Dynamic ultrasonic inspection technology for chinese EMU and application in China
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Abstract wheel-set is an important part of EMU. It directly influences the EMU operation security. In recent years, some harmful circumferential and radial defects are found in the wheel rim, which occur between the periods of two light maintenances. The comprehensive security system of wheel-set has already built in china to guarantee the EMU maintenance quality and operation security. It consists of regular mobile inspection, regular stationary inspection and daily dynamic inspection. An ultrasonic testing technology for EMU wheel-set dynamic inspection and successful application in china is described in this paper.

Keywords EMU, wheel-set, dynamic inspection, ultrasonic inspection

1 Introduction

Railway is one of the most important transportations in the world, its safety is paramount for railway transportation. With the rapid development of china railways, more and more EMU are put into use, it has high speed, large carrying density and other characteristics. The wheel-set of EMU in service can easily produce breakage in wheel rim and wear on tread, it also includes the dangerous circumferential rim crack defect. At present, the complete wheel-set security system has been established in china, and it achieved very good results for guaranteeing safe EMU operation and wheel-set quality maintenance, it includes daily dynamic inspection, regular mobile inspection and regular stationary inspection, as shown in Table 1 and Figure 1.

Table 1 The wheel-set security system of China high-speed railway

<table>
<thead>
<tr>
<th>Level</th>
<th>Periods</th>
<th>Inspection items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daily dynamic inspection</td>
<td>Several days</td>
<td>Wheel rim</td>
</tr>
<tr>
<td>Regular mobile inspection</td>
<td>ab. 180000 to 250000 km</td>
<td>Wheel rim and disk</td>
</tr>
<tr>
<td>Regular stationary inspection</td>
<td>ab.1.2 million km</td>
<td>Wheel rim and disk</td>
</tr>
</tbody>
</table>

Figure 1. The wheel-set security system of China high-speed railway

Daily dynamic system inspects the cracks on wheel tread by EMAT (Electrical magnetic acoustic testing). Some harmful circumferential and radial defects were recently found in wheel rim in one cycle of regular mobile inspection, as shown in Figure 2. In order to ensure the safety of the EMU operation, it is urgent to increase inspection performance in wheel rim for daily dynamic inspection system. A system, which is installed on the entrance depot line and can detect...
the deep defects in wheel rim and flange automatically by ultrasonic array inspection technology, which is introduced in this paper.

Figure 2. The circumferential defects in wheel rim of EMU

2 Work principle
2.1 EMAT principle

EMAT can inspect wheel tread defects by ultrasonic surface wave. EMAT probes are installed beside the track, when the wheel-set is just touching EMAT probe, it will excite electromagnetic ultrasonic surface pulse wave on wheel tread and near-surface, as shown in Figure 3. The wave spread with a small loss along wheel tread and near-surface. When there is defect on wheel tread or near-surface, some ultrasound will be reflected at the end face of the defect and returned along the original propagation path, a defect echo is formed, as shown in Figure 4. But surface wave can only inspect wheel tread and near-surface defects rather than wheel rim defects.

Figure 3. Surface wave excitation principle  Figure 4. Surface wave propagation principle

2.2 Ultrasonic inspection principle

The system uses advanced ultrasonic array inspection technology, it includes angle beam probe (AP probe for short) and TR-straight beam probe (TR probe for short).

(1) TR probe inspection principle

TR probe consists of a transmitting crystal and a receiving crystal, respectively arranged in two pieces of organic glass, as shown in Figure 5.
It has four advantages: (1) High sensitivity, the transmitting crystal is made of high sensitivity piezoelectric material, so its sensitivity is very high. (2) Less clutter and smaller blind spot, the transmitting voltage is not on the receiving crystal directly. So this makes the receiving circuit out of interference and “blockage phenomenon” is avoided. This improves the resolution to detect defect near the surface and greatly reduces the blind spot. (3) Smaller length of proximity zone in workpiece. (4) Focus depth \( f \) is adjustable by adjusting \( \alpha \), \( f \) is from the diamond district center to the upper surface of the tested steel plate, it can be calculated by Formula (1).

\[
f = \frac{U - L \cdot \tan \alpha}{\tan \left( \sin^{-1} \left( \frac{C_2}{C_1} \cdot \sin \alpha \right) \right)} \tag{1}
\]

In Formula (1), \( \alpha \) is the separation angle between transmitting crystal and the surface of tested steel plate, that is angle of arrival; \( U \) is the distance from the piezoelectric chip’s center to the insulation layer’s center; \( L \) is the height of the delay block from the piezoelectric chip’s center; \( C_1 \) is the ultrasound speed in the delay block; \( C_2 \) is the ultrasound speed in steel.

The thickness of wheel rim is from 30mm to 65mm, in order to improve the resolution to detect defect in wheel rim, it is very important to set up the appropriate focus depth of TR probe, different focus depth (5mm, 10mm, 15mm, 20mm) is simulated by CIVA to analysis its sound field, as shown in Figure 6. The focus spot threshold is set to -12dB, when the focus depth is 5mm, the largest sound energy zone is 26.6mm*11.2mm; when the focus depth is 10mm and 15mm, they are larger, respectively 35.7mm*10.8mm and 39.8mm*10.3mm; when the focus depth is 20mm, the zone is 53.7mm*11.5mm. In this system, the 10mm focus depth TR probe is been used.
In the system, a number of TR-straight beam probes are arranged on both sides of track to inspect circumferential defects in wheel rim, there are 8 TR-probes for each module. Half probes are located near rolling circle, half probes are located on the outside of wheel rim. It can cover the area that is from 50mm to 100mm inner wheel rim, its working principle is shown in Figure 7.

Figure 7 Working principle of TR probe

(2) AP probe inspection principle

AP probe inspect defect in wheel rim by transverse wave, it has a big single crystal to produce longitudinal wave, then converted into transverse wave in the second medium. Its sound field is shown in Figure 7. The wave in the near field region has very high energy and clutter, so it can’t be used for inspecting defect. The length of field region related to the wave length and transducer area, as shown in Formula (2).

\[
N = \frac{F_S \cos \beta}{\pi \lambda_{s2} \cos \hat{\alpha}}
\]  

(2)

\(F_S\)-- transducer area

\(\lambda_{s2}\) -- transverse wave length

\(\beta\)-- refraction angle

\(\alpha\)-- incidence angle

In this system, a number of AP probes are arranged on both sides of track. Half probes are located near the rolling circle, The other half probes are located on the outside of wheel rim. With
these probes, the wheel rim and flange area can be full covered to guarantee the radial defects in wheel rim and flange and also tread cracks to be detected. It has strong inspection ability and full coverage, its working principle is shown in Figure 8.

![Figure 8. Working principle of AP probe](image)

In conclusion, the circumferential and radial defect in wheel rim and flange area can be inspected by a number of TR and AP probes. The coverage of TR and AP probes is simulated, as shown in Figure 9.

![Coverage of TR probe](image) ![Coverage of AP probe](image) ![Coverage of TR and AP probe](image)  

**Figure 9** Coverage of TR and AP probe

**2.3 System inspection principle**

The basic principle of the detection system is shown in Figure 10, the precisely trigger sensor S1 and S2 are equidistant installed on right and left side of track to measure speed and time. The calculated time is used for triggering probes on adjacent module and channel switch. The probes must be triggered when the probes are pressed well on by wheel-set, no matter the trigger is advanced or delayed, the results will be incorrect. When EMU is uniformly passing by (8km/h~12km/h for standard) the inspection area, $\Delta t$ is the time difference between sensor S1 and S2. So the trigger time $t$ and channel switch time of each row probe $t_0$ can be obtained in Formula (3), and the time that the probe is triggered N can be obtained in Formula (4).

\[
t + t_0 = \frac{\Delta t}{8} \quad (3)
\]

\[
N = \frac{(t + t_0) \cdot v}{2L} \quad (4)
\]

$v$--- Ultrasonic velocity  

$L$--- Ultrasonic path

![Figure 10. Basic principle of the detection system](image)
The inspection process of the system is fully automatic, no operator is needed on site. When EMU is approaching the detection unit and the running speed meet the system requirement (8km/h~12km/h), the system runs into a state to be tested. Then EMU keep on moving to the detection area, each row of probes are pressed by wheel-sets in turn. Meanwhile, each row of the probes are triggered, the 4 channel ultrasonic signal acquisition card gathers the signal, and sends it to a computer for processing. When the EMU completely passing through the inspection area, the inspection is over.

3 System composition

EMU wheel-set daily dynamic inspecting system includes three parts: local inspection unit, system control unit in the field and remote control terminal, as shown in Figure 11. Among them, the local inspection unit complete the basic inspection and pick up the ultrasonic inspection signal; the system control unit in the field is mainly used for controlling the system, encapsulating and processing inspection data; the remote control terminal is human-computer interaction sites, it mainly complete the input and output of inspection and manage the data and system.

![System Composition Diagram](image)

Figure 11. System composition

3.1 Local inspection unit

Local inspection unit mainly includes the special tracks, ultrasonic probe modules, trigger sensor, ultrasonic electronic units, and coupling water supplying system. Its main function is automatically and exactly to pick up the ultrasonic inspection original signals.

3.2 System control unit

System control unit mainly includes power supplying system, electrical control system, industrial PC and so on, Its mainly function is to control local equipment work, encapsulate and process inspection data, and store up data.

3.3 Remote control terminal

Remote control terminal mainly includes power supplying system, industrial and network equipment. Its mainly function is to remotely monitor work state of local inspection unit, provide user access interface and data network management, analysis and review the inspection data.

4 Calibration

The system need to calibrate regularly by sample wheel-set, which contains four types of defects: groove on wheel tread with 20mm*3mm, Φ3mm side drill hole with 30mm depth, 40mm*30mm oval circumferential defect with 20mm depth and groove in wheel flange with 5mm depth. As shown in Table 2.
Table 2 Artificial defect distribution in the sample wheel-set

<table>
<thead>
<tr>
<th>NO.</th>
<th>Type</th>
<th>Size of defect</th>
<th>Distribution Angle</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Groove in wheel flange</td>
<td>5mm depth</td>
<td>0°</td>
</tr>
<tr>
<td>2</td>
<td>Groove on wheel tread</td>
<td>20mm*3mm</td>
<td>72°</td>
</tr>
<tr>
<td>3</td>
<td>Side drill hole</td>
<td>Ø3*100mm</td>
<td>144°</td>
</tr>
<tr>
<td>4</td>
<td>Oval Circumferential defect</td>
<td>Long axis:40mm</td>
<td>216°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Short axis:30mm</td>
<td></td>
</tr>
</tbody>
</table>

When the inspection model of the system has been opened, then push sample wheel-set through the local inspection unit, as shown in Figure 12. These defects can be inspected by AP probe. And their typical inspection results are given, as shown in Figure 13.

5 Inspection results

The inspection data combine the advanced wheel side view, A-scan and B-scan to analysis. When one of them is chosen, the other views automatically associated with relevant information. Through the comparison of wheel side view, A-scan and B-scan in one page, we can recognize the defects more accurately and quickly, and quantitative and qualitative analysis defects. The defect analysis interface is shown in Figure 12.
6 Application in China

Since September 2013, the system is widely used in the field of China’s vehicle inspection, now there are five sets systems are being used, and seven sets are being implemented, and it has detected four defects successfully and has achieved a very good detection effect. In March 2014, the system in Qingdao North EMU operation depot successfully detected a defect in wheel rim of EMU EMU5-066A 3rd carriage 4th axis 8th wheel. It is a spread fatigue defect, depth about 10mm in wheel rim. Defect analysis interface and defect after lathed 4mm are shown in Figure 12.

7 Conclusion

In this paper, the dynamic wheel-set defect ultrasonic inspection system and its application in China is discussed. When EMU are passing by the inspection area, the system can accurately inspect the defect in wheel rim and wheel flange, automatically analysis the inspection data and give various levels defect alarm with the analysis result. The dynamic inspection system has been widely applied in the field of China EMU trains since Sep. 2013, and successfully detected 4 cases of defects.