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Damage detection in composite laminates based on Hyperbolic Location Method

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Abstract: Hyperbolic location method based on ultrasonic Lamb wave is proposed in this paper. Compared with Ellipse location method, Hyperbolic location method has the advantages of no need of material parameter information, no frequency dispersion relation and no influence of anisotropy. It can be better applied to damage detection of composite laminates
Keywords: Lamb waves, Hyperbolic location method, Composites, Damage imaging

I. INTRODUCTION

Composite materials have been widely used in aerospace, defense industry, civil industry and other fields because of their excellent properties such as low density, high specific strength and high specific modulus. However, due to the complex manufacturing process of the composite material and the harsh service environment, various damages are unavoidable. The occurrence of damage will reduce the strength of the structure and endanger the safety of the structure. Although most composite structures are designed according to damage tolerance guidelines(C. G. Dávila and C. Bisagn 2017), it is still particularly important to detect and evaluate damage before it appears and expands. Lamb waves are widely used in the nondestructive testing of plate structures due to their advantages of long propagation distance, small energy attenuation and large detection range(C. R. Farrar and K. Worden 2007). Among them, the ellipse positioning method based on Lamb wave has a lot of research and development in the application of damage location of plate structures because of its advantages such as simplicity, efficiency, convenience and speed. Bin Yang et al. (2017) developed a defect imaging algorithm using MATLAB based on the ellipse theory in time-dependent domains. Two defect imaging cases were carried out in the WGF/epoxy composite plate to verify the feasibility of the proposed algorithm. Guangtao Lu et al. (2018) developed an algorithm to detect damage size and shape using a lead zirconate titanate (PZT) transducer array for a plate structure. Jian He et al. (2018) used symmetric and anti-symmetric methods, respectively, to determine a crack identification signal by obtained two types of single-mode Lamb waves. Liang Zeng et al. (2019) aim at exploiting information encoded in multipath scattering Lamb wave signals, so that damage imaging could be achieved with as few as possible sensors. On this basis, a modified elliptical method is established to accommodate for these multipath scattering signals for damage imaging. M. Saqib Hameed and Zheng Li (2019) proposed a damage detection method for composite laminates which used piezoelectric (lead zirconate titanate, PZT) transducers to excite/sense the Lamb wave signals. The transducers are arranged on a composite laminate in the form of a network of square detection cells and triangular subcells. The damage location is estimated using the concept of centroid in two-stage detection method. The first stage detection is carried out by exciting a transducer at the center of each detection cell to locate the damaged cell and subcell. The damage localization is improved by exciting an additional transducer at the corner of the damaged subcell during the second stage detection. The damage size is then quantitatively estimated using cubic spline curve (CSC) and elliptical parametric (EP) methods based on the damage edge points. Shuangmiao Zhai et al. (2019) proposed a novel method based on zero-signal filling to improve the imaging accuracy. The effectiveness of discrete ellipse imaging algorithm for the defect detection in curved plates has been investigated experimentally. The experiment with different sensor arrays and different numbers of sensors has been conducted. Experimental results show that the sparse array has a better imaging accuracy and the imaging accuracy improves as the number of sensor increases. The ellipse positioning method needs to know the propagation speed of the guided wave in the material in advance. The propagation speed of the guided wave in the composite material is often difficult to obtain and has anisotropic characteristics. Therefore, the propagation time of the guided wave is difficult to accurately locate. The effect will distort and elongate the waveform, and also reduce the accuracy of acquiring the guided wave propagation time. In view of the limitations of the ellipse positioning method in the detection of composite damage, this paper proposes a new Hyperbolic Location Method (HLM). The method uses a linear sensor array to receive Lamb wave signals, analyzes the phase change of the damage scattered signal, obtains the initial phase of the damage scattered signal at the damage by inverting the phase, and uses the similarity of the initial phase as the damage imaging index to achieve damage location. The Hyperbolic Location Method has the advantages that it does not require material parameter information, does not involve the dispersion relationship, and is not affected by material anisotropy, and is very suitable for damage detection of plate-shaped composite materials. In this paper, the commercial software COMSOL is used for numerical simulation analysis, and the Hyperbolic Location Method is successfully used to locate the damage of the orthotropic composite plate.

II. BASIC THEORY OF HYPERBOLIC LOCATION METHOD

Due to the dispersion, multi-mode and other characteristics of guided waves and the anisotropic characteristics of composite materials, the propagation of Lamb waves in composite materials is very complicated, which makes elliptical positioning methods that rely solely on the propagation velocity information of guided waves cannot be applied to composite Material or damage positioning accuracy is limited. For this reason, this paper proposes the HLM. The HLM is based on the idea that the distance difference between any point on the hyperbola and the two focal points is a fixed value, and the real axis of the hyperbola is determined by the phase difference.

Fig. 1 shows the theoretical schematic diagram of the HLM. In the process of damage location based on ultrasonic guided waves, guided waves propagate through the structure and interact with the damage. The damage can be regarded as a secondary wave source. Damage location can be achieved by analyzing the scattered wave information of the damage. In the theory of HLM, damage scattering signals are received through several linear sensor array elements with equal spacing. In each pair of receiving array elements as shown in Fig. 1, since the array element spacing is sufficiently small, the wave speed of the damage scattered wave propagating along the damage source to each receiving array element is considered to be the same, so the The anisotropy of the composite material will not affect the hyperbolic positioning method. The phase spectrum of the damaged scattered signal at a pair of receiving array elements can be obtained by Fourier transform:

$$\begin{aligned} &F_m(\omega) = \int_{-\infty}^{+\infty} u(x_m, t) e^{-i\omega t} dt \\ &\varphi_m^{\omega} = \arctan\left[\frac{\mathrm{Im}(F_m(\omega))}{\mathrm{Re}(F_m(\omega))}\right] \end{aligned} \quad (m = 1,2) \tag{1}$$

where $u(x_m, t)$ are the wave signals detected by two sensors, x_m are the locations of the sensors, $\mathrm{Im}(\bullet)$ and $\mathrm{Re}(\bullet)$ are the imaginary part and real part of the complex number respectively. The harmonic components of the scattering waves are expressed as

$$u^{\omega}(x_m, t) = A_m^{\omega} e^{i\left(\mathbf{k}_{\mathbf{r}}^{\omega} \bullet \overrightarrow{x_m} \ \ \omega t\right)} \ (m = 1,2) \tag{2}$$

where A_m^{ω} is the amplitude of circular frequency ω, $\overrightarrow{x_m}$ is the vector from the defect point to x_m, $\mathbf{k}_{\mathbf{r}}^{\omega}$ is the wave number of ω along the direction of the scattering wave propagation path. Then the phase difference of each frequency between two measuring points is calculated $\Delta\varphi^{\omega}$, which indicates the path-difference,

$$\Delta l = \Delta\varphi(\omega) / \left|\mathbf{k}_{\mathbf{r}}^{\omega}\right| \tag{3}$$

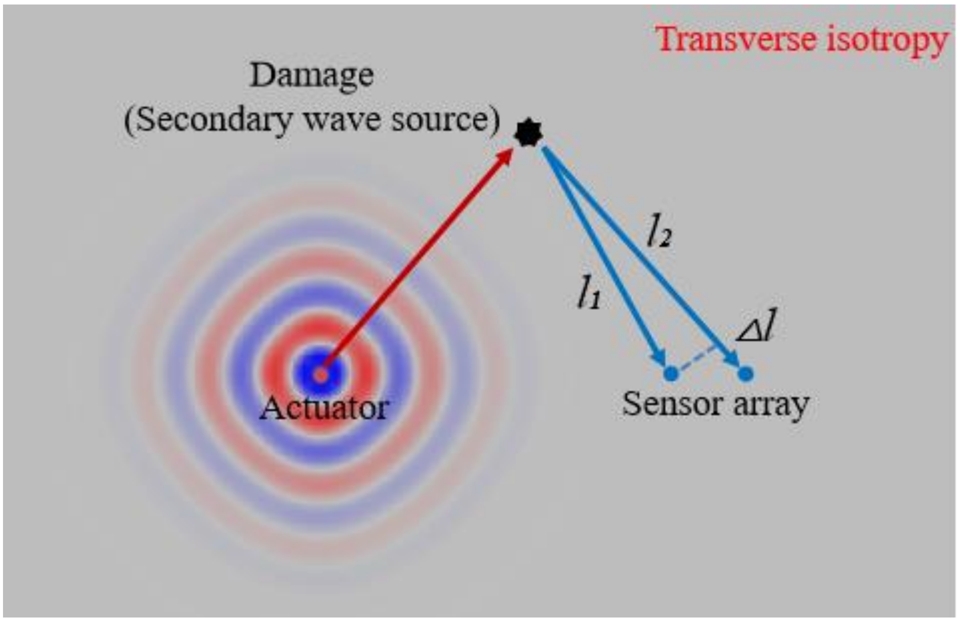


Figure 1: Schematic diagram of HLM

By reversing the phase angles of each frequency from sensors to wave source along the propagation path, the phase spectrum Φ^{ω} of scattering signal at the wave source will be determined by Eq. (4),

$$\Phi^{\omega} = \overline{\varphi^{\omega}} - \Delta\varphi^{\omega} \quad \bar{l}/\Delta l \tag{4}$$

where $\overline{\varphi^{\omega}}$ and $\bar{l}$ are the mean value of phase angle and path distance respectively. It is important to note that, this phase reversal process only could be achieved as the two sensors are close enough to each other, thus the direction of wave propagation from the wave source to each sensor can be considered the same, otherwise, the different velocities in two directions due to the composite laminates character will affect the accuracy of the results. At the damage scattering source, the initial phase of the damage scattered signal reconstructed by each pair of receiving array elements should theoretically have a high consistency. The damage imaging index(DI) is defined as the similarity of the reconstructed phase:

$$DI(x, y) = \frac{C_n(x, y)}{\max\left(C_n(x, y)\right)} \tag{5}$$

Where $C_n(x, y)$ represents the correlation coefficient of the reconstructed phase at (x, y). Take three adjacent receiving array elements as a group, n represents the serial number of each receiving array element, and the phase correlation coefficient is defined as

$$C_n(x, y)\frac{Cov\left(\Phi_1^{\omega}(t), \Phi_2^{\omega}(t)\right)}{\sqrt{Var\left(\Phi_1^{\omega}(t)\right) \; Var\left(\Phi_2^{\omega}(t)\right)}} \tag{6}$$

It can be drawn from Equation 4 that the imaging curve of the HLM is a hyperbola passing damage location. The value of the phase difference is the difference between the distance from each point on the hyperbola to the focal point, and the real axis of the hyperbola is the Φ^{ω} of the damage scattering signal obtained by the change of the phase difference at the damage. The HLM does not involve the dispersion relationship and does not require material parameters. At the same time, the phase solution process is conducted along the guided wave propagation path. The anisotropy of the material does not affect its effectiveness. Therefore, this method is very suitable for damage detection of composite material structures.

III. NUMERCIAL ANALYSIS OF DAMAGE IMAGING IN COMPOSITE LAMINATES

Taking the transversely isotropic composite laminate as the research object, the structural model is shown in Fig. 2, where the size is 300mm*200mm*1mm. The excitation source is located in the center of the board, and the signal receiving array element is set as two linear arrays on the positive half axis of the coordinate axis. Take the through hole with a diameter of 10 mm as the damage, and its position coordinate is (30mm,40mm). The composite material parameters are shown in Table 1.

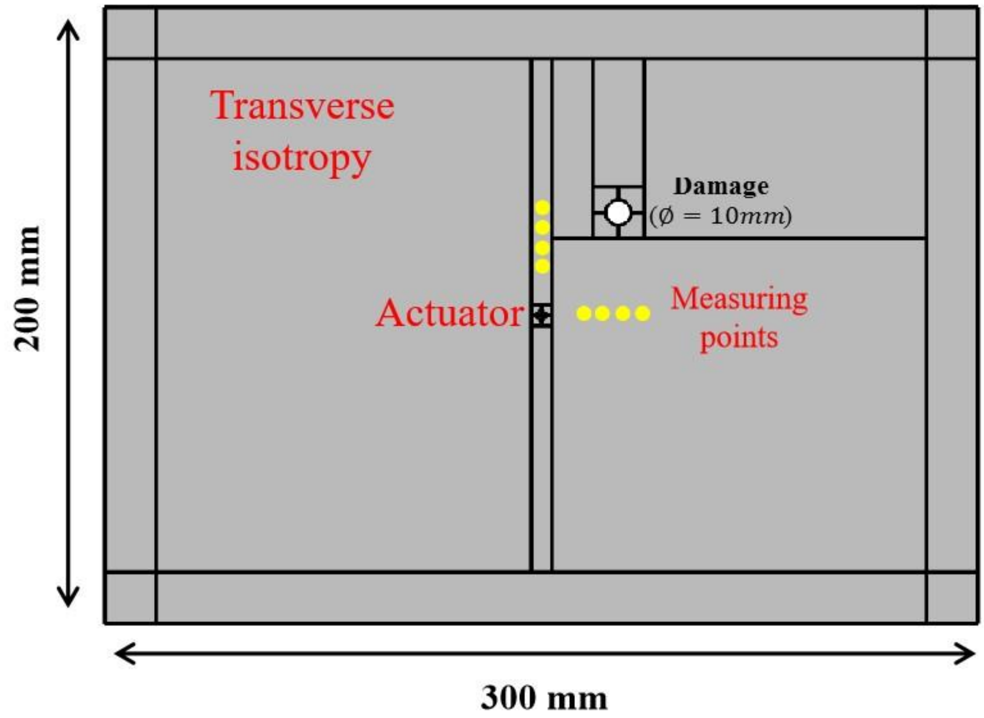


Figure 2: Schematic diagram of the composite laminate and the sensor array

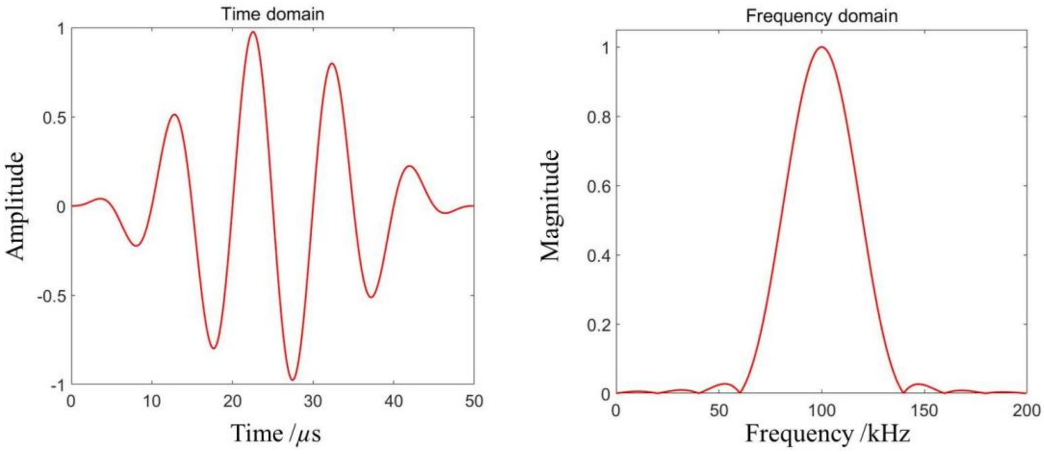
TABLE 1. The parameters of orthotropic composite

Thickness	E_{11}	E_{22}	G_{12}	G_{23}	v_{12}	v_{23}
1mm	178GPa	8.62GPa	5.2GPa	3GPa	0.34	0.3

The external load applied to the board structure is usually called the excitation signal. The excitation signal can be divided into narrow-band excitation and wide-band excitation according to the bandwidth. The broadband excitation contains high-frequency components, and the Lamb wave has multi-modal characteristics in the structure and is affected by the dispersion effect, which makes the signal complex and difficult to analyze. The narrowband excitation is relatively less affected by dispersion, the waveform distortion is not significant, and the signal is simple and conducive to analysis. Under comprehensive consideration, the HLM uses the five-peak wave narrowband signal modulated by the Hanning window as the excitation signal, and its expression is:

$$S = \frac{A}{2}\left[1-\cos\left(\frac{2\pi f_c}{n}\right)t\right]\cdot\sin(2\pi f_c) \tag{7}$$

Where A represents the amplitude of the excitation signal, f_c is the center frequency, 100kHz was chosen in this paper. The time and frequency domain diagrams of the excitation signal are shown in Fig. 3.



(a) (b)

Figure 3: (a)Time domain ;(b) Frequency domain;

In the use of the finite element method to deal with ultrasonic Lamb waves, the mesh size of the model is related to the wavelength of the guided wave propagating in the structure, and the stability, convergence and accuracy of the final calculation result depend on the size of the division precision. In order to improve the accuracy of the calculation results and ensure that the simulation results are closer to the actual results, it is usually required that the grid division size be as fine as possible under the allowable conditions. However, the excessively fine grid size requires a lot of calculation time and requires very powerful computer performance. Therefore, under the condition of satisfying the calculation accuracy while ensuring the solution efficiency, the grid size should meet:

$$\Delta l \leq \frac{\lambda_{\min}}{10} \tag{8}$$

Where $\lambda_{\min}$ is the shortest wavelength of Lamb wave in the model.

In order to take into account the accuracy and efficiency of the finite element calculation results, the solution time step in the finite element should meet the stability requirements of numerical calculation. According to the Newmark time increment scheme, the Lamb wave in the composite material plate contains at least 20 time steps during the period of one cycle of propagation:

$$\Delta t \leq \frac{1}{20 f_{\max}} \tag{9}$$

Where $f_{\max}$ is to calculate the maximum frequency value in the frequency band.

In this study, an ultrasonic Lamb wave with a center frequency of 100 kHz and A_0 mode as the dominant signal is used as the excitation signal, and the corresponding wavelength is 10.9mm. Under comprehensive consideration, the mesh size of the model in the finite element simulation is set to 1 mm, and the time step is selected to be 0.01 μs, taking into account the accuracy requirements and calculation efficiency.

Fig. 4 shows the wave field diagram of the transversely isotropic composite laminate obtained by finite element calculation at various times. Due to the anisotropic characteristics of the composite material, the guided wave propagation velocity is direction-dependent, so the wavefront is elliptical shape.

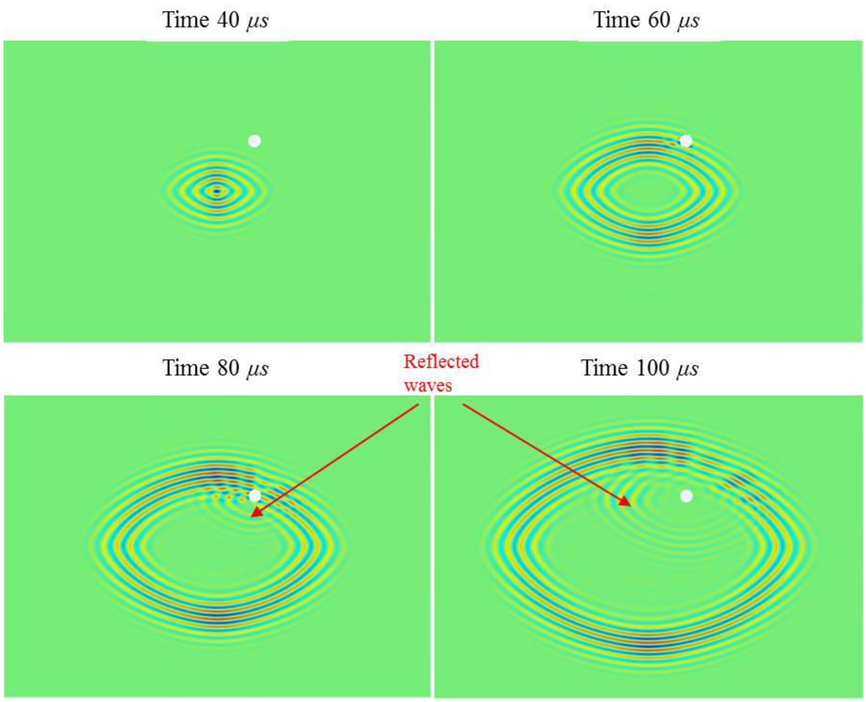
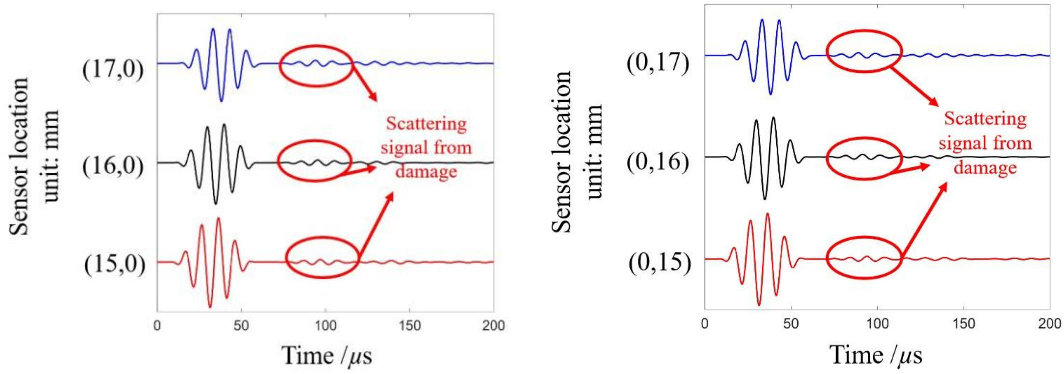


Figure 4: The wave field diagram of transversely isotropic

Two linear array elements located on the positive half axis of the coordinate axis are used to receive damage scattering signals. The position and number of array elements are shown in Table 2. The out-of-plane displacement signal of each measuring point is extracted for damage location imaging, and the signal of the measuring point is shown in Fig. 5.

TABLE 2. The locations and quantities of four sensor arrays

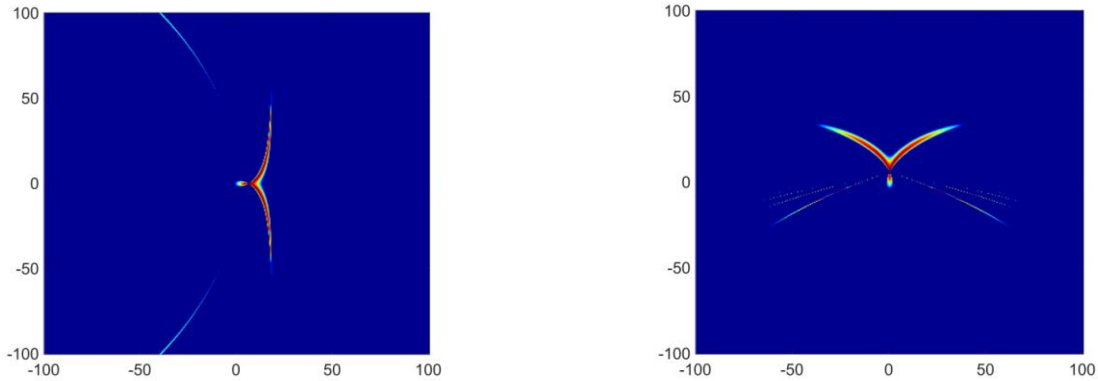
	x axis (positive)	y axis (positive)
sensors location	from 15mm to 17 mm	from 15mm to 17mm
quantity of sensors	3	3



(a) (b)

Figure 5: (a)Signal of measuring points on the x-axis; (b) Signal of measuring points on the y-axis;

According to the theory of the HLM, the imaging matrix can be obtained by three linear arrays with a pitch of 1 mm. Fig. 6 is the imaging matrix obtained by three measurement points of the x-axis and the y-axis respectively.



(a) (b)

Figure 6: (a)Imaging matrix from the x-axis; (b) Imaging matrix from the y-axis;

Adding and fusing the imaging curves obtained from different sets of measuring points can realize the intersection of the hyperbola at the injury, thus achieving the location of the injury. The final imaging result obtained by the HLM is shown in Fig. 7.

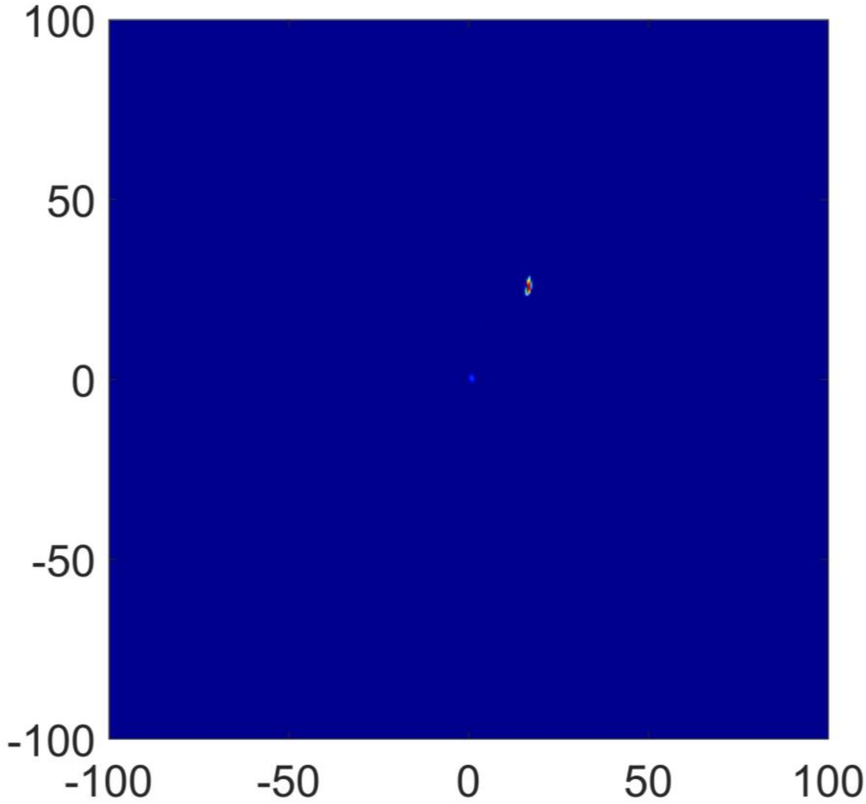


Figure 7: Imaging result by HLM

IV. CONCLUSION

Through numerical simulation, the Hyperbolic Location Method is used to locate the damage of the transversely isotropic composite laminates Compared with the traditional ellipse positioning method, the HLM can realize the composite material damage detection without the need of material parameter information, frequency dispersion relationship and not affected by the anisotropic characteristics of the composite material.

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