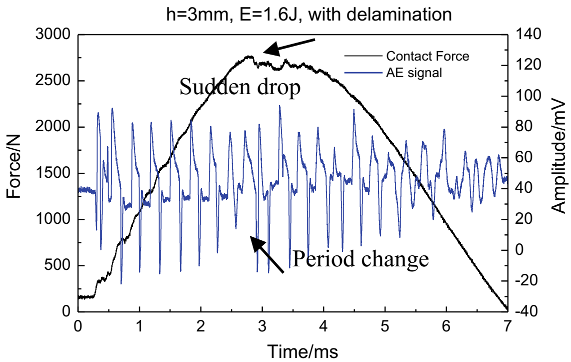


Fig. 4 Force and AE signal (E =1.6 J)

Fig. 5 Force and AE signal (E = 4 J)

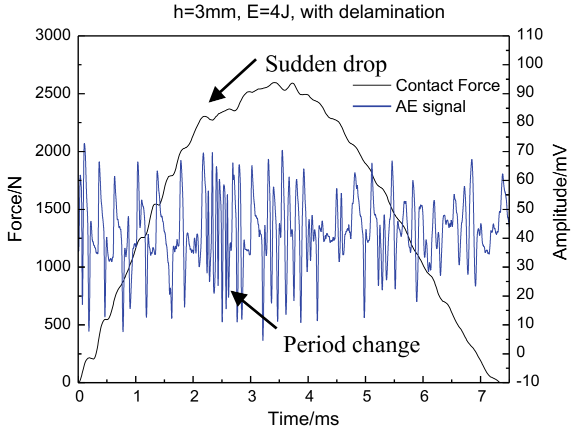


Fig. 6 Force and AE signal (E = 6 J)

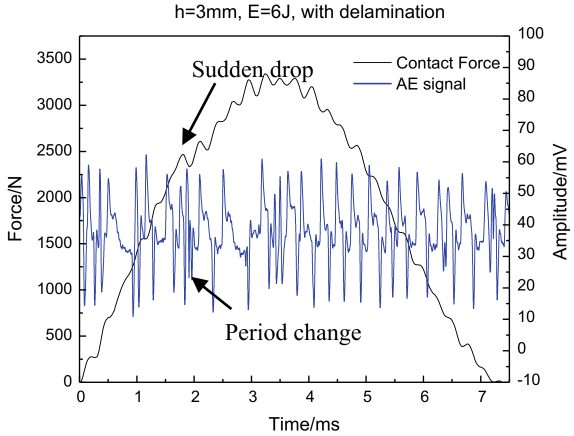
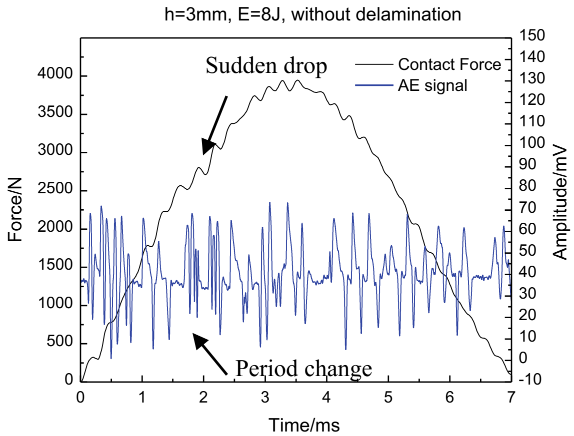


Fig. 7 Force and AE signal (E = 8 J)



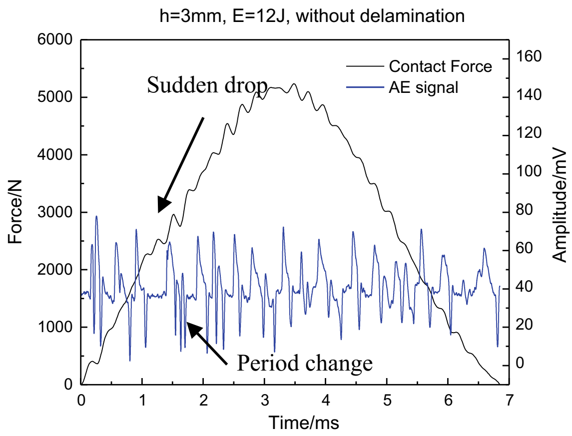


Fig. 8 Force and AE signal (E = 12 J)

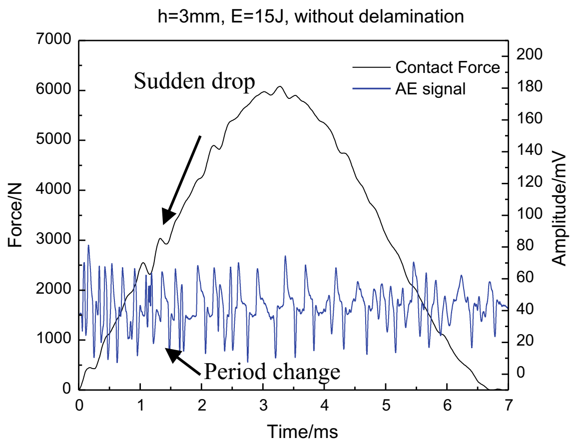


Fig. 9 Force and AE signal (E = 15 J)

Similarly, when the impact energy equals 4, 6, 8, 12 and 15 J, respectively, the contact force in Figs. 5, 6, 7, 8 and 9 has a sudden drop near 2600 N, and then continues to increase to the maximum. Therefore, it can be concluded that when the contact force reaches 2600 N, the laminate would delaminate in the case of big mass impact.

Comparing the AE signals under different impact energies, we can find that when the plate delaminated, a high-frequency signal appears in the AE signal. What's more, the sudden drop in contact force matches well with the high-frequency signal in AE, as shown in Figs. 4, 5, 6, 7, 8 and 9. The IMFs obtained by decomposing the AE signal when the impact energy equals 1.1 and 1.6 J are shown in Figs. 10 and 11.

On the other hand, the failure modes of composite materials can be mainly divided into two categories, namely high-frequency brittle failure mode and medium-low frequency plastic failure mode. The low-frequency brittle mode mainly refers to the cracking of the matrix after impact, while the medium-high-frequency plastic mode mainly refers to the friction between the fiber bundles, delamination, etc. [17]. Therefore, regardless of the magnitude of the impact energy, the IMF1 decomposed by the AE signal will have an abnormal signal at the beginning, which is due to the matrix cracking.

When the impact energy equals 1.1 J, the plate is not damaged. Therefore, the signal decomposed in Fig. 10a is the noise signal, and the frequency is high, while the amplitude is small. In Fig. 10a, the decomposed IMF1 has an abnormal signal at the beginning, which is a signal from the cracking of the matrix. When the impact energy equals 1.6 J, the composite material has minimal damage. In Fig. 11a, there is an abnormal signal around 3 ms, and the amplitude is large, which is the signal of the delamination, as indicated by the arrow. Figures 11b, c show the noise signals with higher frequency and smaller amplitude. At the same time, the summation of other order IMFs of 1.1 and 1.6 J are shown in Figs. 10d and. 11d. It can be seen that except for the first three order IMFs, which have a large amplitude, the summation of other IMFs' amplitude is small, which can be regarded as a normal state.

When the impact energy rose to 4 J, the amplitude of the singular point due to the damage of the composite is much larger than the noise, so the IMF1 decomposed has

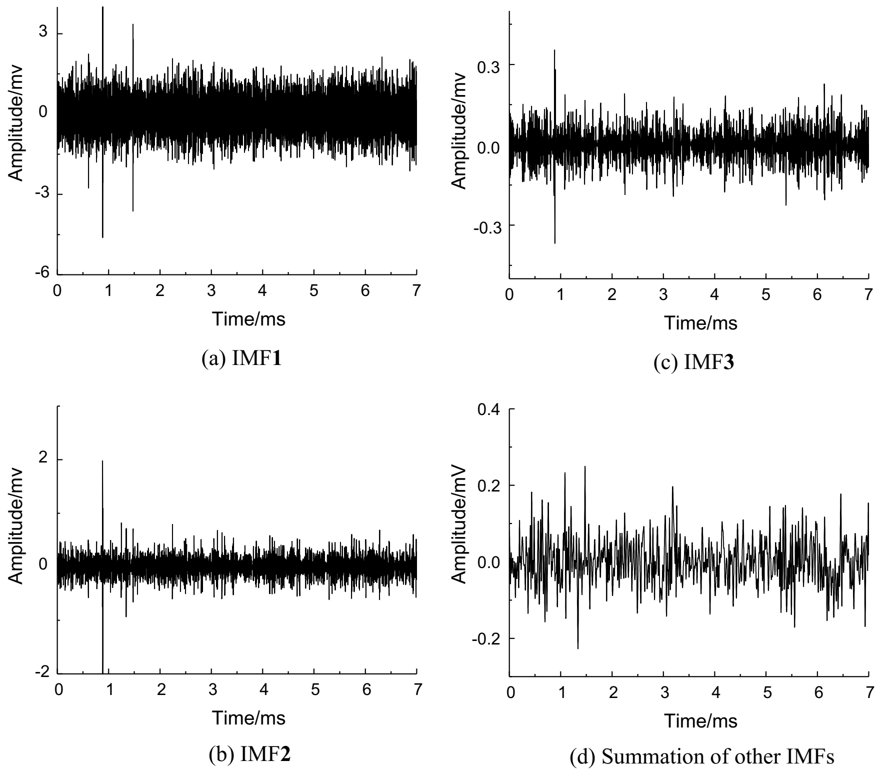


Fig. 10 IMFs (E = 1.1 J)

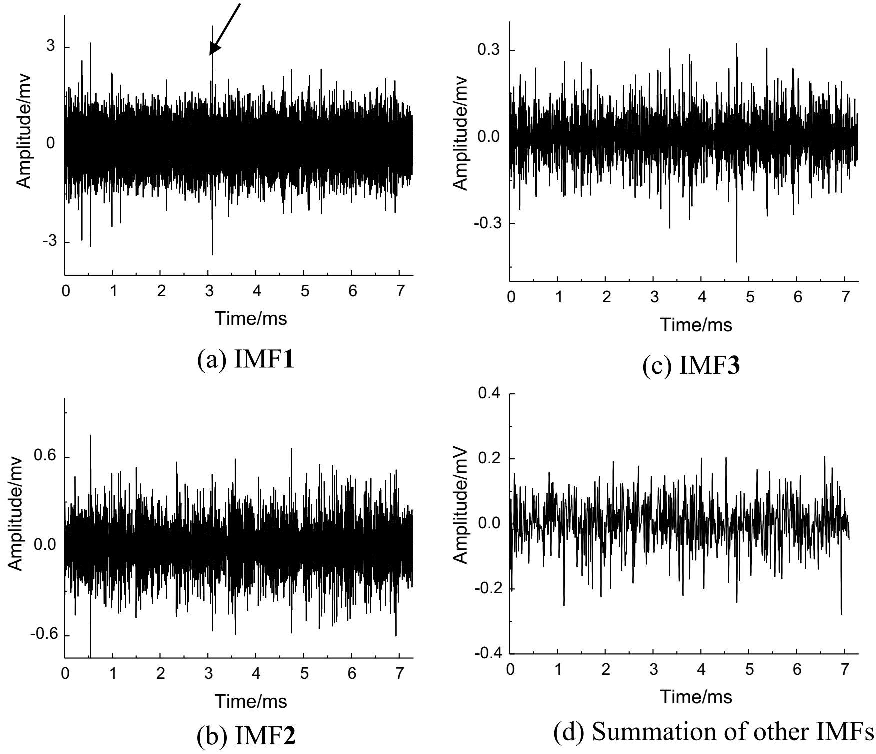


Fig. 11 IMFs (E = 1.6 J)

a higher amplitude and a smaller frequency, as shown in Fig. 12a. Simultaneously, it can be found that due to the obvious delamination damage of the specimen when the impact energy equals 4 J, a fairly obvious abnormal signal can be seen in the first 3 orders of the IMF, as shown in Fig. 12, which is different from that of 1.6 J.

Therefore, when the damage is larger, the abnormal signal is more obvious in the decomposed IMFs, and this feature can characterize the health monitoring signal. The IMF1 s of decomposed AE signal of 6 J ~ 15 J are shown in Figs. 13, 14, 15 and 16.

When the impact energy is gradually increased to 6, 8, 12 and 15 J, as shown in Figs. 13, 14, 15 and 16, the abnormal signal at the beginning of IMF1 is more obvious, that is, the cracking damage of the matrix at the beginning is more obvious. On the other hand, a continuous, high amplitude signal, as indicated by the arrow in Figs. 13, 14, 15, and 16, is caused by delamination, and the time between the abnormal AE signal and the point of the contact force is synchronous.

When the impact energy equals 4 and 8 J, respectively, it can be found that the signal of IMF1 is relatively stable after the first abnormal signal appears, however, as the impact energy increases, it can be found that after the first abnormal signal

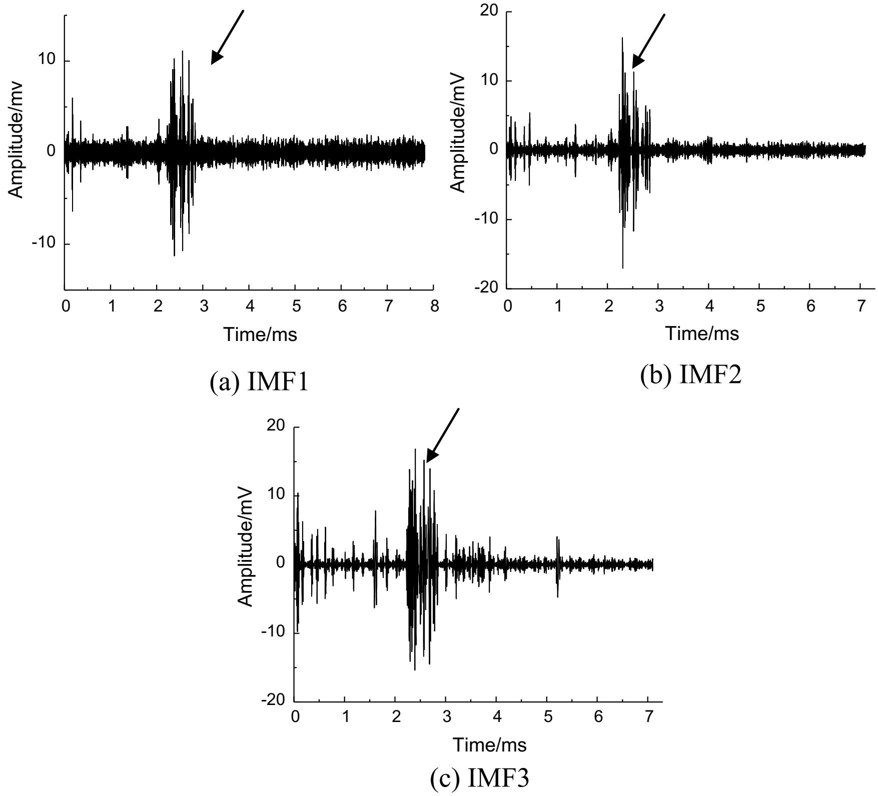


Fig. 12 IMFs (E = 4 J)

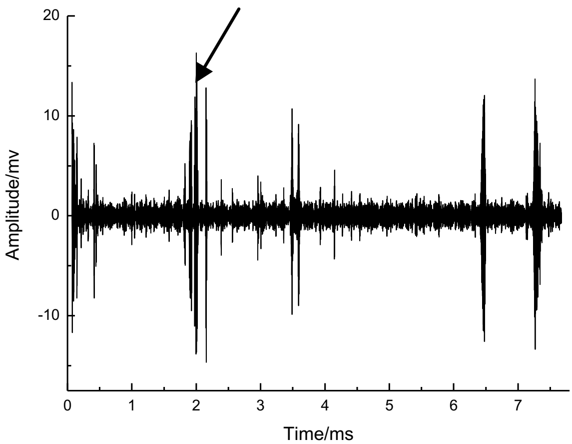


Fig. 13 First IMF (E = 6 J)

Fig. 14 First IMF (E = 8 J)

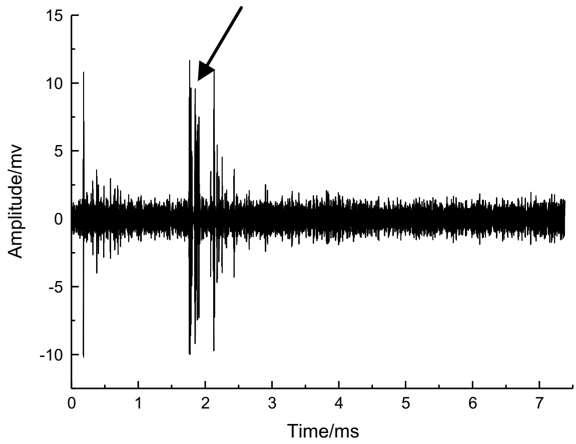


Fig. 15 First IMF (E = 12 J)

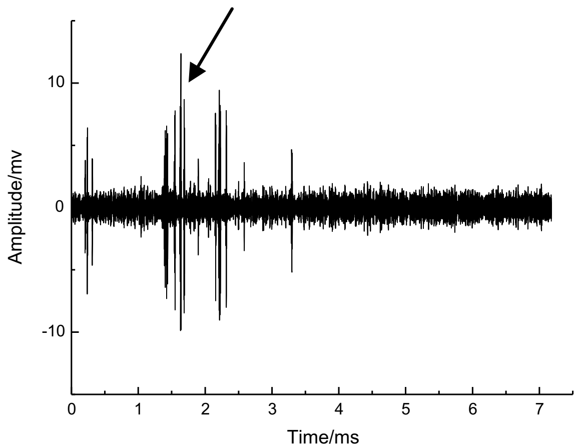
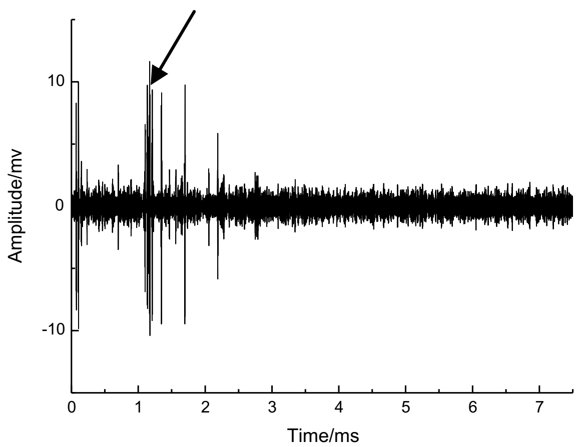


Fig. 16 First IMF (E = 15 J)



appears in IMF1, there are more abnormal signal points when the impact energy equals 6, 12 and 15 J, because matrix damage, new delamination and other complex damage appears after the first delamination.

In addition, the period of various energies are almost equal in drop-weight impact test. When the impact velocity is large, the contact force reaches the delamination threshold force earlier, and the time when the acoustic emission signal shows abnormal is also earlier, which can also help to determine the impact energy. Combined with other measured physical quantities, the AE signal can be used to identify the impact event and determine the damage situation.

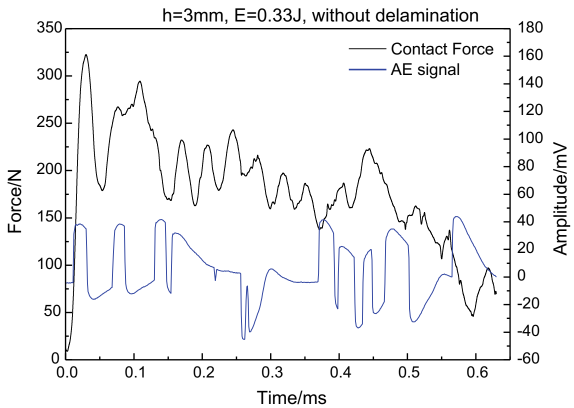
3.2 Small-Mass Impact Test

In the small-mass impact test, when velocities are 5.4 and 24 m/s, the corresponding impact energies equal 0.33 and 6.3 J, respectively. The contact force and AE signals are shown in Figs. 17 and 18.

It can be seen from Figs. 17 and 18 that when the impact energy equals 0.33 J, the force curve is smooth before reaching the maximum value, and after reaching the maximum value, the contact force is slowly decreased. However, when the impact energy equals 6.34 J, the force curve has a sudden drop before reaching the maximum value, and then the force rises with oscillation before reaching the maximum due to new delamination and delamination expansion. Ultrasonic non-destructive checking after impact showed that the laminate did not delaminate at the impact energy of 0.33 J, while the laminate was delaminated when the impact energy equals 6.34 J.

By observing the relationship between the AE signal and the force in Figs. 17 and 18, it can be found that when the impact energy equals 0.33 J, the plate didn't delaminate, and at the same time, it can be seen that the frequency of AE signal does not change suddenly and the IMFs decomposed by EMD has no abnormal point, as

Fig. 17 Force and AE signal (E = 0.33 J)



shown in Fig. 19. As the impact energy increase to 6.34 J, when the contact force reaches 1000 N, a sudden drop occurs and the delamination begins. It is obvious that more high-frequency components appear in the AE signal, as shown in Fig. 18. The frequency of the IMF1 is higher when the impact energy is large. However, as can be seen from Fig. 20, when the force suddenly drops, the characteristics of the high-frequency signal of the AE signal are not obvious. A series of high-frequency AE signal appears when the plates delaminate, and the starting moment represents the moment when damage occurs, but this moment is not obvious. Furthermore, the period of small-mass impact is short, so it's not precise to judge the specific moment and the critical load of delamination. Moreover, when the impact velocity is higher, the impact period is even shorter.

The Fourier transform of the IMF1 is shown in Fig. 21. When the impact energy equals 0.33 J, as shown in Fig. 21a, the maximum amplitude is obtained at a frequency of 500 kHz, which is the high-frequent brittle failure signal generated by the broken of the matrix and signal noise. And other frequency segments have smaller amplitudes.

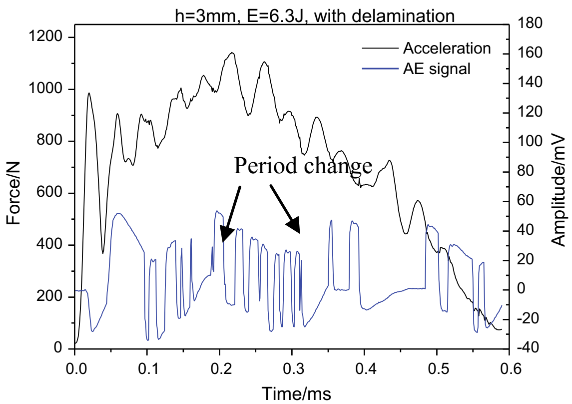


Fig. 18 Force and AE signal (E = 6.3 J)

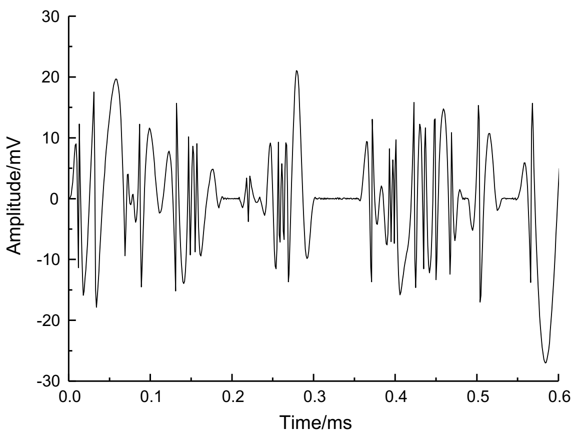


Fig. 19 First IMF (E = 0.33 J)

Fig. 20 First IMF (E = 6.3 J)

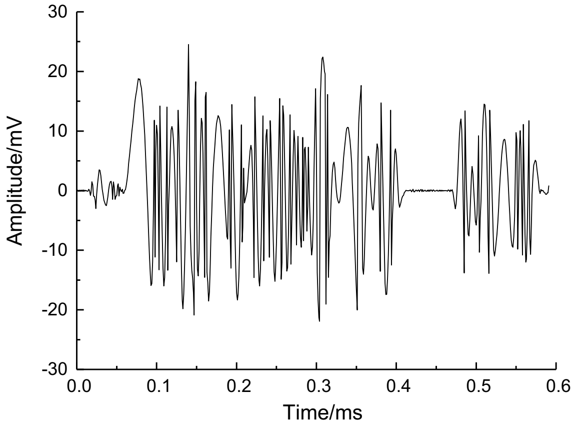
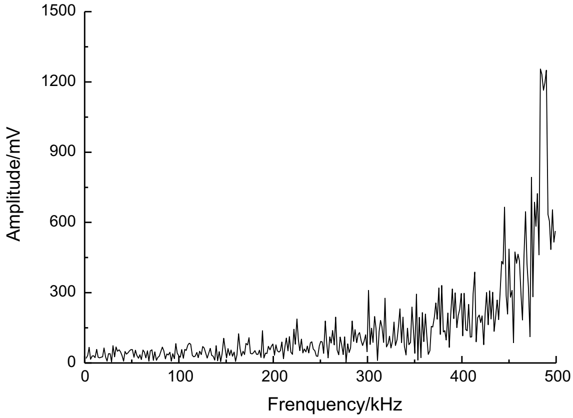
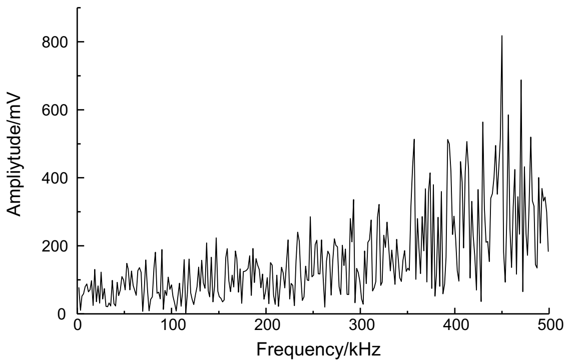


Fig. 21 Frequency domain of IMF1



(a) E=0.33 J



(b) E=6.3 J

While as shown in Fig. 21b, it can be found that the signal with the largest amplitude appears in the frequency range of 450 kHz when the impact energy equals 6.3 J, mainly due to the delamination and friction between the fibers.

4 Conclusion

The drop-weight impact and the small-mass impact were carried on the laminate. The impact force was directly measured with the drop-weight machine and the "mouse-trap" hammer, and the AE signal emitted during the impact was measured by the AE sensor. By comparing force signals and acoustic signals we can find that:

(1) By measuring the contact force, we can find that the contact force will suddenly drop when the contact force reaches the delamination threshold force, in both large mass impact and small-mass impact.
(2) By comparing the contact force and the AE signal, it can be found that when the plate delaminates, the frequency of the AE signal suddenly increases, and IMFs decomposed by the EMD has an obvious abnormal point. So the AE signal can be chosen as a real-time reference for health monitoring.
(3) In the drop-weight impact test, if there is no abnormal point other than one which is generated when the hammer touches the specimen, the plate didn't delaminate. If the impact energy is high enough, simultaneously, there is another abnormal signal in other order IMFs beside IMF1, which can be regarded as a character of composite material damage.
(4) In the small-mass impact test, since the impact time is short, the real-time health monitoring in the time domain is not precise. But the decomposed IMF1 can be analyzed in frequency domain. If the amplitude of the low-mid frequency signal is high, it can be judged that the composite material is delaminated.

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