Design and Application of Phased Array Ultrasonic Guided Wave Transducer for Detecting the Anchor Bolts

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Abstract. To achieve the defect testing of anchor bolts and other buried anchor bolt systems, a phased array ultrasonic guided wave transducer was designed in this paper. By designing the transducer array type, number of array elements, frequency, chip size and scanning mode, it can effectively avoid the interference of thread reflection signals, improve the signal-to-noise ratio and reliability of defect detection results. The transducer was verified by experiment of simulation sample.

Keywords: Anchor bolt; Ultrasonic guided wave; Phased array; Transducer.

1. Background
Anchor bolts are an important foundation part of power transmission line towers, which are buried in concrete foundation. In the process of long-term service, the anchor bolts are subject to electrochemical corrosion under the action of various corrosive media, resulting in the reduction of stress section, threatening the safety and stability of transmission line towers. At present, the research on the nondestructive testing of anchor bolts is mostly limited to the acoustic stress wave method, which is still in the exploratory stage, and the test waveforms obtained are messy and difficult to identify and judge.

2. Literature Study
In order to solve the non-destructive testing problem of anchor bolt systems, Beard M. D. verified that the ultrasonic guided wave method can be used in the nondestructive testing of mine bolts, and the theoretical research and preliminary tests have been carried out[1]. The application of ultrasonic guided wave technology in the detection of underground bolts have been studied by He et al.[2]. The researches show that it is feasible to detect the defects and corrosion of underground bolt systems by using the ultrasonic guided wave method.

The anchor bolt systems can be regarded as an infinite rod, and the ultrasonic cylindrical guided waves can be directly excited by a straight probe on the bolt end face. The guided waves can travel a long distance along the rod, and its reflected echo signal contains the whole information of the rod, so as to realize the detection and evaluation of defects. However, there are some unavoidable problems, such as the interference of threads reflection echo; low signal-to-noise ratio; mechanical scanning difficulty caused by poor coupling of anchor bolt end face; low defect positioning accuracy; low detection efficiency. At the same time, due to the multimode and dispersion characteristics of the guided waves, it is difficult to analyze and process the received signal. The appropriate mode and frequency of guided waves should be selected for different sizes of rods, which increases the difficulty and cost of...
detection.
Phased array ultrasonic testing technology has developed rapidly since it was applied in the field of non-destructive testing in 1987[3]. Compared with the traditional ultrasonic testing technology, it has great advantages. Each array chip can emit ultrasonic independently, and different wave fronts can be generated through different excitation methods. At the same time, dynamic focus, deflection and imaging can be realized through delay technology, in the case of no moving probe. The realization of electronic scanning has a great advantage in the case that mechanical scanning can’t be carried out due to structural constraints. Using phased array sensor to excite ultrasonic guided waves can effectively realize the non-destructive testing of anchor bolts.

Combined with ultrasonic guided waves and phased array delay technology, in this paper, we design a phased array ultrasonic guided wave transducer, which is suitable for the non-destructive testing of anchor bolts and other buried anchor bolt systems. The transducer is made to simulate the sample with artificial defects, which verifies its reliability.

3. Transducer Design

3.1. Transducer Array Type
Common transducer array types are line array, planar (2D rectangular array) and circular array[4], as shown in Fig.1. One dimensional linear array is the most commonly used type at present, which can realize beam deflection and axial focus in the axial plane of phased array. In contrast, the advantage of the circular array is that it can achieve two-dimensional focusing in the beam profile, but it can’t control the deflection of the beam. The beam profile is circular, which can obtain a larger energy concentration, and does not require a large number of arrays. The two-dimensional array can realize the deflection and axial focus of the acoustic beam in all directions. The acoustic beam can not only scan along the wafer arrangement direction, but also swing longitudinally. It has the advantage of three-dimensional imaging. It is the development direction of the ultrasonic phased array transducer in the future, but the processing technology is difficult, resulting in the high cost.

![Figure 1. Common types of phased array transducer array.](image)

(a) One-dimensional linear array (b) Two dimensional rectangular array (c) Circular array

Considering the inspection effectiveness, processing technology and manufacturing cost, one-dimensional sector array, as shown in Fig.2, can be used for the underground anchor bolt systems. The one-dimensional sector array probe is placed on the end face of the anchor bolts, and the guided waves can be excited in the rod through the delay excitation of the chips to realize the circumferential scanning.
3.2. Number of Elements
The focusing effect of ultrasonic beam is better and the image resolution is higher, with the increase of the number of phased array elements and the decrease of main lobe width $\Delta \theta$. Taking $\theta_0 = 0^\circ$, $\lambda = 2D$, the relationship between the number of elements ($n$) and the main lobe width ($\Delta \theta$) is calculated as shown in Fig.3. The main lobe width decreases with the increase of the number of elements. When the number of array elements is between 0 and 16, the main lobe width decreases rapidly; while the number of array elements reaches 16, the increase of array elements has little effect on reducing the main lobe width. In order to get better detection results, 64 array elements are finally determined for detection.

3.3. Frequency
The ultrasonic wavelength and sensitivity is related to the frequency, so it’s important to choose the appropriate frequency to gain the high signal-to-noise ratio to meet the detection sensitivity. The probe with lower frequency should be selected to have larger ultrasonic energy for the material with high attenuation. In the case of similar gain value and attenuation coefficient, the probe with higher frequency should be selected to have better detection sensitivity.
Due to the dispersion and multimode characteristics of guided waves, there are many modes at a specific frequency. It is found that when the frequency is 2-5MHz, the phase velocity difference of each mode is small, while the time difference of signal arriving at the receiving end after the reflection of defects or anchor bolt end face is small. And the dispersion phenomenon is not obvious, which is conducive to signal identification.
2-5MHz is suitable for the buried anchor bolt systems, considering the attenuation coefficient, chip size, probe processing difficulty and other situations.

![Figure 2. One dimensional sector array.](image)

![Figure 3. The relationship between the number of elements ($n$) and the major lobe width ($\Delta \theta$).](image)
3.4. Chip Size
The size of transducer should be selected according to the diameters of anchor bolts. Generally the outer diameter $D$ of transducer is 3-4mm smaller than the diameter of anchor bolts to be detected, which can achieve the best detection effect. Once the outer diameter $D$ and the length of chip $s$ determined, the internal diameter $d$ can be calculated as shown in Fig.2.

The outer arc length $a_1$ of a single chip can be determined by the outer diameter $D$, $a_1 = \pi D/n$, where $n$ is the number of array elements. The near-field region of the ultrasonic field is defined as the region where a series of maximum and minimum values of the sound pressure appear due to the interference of the wave source. The length of the near-field area of the sound field emitted by the chip group can be approximate as $N = A/\pi \lambda$, wherein $N$ is the length of the near-field area of the sound field, $A$ is the area of the chip group, and $\lambda$ is the wavelength of the ultrasonic wave. In this paper, $A$ is equal to the sum of the areas of the eight single chips. The area of a single crystal chip can be approximately obtained by multiplying its length $s$ by its arc length $a_1$. In practice, the gap between single crystals should also be considered. The area of single gap can be obtained by multiplying the length $s$ of single chip by the gap between single chips. The length $B$ of the non-diffusion region of the sound field can be approximately characterized as $1.64N$.

In the non-diffusion region, the sound beam propagates along the bar approximately vertically, and there is no reflected wave from the thread of the anchor bolts. When the sound beam begins to diffuse, if the sound beam is perpendicular to the inclined plane of the threads, the transducer will receive the threads reflection signals, which affect the defect identification.

The standard included angle of thread inclined plane is $60^\circ$, as shown in Fig.4. When the length of the single chip is less than the distance $S$, the transducer chip will not receive the threads reflection signals at the F point. Therefore, in order to avoid receiving the threads reflection signals, the maximum length of the single chip is set as $S$. According to the simple trigonometric geometric relationship, the maximum length of the single chip can be obtained as $s=\sqrt{3}b$, where $b$ is the length of the non diffusion zone of the sound beam. When the length of the single chip is within this range, it can effectively avoid the generation of the threads reflection signals, making the detection result more reliable.

![Figure 4. The diagram of calculation of chip length.](image)

According to the size of the bolts to be tested, the appropriate outer diameter and length of the transducer chip can be obtained, which can effectively avoid the interference of the threads reflection signals.

3.5. Scanning Mode
For the traditional one-dimensional linear array transducer, the excitation mode of the chip is No.1-No.8 for a group, then No.2-No.9 for a group sequentially, the last group is No.57-No.64. After that, the No.1-No.8 chips can be re excited in sequence, and it is not allowed to cross the No.64 chip to No.1 chip.

However, for the one-dimensional sector array in this paper, the chips are connected in turn to form a
ring. It can be excited across the No.64-No.1 chips, while No.58-No.1 chips as a group, No.59-No.2 chips as a group, until No.64-No.7 chips as a group. Then, it will be excited again from No.1-No.8 chips in sequence until receiving the stop signal. This excitation mode can achieve 360° coverage in the circumferential direction, making the detection results more reliable.

4. Experiment

In order to test the transducer, a simulation sample with artificial defects was made. The simulation sample is a \( \phi 46 \times 1600 \text{mm} \) steel rod, and the threads are processed at both ends. An artificial defect with the deepest depth of 6mm is processed at 600mm from the testing end face, as shown in Fig.5.

According to the size of the simulated sample, the key parameters of the transducer are determined: 3.5MHz, 64 array elements, one-dimensional sector array, outer diameter 42mm, inner diameter 12mm, and the chip material is lead zirconate titanate. With the customized anchor bolt corrosion detection system, the simulated sample is tested. The coupling agent is glycerin, and the test results are shown in Fig.6. It shows that the thread reflection waves are effectively eliminated, and the defect reflection signal is obvious with high signal-to-noise ratio and high reliability. The defect location is 594.9mm away from the detection end face, while the deviation from the actual situation is less than 1%. Due to the circumferential scanning of one-dimensional sector array, the circumferential position of the defect can be directly obtained from the testing results, and the relative equivalent of the defect can be obtained from the A-scan view. The accurate positioning and quantitative detection of the defects of anchor bolts and other buried anchor systems can be achieved.

It's found that the transducer can excite the ultrasonic guided waves in the anchor bolt, realizing the rapid detection of defects. Combined with the stress analysis, it can realize the fast detection and life evaluation of the corrosion state of the anchor bolts of the transmission line towers, which has important practical value.
5. Conclusion
In this paper, a phased array ultrasonic guided wave transducer is designed to test the anchor bolt systems. Combining of theoretical analysis and experimental verification, the parameters of the transducer are determined:
(1) The transducer adopts one-dimensional sector array, considering of the inspection effectiveness, processing technology and manufacturing cost.
(2) 64 elements transducer is determined.
(3) The transducer size is designed to improve the signal-to-noise ratio and reliability.
(4) The subaperture array element can be excited cross the first and last chip, which effectively realizes the circumferential scanning.
Compared with the traditional single crystal probe used in other’s work, the one-dimensional sector array transducer effectively avoid the interference of thread reflection echo, with high signal-to-noise ratio, high quantitative and positioning accuracy of defects. The designed transducer is tested and verified on the simulated sample with artificial defects.
Further researches should be carried out on two directions:
(1) Quantification methods of defect. In order to build the relationship between the gain and the defects, a series of simulation samples with artificial defects with different sizes/depths should be made.
(2) Finite element simulation should be carried out on different types of anchor bolts, such as stud bolts or all-thread bolts. It is of great significance to the development of instruments.

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