Research on Controlled Jet Ultrasonic Inspection Method for LZ50 Hot Rolled Large Steel Bars

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Abstract. Ultrasonic inspection is the main method of on-line inspection for large size steel bars. For maximum Φ 600 mm in diameter, single maximum length up to 10 m of LZ50 hot rolled steel bar, to meet the requirement of the on-line inspection efficiency and precision at the same time, adopting controlled jet method that the probe and the workpiece is non-contact, coupled with one certain length water body, and its comprehensive inspection ability is stronger. In the application process of controlled jet method, the self-developed jet coupling module and the zonal inspection technology are used to effectively suppress the turbulence noise and structure echo. The test results show that under the premise of signal-to-noise ratio (SNR) not less than 8 dB, the controlled jet method can effectively identify Φ 3.0 mm artificial flat bottom hole of 5 mm and 300 mm in depth, and verify the effectiveness of the controlled jet method.

Introduction

Hot rolled bar is an important industrial base material, and LZ50 axle steel is a typical material. Due to its high strength and toughness and superior fatigue resistance, it has been widely used in the axle of high-speed, heavy-duty railway vehicles¹-³. The structure of LZ50 steel in hot rolled state, which is also in large bar stage, will affect the performance of steel after heat treatment. In order to ensure the safety and high efficiency of railway operation, it is necessary to conduct ultrasonic inspection on LZ50 steel in hot rolled state. The inspection object is LZ50 hot rolled steel bar, which is Φ 220-600 mm in diameter and is up to 10 m in length. The research shows that the original grain size of hot rolled LZ50 steel is large and distributes between grades 3-0, and the high noise level caused by this will adversely affect the inspection SNR⁴. At the same time, the large inspection range aggravates the attenuation of ultrasonic signal along the sound path, which is not conducive to the acquisition of effective signals. Therefore, a reasonable inspection method should be developed to meet the corresponding inspection requirements.

Industrial sites generally use water as a coupling agent, and it is difficult for conventional ultrasonic coupling method to meet the requirements of on-line inspection for hot rolled steel bar in terms of testing efficiency and quality. The coupling of water immersion method is stable, but the workpiece needs to be immersed in the water tank during the inspection, which increases the complexity of the loading and unloading mechanism in the on-line inspection, reduces the inspection efficiency, and makes the comprehensive inspection ability difficult to meet the requirements. The water membrane method, that the probe is close to the bar surface and a thin water membrane is used as the coupling medium. In this contact inspection method, the probes’ wear degree is serious, and need to be replaced frequently, its comprehensive inspection efficiency is limited. The controlled jet method which the probe and the workpiece is non-contact, it is easy to realize on-line loading, unloading and sorting, and the inspection efficiency is significantly improved. On the other hand, it can effectively reduce the impact of workpiece surface conditions and coupling changes on the inspection, with good anti-interference ability and strong comprehensive inspection ability.
Figure 1 is a schematic diagram of the three inspection methods. Considering coupling condition, inspection efficiency and quality, the controlled jet method is selected as the final inspection method.

Figure 1. Coupling method: (a) water immersion (b) water membrane (c) controlled jet.

Based on the theoretical analysis of the ultrasonic field, this paper designs and realizes the jet cavity which is suitable for the controlled jet method to inspect large bar, so as to suppress the turbulence noise and structure echo and improve the overall inspection SNR. The feasibility and effectiveness of the controlled jet method for on-line inspection of large bar are verified by the experiments on the reference blocks and sample bar.

Jet Coupling Module Design

When the fluid flow field is coupled with the ultrasonic field, the field distribution and boundary conditions of the fluid medium, such as velocity and pressure, will have a significant impact on the distribution of sound field and acoustic propagation. The propagation law of non-uniform attenuation is presented when ultrasonic wave is coupled with turbulent field\(^5\). In this case, the flow state of water will play a decisive role in the coupling effect. Therefore, the control of coupled flow state is a key technology in controlled jet inspection. In addition to reasonably arranging the water circulation system to improve the flow state, it is more effective and important to design a reasonable controlled jet cavity to control the flow state of coupled water, reduce the turbulence degree of water flow as far as possible, reduce signal fluctuation, and ensure the stable propagation of ultrasonic wave in the coupled water.

In the design of the cavity, it is necessary to ensure that the structure of the cavity will not physically block the main ultrasonic signal, and at the same time to smooth the flow of water and reduce turbulence noise. Therefore, it is necessary to design the size of the outlet and the rectifying way of the fluid reasonably.

Outlet

The outlet is mainly concerned with the selection of its outlet diameter to ensure that there is no physical obstruction to the main beam energy. In practical inspection, attention is paid to the distribution of sound pressure on the sound field section. Generally, the beam in the area where the axial sound pressure amplitude decreases by 6dB is used for flaw inspection, and the related diffusion \( \gamma \) is introduced, as shown in Figure 2. Here is the empirical formula for \( \gamma \) outside the near-field region

\[
\gamma = \sin^(-(−1))(0.51\lambda/D_s) \tag{1}
\]

\( \lambda \) is the wavelength of ultrasonic waves in the medium, \( D_s \) is the wafer diameter
In order to ensure that the beam propagation of 6dB descending zone will not be blocked by the water outlet, the water outlet diameter needs to be guaranteed as follows:

\[ D \geq 2L \tan \gamma \quad (2) \]

\( L \) is the distance from the front end of the probe to the water outlet, which should be greater than the length of the near-field region of the probe \( N \), that is

\[ L \geq N \quad (3) \]

**Inlet**

If the fluid enters the cavity in an asymmetric form, a rotary jet will be generated and it will enhance the mixing effect of surrounding fluid, which is not conducive to inspection\(^6\). The position of water inlets should be symmetrical distributed along the axis of the water cavity to avoid the occurrence of rotary jet.

According to the research of Zhenhua Wang\(^7\), under the same conditions, the more water inlets arranged in the circumferential uniform distribution, the more uniform distribution of water velocity in the internal water cavity along the circumferential direction. However, from the perspective of technology and practical application, it is difficult to use overmuch inlets. For this reason, two water inlets are arranged along the circumferential direction in the design. Combined with the porous sieve rectifier structure, the desired rectification effect could be achieved.

**The Porous Sieve**

For the porous sieve structure, its function is to change the flow into the small hole from turbulent flow to laminar flow or nearly laminar flow, and make the flow state more stable. Take water as the fluid passing through the holes, set the radius of the holes as \( r \), the number of small holes as \( N \), and the average velocity of water flowing through the small holes as \( V_0 \). Assuming that the flow state through the hole is laminar flow. According to Reynolds formula, \( R_e < 2300 \), the density of water \( \rho = 1000 \text{kg/m}^3 \), and the kinetic viscosity coefficient of water \( \mu = 1.01 \times 10^{-3} \text{Pa} \cdot \text{s} \), it can be known by calculation that: \( rv < 1.15 \times 10^{-3} \)

The cavity is a circular outlet, the radius is \( R \), and the average velocity of the outlet is \( V_1 \). From the conservation of mass, it can be known that the outlet flow of the cavity is equal to the sum of the inlet flow of all holes, i.e

\[ \pi R^2 V_1 = n \pi r^2 V_0 \quad (4) \]

Combined with the outlet diameter \( D \) of the cavity designed above, it can be seen that the total flow area of the pores should meet the following conditions:

\[ n \pi r^2 > \frac{\pi R^2 V_1}{V_0} \quad (5) \]

Through the above design, combined with the specific specifications, models and parameters of ultrasonic probe, the cavity suitable for controlled jet method is designed, as shown in Figure 3.
Structure Echo Cancellation

In the spatial distribution of the sound field about the disk wave source, the directivity coefficient of the sound field is used to represent the energy distribution at various positions on the cross section of the sound field, represented by $D_c$, as shown in Figure 4\cite{8}. The value is equal to the ratio of the sound pressure $P(r, \theta)$ at any point of the sound field section at a certain distance from the wave source to the sound pressure $P(r,0)$ at the axis on the same cross section. The expression is as follows:

$$D_c = P(r, \theta)/P(r,0)$$ (6)

In the section of the disk source sound field, there exists the position where the sound pressure amplitude is 0. The zero value of the sound pressure closest to the axis in the sound field section is denoted as the first zero value, and the corresponding divergence angle is denoted as the divergence angle of the first zero value of $\theta_0$, and the expression of $\theta_0$ is:

$$\theta_0 = \sin^{-1}(1.22\lambda/D_s)$$ (7)

$D_s$ is the diameter of the disk source.

$|D_c| < 0.15$, when $\theta > \theta_0$. This indicates that the sound pressure amplitude of the outer sound field of $\theta_0$ is very low, and the corresponding sound energy is also low. The energy of the sound field is mainly concentrated in $\theta_0$, where the sound beam is called the main sound beam.

Figure 5 shows the range of area covered in the cavity by $\theta_0$ and $\gamma$, where the axial sound pressure amplitude decreases by 6dB. According to (1) and (7), it can be found that $\theta_0 > \gamma$. This indicates that the coverage range of the main beam is larger than that of the actual inspection beam. For ultrasonic signals in the range of $\theta \propto (\gamma, \theta_0)$, structure echoes will be generated under the
action of the cavity structure. Since this region is in the main energy region of sound waves and there is a high gain during inspection, the structure echoes cannot be ignored.

![Figure 5. Simplified structure echo generation process.](image)

When the controlled jet cavity is applied for actual inspection, the echo signal with fixed position can be found in the A-scan waveform, as shown in FIG. 4. The position of the wave appears after the initial wave and remains unchanged after changing the inspection area, which is in line with the characteristics of structure echo. Removing the cavity, keeping other inspection conditions unchanged, and adjusting the inspection area for several times. It can be found that fixed echo no longer appears in the same position, as shown in Figure 6(a) (b). It can be judged that the fixed signal in A-scan is the structure echo signal.

![Figure 6. Structure echo.](image)

According to the origin of structure echo and the position information of echo signal in the measured A-scan, the location where the structure echo occurs can be estimated, that is the location where the ultrasonic signal is reflected in the cavity. Later adding ring parts on the location, using the outer surface to scatter the high amplitude signal propagating to the ring, change its propagation path, and make the sound energy attenuate in the propagation process, so that the echo signal is not received by the probe, or the inspection will not be affected because the amplitude is too low.

Taking the simplified structure echo generation process in Figure 5 as an example, the ultrasonic signal is reflected near the outlet and received by the probe. In this process, the propagation of signal meets the following conditions

\[
\begin{align*}
2a + b &= vt_f \\
\alpha + \beta &= \pi/2 \\
a \cos 2\alpha &= b/2
\end{align*}
\]

(8)

\[a = (vt_f)/2(1 - \cos 2\beta) . \]

(9)

the length of the occurrence position of structure echo to the probe surface along the sound axis is
\[ c = \sin 2\alpha = \frac{(vt \sin 2\beta)}{[2(1 - \cos 2\beta)]} \quad (10) \]

According to the above principle, we can get the location of structure echo. After the ring is added at this position, the controlled jet cavity is used for inspection again. Its A-scan waveform is shown in Figure 6 (a) (c). It can be found that the original structure echo signal at the fixed position disappears. After changing the inspection area, there is no fixed signal at this position, and no additional fixed waveform is found in the A-scan. It shows that this method is effective to eliminate the echo of structure.

**Ultrasonic Inspection Experiment**

**Preparation for Experiment**

The ultrasonic inspection system used in the test is shown in the Figure 7.

![Figure 7. Experimental equipment.](image)

In the experiment, in order to ensure that the SNR of the near surface area and the core area can be met at the same time, zonal inspection technology is adopted as shown in Figure 8. Along the radial direction of the steel bar, it is divided into several areas with different depths for inspection, and each area is independently equipped with inspection technology.

![Figure 8. Zonal inspection.](image)

The partition settings and probe information used are shown in the Table 1 and Table 2.

<table>
<thead>
<tr>
<th>Number</th>
<th>Depth range [mm]</th>
<th>Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5-45</td>
<td>Line focusing probe</td>
</tr>
<tr>
<td>2</td>
<td>45-55</td>
<td>Line focusing/Flat probe</td>
</tr>
<tr>
<td>3</td>
<td>55-300</td>
<td>Flat probe</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zone</th>
<th>Frequency [MHz]</th>
<th>Wafer Size [mm]</th>
<th>Length of near field [mm]</th>
<th>Focal length [mm]</th>
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</thead>
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<tr>
<td>1,2</td>
<td>5</td>
<td>13</td>
<td>/</td>
<td>102.4</td>
</tr>
<tr>
<td>2,3</td>
<td>2.25</td>
<td>25</td>
<td>245.8</td>
<td>/</td>
</tr>
</tbody>
</table>

According to the target, two reference blocks are made for static experiment, as shown in the Table 3 and Table 4.
Table 3. Flat bottom hole in block 1.

<table>
<thead>
<tr>
<th>Number</th>
<th>Hole diameter [mm]</th>
<th>Depth of hole [mm]</th>
<th>Burial depth [mm]</th>
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<tbody>
<tr>
<td>1</td>
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<td>12</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>3.0</td>
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<td>6</td>
<td>3.0</td>
<td>5</td>
<td>55</td>
</tr>
</tbody>
</table>

Table 4. Flat bottom hole in block 2.

<table>
<thead>
<tr>
<th>Number</th>
<th>Hole diameter [mm]</th>
<th>Depth of hole [mm]</th>
<th>Burial depth [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.0</td>
<td>15</td>
<td>295</td>
</tr>
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<td>2</td>
<td>3.0</td>
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<tr>
<td>3</td>
<td>2.0</td>
<td>10</td>
<td>300</td>
</tr>
</tbody>
</table>

To verify the inspection ability of large bar under dynamic conditions. The sample bar made of LZ50 material is designed and produced, as shown in Figure 9. The workpiece size is Φ 400 mm * 240 mm, with an artificial φ 2.0 mm flat bottom hole in the core.

Figure 9. Sample bar.

**Static Experiment**

In order to verify the suppression effect of the designed controlled jet cavity on turbulent noise, under the condition of using this cavity, a comparative experiment was carried out under the condition of water immersion and controlled jet, and comparing the inspection SNR under the different conditions. Figure 10 show the experimental results of each probe for the corresponding inspection area.

Figure 10. SNR in different conditions.
According to the test results of block 1, it can be found that, compared with the unrectified condition, the controlled jet method after rectification has a significantly higher inspection SNR, indicating that the controlled jet cavity has a good effect on smoothing water flow and suppressing turbulent noise. At the same time, the inspection SNR of each flat bottom hole of the controlled jet method after rectification is lower than the value based on the inspection results under the condition of water immersion, which is consistent with the above analysis that turbulence field induces turbulence noise and reduces SNR. However, the SNR of the two is close, and under the condition of controlled jet method, the SNR of each flat bottom hole is not less than 8dB.

The test result and variation rule of block 2 are similar to that of block 1. Using the controlled jet method to successfully inspect Φ3.0 mm flat bottom hole in depth of 300 mm, with the SNR of no less than 8 dB.

Static experiments show that under the premise of SNR not less than 8 dB, the controlled jet method can effectively inspect Φ 3.0 mm flat bottom hole in depth of 5 mm and 300 mm.

**Dynamic Experiment**

Using the jet cavity, the sample bar was inspected under the conditions of water immersion and controlled jet respectively.

![Figure 11. C-scan image of gate 2.](image)

The scanning method in the experiment is as follows: the bar rotates in situ under the action of rollers. Every rotation, the probe driven by the controlled jet cavity feeds along the axial direction of the bar for a certain distance. The depth range of gate 2 in the controlled jet method A-scan diagram is 190~205mm. The C-scanning results of the two methods are shown in Figure 11.

There are uncolored areas in both conditions. This is due to the existence of large holes in the sample bar during rotation. In the controlled jet method, it takes longer time for the large hole to replenish water, which aggravates the situation and makes the blank area extend greatly along the horizontal direction.

![Figure 12. A-scan waveform of gate 2 in center.](image)

According to C-scan results of Figure 11, the area of high echo signal appears in the central position, and the distance between the area center and the space center is about half of the perimeter of sample bar, which can be preliminarily judged as φ 2.0 mm flat bottom hole. The A-scan waveform of the area center is shown in Figure 12, the depth of the echo signal triggering gate 2 is...
about 198 mm, combined with the flat bottom hole depth 200 mm, it can be confirmed that the location represent the φ 2.0 mm artificial flat bottom hole.

This suggests that under the dynamic condition, the controlled jet method applying the designed cavity can effectively identify the 200 mm deep, Φ 2.0 mm equivalent flat bottom hole.

**Conclusion**

- In the ultrasonic inspection of LZ50 hot rolled large bar by controlled jet method, the jet cavity suitable for controlled jet method is designed and realized from the aspects of outlet size and rectification mode, reducing the turbulence degree of fluid and turbulence noise and improving the inspection SNR.
- According to the theory of ultrasonic field spatial distribution of the probe and the position of echo in the actual inspection waveform, this paper puts forward a method to estimate the echo reflection position of the structure, which can successfully suppress the structure echo and effectively reduce the inspection misjudgment.
- Static test shows that under the premise of SNR not less than 8 dB, the controlled jet method and the cavity can effectively inspect Φ 3.0 mm flat bottom hole in depth of 5 mm and 300 mm; Dynamic test shows that in the situation of close to the real working condition, the controlled jet method can effectively inspect the flat bottom hole with Φ 2.0 mm and 200 mm deep in the sample bar. It is proved that the performance of controlled jet method and cavity can meet the requirements of efficiency and quality of on-line inspection of large bar and reach the practical level preliminarily.

**References**