Ultrasonic Guided Wave Imaging Method Based on Particle Swarm Optimization for Composite Damage Monitoring

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ABSTRACT

Due to the dispersion and multi-mode characteristics of ultrasonic guided waves, many current imaging techniques based on ultrasonic guided waves are prone to artifacts and large imaging spots when they are used for structural damage detection. Therefore, an ultrasonic guided wave imaging method based on particle swarm optimization (PSO) is proposed in this paper to transform the problem of damage imaging into a problem of damage source search. A fitness function for damage imaging location is proposed. The smaller the difference between the travel time of the scattering signal and the travel time of the particle, the larger the amplitude assigned to the particle. The total amplitude of the particle after superposition of all sensing paths is used as the fitness function. The particle with the largest total amplitude is searched for by the PSO algorithm to achieve damage localization. The experimental results show that the proposed method has successfully detected the crack damage of composite and achieved a better imaging effect. It has higher positioning accuracy compared to other imaging methods.

INTRODUCTION

Ultrasonic guided wave [1,2] has become one of the powerful damage detection tools in the field of non-destructive testing (NDT) and structural health monitoring (SHM) due to its sensitivity to structural damage, large detection range and high detection efficiency.

In recent years, various ultrasonic guided wave imaging methods have been developed for structural damage detection and localization. Wang et al. [3] proposed a delay-and-sum (DAS) imaging method, which shifts and superimposes the scattering signal according to the travel time of the imaging points. Hall et al. [4] proposed minimum variance distortionless response (MVDR) imaging, which uses phase information and a time window to effectively improve the signal-to-noise ratio and suppress imaging artefacts compared to DAS. Intelligent optimization algorithms have been developed rapidly in the field of

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NDT and SHM. Chen et al. [6] proposed a defect search algorithm based on sign coherence factor, which combined evolutionary strategy with clustering algorithm to locate damage by searching scatterers. Li et al. [7] proposed a Lamb wave imaging method based on quantum particle swarm optimization, which optimizes the weight vector of MVDR, realizes the imaging location of aluminum plate damage, significantly improves the imaging quality, but the execution time of the algorithm is prolonged. Intelligent optimization algorithms have shown excellent application prospects in improving the quality of damage imaging.

The rest of this article is organized as follows. Section 2 describes the principle of DAS imaging, PSO theory, the proposed fitness function and the flow of the damage imaging method based on PSO. Section 3 conducts an experiment on damage detection of composite materials using the method proposed in this paper, and gives the experimental results and discussion. Section 4 presents the conclusions of this paper.

THEORY AND METHOD

PRINCIPLE OF DAS IMAGING

Delay-and-sum (DAS) is a widely used damage imaging algorithm. The wave packet of the scattering signal *S*(t) contains damage-related information. The travel time *t* of the imaging point (*x, y*) depends on the sum of the distances from the actuator to the imaging point and then from the imaging point to the receiver. The travel time *t* of path *i* relative to the imaging point (*x, y*) is:

$$t(x,y)=\frac{\left|\overrightarrow{D_{Ai}}\right|+\left|\overrightarrow{D_{Ri}}\right|}{c_g} \tag{1}$$

where c_g is the group velocity of the guided wave, $|\overrightarrow{D_{Ai}}|$ is the distance from the imaging point (*x, y*) to the actuator A_i, and $|\overrightarrow{D_{Ri}}|$ is the distance from the imaging point (*x, y*) to the receiver R_i.

An elliptic imaging trajectory is determined by an actuator-receiver pair. The elliptic imaging trajectory of the wave packet of the scattering signal mapped from the time domain to the space domain. The attenuation width of the elliptic imaging trajectory is determined by the size of the scattering signal wave packet. *M* paths are fused, and the image amplitude *P* (*x, y*) is obtained by superimposing the amplitudes of the scattering signal of each path at the travel time.

$$P(x,y)=\sum_{i}^{M}S_i\left(t(x,y)\right) \tag{2}$$

PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is a swarm intelligence algorithm that simulates bird foraging. Assuming that *N* particle are flying in a *D*-dimensional search space, the information of the particle is determined by the velocity and the position. During the search process, the particle updates its information by finding the individual best position and the global best position. The velocity and position of particle are updated as follows:

$$v_i(t+1) = wv_i(t) + c_1r_1(p_i(t) - x_i(t)) + c_2r_2(g(t) - x_i(t)) \tag{3}$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{4}$$

where $v_i(t)$ and $x_i(t)$ represent the velocity and position of i-th particle, respectively. $p_i(t)$ and $g(t)$ are individual best position and global best position, respectively. r_1 and r_2 are random numbers between [0,1]. c_1 and c_2 represent acceleration factors. w represents the inertia factor.

PROPOSED FITNESS FUNCTION

According to the principle of DAS imaging, a fitness function for damage imaging location is proposed. As shown in Figure 1 (a), the travel time of the scattering signal is obtained. The particle is freely distributed in the two-dimensional space, and the travel time from the actuator to the particle and then to the receiver can be calculated. The time domain information is mapped to the imaging trajectory in the spatial domain by means of a mapping function. The travel time of the scattering signal is compared with the travel time of the particle. The smaller the difference between the two, the closer the particle is to the imaging trajectory where the damage is located, and the greater the amplitude assigned to the particle. Therefore, the amplitude of the imaging trajectory decreases from the central trajectory where the damage is located to both sides, and the width of the imaging trajectory is controlled by the attenuation threshold factor. This process is similar to the attenuation of the DAS imaging trajectory. As shown in Figure 1 (b), all sensing paths are fused to obtain the total amplitude of particle. Finally, the particle with the largest amplitude is searched by the PSO algorithm to locate the damage location. The amplitude of the particle in each sensing path is calculated as follows:

$$p_i(x,y) = \begin{cases} 1 - \dfrac{\left|t_i - t(x,y)\right|}{\tau}, & \left|t_i - t(x,y)\right| \le \tau \\ 0, & \left|t_i - t(x,y)\right| > \tau \end{cases} \tag{5}$$

where, τ is the attenuation threshold factor, $\tilde{t_i}$ is the travel time of the scattering signal for the i-th sensing path, $t(x,y)$ is the travel time of the particle. The expression for $t(x,y)$ is as follows:

$$t(x,y) = \frac{\left|\overrightarrow{D_{Ai}}\right|}{v_g(\beta_{Ai})} + \frac{\left|\overrightarrow{D_{Ri}}\right|}{v_g(\beta_{Ri})} \tag{6}$$

where $|\overrightarrow{D_{Ai}}|$ is the distance from the particle (x, y) to the actuator A_i, and $|\overrightarrow{D_{Ri}}|$ is the distance from the particle (x, y) to the receiver R_i, $v_g(\beta_{Ai})$ is the group velocity when the guided wave propagation angle is β_{Ai}, and β_{Ai} is the angle from the actuator A_i to the particle, $v_g(\beta_{Ri})$ is the group velocity when the guided wave propagation angle is β_{Ri} , and β_{Ri} is the angle from the particle to the receiver R_i.

The total particle amplitude is obtained by superimposing all sensing paths, and is used as the fitness function. The formula is as follows:

$$fitness = \sum_{i=1}^{M} p_i(x, y) \tag{7}$$

where M is the total number of sensing paths.

DAMAGE IMAGING METHOD BASED ON PSO

The maximum value of the fitness function is searched through the PSO iteration, and the particle are constantly close to the damage location. When PSO completes the search, the particle position distribution is used for damage imaging. The flow chart of the damage imaging method based on PSO is shown in Figure 2. The specific steps of this method are as follows:

Step 1: Calculate the group velocities in all directions in CFRP. Obtain the travel time of scattering signal from all sensing paths.

Step 2: Set the population size N, acceleration factors c_1 and c_2, inertia factor w, and maximum number of iterations T. Randomly initialize the position and velocity of particle in the population.

Step 3: Calculate the fitness function values of initial generation particle, and obtain the best fitness function value, individual best position and global best position of the initial generation particle.

Step 4: Update the velocity v and position p of particle with Eqs. (3) and (4), respectively.

Step 5: Calculate the fitness function values of current generation particle.

Step 6: Compare the current generation fitness function values and the best fitness function value, and update the best fitness function value, individual best position and global best position.

Step 7: Determine whether the PSO algorithm meets the termination condition. If the maximum number of iterations is reached, the algorithm ends. Otherwise, proceed to step (4) to continue the iteration.

Step 8: Display the optimized particle position distribution in the form of a binary histogram, and the position with the highest brightness in the graph is the damage imaging localization result.

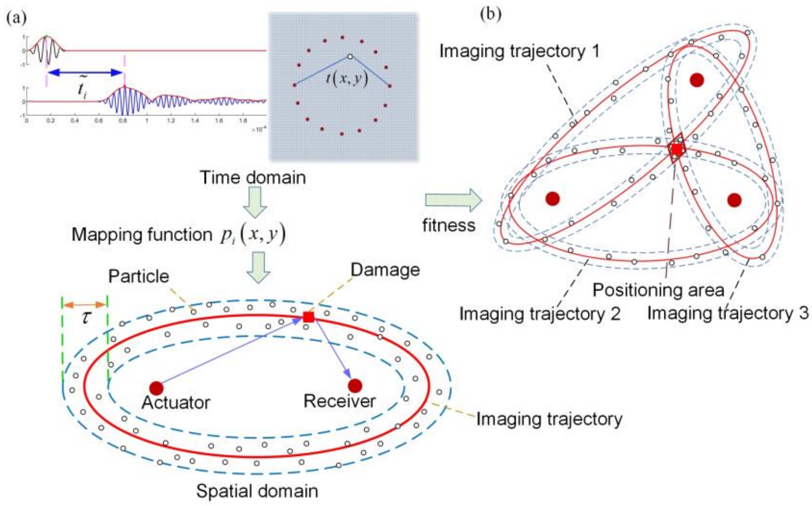

Figure 1. Diagram of fitness function for damage imaging localization: (a) the time domain information is mapped to the space domain to form the imaging trajectory, (b) multi-sensor path fusion damage location.

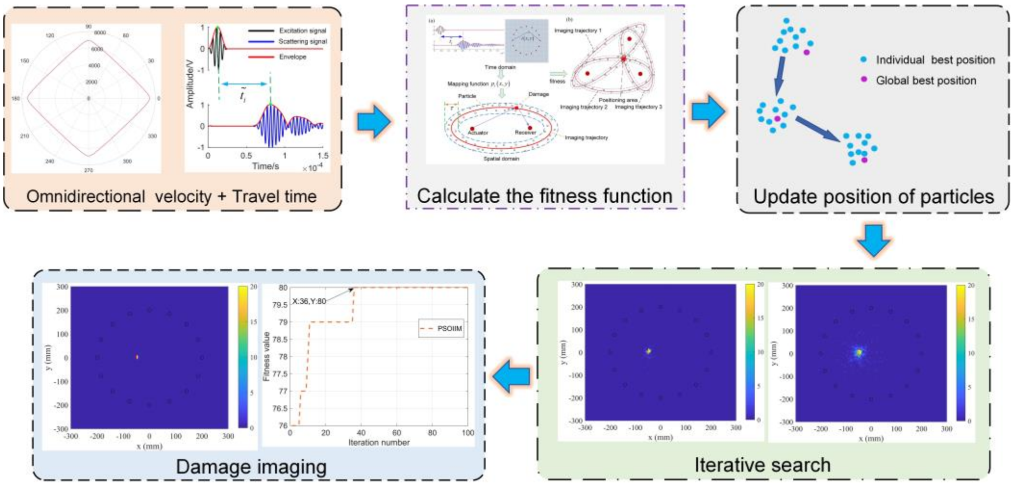

Figure 2 The flow chart of the damage imaging method based on PSO

EXPERIMENTAL SETUP

The experimental setup is shown in Figure 3, including a T300 carbon fiber reinforced plastics (CFRP) plate, a function generator, an amplifier, a data acquisition card and PC. The size of the CFRP plate is $600\ mm \times 600\ mm \times 3\ mm$. The layup form of the CFRP is $[0/90]_{15}$. The piezoelectric lead zirconate titanate (PZT) is used as transmitter and receiver. As shown in Figure 3(b), the PZTs are uniformly distributed on a circle with a radius of 200 mm in the CFRP plate. The crack damage is artificially fabricated on the surface of the CFRP plate, and its size is 5 mm. The center of the CFRP plate is the coordinate origin, and the crack damage is located at (-50 mm, 0 mm). The sinusoidal wave modulated by Hanning window with 5 peaks and 200 kHz center frequency is selected as the excitation signal.

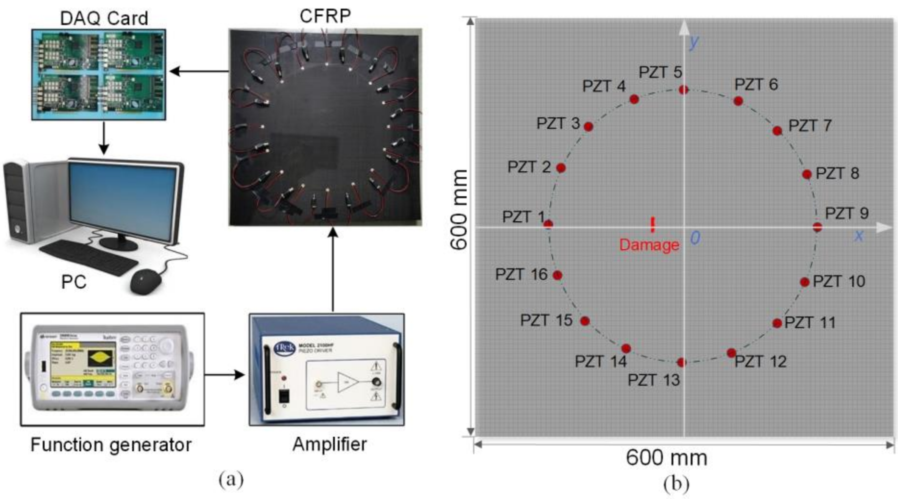

Figure 3 Experimental setup for damage detection of CFRP: (a) connection diagram of experimental setup, (b) distribution diagram of damage and PZT in CFRP plate.

EXPERIMENTS AND DISCUSSIONS

The envelope peak extraction algorithm is adopted to obtain the travel time of the scattering signal. Figure 4(a) shows the process of extracting the travel time of the scattering signal. The omnidirectional guided wave velocity of CFRP is calculated by DC software, and the calculation result is shown in Figure 4(b). The guided wave velocity varies greatly in different directions.

The parameters of the PSO-based imaging method (PSOIM) are initialized, including the population size N is 1000, the maximum number of iterations T is 100, the parameter range of position p is set to [-300, 300], and the parameter range of velocity v is set to [-30, 30]. The MATLAB function "histogram2" is used to plot the distribution of the population. The step size is set to 5 mm in x and y directions. The dynamic range of the "histogram2" is set between 0 and 20. The control parameter $\tau = 4\ us$.

Then, DAS, GA-based imaging method (GAIM), velocity anisotropy probability imaging method (VAPIM) and PSOIM are used to detect the damage of CFRP structure. Among them, the parameters of GAIM are consistent with PSOIM, and the same fitness function is applied. Figure 5(a)-(d) shows the detection results of different imaging methods. Figure 5(a) illustrates the detection result of DAS. The imaging result is seriously deviated from the actual damage location, and false imaging are generated. Figure 5(b) shows the detection result of VAPIM. This method has corrected the wave velocity of CFRP structure. The brightest part of the imaging results appears at the damage location, but artifacts appear on the left and right sides of the damage. Figure 5(c) displays the detection result of GAIM. In the graph, the imaging spot is almost located at the actual damage position. However, the imaging result produces artifacts. Figure 5(d) reveals the detection result of PSOIM, and the imaging spot accurately describes the position of actual damage.

Figure 6(a) illustrates the convergence curves of the fitness function for GAIM and PSOIM. It can be seen from the diagram that the fitness functions of the GAIM and the PSOIM have converged in the 40th and 36th generation, respectively. It shows that the convergence speed of PSOIM is faster. Figure 6(b) shows the comparison of the positioning errors for different imaging methods. It can be seen from the drawing that the positioning error of DAS is the largest. Compared with DAS, the positioning error of VAPIM after wave velocity correction is greatly reduced, but the positioning error is still more than 10 mm. The positioning errors of GAIM and PSOIM are less than 10 mm, among which PSOIM has the best positioning performance.

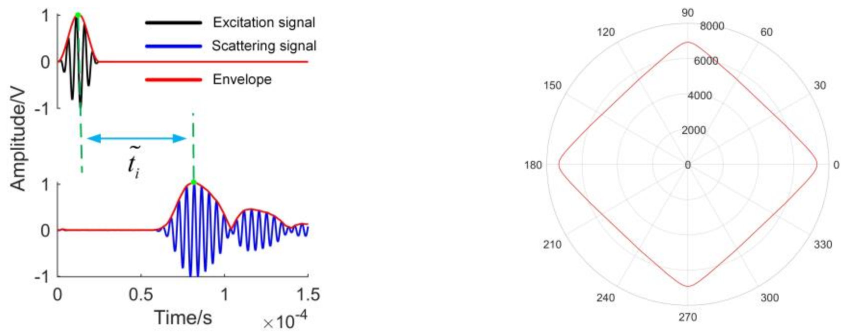

Figure 4 (a) Travel time of scattering signal, (b) omnidirectional guided wave velocity of CFRP

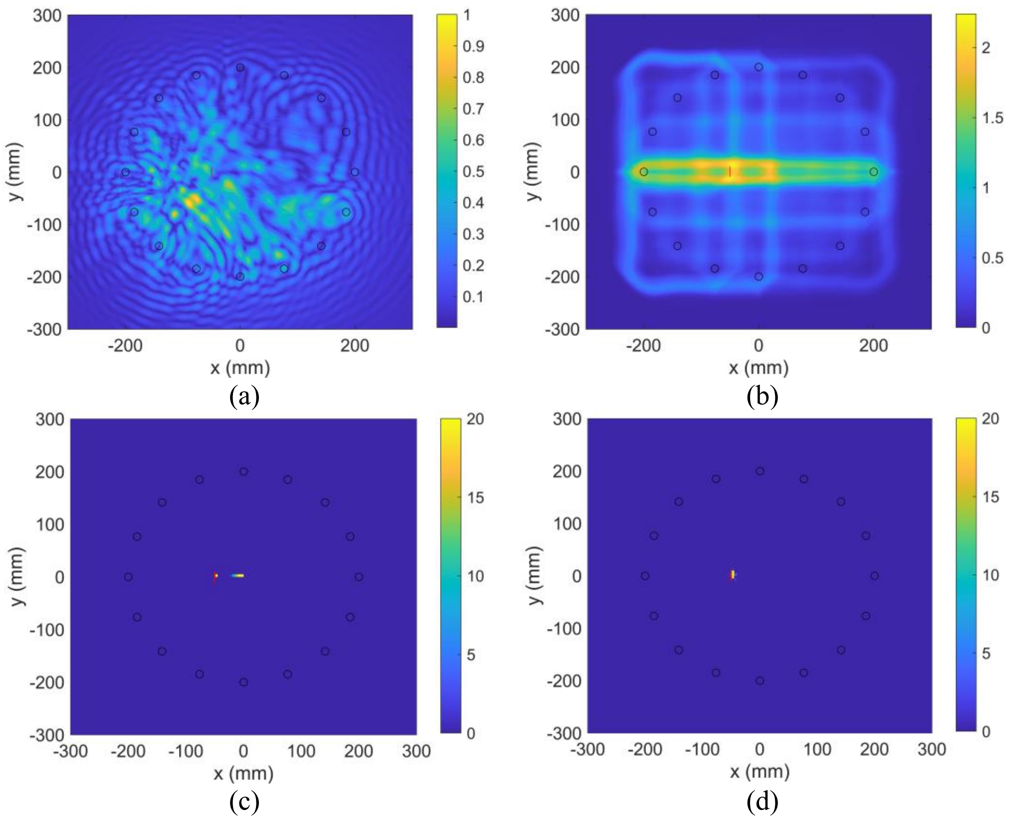

Figure 5 Comparison of imaging results of different methods: (a) imaging result of DAS, (b) imaging result of VAPIM, (c) imaging result of GAIM, and (d) imaging result of PSOIM.

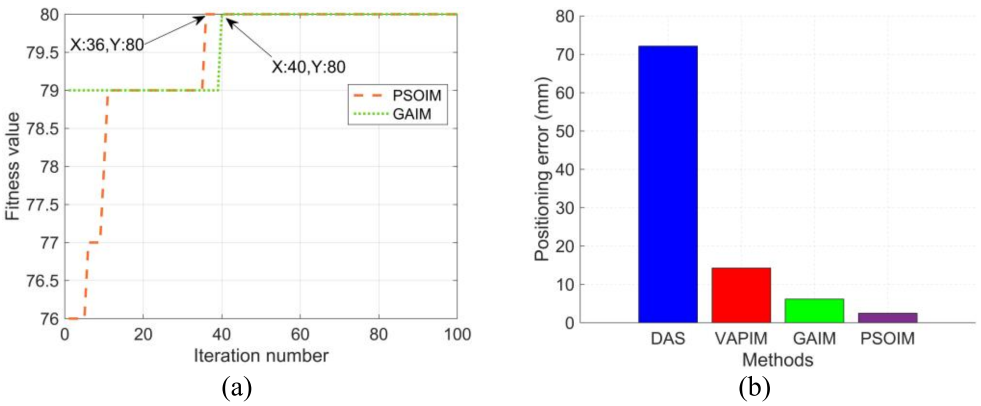

Figure 6 (a) Fitness function convergence curves for GAIM and PSOIM, (b) positioning errors for different imaging methods.

CONCLUSIONS

In order to improve the damage imaging accuracy of composites, an ultrasonic guided wave imaging method based on PSO is proposed, which transforms the damage imaging problem into damage sources search problem. Experimental results show that compared with other imaging methods, the proposed method has lower positioning error, and more accurately displays the location of the damage, eliminating imaging artifacts.

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