Abstract

The wheelsets of the railway rolling stock are periodically inspected by non-destructive testing to ensure the safety in the passenger and freight transportation. A first generation of automatic test benches is applied since more than a decade for periodic in-service inspection of solid axles. These test benches using the ultrasonic phased array technique to detect transverse cracks at the surface of the axles of mounted wheelsets at an early stage.

We present a new generation of these test benches using new phased array devices. The phased array devices are characterised by a large number of channels, a high signal-to-noise ratio and small dimensions. Hence multiple devices can be placed close to the ultrasonic probes, so that interferences, caused by long transducer cables, can be reduced. Furthermore the probes can operate in parallel and so the inspection time can be shortened. Adapted phased array probes allow the inspection of coated and thick coated axles with high sensitivity. Hence the preparation of the surface by sandblasting and the re-coating of the axles are not required. The new database-supported software controls the inspection process and allows a fast analysing and reporting of the inspection data by a clear and easy operable user interface. The customers expect a long service life, low service costs and a high availability of the new test benches.

Keywords: Ultrasonic Testing (UT), phased array, railway, in-service inspection, test bench, wheelset, solid axle, transverse cracks

1. Introduction

The wheelsets of the railway rolling stock are periodically inspected by non-destructive testing to ensure the safety in the passenger and freight transportation. A first generation of automatic test benches is applied since more than a decade for periodic in-service inspection of solid axles [1]. These test benches using the ultrasonic phased array technique to detect transverse cracks at the axle surface of mounted wheelsets at an early stage.

The tasks for a redesign of the testing technique are defined by the practical experiences with the first test benches and new requirements. Railway axles are usually coated with a protective layer to prevent mechanical and corrosion damages. The ultrasonic testing has to work at different surface conditions such as lacquered, sand blasted, sanded or turned as well as without removing the protective layer in the in-service inspections. New thick coated layers are a challenge for the ultrasonic technique. Complex geometries in the coupling area at the surface of the axles and a short inspection time are further challenges. Latest developments in ultrasonic devices, probes and in the inspection software are available for these tasks.

We present a new generation of the test benches ordered by the Deutsche Bahn AG, shown in figure 1. The development of the inspection concept and the probe design supported by a theoretical modelling was made by arxes-tolina. The phased array devices and the inspection software for the test benches was developed and delivered by Fraunhofer.
2. Ultrasonic inspection concept

The objective of the ultrasonic inspection system is to scan the external surface of solid railway axles completely without demounting the wheels, the brake discs and the bearing rings from the wheelset. The ultrasonic testing has reliable to detect cracks whose surface lies orthogonal to the axial plane, so called transversal flaws. The deep of the flaws to be detected is 2 mm. The system has to test axles with a shaft diameter in a range from 160 mm up to 175 mm and to complete an inspection within 4 minutes. The circumferential scanning resolution has to be approximately $1^\circ$ and the axial resolution has to be less than or equal to 1 mm.

Axles with mounted wheels, brake disks and bearing rings have a limited coupling area at the surface. Axles with 3 brake disks have only 4 useable axial coupling areas, shown in figure 2. We use 4 vertical lances with probe holders for the positioning of the probes in fixed axial positions. Each lance can carry 2 probes. At the outer lances only one probe (A1, B1) is active in the inspection process. Hence two probes with several adaptions to the coupling surface can be selected in this position. The 3 coupling positions (1, 2, 3) are symmetric to the middle of the axle. The 6 active phased array probes are scanning in the both axial directions A and B with a steering range of the shear wave from approximately $33^\circ$ to $73^\circ$. With a mechanical rotation of the wheelset the surface of the axles can be full covered by the ultrasonic beams.
6 phased array transducers with a range of the steering angles from 33° to 73°

A1 B1 A3 A2 B2 B3
Side A Side B

Figure 2. Ultrasonic inspection concept for solid axles

3. Ultrasonic equipment

3.1 Ultrasonic probes

The probes are characterised by a high sensitivity to compensate the damping effect of the coating and are applicable in a wide range of axle diameters. They are adaptable to complex surface geometries. The probe transmits a longitudinal wave, which will be refracted to a shear wave by the wedge. The steering angle ranges from 0° for the back wall echo as indication of the acoustical coupling, up to 90° for the Rayleigh wave.

We use 8 identical phased array probes in the test bench, shown in figure 3. The adaption to several surface geometries will be realised by different wedge geometries. Two of the probes are adapted by the wedge to a saddle shaped surface (figure 3 left bottom). The other 6 wedges are adapted to a cylindrical surface (figure 3 left top). The wedges are replaceable and wearless by a replaceable wear protection. For the acoustical coupling we apply the gap testing technique with water as coupling media. The gap is lower than 1 mm depending from the axle diameter at the coupling position.

Figure 3. Phased array probe, left top: with standard wedge, left bottom: wedge with adaption to the saddle
The phased array consists of 32 long elements to generate a small and high sensitive sound field in the passive aperture of the probe. However the simulation of the plane linear phased array shows a strong divergence, caused by the defocusing of the curved surface of the axle. Figure 4 top shows the cross section of the sound field in the passive aperture. The sound filed is calculated for the natural refracted beam angle (all delays are zero) on a wedge with adaption to a cylindrical surface with 170 mm diameter. A focal zone is not observable in the simulation.

To obtain a feasible sensitivity of the probe we have to focus the sound field in the passive aperture. We apply a mechanical focusing with curved transducer elements to compensate the defocussing by the curved surface. The simulation results of the curved array in figure 4 bottom shows the expected sound field of a probe with a large aperture. The beam is small and the natural focal zone is close to the opposite surface of the axle.

### 3.2 Ultrasonic devices

![Ultrasonic phased array device PCUS® pro Array](image)
The beam of the phased array probes will be electronically steered with 3 PCUS® pro Array devices, shown in figure 5. Each device with 64 independent transmitters and 16 multiplexed independent receivers is connected with two probes. The transducers will be excited with a 180 V rectangular pulse. The received signals will be sampled with 80 MHz.

The devices are characterised by a high signal-to-noise ratio and a small form factor of 190 x 190 x 65 mm³. It is powered with 12 V low voltage. Hence multiple devices can be placed close to the ultrasonic probes, so that interferences, caused by long transducer cables, can be reduced. Four counters for encoder signals are available for position dependent triggering. Furthermore the probes can operate in parallel with data transfer, parameterising and control via a high-speed USB 2.0 interface, which allows a short inspection time.

### 3.3 Software for ultrasonic testing

The phased array devices and the mechanical functions of the test bench will be controlled by the inspection software PCUS® pro Lab. This new database-supported software controls the inspection process and allows a fast analysing and reporting of the inspection data by a clear and easy operable user interface, shown in figure 6. The database includes the complete parameterisation of the phased array technique and the inspection process. Parameters, which are defined by the contour of the axle, will be calculated automatically. The software can be easily adapted to different inspection methods.

![Figure 6. User interface of the inspection software PCUS® pro Lab](image)

The testing results are clearly represented in B- and C-scans, shown in figure 7. The quality of the acoustical coupling, based on the back wall echo, is monitored for each probe as a green line beside the C-scan. The visualisation of the data parallel to the inspection process allows a quick evaluation of the indications after the completion of the data recording. Several tools are available for evaluation and reporting such as:

- zooming,
- amplitude measurement,
• position measurement,
• maximum value detection,
• access to recorded A-scan data,
• adjustable colour map,
• adjustable reporting level,
• automatic transfer correction,
• automatic removing of circumferential echoes,
• automatic rotation of the wheelset to the circumferential position of a selected indication to show the online A-scan,
• offline presentation of recorded inspection data.

Figure 7. Presentation of the inspection data

4. Special features

4.1 Inspection and Revision Management System IRMS

The database-supported Inspection and Revision Management System IRMS from arxes-tolina is applied for the permanent storage and management of the inspection data and the testing results. It enables the local and network access to the saved inspection data for revaluation and comparison at periodic in-service inspections and allows the generation of testing reports.

4.2 Removing of circumferential echoes

Flaw indications may be hidden by circumferential echoes from the cross-sectional variations, shown in the blue oval in figure 8. We use a method for indicating and masking of these circumferential echoes without manipulation of the indication amplitudes in the C-scan in contrast to other methods, which was presented in the past.
4.3 Steering across curved surfaces

Special designs of solid axles may have a very small coupling area at the surface between the wheel seat and the brake seat, which is formed as saddle, shown in figure 10. For the beam steering across such two-dimensional curved surfaces we developed a special delay law calculator. The difference between the standard delay law and the adapted delay law is shown in figure 9. The 2 mm deep tangential saw cuts in the blue oval cannot be detected with the standard delay law.

Figure 8. Removing of circumferential echoes, left: hidden indication in blue oval, right: visible flaw indication

Figure 9. Beam steering across the saddle, left: without focusing, right: with adapted delay law
4. Conclusions

In this paper we presented new test benches for the ultrasonic testing of solid axles. These test benches are characterised by new and innovative developments in the inspection technique, the hardware and software.

New developed phased array probes were designed for the inspection of coated and thick coated railway axles. The probes are characterised by a high sensitivity to compensate the damping effect of the coating and are applicable in a wide range of axle diameters. They are adaptable to complex surface geometries and have a long lifetime by their wearless construction.

The applied phased array devices are characterised by a large number of channels, a high signal-to-noise ratio and small dimensions. Hence multiple devices can be placed close to the ultrasonic probes, so that interferences, caused by long transducer cables, can be reduced. Furthermore the probes can operate in parallel and so the inspection time can be shortened.

The new database-supported software controls the complete inspection process and allows a fast analysing and reporting of the inspection data by a clear and easy operable user interface. The permanent storage and access for the inspection data are enabled by an all-purpose inspection and revision management system. The new method for removing circumferential echoes from the C-scan presentation of the inspection data can make visible hidden flaw indications.

References