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Error Analysis of Time Delay Based on Ultrasonic Phased Array Structural Health Monitoring

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Abstract. Ultrasonic phased array technology becomes significant in structural health monitoring with its flexible beam deflection and strong focusing performance. The transducer is used to complete the multiple directions scanning of the structure. During the process of beam scanning, the signal exciting from each element needs to add a time delay in time domain, due to the difference to the distance from each element to the far field target point, so that the excitation signal can reach the target point and the far field at the same time. Besides, in the process of receiving and transmitting process, it also needs to add a time delay for the response signal, so that the sensor can receive the reflection signal from the preset deflection angle. Therefore, the error will be generated in the calculation of time delay. Making the anti-rust aluminum plate as the experimental object, the process of ultrasonic phased array structural health monitoring will be introduced. And then the reason of time delay error will be pointed out and analyzed.

Keywords: error analysis, excitation signal, response signal, structural health monitoring, time delay, ultrasonic phased array

1 Introduction

Structural health monitoring uses the sensor technology and advanced signal processing methods, in the early time when structural damage occurred, for real-time monitoring of response of the detected structure and properties of the target system. So it is a technology on the performance of structure and damage of detection [1-4]. Ultrasonic phased array monitoring and imaging technology is a new development direction in the field of structural health monitoring. Ultrasonic phased array structural health monitoring is a technology that uses ultrasonic phased array transducer to scan the structure. Ultrasonic phased array transducer is an array composed of multiple independent piezoelectric elements arranged in a certain way in space. Each piezoelectric element is an array, and when each element excites the signal with the same frequency, the sound issued by them is irrelevant. And the ultrasonic wave will be a beam with a spatial interference specific directivity or focusing characteristics in the space. Using the electronic technology, exciting each element controlled by certain rules and timing, a new wave front will be formed by emitting ultrasonic waves by each array element in the array [5-6]. This effect is equivalent to the change of the spatial arrangement of the transducer beam form, so as to change the

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transducer array radiation direction. Similarly, in the process of receiving the reflection wave, the reception of array and the synthesis of signal are controlled by certain rules and timing, then the synthesis results are displayed in the appropriate form [7]. Therefore, the phased array controls the direction of beam by controlling the time delay of the transmitting and receiving of each piezoelectric element to realize the multiple directions scanning of the structure.

Ultrasonic phased array technology has several incomparable advantages compared with the traditional ultrasonic monitoring method, and the most significant feature is its flexible and effective control of beam pointing [8-11]. At the same time, it can quickly deflection or move the sound beam so as to realize the beam scanning by phase control, without complicated mechanical scanning device. Besides, it can complete the accurate monitoring of complex structural damage. The significant advantages of ultrasonic phased array technology have been greatly developed and applied in ultrasonic detection. Therefore, the ultrasonic phased array technology is also getting more and more attention and concern.

In phased array structural health monitoring, because the distance between each element and the far field target point is not the same, and the propagation velocity of the ultrasonic is same in the same structure, the arrival time to the far field target point from each element is also different. It is needed to make corresponding compensation to signal excited by each element in time, so that the excitation signal can reach the far field target point at the same time. Besides, with the same material, the process of transmitting corresponds to the receiving of the ultrasonic wave. By controlling the time delay of the array element to transmit the signal, the sensor can receive the reflection signal on the preset deflection angle. However, in the experiment, the time uses the point as a unit, while the additional time delay uses “ms” as a unit. Therefore, the calculation of the time delay is related to the existence of errors. In this paper, the anti rust aluminum plate works as the experimental objects in the experiment, and the error of time delay is been analyzed.

2 Phased Array Acoustic Beam Scanning Algorithm

The structure of multi-direction scanning can be completed, due to the phased array transducer with multi-array element for health monitoring of ultrasonic phased array structure [12-14]. The ultrasonic phased array transducer uses electronic scanning beam to realize the focusing or deflection of the structure plane. In the principle of ultrasonic phased array scanning, M array elements place uniformly-spaced in the *xoy* cartesian coordinate system along the x axis, and the distance between adjacent elements is d. Point $P(r,\theta)$ is the far field target, r is the distance between point P and the origin point, and θ is the corresponding beam deflection angle of point P, namely θ is the intersection angle between point P and the x axis. The schematic diagram is shown in Fig. 1.

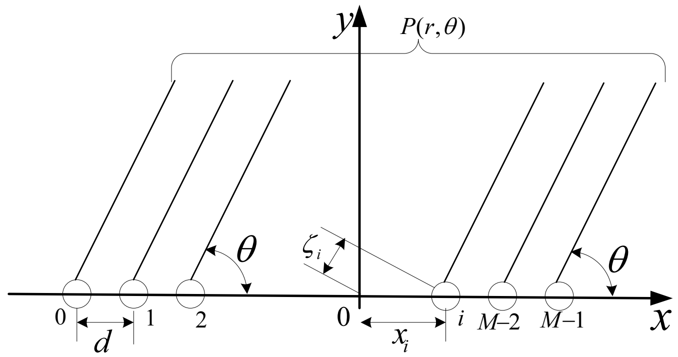


Fig. 1. Ultrasonic phased array detection schematic

The central position of all elements of the linear array is established as the origin of the right angle coordinate system. Then the coordinate of the *i*th element array can be expressed as $(x_i, 0)$, $i = 0, 1, \ldots, M-1$.

$$x_i = \left(i - \frac{M-1}{2}\right) \cdot d \quad \textbf{(1)}$$

In the process of signal transmission, point $P(r,\theta)$ in the far field region can receive the signal which is the cumulative of excitation signal of each element after spreading a certain distance in the structure. Meanwhile, the arrival time to the point P from each element is also different. It needs to add a time delay $\Delta t_i(\theta)$ to the signal excited by each element. So the received signal at the point P can be expressed as bellow.

$$S_P(r,\theta) = K_1 \cdot \sum_{i=0}^{M-1} S_e\left(t - \frac{r}{c} + \delta_i(\theta)\right) \quad \textbf{(2)}$$

where $S_e(t)$ is the excitation signal; K_1 is the amplitude attenuation coefficient after a certain distance spread by the excitation signal in the structure; r/c is the time required by the excitation signal spreading from the origin of coordinates to point P in the far field region; c is the propagation velocity of ultrasonic wave in the structure; $\delta_i(\theta)$ is the time difference between the time received by ith array element arrived at the point P and the coordinate origin, where $\delta_i(\theta) = x_i \cdot \cos\theta / c$, $i = 0,1,\ldots,M-1$.

The time difference is caused by the wave path difference between the distance from the ith array element to the point P and the one from the ith array element to the coordinate origin. If the time delay $\Delta t_i(\theta)$ is equal to the time difference $\delta_i(\theta)$, namely $\Delta t_i(\theta) = \delta_i(\theta) = x_i \cdot \cos\theta / c$, $i = 0,1,\ldots,M-1$, the point P in the far field region can receive the signal with the maximum energy. At this time, the maximum of beam direction for θ, and the signal at the point P can be expressed as below.

$$S_P(t) = K_1 \cdot M \cdot S_e\left(t - \frac{r}{c}\right) \quad \textbf{(3)}$$

Making the beam direction for θ, the time delay of the excitation signal excited by each element is shown below:

$$\Delta t_i(\theta) = \frac{x_i \cdot \cos\theta}{c} = \frac{\left(i - \frac{M-1}{2}\right) \cdot d \cdot \cos\theta}{c} \quad \textbf{(4)}$$

where the subscript i indicates the number of piezoelectric components which is worked as a driver.

When the time delay is $\Delta t_i(\theta) = x_i / c$, that is $\theta = 0^\circ$, the direction of the beam is pointing to the direction of the array; when the time delay is $\Delta t_i(\theta) = 0$, that is $\theta = 90^\circ$, the beam direction is the direction of the y axis. By controlling the time delay of the array element to transmit the signal, the deflection direction of the main beam can be controlled according to the preset deflection angle.

In the same material, the process of transmitting corresponds to the receiving of the ultrasonic wave. By controlling the time delay of the array element to transmit the signal, the sensor can receive the reflected signal on the preset deflection angle. When the array element receives the reflection signal from the point P, adding a time delay $\Delta t_i(\theta)$ to the response signal received by each element, making the ith array element as a sensor, the received signal reflected by the point P in the far field can be obtained.

Making the signal beam scanning in the range of the monitoring angle, when the beam deflection angle corresponds to the damage location direction, the amplitude of the echo signal is the maximum. Otherwise, when the beam deflection angle deviates from the damage location direction, the amplitude of the echo signal is attenuated. By using the target angle measurement principle, the angle of the damage is the direction where the amplitude of the echo signal is the largest.

When the signal in the direction of the damage is known, the distance between the location of the damage and the origin of the coordinate can be determined according to the formula (3). That is, the arrival time can be calculated from the direction of damage, and then the distance from the target to the origin can be obtained according to the structure of the speed of ultrasonic propagation.

$$r = \frac{c \cdot t}{2} \quad \textbf{(5)}$$

Above all, the flow chart of structural health monitoring using the principle of phased array is shown in Fig. 2.

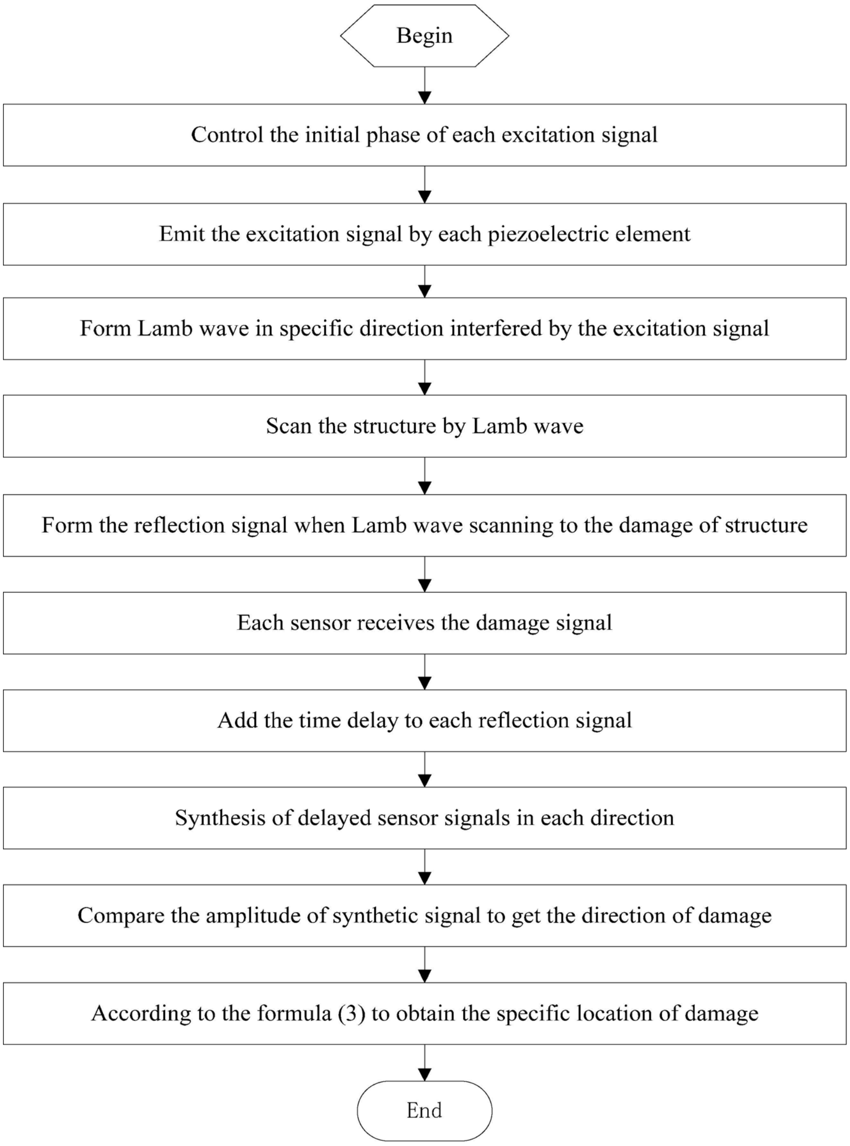


Fig. 2. The flow chart of ultrasonic phased array structural health monitoring

3 Error Analysis of Time Delay

The excitation signal excited by each driver in different directions can be obtained by the base excitation signal after adding the time delay. The control of time delay is the essence of the triggering time of excitation signal excited by the driver in different monitoring direction. Time delay is calculated by the piezoelectric element labeling which works as the driver and the monitoring angle. Moreover, the excitation signal of each driver in different directions can be calculated by adding the additional time delay to the base excitation signal from different drivers in different directions [15].

Ultrasonic signal will generate echo signal when it encountered the defect. The time error of the echo signal arriving to each array element will be exacted, due to the detection encountered by the ultrasonic launched by the transducer. According to the time difference of the echo signal arriving to each element, time delay compensation will be made for each array signal respectively, that is to say, a time delay will be added for reflection signal.

The differential signal is obtained by subtracting the response signals of the health structure and damage structure, so it can also be divided into two parts: excitation and reception. Besides, the additional time delay of the excitation signal and the response signal can be indicated to the additional time delay of the differential signal. Therefore, in this paper, the error of time delay will be analyzed with the performance of the time delay of differential signal.

After adding the time delay to all differential signals, the total synthesis signal of the angle is accumulated with the signal in each angle. The synthetic signal was normalized, that is, the relative amplitude of the point is obtained by comparing the signal amplitude of each point with the maximum amplitude of signal. Then making a comparison of signals in different directions, the angle where the maximum amplitude (the relative amplitude is 1) of the signal is the angle of the damage.

Making a comparison of synthesis signals in different angles, the direction where the maximum energy of the signal is the direction of the damage. Then analyzing the damage direction of synthetic signal, the pole diameter of the signal location can be determined with the equation (5), so as to determine the damage location, the angle error compared with the actual damage location, and the distance error.

The calculation of the angle error is direct subtraction obtained by monitoring the angle of damage location and the angle of real damage location. Besides, the distance error is calculated by cosine theorem, and can be shown as below.

$$\begin{cases} \Delta\theta = \left|\theta_m - \theta_r\right| \\ \Delta r = \sqrt{r_m^2 + r_r^2 - 2\cdot r_m \cdot r_r \cdot \cos\left(\Delta\theta\right)} \end{cases} \tag{6}$$

where $\Delta\theta$ is the angle error between monitoring damage and actual damage, θ_m is the angle of monitoring damage location, θ_r is the angle of actual damage location, Δr is the distance error between monitoring damage and actual damage, r_m is the distance of monitoring damage location, and r_r is the distance of actual damage location.

In the isotropic plate structure, the wave velocity is same in all directions, so that the main reason of the error is the calculation process of the time delay $\Delta t_i\left(\theta\right) = \left(i - \frac{M-1}{2}\right)\cdot d\cdot\cos\theta / c$.

The sampling frequency is *fs*, the time delay corresponding points are $\Delta t_i\left(\theta\right)\cdot f_s$. The value is not necessarily an integer, so in the implementation process, the error in calculation will be exacted due to the corresponding relation conversion between $\Delta t_i\left(\theta\right)$ and the number of points after rounding operation. The rounding error can be expressed as below.

$$round\left(\Delta t_i\left(\theta\right)\cdot f_s\right) = \Delta t_i\left(\theta'\right)\cdot f_s \tag{7}$$

where *round*(·) is the rounding operation in numerical calculation, θ is the ideal monitoring angle, θ' is the angle of the introduced error where $\theta' = \theta + \Delta\theta$, and $\Delta\theta$ is the error of angle. $\Delta t_i\left(\theta\right)$ is the ideal time delay where $\Delta t_i\left(\theta\right) = \left(i - \frac{M-1}{2}\right)\cdot d\cdot\cos\theta / c$, and $\Delta t_i\left(\theta'\right)$ is the time delay due to the introduced error where $\Delta t_i\left(\theta'\right) = \left(i - \frac{M-1}{2}\right)\cdot d\cdot\cos\theta' / c$.

In addition, due to the different type and performance of the material, the propagation velocity in the structure of ultrasonic wave *c* will not be obtained exactly. The error of the wave velocity will be difficult to calculate without definite formula. In the experiment, the error of the wave velocity is not be analyzed into the time delay, and the average velocity is chosen as the wave velocity.

4 Experiment and Result

In the experiment, the experiment object is the anti-rust aluminum plate, and the basic size is 2000*mm*×1200*mm*×1.5*mm*. Eight piezoelectric elements are composed of a linear array in the structure, and the radius and thickness of each piezoelectric array element in the linear array are 4*mm* and 0.48*mm*, respectively. Besides, the spacing between adjacent piezoelectric elements are 12*mm*, and each array element is labeled with 0~7, as shown in Fig. 3. Meanwhile, the sampling frequency is *fs*=1.6*MHz*.

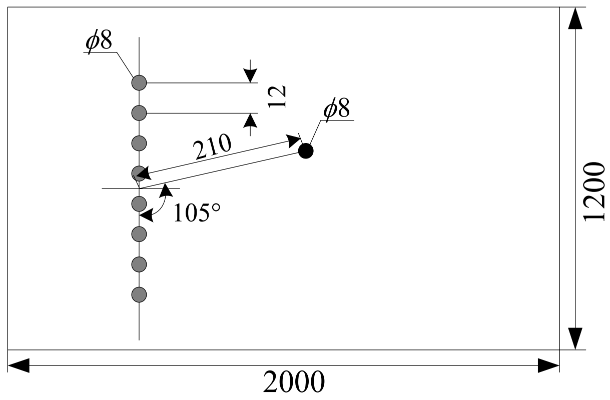


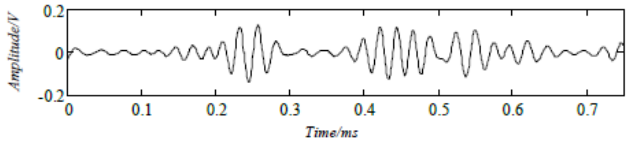
Fig. 3. Schematic diagram (unit/*mm*)

When the piezoelectric element is used as the driver, the five wave peak narrow band sinusoidal modulation signal is excited, the maximum amplitude of the signal is 5*V*, the center frequency is 40*KHz*, and the piezoelectric element as the sensor sampling frequency is 1.6*MHz*. The array element number *M* is 8, the distance between the array elements is 12*mm*, and the wave velocity of Lamb wave in the aluminum plate structure is 1.5*km/s*.

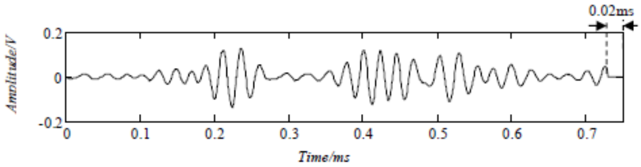
Eight array elements in the linear array stimulate the excitation signal in turns. The whole process makes an array element as a drive transmitting signal, and makes the other seven elements as the sensor receiving the reflection signal. So each degree corresponds to 56 differential signals, then 10080 differential signals can be obtained after completing the monitoring from 0 degree to 180 degree. An example is made to explain the process, because of large amount of the signal, making the 0 degree direction of No.0 element as a drive, and making the No. 1, No. 3, No. 5 and No. 7 arrays as the sensors. The time delay is calculated according to the formula (4). And the time delay of differential signals S_1, S_3, S_5 and S_7 are displayed respectively, as below: $\Delta t_1(\theta) = -0.02ms$, $\Delta t_3(\theta) = -0.004ms$, $\Delta t_5(\theta) = 0.012ms$, $\Delta t_7(\theta) = 0.028ms$. The differential signals S_1, S_3, S_5, S_7 and the time delay waveform of differential signals is shown in Fig. 4.

In this experiment, the number of piezoelectric elements is M=8, the array element spacing is d=12*mm*, the sampling frequency is fs=1.6*MHz,* and the wave speed of the Lamb wave in the structure is 1.5*km/s*.

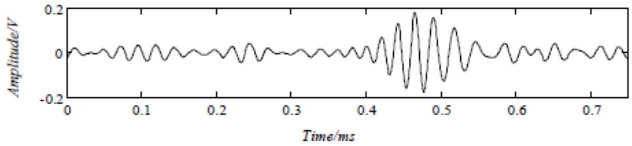
Compared with the synthetic signal at each angle, the angle of the strongest signal is the direction of the damage, and then the synthetic signal of the direction of the damage is analyzed. According to equation $r = \frac{c \cdot t}{2}$, the pole diameter of the signal in polar coordinates can be determined, so as to determine the damage location is (107°, 217*mm*). Besides, according to equation $\begin{cases} \Delta\theta = \left|\theta_m - \theta_r\right| \\ \Delta r = \sqrt{r_m^2 + r_r^2 - 2 \cdot r_m \cdot r_r \cdot \cos(\Delta\theta)} \end{cases}$, the angle error compared with the actual damage location of (105°, 210*mm*) is 2°, and the distance error is 7*mm*. As shown in Fig. 5, the horizontal axis represents the distance between the monitoring point and the coordinates of the center, and the vertical axis represents the angle between the monitoring point and the coordinates of the center. In the image, the gray value in different locations represents the superimposed amplitude of all the reflected signal of the position. The gray from dark to bright represents the amplitude of the signal energy from small to large, the synthesis signal location of the strongest energy point (i.e., highlights) represents the location of damage, and the remaining area is due to the noise caused by the beam transmitting and receiving process.



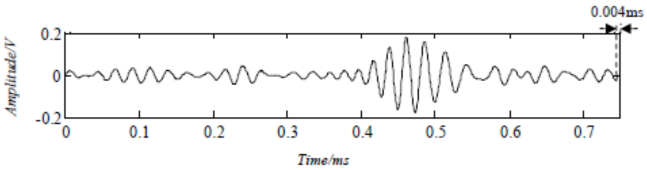
(a)The differential signal S_{01}



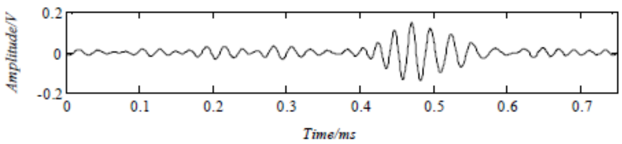
(b)The differential signal S_{01} after time delay



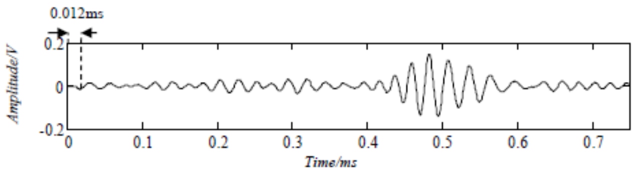
(a)The differential signal S_{03}



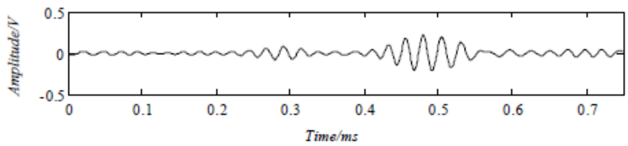
(b)The differential signal S_{03} after time delay



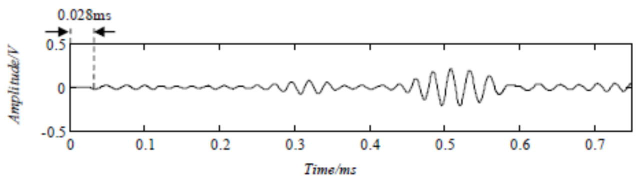
(a)The differential signal S_{05}



(b)The differential signal S_{05} after time delay



(a)The differential signal S_{07}



(b)The differential signal S_{07} after time delay

Fig. 4. The time delay waveform of differential signal

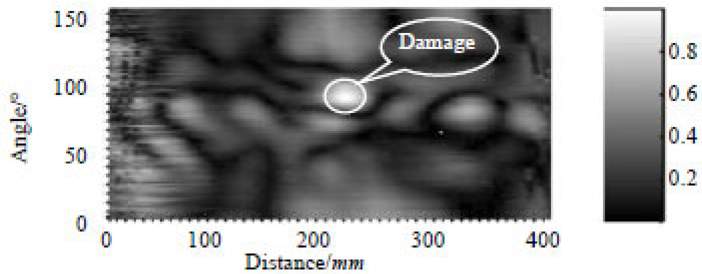


Fig. 5. Results of damage location monitoring

According to the equation (7) $round\left(\Delta t_i\left(\theta\right)\cdot f_s\right)=\Delta t_i\left(\theta'\right)\cdot f_s$, it indicates that in the direction of damage location where θ=105°, the maximum error introduced by the calculation process is $\Delta\theta'$=2.8°. However, in actual monitoring, the monitoring angle error is 2°, which is in the range of maximum monitoring error caused by the time delay calculation.

5 Conclusion

Ultrasonic phased array technique can help to achieve high-speed, full-direction and multi-angle detection by the flexible and controllable synthesized ultrasound beam, which is achieved by exciting each element of an ultrasonic array transducer with independent phase delay. However, in the process of signal transmitting and receiving, an additional time delay is needed in order to ensure that the driver can reach the emission of different sensors at the same time, or different sensors can receive signals at the same time. According to the time delay formula, the error of the additional time delay will appear in the process of determining the damage location. Meanwhile, the error of time delay can be divided into two parts. And the mainly reason is the rounding operation of the time delay calculation in the implementation process. This paper makes an analysis of the time delay error by the experiment of the anti rust aluminum plate. It is indicated that the error between theory and experiment is in the range of maximum monitoring error. Therefore, in order to facilitate the theoretical study, the error is negligible in practical applications.

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