A STUDY ON ULTRASONIC DETECTION OF FLAWS IN WELDS OF RAILS

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INTRODUCTION

During manufacture and in service, various defects might emergence in rails. Some defects are volume ones, and others are planar ones, like facula, greyness, non-welded together and fatigue crack. Planar defects are very dangerous. They not only reduce the effective section of rail, but also bring on stress concentration. It is important to detect all the defects to make sure security of transportation. The detection is very difficult owing to complicated shape of cross, large thickness in some places, uncertain positions of defects. The method of detecting the planar defects and the defects located at the rail fillet, for terms of the different parts of a rail, see Fig.4, were mainly discussed in this paper.

The Detection of Planar Defects

Right Angle Reflection

The detection of planar defects was done by the right angle reflection principle as shown in Fig. 1. Acoustic wave reflected from defect was reflected again by bottom surface or side surface and then returned to test surface along parallel direction with incident acoustic wave. According to geometry, it is easily proved that the distance \( L \) between the two probes is:

\[
L = 2htg \beta
\]  

(1)

Here \( \beta \) is the refracting angle of probe and \( h \) is the height of the defects from the bottom.
It can be seen that \( L \) is related to \( \beta \) and \( h \). The larger the refracting angle of probe is, the farther the distance \( L \) is needed; If \( h \) is bigger, \( L \) is bigger and vice versa.

When \( h \) is small enough that \( L \) is less than the diameter of the probe, the probe can receive the reflection echo by itself. This is the principle of detecting planar defects by single probe. When \( h \) is large, the defect is too far away from the bottom surface, the \( L \) is larger and the probe can not receive reflective wave by itself. The dual probes must be used in detecting. When the two probes were placed according to the situation shown in Fig. 1, it is called pitch and catch scanning detection. Another detecting scheme was called "K" type scanning as shown in Fig. 2. It can be used for the detection of the defects on rail bottom and head, whereas the pitch and catch scanning can be used for detecting defects on rail lumbus.

The path length of the two types of scanning detection is both constant (the path length of pitch and catch scanning detection is double that of "K" type's), it is not related to the position of defects at the welds. Thus, the position of flaw echo is changeless on the screen. This brings on much convenience for flaw estimating. During scanning, the probe pairs must be moved oppositely at the same speed. Hence, special mechanical devices were needed.

**Measurement of the Defects Size**

When the detection is done by single probe, incident and reflected wave at the defects pass through the same distance. When dual probe is used, the path length is not equal. Though total distance that acoustic wave passes through is changeless, the echo height for the same defect varies with the change of defective position because of different spread extent of acoustic wave.

Suppose that the defect is small plane flaw and is located at far field of the probe, the path length incident acoustic wave is \( x_1 \), the path length of reflected acoustic wave is \( x_2 \). If the influence of the states of rail surface is ignored and only the relative peak value of reflected wave is concerned, according to the rule in the far field that acoustic pressure is inversely proportional to the distance \(^{-1}\), the reflected acoustic
Table 1. The peak values reflected from planar bottom holes in different depth.

<table>
<thead>
<tr>
<th>H (mm)</th>
<th>5</th>
<th>30</th>
<th>60</th>
<th>90</th>
<th>120</th>
<th>150</th>
<th>165</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>near field</td>
<td>27.3</td>
<td>22.1</td>
<td>20.7</td>
<td>20</td>
<td>19.9</td>
</tr>
<tr>
<td>theoretable Value (dB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Practical detection Value (dB)</td>
<td>27</td>
<td>27</td>
<td>28</td>
<td>26</td>
<td>22</td>
<td>21</td>
<td>19</td>
</tr>
</tbody>
</table>

The pressure of defects $p$ can be expressed:

$$p = \eta \frac{s}{x(m-x)} \tag{2}$$

$$m = x_1 + x_2$$

$x$ is $x_1$ or $x_2$

Where $s$ is defect area, $\eta$ is the coefficient that is related to probes, workpieces and the reflected rule of defects. It can be seen that the reflected acoustic pressure of defects or its size is reversely proportional to the product of $x_1$ and $x_2$. The bigger the product is, the lower the echo height is and contrarily, the higher the peak value of echo height is.

Let $dp/dx=0$ in the equation (2), we obtain: $x=m/2$, that is: $x_1=x_2$

Here the peak value of reflected wave reaches least value. If there is the same value of defects for the pitch and catch scanning detection, when the defects are near the top of welds, the echo height of reflection is high. When they are near the bottom, the echo height of reflection is low or there is a small size.

Table 1 lists the reflected peak value of a planar bottom hole of $\Phi 3$ varying with its position at $\beta = 37$, $\lambda = 1.18\text{mm}$ of probe, $\lambda$ is the wave length of the ultrasonic wave. The length of near field is about 40mm. $H$ is the distance between defects and test surface. The height of rail is 176mm. It is seen that the echo height almost does not vary with $H$ at the near field area. At the far field, it gradually decreases with the increasing of $H$. This is predicted in (2).

**Rail Fillet Detection**

At the rail fillet, there is a small cross section, low mechanical strength and large stress. Sometimes, a tiny defect brings on the rupture of rail. It is one of the most dangerous defects in rails.

**The Geometric of Acoustic Wave Propagation**

At rail fillet, the detection is done by single probe method going along the tilt of rail bottom. The direct scan detect the lower part of welds and the single bounce detects the upside. Here test surface is not parallel to the reflected surface of rail bottom. The single bounce is not in the longitudinal section.

In order to select the condition of flaw detection reasonably, the propagation rule of acoustic wave at rail fillet must be carefully studied. Therefore, the coordinate system is established as shown in Fig.3. X-axis is parallel to the side surface of rail.
bottom. Z-axis is perpendicular to the test surface and vertical uprising. The origin o is located on the test surface. $\Psi$ is the offset angle of probe that is relative to xoz coordinate plane. $\theta$ is the tilt angle of the inclined plane of rail bottom. c is the distance between the origin and crossing point of z-axis and rail bottom. $\beta$ is refracted angle. Point of incidence is located at the origin. It can be proved: [2]

1. The sound track equation of direct scan O01:

$$\frac{x}{\sin \beta \cos \psi} = \frac{y}{\sin \beta \sin \psi} = \frac{z}{-\cos \beta}$$

(3)

2. The acoustic wave coordinates that is located at the reflection point at rail bottom O1:

$$x_1 = \frac{kc \cos \psi}{1 + k \tan \theta \sin \psi}, \quad y_1 = \frac{kc \sin \psi}{1 + k \tan \theta \sin \psi}, \quad z_1 = -\frac{c}{1 + k \tan \theta \sin \psi}.$$  (4)

Here, $k = \tan \beta$

3. The sound track equation of the secondary wave O1O2:

$$\frac{x - x_1}{\sin \beta \cos \psi} = \frac{y - y_1}{\sin \beta \sin \psi \cos 2\theta - \cos \beta \sin 2\theta}$$

$$= \frac{z - z_1}{\sin \beta \sin \psi \sin 2\theta + \cos \beta \cos 2\theta},$$  (5)

4. The included angle between the secondary wave and xoz coordinate plane:

$$\xi = \sin^{-1}(\sin \beta \sin \psi \cos 2\theta - \cos \beta \sin 2\theta)$$  (6)

5. When the axis of the secondary wave hit the center of defects (m, n), the $\beta$ and offset angle $\Psi$ of probe meet the following relation:

$$k \sin \psi = \frac{m \cos 2\theta + (n + c) \sin 2\theta}{-m \sin 2\theta + (n + c) \cos 2\theta + c}, \quad (K = \tan \beta)$$  (7)

The Inflection Angle And Detecting Position of Probe

Owing to the planar defects in the welds is parallel to rail section, that is to say, it is parallel to yoz coordinate plane, for obtaining the maximal reflection of defects, the
Rail Fillet

Fig. 4  Flaw detection method of welded seam of rail.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>The comparison of calculating value and practical detection value of probes.</th>
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<tbody>
<tr>
<td></td>
<td>6.34 °</td>
</tr>
<tr>
<td>probe</td>
<td>Calculating Value</td>
</tr>
<tr>
<td>β =64 °</td>
<td>6.3</td>
</tr>
<tr>
<td>β =68 °</td>
<td>5.2</td>
</tr>
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</table>

secondary wave must be parallel to xoz coordinate plane. Therefore, let ξ =0 in the equation (6), and we obtain:

\[ ψ = \sin^{-1}(\tan^2 \theta \tan \beta) \quad \text{or} \quad \tan \beta \sin \psi = \tan^2 \theta \quad (8) \]

It can be seen that ψ is related to the β and the tilt angle θ of rail bottom. Table 2 lists the value of inflection angle required of the probes β =64 ° and β =68 ° under the different tilt angle of rail bottom. It is seen that the calculating value and practical detection value are quite the same.

When the offset angle of probe is selected in term of the equation (8), we can figure out by the equation (7) that the transverse distance m between defects and incident point is:

\[ m = c \sin^2 \theta \quad (9) \]

The Selection of Flaw Detection Method

When the flaw detection process of welds of rails is determined, we divide the section of rail into four regions as shown in Fig.4: lumbar part is region 1, and pitch and catch scanning detection is done using the probe of β =37 °. The bottom is region 2, and the scanning detection of type “K” is done using array. Rail fillet is located at region 3, and scanning detection is done using the single probe of β =64 ° or β =68 °. When probes move fore-after and left-right, it deflects an angle ψ relative to side face and swing in the range of the angle. The head is region 4, besides the scanning detection of type “K” is done from both sides, we also use single probe of β =68 ° to do. The deflective angle of probe and deflective rule of rail fillet detection has been proved through practice. The above scanning detection forms have obtained good detection effect.
REFERENCES

2. Li Lianxiu etc., A Study on Ultrasonic Detection of Transverse Defects in the Rail Head, Seventh Asian-Pacific Conference on NDT, p.294–298.