Transducer and Testing Scheme Design of Phased Array Ultrasonic Detection for Wind Turbine Main Shaft in Service

Zhengbin Xu1*

1China Datang Corporation Science and Technology Research Institute Co., Ltd
Northwest Electric Power Test and Research Institute, Xi’an, Shaanxi, 710021, China
*Corresponding author’s e-mail: xearch@163.com

Abstract. The wind main shaft is the important component for connecting the hub and gearbox, transmitting axial thrust and rotating torque in a high-power wind turbine. Defects of structural damage occur more often in the main shaft bearing constraints front end surface based on the previous study. New type of phased array ultrasonic testing technology is used for the first time, and the theoretical design is dedicated to the wind main shaft detection of phased array ultrasonic testing customized transducer and scheme. A suitable transducer parameter range and detection scheme are determined well.

1. Introduction

As a typical representative of clean and renewable energy, wind energy has been highly valued in recent years[1-3]. Wind turbine also ushered in the period of high-speed development, and the overall development trend toward higher power and higher reliability[4-5]. As a key link in the transmission chain of a high-power wind turbine, the main shaft plays an important role in connecting the hub and gearbox, transmitting axial thrust, rotating torque and aerodynamic bending moment, structural reliability of main shaft directly affects the operation safety of the whole wind turbine[6]. With the increase of the running time of the wind turbine, the fracture of the main shaft has been reported frequently[7-8].

Improper quality control in the design, manufacture, installation and operation of the main shaft may affect its structural reliability, but timely detection of possible structural defects is the key to prevent accidents for the wind turbine in service[9-10]. At present, the main shaft testing in service remains reference standards for regular manufacturing ultrasonic testing, but the conventional ultrasound used probe with detecting beam angle for fixed value is strictly limited to scan the scope and characteristics angle, and the detection efficiency and defect detection rate are low[11]. On the other hand, the greatest problem in the main shaft inspection in service is the limited environment, and the original testing sequence cannot be fully implemented, and it is unable to meet the requirements of quality evaluation. Phased array ultrasonic testing technology in recent years is a new detection method developed on the basis of conventional ultrasonic testing with higher efficiency, higher defect detection and more visual results. The most important thing is that it can use electronic beam control to realize large area scanning in a very small surface, just good at limited conditions to be tested[12].

At present, there is basically no research on the new phased array ultrasonic detection technology for the main shaft in service. In this study, phased array ultrasonic detection transducer and scheme design are carried out for the weak parts of the two-point supporting main shaft, so as to realize the detection of the main shaft in service.
2. Material and structure of the main shaft
The main shaft in this study is the two-point supporting structure of a doubly-fed asynchronous wind generator, and the material is 34CrNiMoA. After on-site material review by the direct-reading fluorescence spectrometer, its composition conforms to the standard range. And the specific verification results and the standard range[13] are in the Table 1 below.

| Element | C | Si | Mn | Cr | Mo | Ni | V | Cu |
|---------|---|----|----|----|----|----|---|----|
| Specific verification results | — | 0.32 | 0.66 | 1.53 | 0.22 | 1.49 | 0.17 | 0.12 |
| Standard range | 0.30-0.38 | ≤0.40 | 0.50-0.80 | 1.30-1.70 | 0.15-0.30 | 1.30-1.70 | ≤0.25 | ≤0.20 |

The main shaft is a hollow-through shaft with a total length of 1768mm, an outer diameter of 519mm and a central hole diameter of 120mm. The main structure is composed of five parts, as shown in Figure 1 below. From the flange side, it is in turn with flange (200mm in length and 135mm in thickness), transition variable section area (119mm), bearing restraint surface area (507mm), shaft body area (342mm), and nested joint area (600mm).

Figure 1. Schematic diagram of the main shaft structure.

According to relevant literatures[14-15], the stress of the wind turbine shaft under ultimate working conditions is mainly concentrated on the surface of the front end of the bearing constraint (shaft shoulder, the red arrow in Figure 1 indicates the position), and the maximum stress position inside the shaft develops to the Y-axis. In view of the above weak parts, the inspection of the main shaft in-service is studied.

3. Design of phased array ultrasonic testing scheme

3.1. Quality requirements
As mentioned above, since the study position is covered by the bearing, surface detection such as magnetic powder testing and eddy current testing cannot be carried out, so the ultrasonic testing that can detect surface and internal defects can only be selected now. At present, there is no corresponding standard for ultrasonic testing of the main shaft, only refer to relevant standard [16].
3.2. Detection scheme

3.2.1. Detection surface. According to the testing environment of the main shaft in service, the testing surface can be flange face end face and shaft body area, as shown in Figure 2 below. One end platform area available range for Φ440 mm to Φ800 mm. Shaft surface detection area is about 507 mm and divide about 25 mm perpendicular distance Z from research position.

![Figure 2. Schematic diagram of available test surface for wind turbine main shaft.](image)

3.2.2. Detection mode. According to the characteristics of the flange surface location restricted area and complete coverage detection requirement of the shaft shoulder position, flange surface platform area appropriates circular manual sawtooth scanning combined phased array sector scan mode. This mode can not only guarantee a complete coverage of scan, at the same time all kinds of defects (especially crack) by multi-angle beam scanning is of great help to defect detection rate. For shaft surface detection, since the study position is covered by bearings and there is a certain distance between the test position and the study position, axial linear scanning is selected as an auxiliary means for flange surface platform area detection to improve the defect detection rate.

3.2.3. Scanning beam type. In order to improve the defect detection rate and inspection effect as much as possible, the ultrasonic beam should be covered in two directions at least, and two directions are preferable to be perpendicular. According to the selection of the above scanning method, the flange surface platform area has been able to complete sound beam coverage, but the angle has some limitations. Combined with the secondary wave scanning of the shaft surface, full coverage can be achieved.

3.2.4. Focusing parameter. In phased array ultrasonic detection, focusing scan can enlarge the detection range to a greater extent and obtain better detection effect. The phased array ultrasonic near field can be obtained by using equation 1[12], where K is the near field correction coefficient, L is the probe length, W is the probe width, f is the probe frequency, and v is the corresponding sound velocity. The probe parameters will be validated later.

\[ N = KL^2f / 4v \]  

In combination with the spindle structure parameters, the depth focusing mode is selected for the detection of flange end face and shaft face. Among them, the focusing depth of flange end face detection is 300mm, while the focusing depth of shaft face detection is 480mm.

3.2.5. Scan angle. According to the detection requirements of the main shaft, sector scanning is adopted. In order to ensure the effectiveness of electronic scanning sound beam energy, the shaft
scanning expansion Angle of the two detection positions of the main shaft should not exceed ±15 degrees. Therefore, the scanning Angle of the shaft end face is -15 degrees to +15 degrees.

3.3. Transducer design
The ideal phased array ultrasonic probe should be able to guarantee the physical coverage of the scanning process, as well as sufficient sensitivity, resolution and signal-to-noise ratio, good focusing and deflection ability, and low price and use cost.

3.3.1. Type. There are many types of phased array ultrasonic probes, which can be divided into linear array, two-dimensional matrix array, ring array, etc. Among them, linear array is easy to design, manufacture, program and simulate. The main shaft structure is relatively simple and adopts linear array.

3.3.2. Frequency. The probe frequency has great influence on the detection. The higher the frequency is, the higher the sensitivity and resolution will be. However, the higher the frequency is, the greater the attenuation will be. In practical detection, all factors should be analyzed comprehensively and the frequency should be selected reasonably. Considering material characteristics, current manufacturing level, influence of workpiece thickness on acoustic attenuation and relevant test results, the frequency of this study is selected as 0.5MHz-2.25MHz.

3.3.3. Aperture. Higher probe frequency and larger detection aperture can bring better detection resolution and more ideal focus. The above detection frequency is lower, so a larger aperture should be selected as far as possible. However, with the increase of using aperture, the probe and wedge will be larger and cost will be higher. Considering the limitation of detection position and characteristics of long sound path in this study, the size of the detection chip is selected as 12-24mm.

3.3.4. Number and spacing of elements. The number and spacing of elements are important parameters that affect the quality of detection. With the increase of array spacing, the signal quality in the sound field tends to be worse. When the critical value of 0.67λ is reached, the possibility of gate lobe is increased and the deflection ability of beam becomes worse. With the decrease of array spacing, the signal quality in sound field tends to be better and the beam deflection ability is enhanced. However, as the element spacing decreases, the number of elements that need to be stimulated simultaneously will increase, and the probe price will also soar and make the detection cost too high. Considering that the selected frequency is low, the aperture should be enlarged as much as possible to improve the detection quality. In order to get a better effect and ensure a smaller array spacing, the excitation chip is designed as 32 in this study to ensure the detection quality.

3.3.5. Wedge. The wedge can adjust the angle of center sound beam and reduce the wear of probe. The corresponding wedge is usually selected according to the probe used. Comprehensively considering the requirements of detection angle and workpiece thickness, longitudinal wave probe is preferred for flange end face detection in this study, and 0 degree longitudinal wave wedge is selected for wedge to ensure the rusty penetration ability and reduce attenuation. Shear wave probe is selected for shaft surface detection, and shear wave wedge at 45 degrees is selected for wedge to ensure scanning coverage.

4. Conclusion
In this study, a unique phased array ultrasonic detection method is designed for the common two-point supported spindle of the wind generator through theoretical analysis. The following conclusions are drawn:

(1) Through theoretical design, the combination of flange end face and shaft surface can achieve good coverage of defects at the shaft shoulder position.
(2) Detailed selection of detection scanning surface, scanning mode, probe frequency, aperture, number of chips, array spacing and wedge is analyzed one by one, and the detailed parameters were determined.

Acknowledgments
I would like to thank China Datang Corporation Science and Technology Research Institute Co., Ltd Northwest Electric Power Test and Research Institute for providing financial support for this research.

References
[1] Oladapo, O.O., Akrama, K., Hossein, D. (2020) Deployment of onshore wind turbine generator topologies: Opportunities and challenges. International Transactions on Electrical Energy Systems, 5:30.
[2] Christoph, B., Gerda, D., Sebastian, B., Christoph, Z. (2020) The future need for flexibility and the impact of fluctuating renewable power generation. Renewable Energy, 149.
[3] Poul, A., Neven, D., Younes, N., Hrvoje, M., Soteris, K. (2020) Sustainable development using renewable energy technology. Renewable Energy, 146.
[4] Will, G., Andrew, M., Mark, B., Ryan, W., Nikita, G.S., Erik, E, Eric, O’S.(2020) Motivations and options for deploying hybrid generator-plus-battery projects within the bulk power system. The Electricity Journal, 5:33.
[5] Jacob, L, Pablo, H., Stefan, P., Lauren, K.(2020) The offshore-onshore conundrum: Preferences for wind energy considering spatial data in Denmark. Renewable and Sustainable Energy Reviews, 121.
[6] Han, X., Hu, X, Li, Y., Wang, X., Dai, H.(2012)Optimal Design of transmission Chain of doubly-fed Wind Turbine. Journal of Solar Energy, 07:1988-1994.
[7] Polaris network.(2015)Accident happened Repower wind power units collapse accident may be caused for the main shaft fracture. http://news.bjx.com.cn/html/20151216/692005.shtml.
[8] E road wind turbine net.(2014)A wind turbine main shaft fracture cause analysis and processing. https://fengji.mmfj.com/news/detail-39177.html.
[9] Xi, R.(2013)Assembly Process Quality Control of wind turbine spindle and Bearing pedestal. China Heavy Equipment, 02:40-41.
[10] You, M.(2012)Production process and quality control of nodular iron castings for large wind power spindle. Modern cast iron, 06:23-26.
[11] Cao, H.(2018)Research on ultrasonic Testing Technology of Fan Spindle in service. Large Casting and Forging Parts, 01:48-49.
[12] Wang, Y., Li, Y., Chen, H.(2014)Ultrasonic phased array detection Technology and Application. National Defense Industry Press, Beijing.
[13] JB/T12137-2015, Shaft forging used for Wind turbine-technical conditions. China Standards Press,Beijing.
[14] Du, J., Niu, X., He, Y., Lu, X.(2013)Fatigue analysis of megawatt wind turbine spindle. Journal of solar energy, 04:591-597.
[15] Zeng, C.(2011)Modeling research and Application of Wind turbine Spindle System Structure Analysis. Chongqing University.
[16] EN 10228-3:1998, Ultrasonic Testing for Ferrite or Martensitic SteelForgings.