Ultrasonic On-line Monitoring Technique
for Wind Turbine Shaft

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ABSTRACT

For the wind turbine, the main shaft is subject to complex stress. Cracks are easily generated and expanded from the outer surface, which seriously threaten the safety of the wind turbine. In order to monitor the main shaft in service, this research carries out an on-line monitoring method and an integrated system for the surface-opening transverse cracks on the outer circumference of the main shaft. An annular array of ultrasonic transducers is constructed at the end face of the shaft by piezoelectric elements. The parameters of the array are determined and optimized by the ultrasonic field characteristics to achieve the coverage of the stress concentration region. An on-line ultrasonic monitoring system is also developed, which integrates detection terminals, a sensor array and the operating software. The detection terminal is composed of a voltage pulser, a receiver and a multiplexing unit. The detection terminal moves synchronously with the main shaft, dealing with multi-channel excitation and signal acquisition. The software not only manages the entire inspection process, but also achieves defect imaging by electronic scanning. The experimental results show that 5mm depth transverse crack can be examined, and the defect location error is less than 2.5%. This will provide an effective on-line structure health monitoring technique for wind turbine shaft.

1. Introduction

With the development of the exploitation and utilization of wind energy, more and more attention has been attracted to the health status of critical components in wind turbines[1]. At present, horizontal axis wind turbine is the mainstream of wind power generation[2-3], which is mainly composed by mechanical transmission system, electric power system and control system. As the core component of the transmission system, the main shaft directly bears the torque transmitted from the wind turbine hub, which is the first energy transmission carrier after the conversion of wind energy into mechanical energy. The in-service main shaft is not only suffered from the erosion caused by severe working conditions, but also subjected to complex stress such as torque, axial thrust and pneumatic bending moment. Defects are easy to arise in the above situation[4], which seriously threatens the safety of wind turbines[5]. To ensure the safety of in-service wind turbine, it is vital to carry out the inspection of in-service main shaft and take examinations to protect it against risks.

Due to the heavy torque on the shaft outer circumference, it is easy to cause opening cracks. Cracks might gradually expand to the inner, forming a transverse crack. Such cracks often occur at the joint between the main shaft and the bearings, which seriously impair the performance of the main shaft[4]. At present, conventional ultrasonic flaw detectors and UT-probes are used to detect high-stress areas in the shaft manually[6]. However, this method exists many limitations, such as effects of human factors[7].
difficulties in identifying defect signals\textsuperscript{[8]}, impediments in imaging the defects. Additionally, it is hard for inspectors to enter into the hub or nacelle at hundreds of meters, the detection period is limited, the wind turbine needs to be stopped during detection, and so on. Therefore, up to now, the online detection of wind turbine shaft has not been well implemented\textsuperscript{[9–10]}.

In order to overcome limitations and meet the requirement of structure health monitoring of the main shaft in service, on-line monitoring method and system are carried out for the surface-opening transverse cracks on the outer circumference of the main shaft. The area where cracks appear frequently is covered by acoustic beam using ultrasonic sensor array. Ultrasonic wave emission, acquisition, and channel selection are achieved by high-frequency signal excitation, reception, and multiplexer to perform the electronic scanning. The wireless transceiver technology is used to transmit detection information. The aim of this research is to provide a method for shaft structure health monitoring without manual work and no downtime.

2 End-face array detection method

The main shaft is generally fixed in nacelle by bearing, connected between the hub and the gearbox\textsuperscript{[11]}. The main shaft is almost in a closed space. However, the end face of main shaft is exposed in the hub, which can be used as the testing surface. The detection area of shaft is the joint between the shaft and the bearing.

For the transverse crack in the detection area, sensor array composed by a number of piezoelectric elements is exploited. The main beams of piezoelectric elements are used to cover detection area. The elements in array are excited by time-division, and electronic scanning is performed in the detection area. The piezoelectric elements are fixed on the end surface of the main shaft in the form of a circularity, as shown in Fig. 1.

\begin{figure}[h]
  \centering
  \includegraphics[width=0.5\textwidth]{sensor_array_diagram.png}
  \caption{Diagram of sensor array layout}
  \end{figure}

Since the transverse cracks are located on the near surface of the outer circumference of shaft, the ultrasound radiated from sensor exists side-wall effects. In the case of the pulse-echo method the minimum distance between the beam axis and a side wall required to avoid disturbing influences can be estimated as follows\textsuperscript{[12]}.

\begin{equation}
  d_{\text{min}} > \sqrt{2a\lambda}
\end{equation}

Where $d_{\text{min}}$ is the minimum distance of element from an edge, to avoid interference by the side wall; $a$ is the distance from the defect to the test surface; $\lambda$ is ultrasonic wavelength.

Therefore, it is easy to calculate the distance between each element and the centre of the end face, as shown in Fig. 2.

\begin{equation}
  R = \frac{D}{2} - d_{\text{min}}
\end{equation}

Where $R$ is the distance from each element to the centre of the end face; $D$ is the diameter of the detection area of shaft.
The angular characteristics of a given element acting as transmitter is the same as when it acts as a receiver. The angles of divergence are given by the relation:

\[ \gamma = \frac{2J_1(kR_s \sin \gamma)}{kR_s \sin \gamma} = 10^{\frac{\Delta G}{20}} \]

Where \( \gamma \) is the angle of divergence whose sound pressure falling \( \Delta G \).

In order to ensure detection sensitivity in the main beam coverage of elements, the relationship between detective sensitivity and beam directivity can be determined according to the sound pressure distribution law of beam section. According to [12] the sound pressure on the \( M(r_0, \theta) \) in the space is given by the formula (3)

\[ P(r_0, \theta) = \frac{P_0 F_s}{\lambda r_0} \left[ \frac{2J_1(kR_s \sin \theta)}{kR_s \sin \theta} \right] \]  \hspace{1cm} (3)

Where \( P_0 \) is the initial sound pressure; \( F_s \) is the area of the sound source; \( r_0 \) is the distance from the point \( M \) to the sound source; \( k \) is the wave number; \( \theta \) is the angle between \( r_0 \) and the sound source axis; \( R_s \) is the sound source radius; \( J_1 \) is the first-order Bessel function.

The relationship between the sound pressure attenuation and the angle of divergence on the beam section can be expressed as:

\[ \Delta G = 20 \log_{10} \frac{P(r_0, 0)}{P(r_0, \theta)} \]  \hspace{1cm} (4)

Where \( \Delta G \) is the sound pressure attenuation. Bring equation (3) into equation (4):

\[ \frac{2J_1(kR_s \sin \gamma)}{kR_s \sin \gamma} = 10^{\frac{\Delta G}{20}} \]  \hspace{1cm} (5)

The main beam cross-section radius can be obtained:

\[ r = H_t \times \tan \gamma \]  \hspace{1cm} (7)

Where \( r \) is the radius of beam cross section. \( H_t \) is the distance from the upper boundary of the detection area to the end face.
In order to cover the entire surface and near surface of the detection area, the beams of elements in the sensor array are overlapped. The number of elements required in sensor array is as follows:

\[ N = \frac{2\pi R}{r} \]  

(8)

The N elements are evenly distributed on the end face of the shaft with a radius R to form a sensor array. Therefore, the location of sensor array is determined.

3 Online monitoring system

3.1 System architecture

The ultrasonic on-line monitoring system is composed of server, router, detection terminal and sensor array, as shown in Fig. 3. The detection terminal is made up of wireless transceiver unit, excitation and reception unit, and multiplex unit.

![Diagram of online monitoring system](Image)

**Figure 3. Diagram of online monitoring system**

The detection command (channel number, gain) is sent from the control center to the server via internet of things. The server sends them to the detection terminal via the router. The element, selected by multiplex unit according to the channel number, is excited. The element radiates the ultrasonic wave to the shaft and receives the echo signal. The reception unit amplifies the echo signal according to the gain in detection command. After filtering and AD(Analog to Digital) conversion, echo signal is transmitted to the server wirelessly. The detection data is sent back to the control center to continue next detection loop.

3.2 Excitation and Reception Unit

The excitation and reception unit is the critical part in system terminal, which regulated by FPGA(Field Programmable Gate Array). The functional block diagram is shown in Fig. 4.
The excitation unit is equipped with bipolar pulse output. The high voltage module is provided by secondary power supply. The 24VDC is converted into ±150VDC for pulse excitation. Parallel capacitors and high power supplies are connected to the high-speed FETs (Field Effect Transistor) for energy storage. FPGA outputs two IO signals to control the driver according to the pulse frequency. FETs are driven to output bipolar pulse according to the IO signal timing. The matching network, composed of passive components, is matched with the impedance of the piezoelectric element and the output terminal to improve the efficiency of excitation.

The reception unit is equipped with full depth echo acquisition of the shaft. Since the amplitude of the echo obtained is small, the reception unit is designed with a secondary amplification. The first amplification is a fixed-gain amplifier, and the gain in the second amplification can be adjusted by detection command. The bandpass filtering is carried out to improve the signal to noise ratio after signal amplification. The digitization of the echo signal is done by the A/D converter, and the data is output to the FIFO (First In First Out) in FPGA to complete the signal acquisition.

### 3.3 Multiplex Unit

The ultrasonic on-line monitoring system performs an electronic scan by sensor array. The multiplex unit plays the role of switching to excite or receive different element. The multiplex unit is composed of the decoding and switching circuit, as shown in Fig. 5. Based on the 4-16 decoder, maximum 256 channels selection can be implemented. Seventeen decoders are used for logical combination. The output of the decoding circuit is connected to the each switching circuit. The switching circuit consists of NPN transistor, signal relay and protection circuit.
When one channel is selected, one low level would be output from decoding circuit, and the relay coil would be driven to close by transistor, which establishes a channel loop. The bipolar pulse is applied to the piezoelectric element via the channel loop, and then picked echo signal is fed back to the reception unit. The protection circuit works during the switching of the signal relay coil to prevent damage from abnormal voltage and electromagnetic interference.

4 Experiment

4.1 Sample Design

The experiment was carried out on a small shaft sample whose material was 42CrMo4. The test surface was the upper end face of the main shaft. The shaft parameters are shown in Fig. 6.

![Figure 6. Specification of shaft sample](image)

There are two artificial transverse crack in the detection area of shaft. The specific parameters are shown in Table 1. Record the angle according to the clock position. The counterclockwise angle is negative, and the clockwise angle is the positive.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DEFECT 1</th>
<th>DEFECT 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arc Length</td>
<td>30 mm</td>
<td>35 mm</td>
</tr>
<tr>
<td>θ-Location</td>
<td>-(22~16)°</td>
<td>+(16~23)°</td>
</tr>
<tr>
<td>Z-Location</td>
<td>832 mm</td>
<td>834 mm</td>
</tr>
<tr>
<td>Depth</td>
<td>2.5 mm</td>
<td>3.5 mm</td>
</tr>
<tr>
<td>Width</td>
<td>&lt;1.5 mm</td>
<td>&lt;1.5 mm</td>
</tr>
</tbody>
</table>

4.2 Experiment Setting

Considering the condition of shaft sample, longitudinal piezoelectric transducers are selected with 2.5MHz and Φ20mm in diameter. The measured velocity is 5928m/s. According to the sensor array arrangement, the detection parameters are determined as follows: \(f=2.5\text{MHz}, r_0=20\text{mm}, c_L=5928\text{m/s}, H_1=800\text{mm}, H_2=1000\text{mm}, D=560\text{mm}\).

The \(d_{\text{min}}\) is calculated according to equation(1) to avoid the sidewall interference. When \(a=H_2\) is taken, it is ensured that the near surface defects in the detection area are not affected by the sidewall interference. Therefore, \(d_{\text{min}}\) should satisfy the following formula.
\[ d_{\text{min}} > \sqrt{2 \times H \times \frac{c_l}{f}} = 68.87 \text{mm} \]

It is assumed that the sound pressure at the edge of the beam is no lower than 12dB of the beam axis. According to the formula (2~8) : \( \gamma = 4.79 \, ^\circ \), \( r = 67.01 \, \text{mm} \), \( R = 211.13 \, \text{mm} \), \( N = 19.79 \). \( R = 210 \, \text{mm} \), \( N = 20 \) in operation.

The 20 elements are equally distributed on the end face of the shaft to form a sensor array with a radius of 210 mm, as shown in Fig. 7.

The server in the online monitoring system is replaced by a portable computer in this experiment. The detection gain is set as 43dB, and the number of channels is set as 20. The shaft sample is scanned in order from 1 to 20.

4.3 Results and Discussions

4.3.1 Detection Results

In the experiment, 20 sets of ultrasonic original signals were collected. Those signals were rearranged by angle and interpolated, and then imaged according to B-scan image\(^{[13]}\), as shown in Fig. 8. In the Fig. 8, the abscissa indicates the circumferential angle of the sensor array, and the ordinate indicates the distance to the end face of the shaft. To display the detection results more clearly, only the image data within the detection area (800~1000) is intercepted.

![Figure 8. B-scan image of shaft under end-face testing](image)
In the Fig. 8, two artificial defect images in the shaft sample can be observed. Their angular positions are near -19.44° and 19.08°, and their depths are 833.4mm and 836.8mm respectively. The relative errors of experimental and standard values were 2.31% and 2.15%, and the differences between them are that the echo path is not on the acoustic axis of transducer.

It also can be seen from Fig. 8 that the signals received by each transducer have the same echo at a fixed position, which is judged as structural echo\(^\text{[12]}\). The original echo signal obtained by the 2nd transducer (\(\theta=18^\circ\)) is shown in Fig. 9.

![Figure 9. Original signal of NO.2 element](image)

Figure 9 shows that the structural echo path is 1736.40 (868.2×2) mm. According to the position of the transducer, the contour 2, the inner wall of the main shaft and the reflection theorem, the path of the echo is calculated: The ultrasonic wave is radiated from the transducer, and it is reflected back to the transducer on the inner wall of the main shaft after interacting with the contour 2 (depth is 787.00mm) as shown in Fig. 10.

![Figure 10. Path of structural echo](image)

In Fig. 10, the structural echo path is 1699.97mm. Compared with experimental data, the relative error is 2.1%. The error mainly comes from the following aspects: the center hole and the contour 2 of the main shaft sample deviate from the actual value; The simulated ultrasound is an idealized beam line, which is different from the sound received from transducer in actuality.
4.3.2 Discussions

The artificial defects listed in Table 1 represent only a kind of transverse crack with shallow depth, which is difficult to detect. There are many factors related to the detection capability and imaging effect, including detection distance, defect depth, noise of the monitoring system, sensor array consistency, transducers and their positions, and the structural complexity of the shaft. The depth of artificial defects in this experiment is less than 5mm, while the detection distance is up to 830mm. In addition, the reflective surface of defects is not on the acoustic axis of the transducers. Those factors cause a lower amplitude of the defect echo.

The results in Fig. 8 show that structural echoes existed in the detection area. The appearance of the structural echoes is related to the position of the sensor array, the angle of divergence of the transducer and the shaft shape. The position of the structural echoes can be obtained by means of acoustic path calculus, finite element simulation, and sample test before detection. The B-scan imaging also helps to judge the structural echoes. The discontinuity of the structural echoes in the image is related to the amplitude difference of the echo received by each transducer. During the detection process, structural echoes can be quickly identified by similar images at different angles.

The shaft detection process is interfered by non-defect wave. It is often the case that the amplitude of the non-defect wave is larger than the defect wave, and the defect is generated near the place corresponding to the non-defective wave, which increases the difficulty of detection. In the early stage of crack, the reflection condition of the acoustic wave is poor, resulting in low echo. However, the on-line monitoring of the main shaft is a continuous process, the position and amplitude of the structural echoes are stable as well as the noise during this period. As the small crack expands inward, its echo amplitude will gradually increase. In the process of monitoring, the monitoring system can determine whether there is a crack expansion at this position by a change in the amplitude and width of the structural echoes over a period of time, and then identify the crack.

The position of the sensor array at the end face of the shaft is determined by considering the entire detection area (800mm–1000mm) to avoid sidewall interference. The defect echo for a depth is not necessarily the largest, but the arrangement ensures the detection sensitivity of whole detection area. The detection sensitivity can be further improved by arranging annular sensor arrays of different diameters, but the number of channels of the system needs to be increased.

5. Conclusions

- The on-line monitoring system for the transverse crack on the circumferential surface of the wind turbine main shaft has been achieved, which helps to realize the online health evaluation of the main shaft.
- The sensor array used in the ultrasonic on-line monitoring system is excited by time-division to implement the electronic scanning. The inspectors do not need to enter the hub for detection, and no downtime needed for wind turbine.
- It is concluded from the experiment that the two artificial defects can be detected and defect location error is less than 2.5%.
- Wireless technology is applied in the system to transmit detection information, without occupying the limited electrical interface and transmission cable in the wind turbine.

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