

1587. A spatial filter and two linear PZT arrays based composite structure imaging method

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Abstract. Aerospace structures make increasing use of composite materials which can generate inner damage easily by outer impact. Thus, the damage and impact monitoring of composite structures is an important research topic of structural health monitoring (SHM) technology. Among existing SHM methods, piezoelectric transducer (PZT) array and Lamb wave based structural imaging method has become an effective approach to monitor the damage and impact. However, the anisotropic feature of the composite structures makes it difficult to achieve accurate damage and impact localization which are dependent on Lamb wave group velocity. In recent years, a linear PZT array and spatial filter based damage imaging method has been developed. But this method is only applied to damage monitoring at the current stage and it also needs the Lamb wave group velocity to fulfill the damage localization. In this paper, a spatial filter and two linear PZT arrays based structural imaging method for composite structures is proposed. With this method, an acoustic source angle-time image for each linear PZT array can be obtained by using the spatial filter technique. Then, it is transformed to an acoustic source probability-angle image of the linear PZT array. Based on the probability-angle image, the angle of the acoustic source relative to the linear PZT array can be estimated accurately. By fusing the two probability-angle images of the two linear PZT arrays, the acoustic source can be localized accurately without using the Lamb wave group velocity. Damage and impact can be both considered to be acoustic source on composite structure. Thus, they can be localized easily and accurately by using the proposed structural imaging method. This method is validated on a carbon fiber composite laminate plate, including damage imaging and impact imaging. The imaging and localization results are in good agreement with the actual damage and impact positions, and the maximum localization error is no more than 1 cm.

Keywords: structural health monitoring, composite structure, damage imaging, impact imaging, spatial filter, linear piezoelectric transducer array.

1. Introduction

Composite materials have been widely applied to aircraft structures in recent years, such as B787 and A350XWB [1-3]. However, the composite structures are susceptible to impact which can lead to structural inner damage easily. Hence, damage and impact monitoring of composite structures is always an important research topic in the field of Structural Health Monitoring (SHM) [4]. In the existing SHM methods, much attention has been paid to piezoelectric transducer (PZT) and Lamb wave based SHM method because it has the capability of active and passive monitoring as well as large monitoring range [5-7].

In recent decade, structural imaging methods based on PZT array and Lamb wave have been widely studied, such as delay-sum imaging [8, 9], time reversal focusing imaging [10-13], probability-based imaging [14, 15], phased array imaging [16-18], system identification [19], multiple signal classification method [20], etc. These methods utilize a large number of actuator-sensor channels from PZT array to map the structure and produce a visual indication of damage or impact position. It has the advantages of high signal-to-noise ratio, large scale structure

monitoring and better fault tolerance of damage or impact localization [4].

All the aforementioned structural imaging methods are performed in time domain or frequency domain. Comparing with that, the analysis of Lamb wave in spatial-wavenumber domain is an effective approach to distinguish signal propagating direction and various signal modes. Thus, the spatial-wavenumber filtering technique has been gradually studied in recent years [21-23]. Considering the research on the spatial filter based structural imaging method, Purekar [24] used the spatial filter and a linear PZT array to realize damage imaging of an aluminum plate combining with the wavenumber mode obtained by using finite element modeling. Yuan [25] developed the spatial filter method for damage imaging of a composite plate without using any wavenumber model. However, these methods need Lamb wave group velocity to realize damage localization at the current stage. The anisotropic feature of the composite structures can lead to low damage localization accuracy. And the spatial filter is only applied to damage monitoring in the researches mentioned above. But the damage and impact are both needed to be monitored for composite structures.

To solve these problems mentioned above, this paper proposes an imaging method for damage and impact localization of composite structures based on the spatial filter and two linear PZT arrays without using Lamb wave group velocity. In this method, two linear PZT arrays are adopted to acquire Lamb wave signals introduced by structural damage or impact. The angle of the damage or impact relative to each PZT array is estimated based on a probability-angle image obtained by using the spatial filter. And then, the probability-angle images of the two linear PZT arrays are fused together and transformed to be a damage or impact coordinate image. Finally, the damage or impact position is estimated accurately by using a coordinate probability weighted algorithm based on the coordinate image.

The rest of this paper is organized as follows. The spatial filter is introduced and discussed in Section 2. In Section 3, the structural imaging method based on the spatial filter and the two linear PZT arrays without using the Lamb wave group velocity is proposed. In Section 4, the proposed imaging method is validated on a carbon fiber composite laminate plate. Finally, the conclusion is made in Section 5.

2. The principle of spatial filter

A linear PZT array constructed by M PZTs is placed on the surface of a structure as shown in Fig. 1. The PZTs are numbered as $m = 1, 2, \dots, M$. A Cartesian coordinate is constructed on the structure and the center point of the linear PZT array is set to be the origin point. The distance between each two adjacent PZTs, which is also equivalent to the spatial sampling rate, is denoted as Δx .

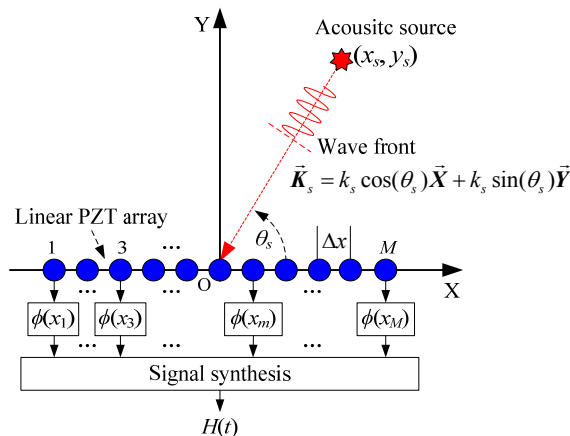


Fig. 1. Schematic diagram of the spatial filter

As illustrated in Fig. 1, an acoustic source occurs and excites Lamb wave signal in the structure. The position of the acoustic source is unknown and supposed to be (x_s, y_s) , and the angle is assumed to be θ_s . The wavenumber of the Lamb wave signal is denoted as \vec{k}_s , and it contains the information of the Lamb wave propagation direction relative to the linear PZT array. The output of the PZT located at $(x_m, 0)$ is represented as $f(x_m, t)$, where $x_m = ((2m - 1) - M)\Delta x/2$, m is the label of PZT. Finally, the output synthesis signal of the linear PZT array for the acoustic source can be expressed as Eq. (1), in which, t is the sampling time:

$$H(t) = \frac{1}{M} \sum_{x=x_1}^{x_M} f(x, t). \tag{1}$$

By applying a weight function $\phi(x)$ to the output signal of each PZT, Eq. (1) can be rewritten to be Eq. (2). The output feature of the linear PZT array is dependent on the weight function. It is represented as Eq. (3), in which, θ' is the angle of the weight function:

$$H(t) = \frac{1}{M} \sum_{x=x_1}^{x_M} \phi(x)f(x, t), \tag{2}$$

$$\phi(x) = \cos(xk_s \cos \theta') + i \sin(xk_s \cos \theta'). \tag{3}$$

By using the spatial-wavenumber transform, Eq. (3) can be transformed to be Eq. (4):

$$\Phi(\theta) = \int_{-\infty}^{+\infty} e^{ik_s x \cos \theta'} e^{-ik_s x \cos \theta} dx = 2\pi k_s [\delta(\cos \theta' - \cos \theta)], \tag{4}$$

where δ is the Dirac function which is expressed as Eq. (5):

$$\delta(\cos \theta' - \cos \theta) = \begin{cases} 1, & \cos \theta' = \cos \theta, \\ 0, & \cos \theta' \neq \cos \theta. \end{cases} \tag{5}$$

It can be seen from Eq. (4) and Eq. (5) that the weight function can pass through the signal of angle $\theta' = \theta$ and reject the signal of the other angles $\theta' \neq \theta$ in the range of $[0^\circ, 180^\circ)$. Therefore, similar to frequency domain signal filter, the weight function shown in Eq. (3) can be interpreted as a spatial filter. Finally, the filtered output synthesis signal of the linear PZT array, which is represented as Eq. (6), can be obtained by combining Eq. (3) with Eq. (2):

$$H(\theta', t) = \frac{1}{M} \sum_{x=x_1}^{x_M} [\cos(xk_s \cos \theta') + i \sin(xk_s \cos \theta')]f(x, t). \tag{6}$$

The angle θ' of the spatial filter can be changed in the range of $[0^\circ, 180^\circ)$ with the angle resolution $\Delta\theta$ to search the direction of the acoustic source. Then an angle-time image of the acoustic source can be obtained by imaging the filtered output synthesis signal at each angle [24].

The structural damage and impact can be both considered to be acoustic source on a structure [13]. Thus, the angle-time image of the damage or impact can be obtained by using the spatial filter. The direction of the damage or impact relative to the linear PZT array can be estimated based on the angle-time image directly. If the Lamb wave group velocity is known beforehand, the distance of the damage relative to the linear PZT array can be also obtained based on the angle-time image. But the distance of the impact is difficult to be obtained because there is no excitation reference time [13]. For anisotropic composite structures, the Lamb wave group velocity is different at different propagating direction. Thus, the damage localization error would

be high by using the group velocity directly. In addition, this method can not be applied to estimate the distance of the impact. To solve these problems mentioned above, a spatial filter and two linear PZT arrays based structural imaging method is proposed in this paper.

3. Spatial filter and two linear PZT arrays based structural imaging method

There are two linear PZT arrays placed on a structure, as shown in Fig. 2. The two linear PZT arrays are labeled as No. I and No. II, which are set to be along the X - and Y -axes respectively. The center point of the No. I PZT array is (x_I, y_I) and the center point of the No. II PZT array is (x_{II}, y_{II}) . If there is an acoustic source (a damage or an impact) located at (x_s, y_s) , then it will introduce Lamb wave signals propagating in the structure. By using the spatial filter, the angle-time image of the acoustic source relative to a linear PZT array can be obtained without using the Lamb wave group velocity.

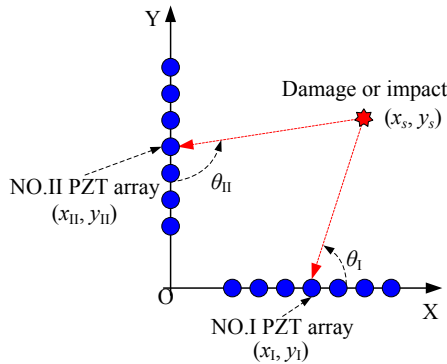


Fig. 2. The composite structure imaging method

In the angle-time image, the energy of the filtered output synthesis signal at angle θ' can be calculated by using Eq. (7), in which, T is the signal sampling length:

$$E(\theta') = \frac{1}{T} \sum_{t=0}^T |H(\theta', t)|. \tag{7}$$

Then a probability-angle plot of the acoustic source can be obtained by normalizing the energy of filtered output synthesis signal at each angle. The angle of position (x, y) relative to the linear PZT array can be obtained by Eq. (8). According to the probability-angle plot, the probability $p_n(x, y)$ of the position (x, y) relative to the linear PZT array can be obtained. After searching all the probabilities of the positions on the structure, an acoustic source angle image relative to the linear PZT array can be obtained by imaging the probability of each position on the structure:

$$\begin{cases} \theta_n(x, y) = \arctan\left(\frac{y - y_n}{x - x_n}\right), & (x \neq x_n, n = I, II), \\ \theta_n(x, y) = 90, & (x = x_n, n = I, II). \end{cases} \tag{8}$$

As shown in Fig. 2, the final probability $p(x, y)$ of the position (x, y) can be obtained by fusing the acoustic source angle images of the two linear PZT arrays, which is expressed as Eq. (9):

$$p(x, y) = \frac{p_I(x, y) + p_{II}(x, y)}{2}. \tag{9}$$

Finally, an acoustic source coordinate image can be obtained by imaging the probability of

each position. And the acoustic source can be localized based on a coordinate probability weighted algorithm which is expressed as Eq. (10):

$$\begin{cases} x_D = \left[\frac{\sum_{x_i=0}^X \sum_{y_j=0}^Y x_i \cdot p(x_i, y_j)}{\sum_{x_i=0}^X \sum_{y_j=0}^Y p(x_i, y_j)} \right] \\ y_D = \left[\frac{\sum_{x_i=0}^X \sum_{y_j=0}^Y y_j \cdot p(x_i, y_j)}{\sum_{x_i=0}^X \sum_{y_j=0}^Y p(x_i, y_j)} \right] \end{cases} \quad (10)$$

where (x_D, y_D) is the weighted position of the acoustic source, (x_i, y_j) is a position on the structure, $p(x_i, y_j)$ is the probability of position (x_i, y_j) , X and Y is the maximum value of x and y respectively.

Based on the above research, the implementation process of the spatial filter is given in Fig. 3 first. And then, the composite structure imaging method based on the spatial filter and two linear PZT arrays is shown in Fig. 4.

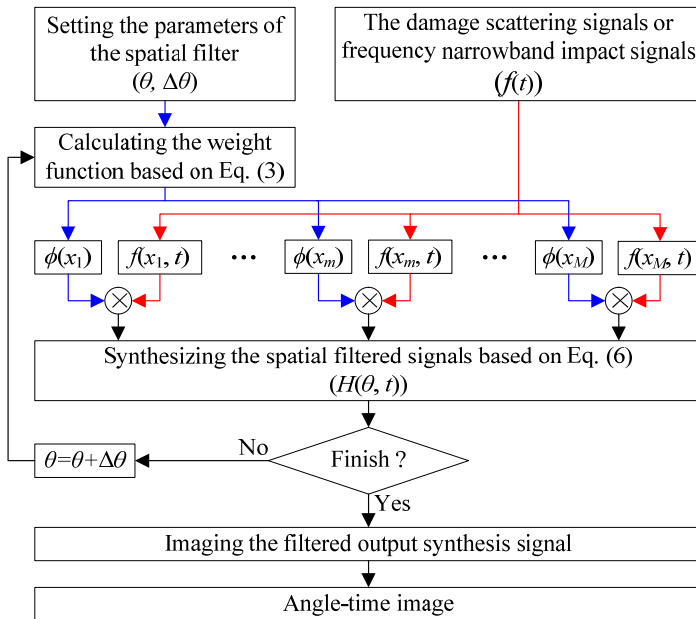


Fig. 3. Implementation process of the spatial filter

There should be noted that the Lamb wave signal is required to be frequency narrowband signal to realize spatial filter. For damage localization, this requirement can be satisfied because a frequency narrowband excitation signal can be used to excite frequency narrowband Lamb wave signal. But for impact localization, the impact response signal is frequency wideband. Thus, the complex Shannon wavelet transform is adopted to extract frequency narrowband signal from the impact response signal to fulfill the spatial filter.

The continuous complex wavelet transform of a signal $f(t)$ can be defined as [13, 26]:

$$z(t) = WT(a, b) = |a|^{-\frac{1}{2}} \int_{-\infty}^{\infty} f(t) \psi_{\text{shan}-a,b} \left(\frac{t-b}{a} \right) dt, \quad (11)$$

where a and b are scale factor and time factor respectively. The mother function of the complex

Shannon wavelet transform is defined as Eq. (12) [13]:

$$\psi_{\text{shan}-a,b}(t) = \sqrt{f_b} \text{sinc}(f_b t) e^{2\pi i f_c t}, \quad (12)$$

where f_b and f_c are the frequency band and the central frequency of the wavelet. The function of sinc is represented as Eq. (13):

$$\text{sinc}(t) = \begin{cases} 1, & t = 0, \\ \frac{\sin(\pi t)}{\pi t}, & t \neq 0. \end{cases} \quad (13)$$

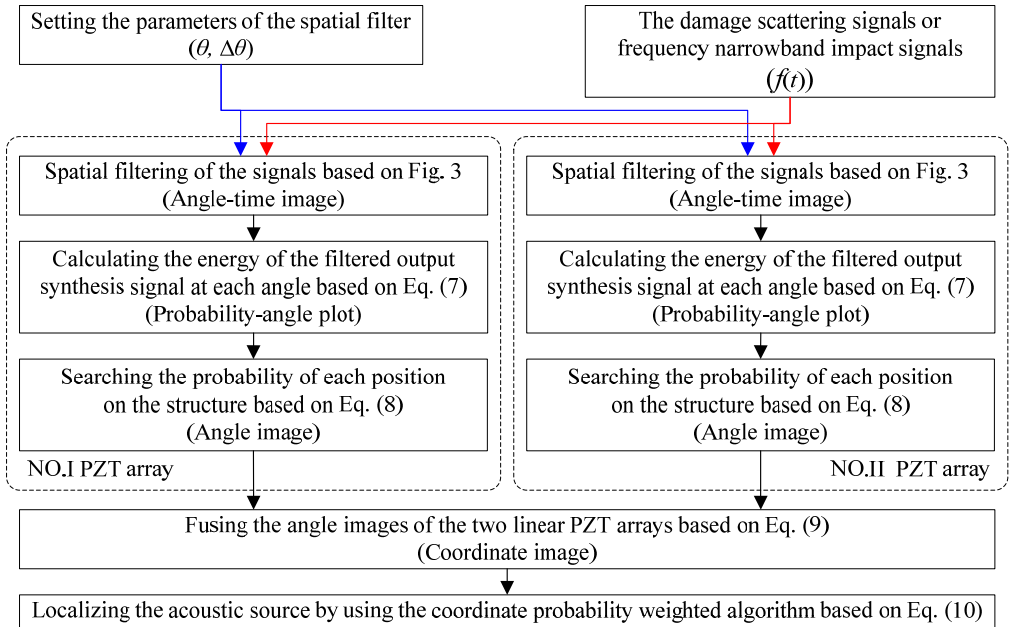


Fig. 4. The implementation process of the composite structure imaging method

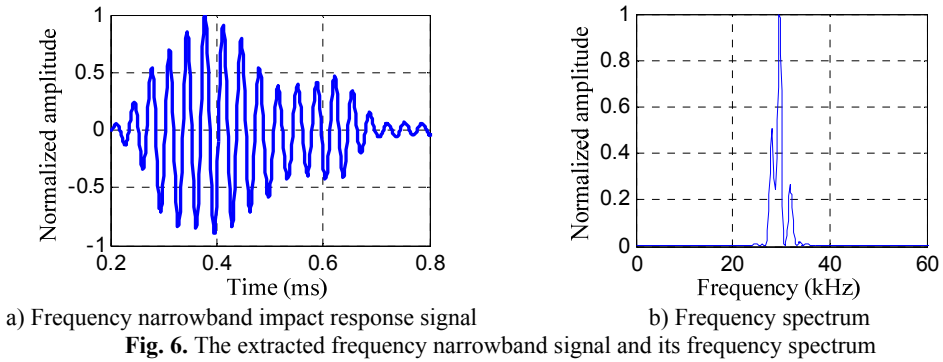
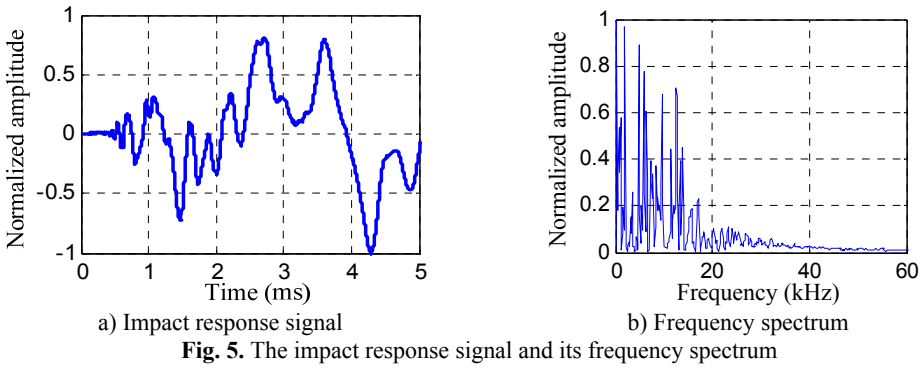
The Fourier transform of Eq. (12) can be represented as Eq. (14):

$$\Psi_{\text{shan}-a,b}(\omega) = \begin{cases} \sqrt{\frac{2\pi}{\omega_b}}, & \omega_c - \frac{\omega_b}{2} < \omega \leq \omega_c + \frac{\omega_b}{2}, \\ 0, & \text{others,} \end{cases} \quad (14)$$

where $\omega_c = 2\pi f_c$, $\omega_b = 2\pi f_b$, $\omega_c > \omega_b/2$.

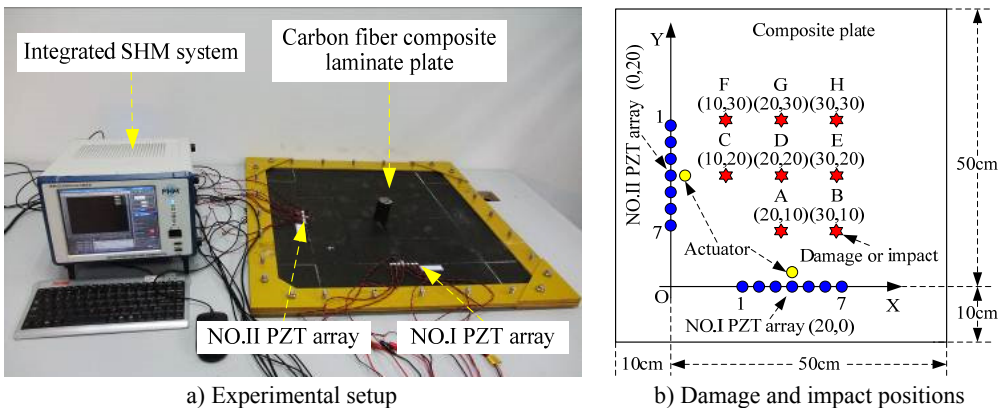
Eq. (14) indicates that the central frequency of the frequency spectrum of the complex Shannon wavelet function is at ω_c and the frequency band is limited in the range of $(\omega_c - \omega_b/2, \omega_c + \omega_b/2]$. It means that the continuous complex Shannon wavelet transform of a signal $f(t)$ is a frequency narrowband signal of central frequency ω_c and frequency band $(\omega_c - \omega_b/2, \omega_c + \omega_b/2]$. Based on this principle, the continuous complex Shannon wavelet transform can be used to extract the frequency narrowband signal from the frequency wideband impact response signal.

A typical impact response signal and the corresponding frequency spectrum in the following experiment are shown in Fig. 5. The frequency range of the impact response signal is 0-60 kHz approximately. By setting the frequency band to be $0.2\omega_c$, the frequency narrowband signal of central frequency 30 kHz is extracted from the impact response signal, as shown in Fig. 6.



4. Experimental validation

The validation experimental system shown in Fig. 7 is consisted of a carbon fiber composite laminate plate, an integrated SHM system [27] and two linear PZT arrays. The dimension of the composite plate is $60 \times 60 \times 0.216$ cm (length \times width \times thickness). The composite plate is stacked by 18 single layers and the ply sequences is $[45/0/-45/90/0/-45/0/-45/0]_s$. The material property of each layer is given in Table 1.



Each linear PZT array is constructed by 7 PZT-5A sensors and the distance between each two adjacent PZTs is 1 cm. The diameter and thickness of the PZT are 0.8 cm and 0.048 cm respectively. The distance between the center point of a linear PZT array and the boundary of the composite plate is 10 cm. The PZTs in No. I PZT array are labeled as PZTI-1, PZTI-2, ..., PZTI-7

respectively and the PZTs in No. II PZT array are labeled as PZTII-1, PZTII-2,..., PZTII-7 respectively. A PZT used as an actuator for Lamb wave excitation is bonded at the above center position of each linear PZT array.

As shown in Fig. 7, a Cartesian coordinate is built on the structure. The X -axis is set along the No. I PZT array and Y -axis is set along the No. II PZT array. The center point of the No. I PZT array is (20, 0) cm and the center point of the No. II PZT array is (0, 20) cm. The monitoring area is 50×50 cm. The damage and impact positions labeled A to H are shown in Fig. 7 and Table 2. The angle is defined according to counterclockwise direction relative to the X -axis. 8 damages are applied on the positions A to H for damage imaging validation, and 8 impacts are also applied on the positions A to H for impact imaging validation.

Table 1. Material property of single layer of the carbon fiber composite laminate plate

Parameter	Value
0° tensile modulus (GPa)	135
90° tensile modulus (GPa)	8.8
±45° in-plane shearing modulus (GPa)	4.47
Poisson ratio μ	0.328
Density (kg·m ⁻³)	1.61×10 ³

Table 2. The damage and impact positions for method validation

Position	Actual coordinates (cm)	θ_I (°)	θ_{II} (°)
A	(20,10)	90.0	63.4
B	(30,10)	45.0	71.6
C	(10,20)	116.6	90.0
D	(20,20)	90.0	90.0
E	(30,20)	63.4	90.0
F	(10,30)	108.4	135.0
G	(20,30)	90.0	116.6
H	(30,30)	71.6	108.4

For damage imaging validation, the method of applying damage on the structure is bonding a mass block on the structure to change the local stiffness of the structure at the bonding area [28]. The excitation signal is modulated five-cycle sine burst. The center frequency of the excitation signal is 50 kHz and the amplitude is ±70 Volts. The sampling rate is 10 MHz and the sampling length is 8000 samples including 1000 pre-samples. The trigger voltage is 5 Volts.

The validation process of damage imaging is described as follows: (1) the Lamb wave signals of the two linear PZT arrays are acquired as the health reference signals f_{HR} when the structure is in health status. (2) Damage is applied at each position shown in Table 2 and the corresponding Lamb wave signals of the two linear PZT arrays are acquired as the on-line monitoring signals f_{OM} . (3) The composite structure imaging method is applied to damage imaging and localization.

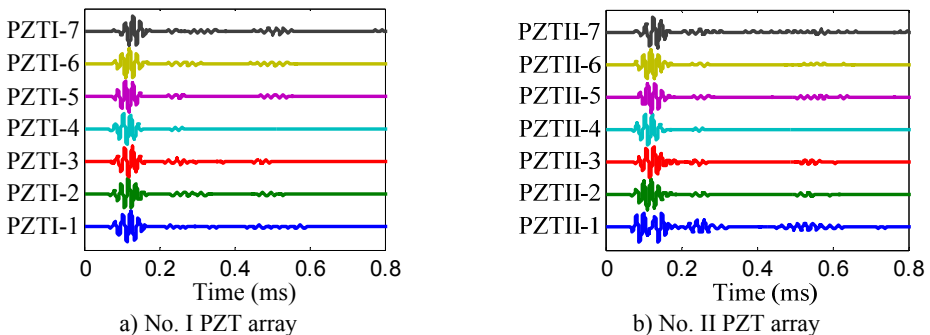


Fig. 8. Health reference signals

The damage imaging of position B is chosen to be an example to show the damage imaging method. The health reference signals f_{HR} and on-line monitoring signals f_{OM} of the two linear PZT arrays are shown in Fig. 8 and Fig. 9 respectively. The damage scattering signals extracted by subtracting f_{OM} from f_{HR} are shown in Fig. 10.

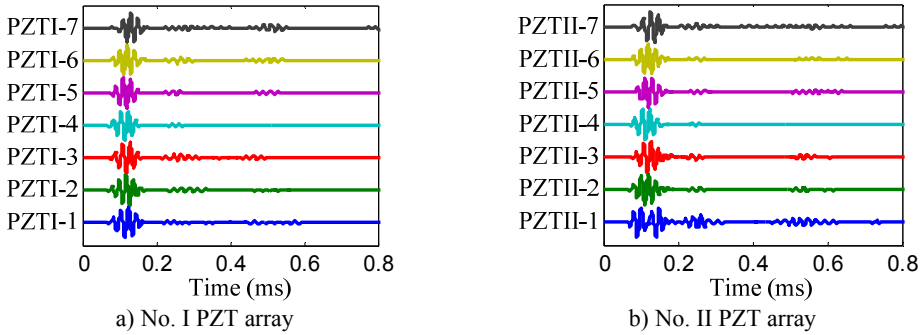


Fig. 9. On-line monitoring signals

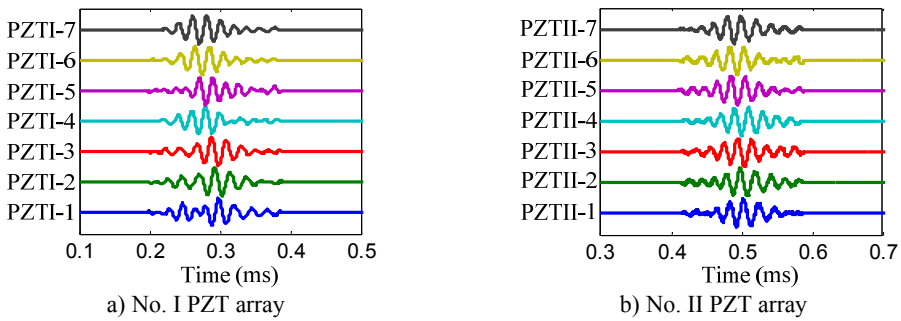


Fig. 10. Damage-scattering signals

The angle searching range of the spatial filter is set to be $[0^\circ, 180^\circ]$ and the angle resolution is $\Delta\theta = 0.36^\circ$. The damage angle-time image of each linear PZT array can be obtained by spatial filtering the damage-scattering signals, as shown in Fig. 11. Based on Eq. (7), the damage probability-angle plot can be obtained, as shown in Fig. 12. By searching all the damage probabilities of the positions on the plate based on Eq. (8) and the damage probability-angle plot, the damage angle image of each linear PZT array can be obtained, as shown in Fig. 13. After that, the damage coordinate image can be obtained by fusing the damage angle images of the two linear PZT arrays, as shown in Fig. 14. Finally, the damage position (29.3, 9.5) cm can be calculated by using the coordinate probability weighted algorithm, and the damage localization error is 0.86 cm.

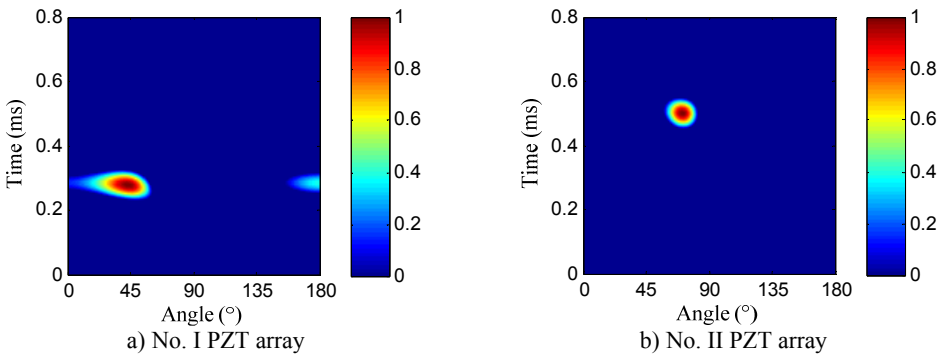


Fig. 11. Damage angle-time images

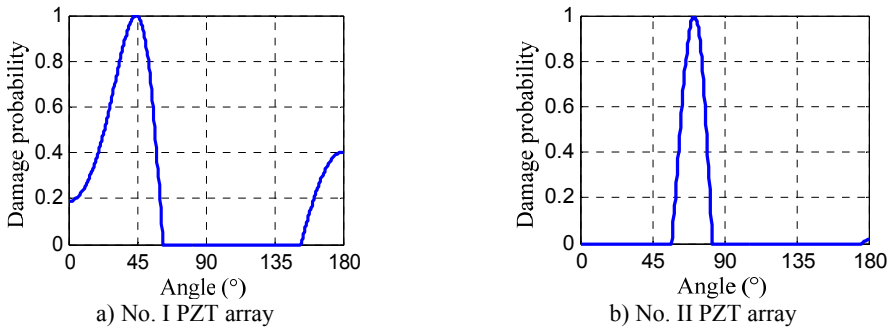


Fig. 12. Damage probability-angle plots

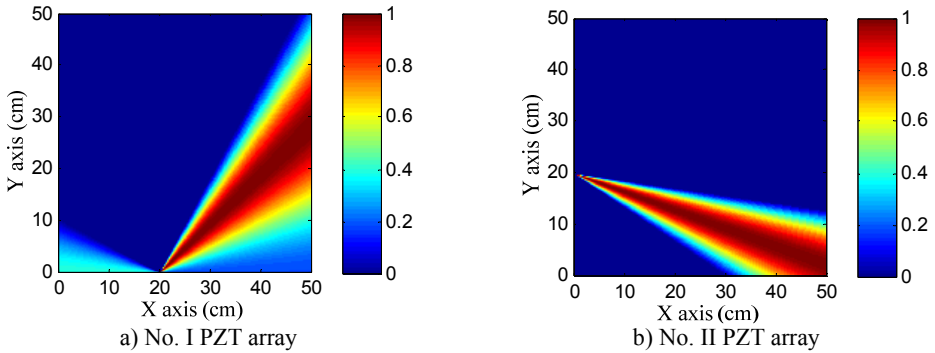


Fig. 13. Damage angle images

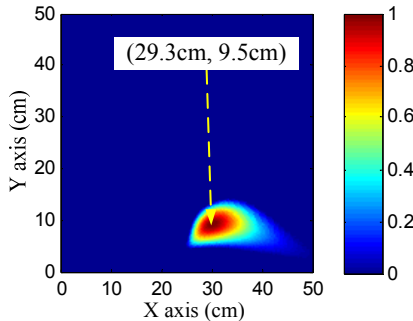


Fig. 14. Damage coordinate image

According to the damage imaging process of position B discussed above, the imaging and location results of the 8 damages, and the distance errors comparing with actual damage positions are listed in Table 3. It indicates that the maximum damage localization error is no more than 1 cm.

An impact hammer is used to introduce an impact of 2 J energy on the structure. 8 impacts are performed at the positions shown in Table 2 by using the impact hammer in turn. The trigger voltage is 1 Volts, the sampling rate is 1 MHz, and the sampling length is 5000 samples including 1000 pre-samples.

The impact imaging of position B is chosen to be an example to show the impact imaging method. The impact response signals of the two linear PZT arrays are shown in Fig. 15 and the frequency narrowband signals extracted from impact response signals by using the complex Shannon wavelet transform are shown in Fig. 16. The center frequency of these frequency narrow band signals is $f_c = 30$ kHz and the frequency band is 6 kHz.

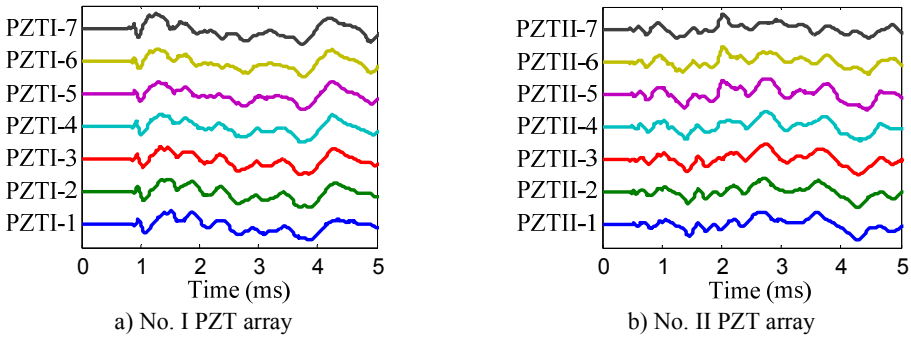


Fig. 15. Impact response signals

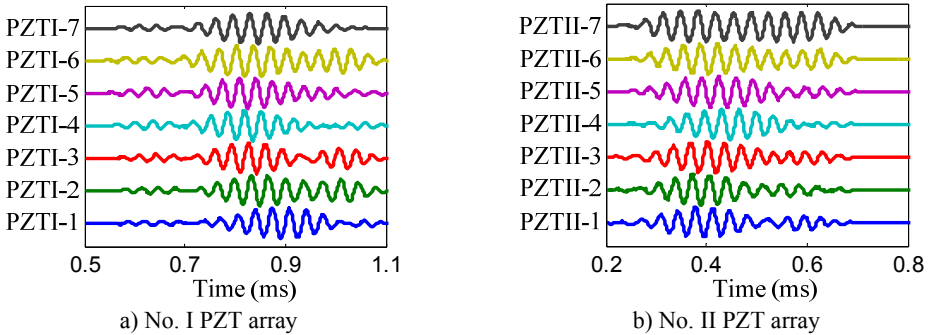


Fig. 16. The extracted frequency narrowband signals

The parameters of the spatial filter are set to be the same with damage imaging. The impact angle-time image of each linear PZT array can be obtained by spatial filtering the frequency narrowband signals, as shown in Fig. 17. Then the impact probability-angle plot of each linear PZT array can be obtained by using Eq. (7), as shown in Fig. 18. By searching all the impact probabilities of the positions on the plate based on Eq. (8) and the impact probability-angle plot, the impact angle image of each linear PZT array can be obtained, as shown in Fig. 19. Then the impact coordinate image can be obtained by fusing the impact angle images of the two linear PZT arrays, as shown in Fig. 20. The impact position (29.1, 10.4) cm can be calculated by using the coordinate probability weighted algorithm, and the impact localization error is 0.98 cm.

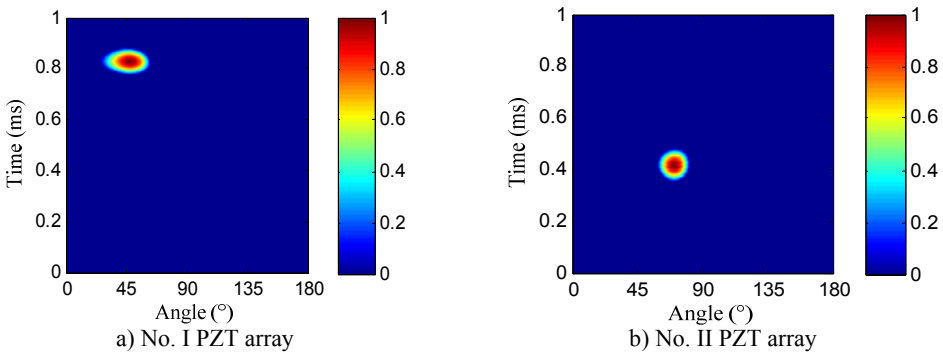


Fig. 17. Impact angle-time images

According to the impact imaging process of position B discussed above, the impact imaging and location results of the 8 impacts, and the distance errors comparing with the actual impact positions are listed in Table 3. It indicates that the maximum damage localization error is no more than 1 cm.

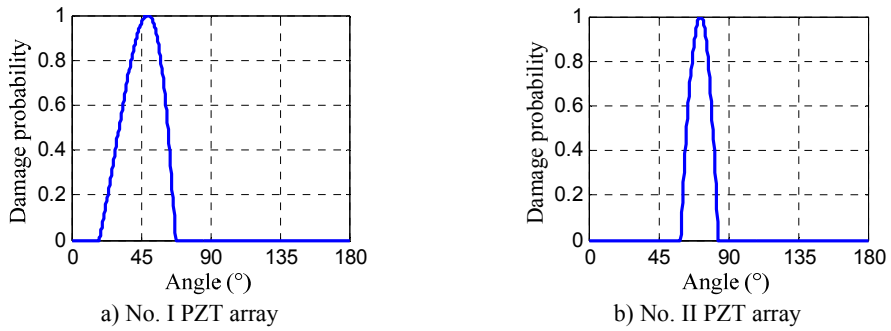


Fig. 18. Impact probability-angle plots

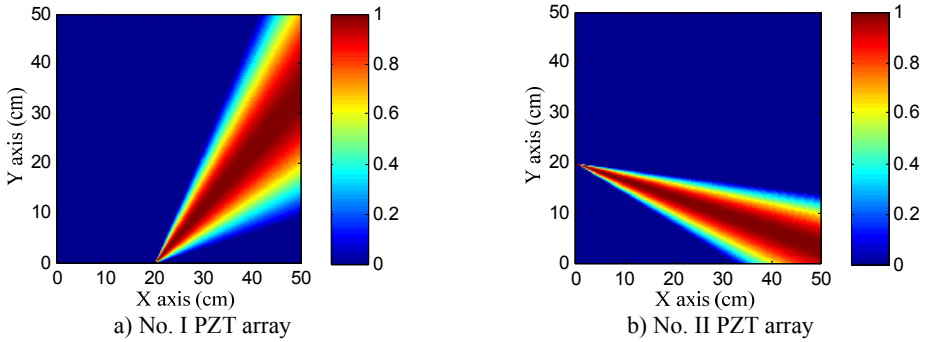


Fig. 19. Impact angle images

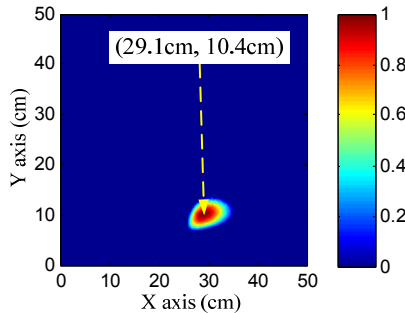


Fig. 20. Impact coordinate image

Table 3. Damage and impact localization results without using Lamb wave group velocity

Position	Actual coordinates (cm)	Damage		Impact	
		Location (cm)	Distance error (cm)	Location (cm)	Distance error (cm)
A	(20, 10)	(19.7, 9.4)	0.67	(19.5, 10.7)	0.86
B	(30, 10)	(29.3, 9.5)	0.86	(29.1, 10.4)	0.98
C	(10, 20)	(10.8, 19.7)	0.85	(10.3, 19.7)	0.42
D	(20, 20)	(19.6, 19.1)	0.98	(19.4, 19.3)	0.92
E	(30, 20)	(29.5, 19.5)	0.71	(29.4, 19.3)	0.92
F	(10, 30)	(10.7, 30.6)	0.92	(10.8, 30.5)	0.94
G	(20, 30)	(19.7, 29.9)	0.32	(19.5, 29.4)	0.78
H	(30, 30)	(29.3, 29.8)	0.73	(29.1, 29.9)	0.90

5. Conclusions

This paper proposes a spatial filter and two linear PZT arrays based composite structure

imaging method. Each PZT array can be used to estimate the angle of the acoustic source accurately based on the spatial filter. By fusing the angle estimation results of the two linear PZT arrays, the acoustic source can be localized accurately without using the Lamb wave group velocity. This method can be applied to damage and impact localization of composite structures easily and accurately. The validation results on a carbon fiber composite laminate plate show that the damage and impact localization errors are less than 1 cm. However, detailed research also needs to be performed on real aircraft composite structures in the future.

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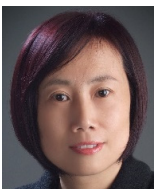
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