A Multi-Frequency Virtual Time-Reversal Technique for Impact Localization on Stiffened Woven Composite Structures Using A0 Mode Lamb Wave

XU ZENG, DESHUANG DENG, LEI YANG
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ABSTRACT

Woven composite structures play an important role in the engineering field. Due to their poor impact resistance, passive structural health monitoring (SHM) techniques for impact localization have attracted much attention. In this study, A multi-frequency virtual time-reversal technique for impact localization on stiffened woven composite structures using A0 mode lamb wave is proposed according to the time reciprocity principle. A sparse piezoelectric sensor network mounted on the structure is used to receive impact response signals. The received impact response signals are decomposed into multi-frequency narrowband wave components using the continuous wavelet transform. Virtual time-reversal is performed for each frequency narrowband wave component, multiple frames of the wavefield image corresponding to different wave speeds in a wave speed interval are reconstructed separately at the moment of impact occurrence. The maximum field value is searched for all frames of the wavefield image, and the wave speed corresponding to the maximum field value is identified as the group velocity of the A0 mode lamb wave at that frequency, and the image in which the maximum field value is located is considered as the effective imaging result at that frequency. The focus level of the effective imaging results for each frequency is calculated and used to determine whether the imaging results are retained. Finally, image fusion for impact localization using all retained imaging results is realized. The proposed method has the following advantages: (a) it can be applied to stiffened plate structures; (b) it doesn't require any prior knowledge of structure, which is attractive for passive monitoring systems; (c) it minimizes the interference of noise and locates impact events automatically in multiple time-frequency domains; (d) it doesn't rely on the transfer function. The effectiveness of the proposed method is experimentally assessed on a stiffened woven composite plate. The results show that this method can estimate the impact position reliably with acceptable accuracy for engineering applications.

Keywords: Multi-frequency; Time-reversal; Impact localization; Woven composite; Lamb wave

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INTRODUCTION

Due to their advantages of high specific strength, high specific stiffness, and strong designability, composite materials are widely used in aerospace, ocean engineering, rail transit, and other fields. Among them, woven cladding has played a very important role in the engineering field in recent years due to its convenient forming, excellent damage expansion resistance, and better impact resistance than traditional laminates. However, in the process of manufacturing, transportation, and service, composite materials will inevitably be affected by low-speed external impact loads, which may cause invisible "internal injuries" (including matrix cracking, delamination, and fiber fracture, etc.), seriously threatening the health and safety of the structure. Impact monitoring technology can monitor the impact events of composite structures in real-time and online, which is of great significance for the health and safety maintenance of composite structures, so it has been a wide concern [1].

The primary task of impact monitoring technology is to determine the impact location. At present, the representative methods include the geometric method [2], time reversal method [3], reference database method [4], and machine learning method [5]. Geometric methods are first developed because of their simplicity and high efficiency. However, the key to the geometric method is to obtain an accurate arrival time, which is difficult to obtain the accurate arrival time difference due to the influence of operating environment noise, boundary reflection, and stiffeners. This indicates that the geometric method is difficult to obtain high-impact positioning accuracy on complex structures with stiffeners. The time reversal method based on the reciprocity principle is attractive because it does not require a priori information of structure. However, the existing methods either need to measure wave velocity or rely on full-wave field measurement equipment, which limits the impact monitoring capability of the time reversal method on structures. The reference database method is applied because it can obtain satisfactory positioning accuracy in the case of fewer sensors, but it takes a lot of time to build the reference database. In addition, the performance of the algorithm is poor under the condition of fewer training points. Machine learning methods are also introduced into impact location because of their ability to adapt to structures with complex wave fields. For existing problems, an adaptive time reversal focusing impact location method is proposed. Since this method does not require prior knowledge of wave velocity and structure, it has a good application prospect in the stiffened woven composite plate structures.

IMPACT LOCALIZATION METHOD

In reality, it is difficult to receive the sensor excitation signal at all positions in the monitoring area, and then determine the focusing position of the time reversal signal, to achieve impact positioning. In this paper, adaptive virtual time reversal focusing imaging is realized by signal processing. Figure 1 shows a schematic diagram of the virtual time reversal focusing imaging method. The structure monitoring area is grid divided, and the Cartesian coordinate system is established. It is assumed that the grid point (x, y) is the position of the impact source, and the distance from it to the sensor PZT$_i$ is $L_i(x, y)$:

$$L_i(x,y)=\sqrt{(x-Sx_i)^2+(y-Sy_i)^2} \tag{1}$$

Where, (Sx_i, Sy_i) is the coordinate of sensor PZT$_i$.

The distance difference between sensor PZT$_i$ and PZT$_1$ to grid point (x, y) is D_i (x, y):

$$D_i(x,y) = L_i(x,y) - L_1(x,y) \tag{2}$$

Narrowband Lamb wave signals V_i (i = 1, 2... n) of all sensor impact response signals are extracted by Wavelet transform.

For the grid point (x, y), the time difference of the narrowband Lamb wave signal propagating to the sensor PZT$_i$ and PZT$_1$ τ_i:

$$\tau_i = \frac{D_i(x,y)}{Cg} \tag{3}$$

Where Cg is the group velocity of narrow band Lamb wave.

Taking the time length Δ containing direct waves, the narrowband Lamb wave signals of all sensors are time-reversed, and synthesize signal $P(t)$ at grid points:

$$P(t) = \sum_{i=1}^{n} VTR_i(\Delta - t - \tau_i) \tag{4}$$

Where VTR_i (Δ-t) is the time reversal signal of the narrow-band Lamb wave.

According to the time reversal focusing principle, the synthetic signal will be focused on the impact source. Set a reasonable iteration interval [$Cg_{\min}$, $Cg_{\max}$], take $Cg_{\min}$ as the initial value and ΔCg as the step length to determine the iteration group speed Cg:

$$Cg = Cg_{\min} + (k-1) \cdot \Delta Cg \tag{5}$$

Then, the maximum envelope amplitude of the synthesized signal is taken as the pixel of the grid point, and the virtual time reversal focusing imaging results corresponding to different group velocities are iteratively calculated I (Cg, x, y):

$$I(Cg,x,y) = \max(\tilde{P}(t)) \tag{6}$$

Where, "~" is the envelope of the signal.

When Cg = $Cg_{\max}$, the iteration terminates. According to the maximum pixel curves of virtual time reversal imaging corresponding to different group velocities, the group velocities of narrowband Lamb wave $\overset{\wedge}{Cg}$ are determined as follows:

$$\overset{\wedge}{Cg} = \arg\max_{Cg}(I(Cg,x,y)) \tag{7}$$

The adaptive time reversal focusing image is $\hat{I}(x,y)$:

$$\hat{I}(x,y) = I(Cg = \overset{\wedge}{Cg}, x, y) \tag{8}$$

The energy focus degree is calculated for the adaptive time-reversal focusing image by narrowband Lamb wave signals:

$$E = 1 - \frac{m}{M} \tag{9}$$

Where m is the number of the grid points whose pixel value is higher than 85% of the maximum pixel value in M grid points of the adaptive time reversal focusing image.

Considering multi-frequency Lamb wave signals can be extracted from impact respose signals, the focusing agree threshold E_0 is set. The multi-frequency adaptive time-reversal focusing images whose focusing agree is lower than E_0 are abandoned, and the multi-frequency adaptive time-reversal focusing images whose focusing agree is higher than the focusing threshold E_0 are retained and fused by multiplication to obtain Y_f :

$$Y_f = \prod_{f=1}^{V} \hat{I}_f \quad (10)$$

Where V is the total number of retained adaptive time-reversal focusing images, and f represents the central frequency of the Lamb wave signals for time-reversal focusing imaging. The grid point coordinates corresponding to the largest pixel of the fusion image are used as the predicted actual impact position.

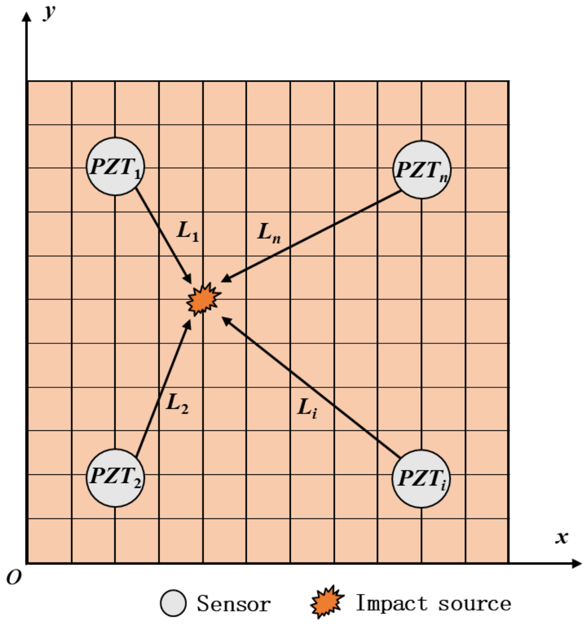

Figure 1. Schematic diagram of impact localiation method.

EXPERIMENTAL VALIDATION

Experimental studies using a stiffened woven composite structure is conducted to investigate the effectiveness of the proposed method.

EXPERIMENTAL SETUP

As shown in Figure 2, an experiment was carried out on a stiffened woven composite plate structure to verify the effectiveness of the method. The size of the stiffened woven composite plate is 800 mm × 400mm (length × width) and contains two L-shaped stiffeners. The bottom width of the two stiffeners is 30mm, the length is 400mm, the belly height is 30mm and the span is 300 mm. The structural material is carbon fiber fabric T700SC-12k, and the material parameters are as follows: E1 = 56 GPa, E2 = 55 GPa, E3 = 8.7 GPa, G12 = G13 = G23 = 4 GPa, ν12 = 0.042, ν13 = ν23 = 0.34, Both laminate and stiffeners lay-up are $[0/90]_3$. It should be pointed out that the velocity distribution of the A0 mode Lamb wave is almost isotropic on the orthogonal lay-up. Twelve P-51 piezoelectric sensors with a diameter of 16 mm and thickness of 0.5 mm are pasted on the surface of the structure. A Cartesian coordinate system is established with the lower left corner of the plate as the origin. The numbering and coordinates of the sensors are shown in TABLE I. The two ends of the structure are fixated with clamps, and the impact event is stimulated by the free fall of the steel ball. The impact response signal received by the sensor is collected by the passive dynamic data acquisition system, with a sampling rate of 200 kHz.

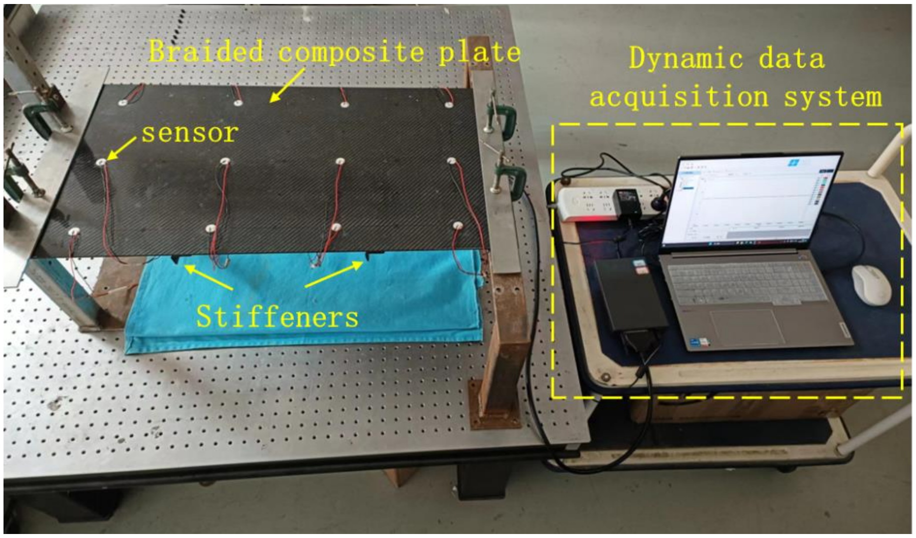

Figure 2. Experiment setup.

TABLE I. POSITION COORDINATES OF SENSORS

No.	Coordinate/mm	No.	Coordinate/mm	No.	Coordinate/mm
P1	(100, 50)	P5	(100, 200)	P9	(100, 350)
P2	(300, 50)	P6	(300, 200)	P10	(300, 350)
P3	(500, 50)	P7	(500, 200)	P11	(500, 350)
P4	(700, 50)	P8	(700, 200)	P12	(700, 350)

IMPACT RESPONSE SIGNAL PROCESSING

The test impact is carried out at the position of (300mm, 275mm) on the plate. The impact response signal of the piezoelectric sensor P6 acquired is shown in Figure 3(a), and Figure 3(b) is the spectrum of the impact response signal. It can be seen from the spectrum that the energy of the impact response signal is mainly concentrated in the range of 0 ~ 10 kHz, and the energy of the signal larger than 10 kHz is very small. For wavelet transform, the higher the frequency, the higher the time resolution of the signal. But for the mode of Lamb wave signal, the higher the frequency of the signal, the more complex the signal mode is. Generally, the Lamb wave below 100 kHz mainly consists of A0 and S0 modes, and the A0 mode is dominant [6]. A narrow-band Lamb wave signal with a center frequency of 5 kHz is extracted from the impact response signal by using wavelet transform, as shown in Figure 3(c). The first direct wave is seen in the extracted narrow band Lamb wave. In addition, the envelope signal of the narrowband Lamb wave calculated according to the Hilbert transform is shown in Figure 3(c). It can be seen from the figure that the envelope of the narrowband Lamb wave signal has an obvious peak at the position of the direct wave. The time reversal of narrowband Lamb signals is shown in Figure 3(d). In this paper, time reversal signals will be used for signal synthesis in the structure monitoring area, and envelope features will be used for virtual time reversal focusing imaging.

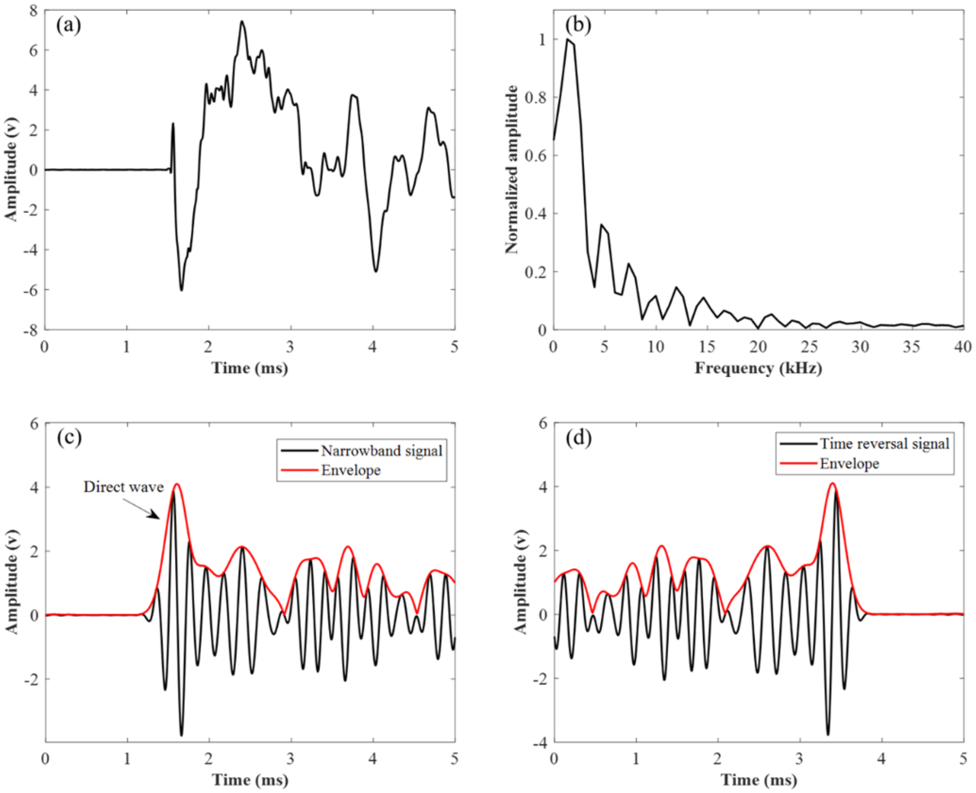

Figure 3. (a) Impact response time domain signal; (b) Impact response frequency spectrum; (c) Narrowband Lamb wave signal with center frequency of 5 kHz and its envelope; (d) Time reversal signal and envelope.

RESULTS AND DISCUSSION

According to the impact localization process of the proposed time reversal focusing method, the impact event at the position (300 mm, 275 mm) was identificated, and the results were shown in Figure 4. Figure 4(a) shows the virtual time reversal imaging results calculated iteratively with different group velocities. It can be seen from the figure that the virtual time reversal imaging results corresponding to different group velocities have different degrees of focusing. According to the time reversal focusing principle, the impact source focusing is only related to the transfer function of the structure. Therefore, with the correct group velocity, the wave field can be reconstructed and focusing can occur. Further, according to the maximum image pixel curve corresponding to different group velocities (see Figure 4(b)), the virtual time reversal imaging result corresponding to the maximum pixel is the adaptive time reversal focusing image, as shown in Figure 4(c). In the figure, the black "×" represents the actual impact position, and the red "×" represents the predicted impact position. It can be seen that the predicted impact position is consistent with the actual impact position, indicating the effectiveness of this method.

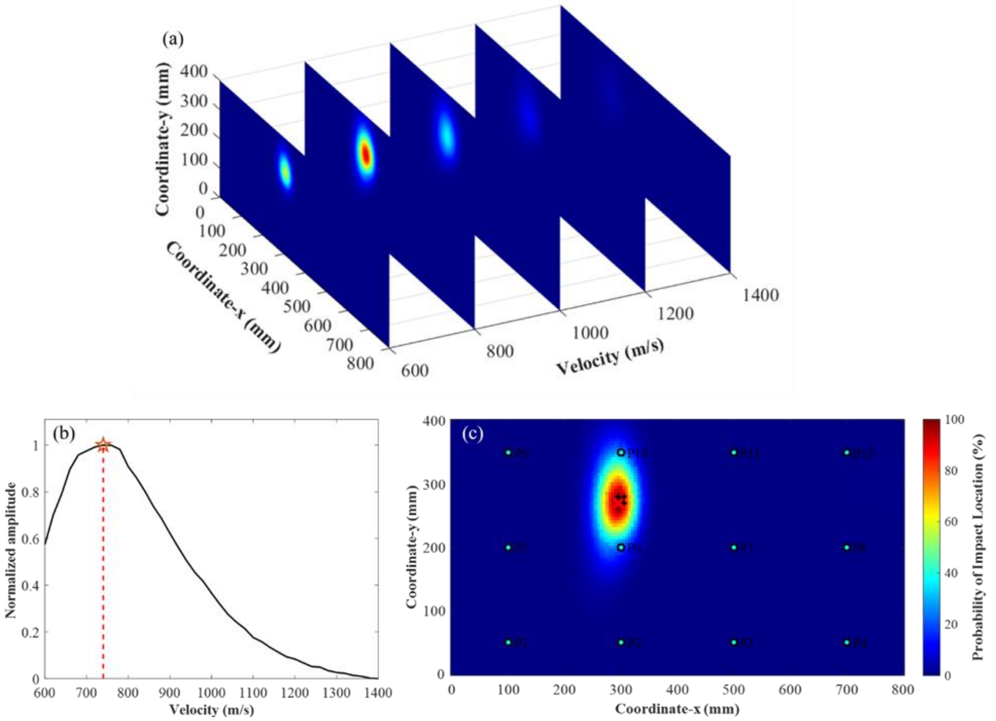

Figure 4. (a) Iterative calculation of virtual time reversal imaging results corresponding to different group velocities; (b) The curve of different group velocity and their corresponding maximum image pixel values; (c) Adaptive time reversal focusing image

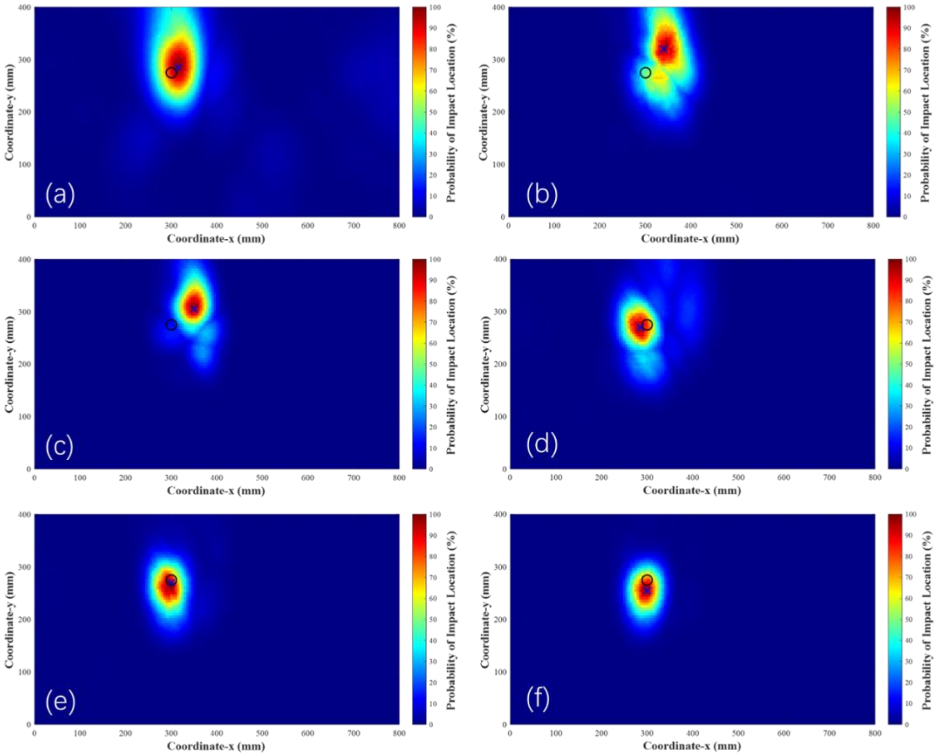

Figure 5. Multi-frequency narrowband wave impact imaging results: (a) 5kHz, (a) 6kHz, (a) 7kHz, (a) 8kHz, (a) 9kHz, and (d) 10kHz.

Figure 5 shows the imaging results of narrowband wave signals of six frequencies of 5kHz, 6kHz, 7kHz, 8kHz, 9kHz and 10kHz respectively for the position with coordinates of (300 mm, 275 mm). In the Figure 5, "o" represents the actual impact position, and "×" represents the predicted impact position. The imaging focusing threshold set by the invention is 85%. From the imaging results shown in Figure 5, it is calculated that the energy focus degree of narrowband wave signals with frequencies of 6kHz, 7kHz and 8kHz is less than 85%, which is abondoned. The energy focus degree of narrowband wave signals with frequencies of 5kHz, 9kHz and 10kHz is greater than 85%. As effective images, image fusion is carried out, as shown in Figure 6, the positioning results of multi-frequency fusion imaging. It can be seen that the imaging results have good focusing and high positioning accuracy, indicating that the method can be better applied to the stiffened woven composite plate structure.

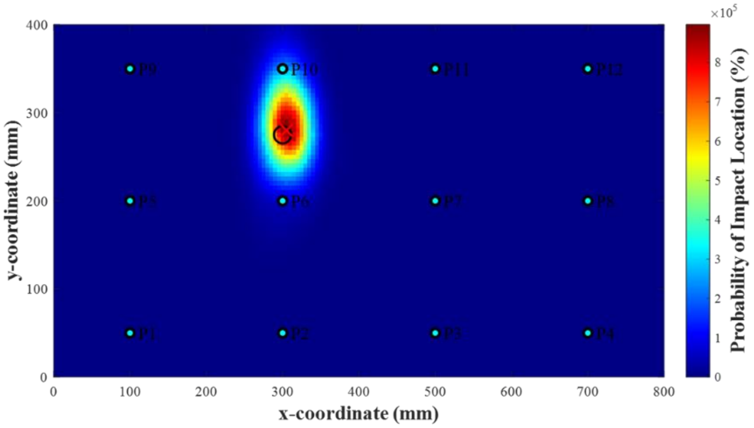

Figure 6. Multi-frequency fusion results.

CONCLUSION

In this paper, a multi-frequency virtual time reversal focusing impact localization method is proposed, which wave velocity measurement or prior knowledge of structure, and the implementation process is simple. The effectiveness of the proposed method is verified on a stiffened woven composite plate with an overall size of 800 mm × 400 mm (length × width). The narrowband Lamb wave signals of specific center frequency can be extracted by using continuous wavelet transform, and the wave-field can be synthesized in the monitoring area using the reversed lamb wave signals. By introducing the energy focusing degree, the multi-frequency fusion can be realized, impact localization accuracy and imaging resolution have been improved.

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