Application of New Front-end Electronics for Non-destructive Testing of Railroad Wheel Sets

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Abstract. For more than 6 years, the automated ultrasonic and eddy-current systems for the inspection of railroad wheel sets, developed by Fraunhofer IZFP and Fraunhofer TEG, have been field-hardened through daily operation at various maintenance facilities of the Deutsche Bahn (DB). The testing stations are equipped with IZFP's multi-channel electronics, a modular PC integrated system operating inside 19" rack-mounted industrial computers.

Special requirements for new installations of stationary systems (AURA) and underfloor testing stations (UFPE) called for the development of state-of-the-art miniaturized front-end ultrasonic and eddy-current test instrumentation. This innovation offers new dimensions for the concept and design of such systems, including features providing effortless maintenance of the inspection systems.

Due to the small size of the electronic modules they can be placed in close proximity to the transducer assembly. High-speed networking techniques ensure the transfer of all the acquired digital ultrasonic and eddy-current data from the front-end modules to the workstation responsible for data acquisition and analysis. The new front-end technology is applied for the testing stations of the latest generation.

One example is a system installed at the DB plant Krefeld, specifically designed for the ultrasonic testing of ICE train drive wheels. The transducer assembly for wheel rim and disk inspection includes hot-swap modules with integrated UT front-end modules adapted to inspect specific wheel disk configurations.

A second example represents testing equipment operating at the Süddeutsche Rail Service GmbH, Kaiserslautern. Ultrasonic and eddy-current front-end modules are responsible for the inspection of the wheel rim of disassembled wheel sets of freight cars. In addition to the wheel rim the solid axle is inspected in the same test stand using GE's Phased Array system.

Miniaturized front-end modules are also advantageous for the inspection with the wheel sets installed at the train. The concept of such an underfloor testing system is outlined.

Introduction

The rapid progress in the development of highly integrated miniaturized electronic component parts and processors in combination with modern networking technologies provides the basis for completely new concepts designing multi-channel ultrasonic and eddy-current testing equipment for industrial applications.

Up to now the usual way to assemble a testing station is illustrated in the bloc diagram shown in Figure 1. The cables used to connect the ultrasonic probes and/or eddy-current sensors to the testing electronics often have to bridge larger distances which might cause a loss of signal strength and also of signal quality under the influence of electromagnetic interference (EMI) in industrial environments. From this point of view it is favourable to separate the ultrasonic and eddy-current electronics from the data acquisition unit to place it near to the probe system. This can be achieved with IZFP's front-end technology which even allows integrating the electronics into the sensor system carrier.

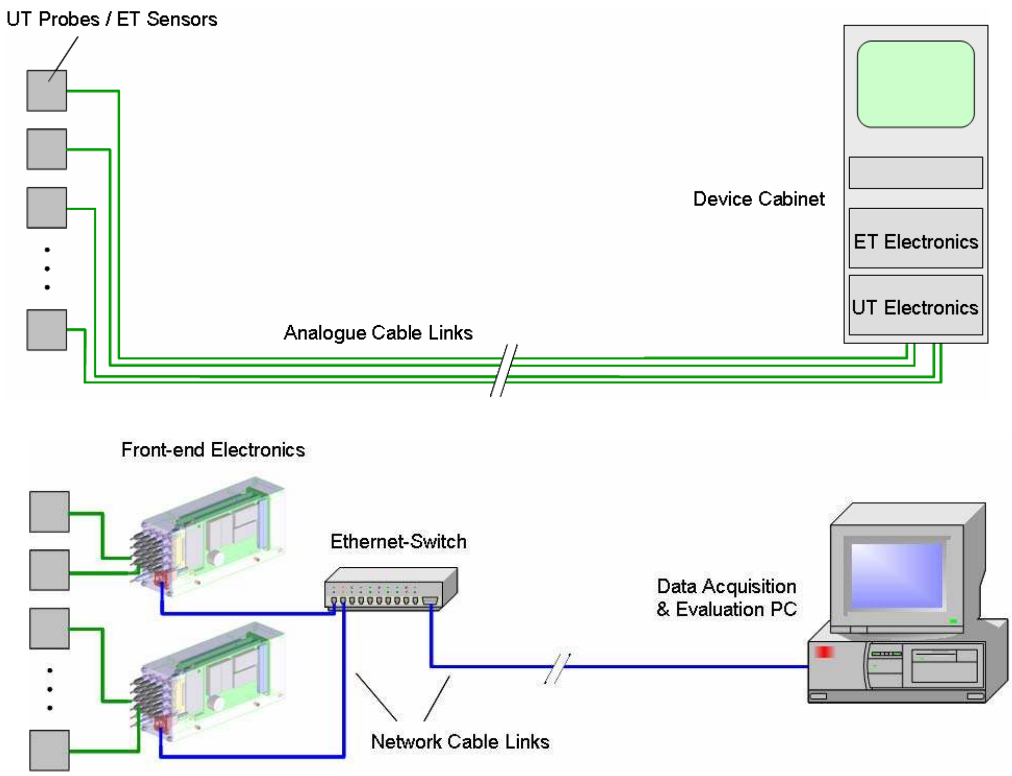

Figure 1: Conventional (top) and Front-end Based (bottom) NDT System Configuration

1. Front-end Technology

1.1 Ultrasonic Front-end

In today's market for automated ultrasonic testing systems, flexible electronic modules are required which can be adapted to a large variety of inspection tasks within a short time and with an acceptable budget.

To fulfil these requirements, the IZFP has developed 16-channel ultrasonic front-end modules which can be networked over Ethernet to provide testing systems with an arbitrary number of channels. The front-end technology can be applied e.g. for testing of piping and vessels in chemical, petrochemical, and power plants or production-line and pre-service inspection of steel products.

The following advantages are made available by IZFP's front-end technology:

- Transmission of digital test data to the host computer over Ethernet
- Simple networking of the required number of front-end modules
- Small size through application of highly integrated microelectronic circuitry

- Customized housing up to protection class IP 67
- Renunciation of cooling systems through low heat dissipation
- Independence on the host computer's hardware and operating system
- Long product's life cycle

The compact design of the 16/24-channel (16 Transmitter, 24 Receiver) circuit board (Figure 2) allows setup of complex testing systems at a minimum space. All analogue and digital components required for ultrasonic inspection are contained on a single board. A TGC module permits entry of any characteristic lines (DAC or DGS) for the compensation of acoustic and/or other material-related energy losses in a range of 80 dB. For the analogue to digital conversion, a high resolution A/D converter is used (14 bits, 50 MS/s). An on-board Power-PC operating under QNX is responsible for system control and data transmission over Ethernet. To achieve a high degree of miniaturization, ball grid arrays are used. The applied gate array technology permits of fast implementation of various data acquisition modes, to record e.g. gated data, ALOK data, A-scans, and RF-data.

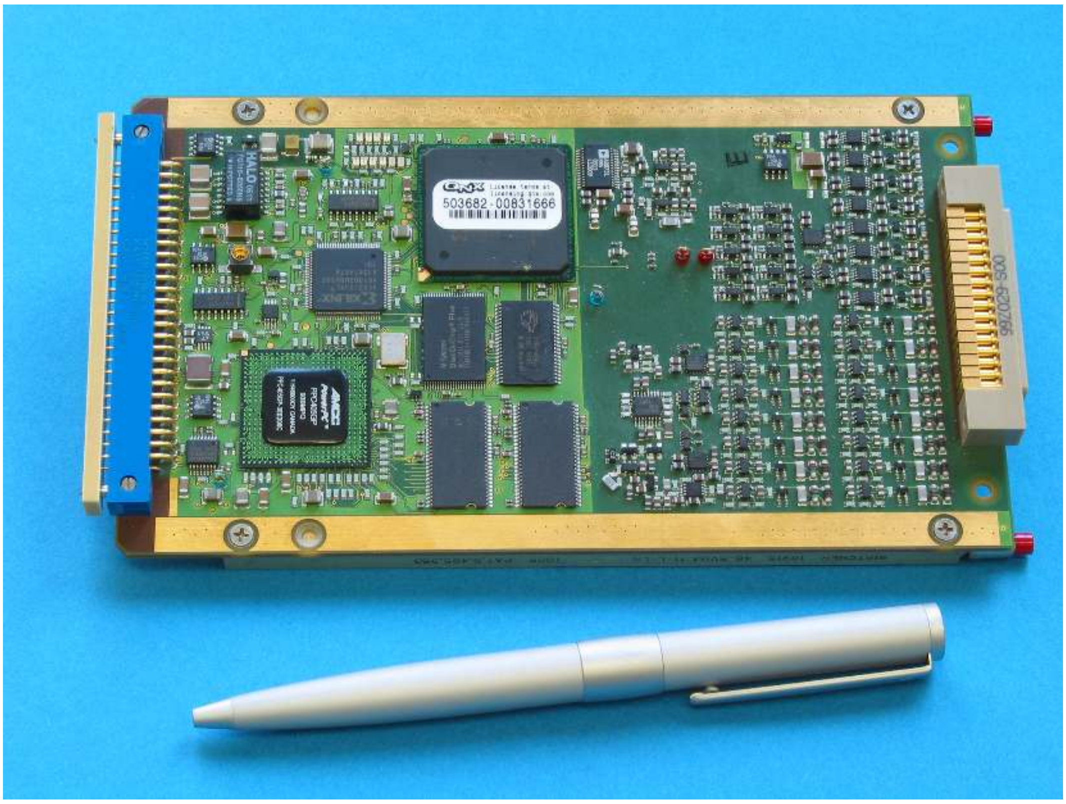

Figure 2: 16 Transmitter / 24 Receiver Ultrasonic Front-end Circuit Board

The Ethernet interface with TCP/IP protocol allows safe networking of front-end modules and data exchange with higher order computer systems necessary for inspection parameter setting, data acquisition, evaluation of test data, result display, and documentation. The network cable designed according to the Power-Over-Ethernet standard is also responsible for the power supply of the front-end modules. The Ethernet connector on the front-end side is waterproof appropriate to IP 67.

Transmitter and receiver channels can be allocated in arbitrary combinations, even using channels in different frond-end modules. In case several front-end modules are applied, they can be operated also in parallel mode. In the standard version of the front-end housing the ultrasonic transducers are connected by the waterproof Lemo03 connectors.

1.2 Eddy-Current Front-end

IZFP's WS98™ eddy-current board is designed for PC-aided eddy-current testing. In combination with suitable software, the WS98™ is a complete multi-frequency eddy-current instrument, and by using the modular design concept, it permits multi-channel operation with a multitude of sensor and frequency channels. The broad analogue bandwidth and subsequent numerical filters allow of contemporary signal processing algorithms and new testing concepts with high-speed multiplexing. Powerful data processing, real-time numerical filtering, and regression analysis are provided by the on-board digital signal processor (DSP).

All hardware and firmware functions are software-controlled. The software package, running under Windows2000® and WindowsXP®, consists of three modules:

- PC Software for setup and control of the eddy-current system
- Ethernet Module Software managing the specific ET parameters, handling of communication over Ethernet, processing of the DSP data, and data transfer to the computer
- Software providing digital data filtering (data reduction, high pass, low pass, and regression analysis), fast multiplexing of sensors and/or testing frequencies, setup of hardware functions (e.g. frequency generation, gain, A/D conversion, etc.)

Features:
- Modular hardware and firmware design
- Extensive use of numerical processing, replacing conventional analogue circuitry
- High long-term stability, dynamics, and reproducibility of the ET signals
- Test frequency ranging from 10 Hz to 10 MHz
- A/D conversion at 16 bit (156 kHz sampling rate)
- Time-multiplexing mode for sensors and/or frequencies with multiplexing rates of 2 kHz and more at test frequencies above 100 kHz
- High and low pass digital filters
- Online signal processing in multi-frequency mode for noise suppression
- 4 real-time digital inputs

Options:
- External trigger or gate inputs
- Active cable and sensor drivers for large sensor-to-instrument distances
- External synchronization for multi-board systems

Simple portable inspection devices as well as complex multi-channel inspection solutions with real-time process integration can be realised using the hardware and software capabilities of the WS98™ eddy-current front-end for applications like flaw detection, materials characterization (e.g. measuring of hardness, hardness depth), and layer thickness measurement.

1.3 Common Features of Ultrasonic and Eddy-Current Front-end Systems

Because of the small size of the ultrasonic and eddy-current front-end modules, the inspection electronics can easily be installed in close proximity to the ultrasonic probes respectively eddy-current sensors. With this kind of configuration, totally new possibilities for the design of inspection systems and simplified inspection services can now be implemented. In particular, short cable lengths for analogue signal transmission between probes/sensors and front-end modules can be realized to significantly reduce parasitic induction or interference, common in industrial shop floor environments. Digital data can be transferred to the host computer over long distances using the Ethernet link.

For data acquisition in combination with a scanner system or any other handling-machine applied for testing in a production line, the front-end modules are linked to an interface which is responsible for processing the encoder pulses provided by motor drives. The encoder pulses are converted into position data which are transferred as a serial data stream to the front-end units including a so-called Cycle Trigger Pulse (CTP) which initiates firing of the ultrasonic transducers or acquisition of eddy-current data at a predetermined position.

2. Wheel Set Testing Stations Based on the Front-end Technology

Before the availability of ultrasonic and eddy-current front-end modules, all AURA testing stations were equipped with IZFP's PCUS 40 multi-channel ultrasonic electronics, a modular PC integrated system operating inside 19" rack-mounted industrial computers. These AURA systems feature a maximum of 68 ultrasonic channels and 8 eddy-current channels [1-4].

New requirements for new installations of stationary AURA systems and underfloor testing stations (UFPE) called for the development of state-of-the-art miniaturized front-end ultrasonic and eddy-current test instrumentation.

2.1 Testing Station for ICE Train Drive Wheels

In addition to the existing AURA system for the inspection of disassembled wheel sets, the DB plant in Krefeld has recently installed a second AURA module (Figure 3), specifically designed for the ultrasonic testing of ICE Train drive wheels. This system is an essential part of the maintenance services offered by the Krefeld plant. ICE wheel sets can be refurbished and inspected directly at their maintenance facilities.

The wheel rim and disk are inspected for surface cracks and volume defects. The transducer assembly for wheel rim and disk inspection (Figure 4) consists of two fixed modules used for all types of wheel set, and additional hot-swap modules adapted to inspect specific wheel disk configurations.

For each fixed module, separate UT front-end electronics are integrated in close proximity to the transducer assembly (Figure 5). Each hot-swap module has an integrated UT front-end. Depending on the design of the wheel to be inspected, the handling unit takes the applicable module, including the UT front-end, from the pick-up shelf and positions it, together with the fixed modules, in the appropriate location on the wheel to be tested.

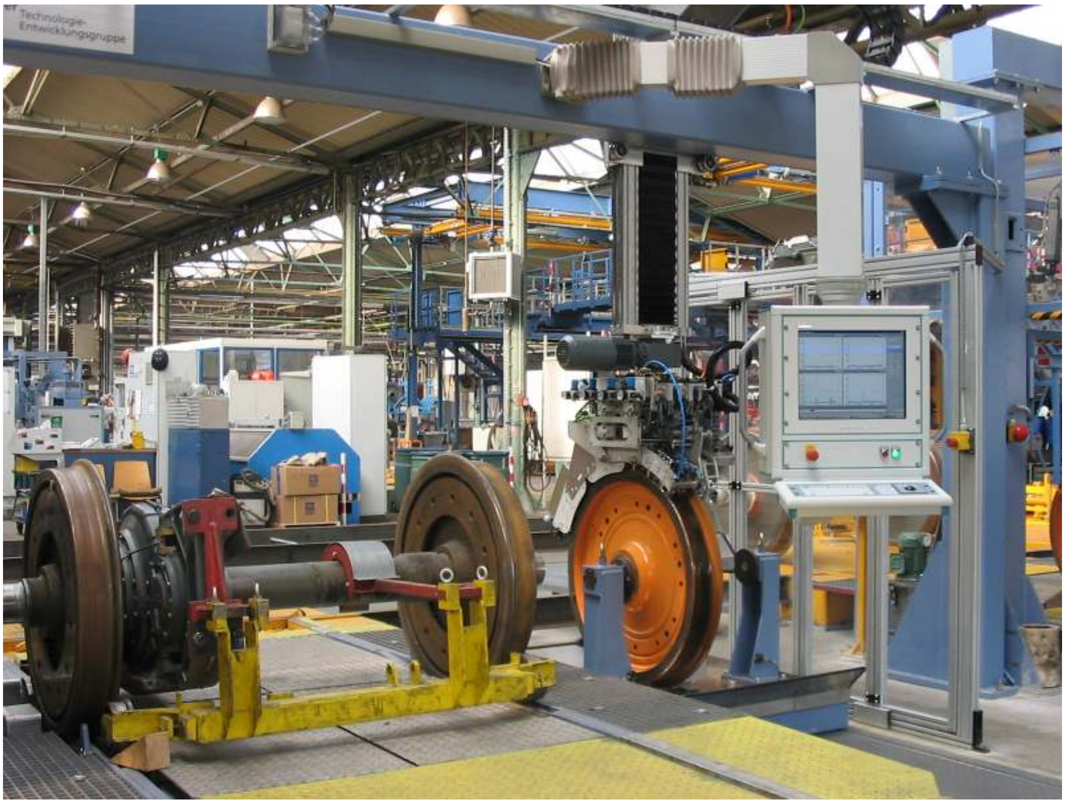

Figure 3: Ultrasonic Testing Station for ICE Train Drive Wheels at the DB Works Krefeld

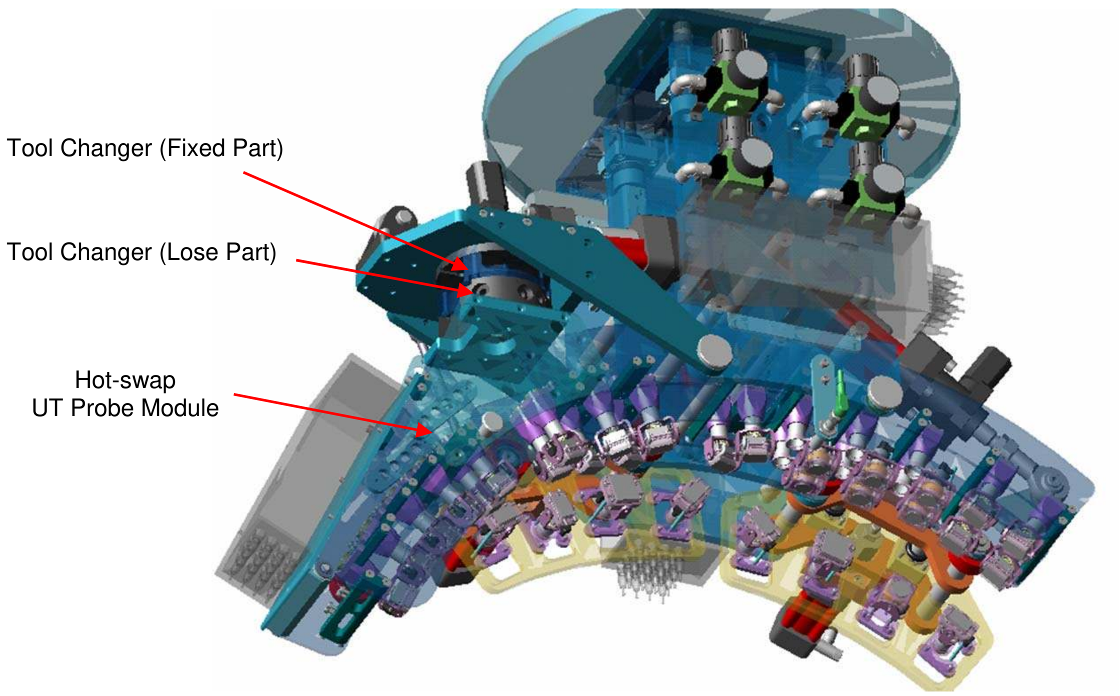

Figure 4: Ultrasonic Transducer Assembly with two Fixed Modules and one Hot-swap Module

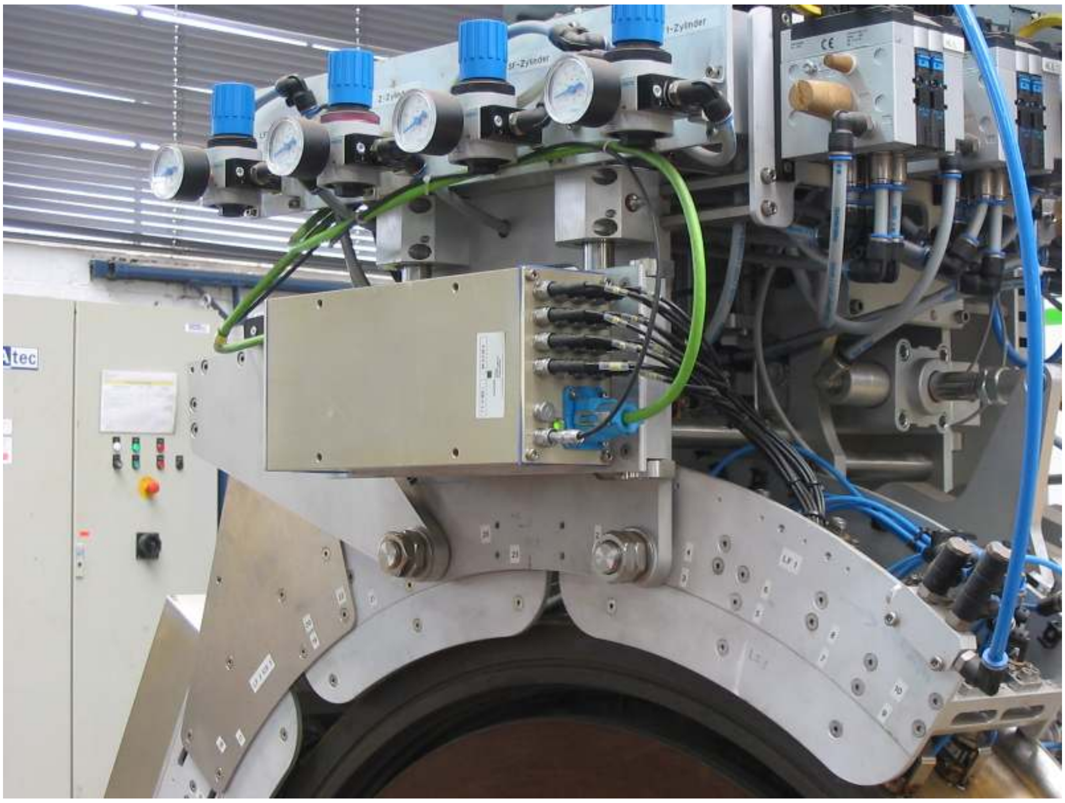

Figure 5: UT Front-end Electronics Mounted to the Probe System Carrier

The docking of the flexible module is achieved via the tool changer, which also provides the coupling liquid and the transfer of digital ultrasonic signals. Three 16-channel front-end modules are active during the inspection of the wheel set. State-of-the-Art networking techniques ensure the transfer of all the digital ultrasonic data acquired to the workstation responsible for data acquisition and analysis.

Ultrasonic inspection is provided by inducing ultrasonic waves on the inside face of the wheel rim and on the running surface. Up to 34 transducers are used for the inspection of one wheel, including the rim and disk. The front-end electronics and the testing software enable complete A-scans to be recorded. This is important for distinguishing the difference between potential crack signals and irrelevant geometric indications, caused by geometric reflections from wheel disk transitions and, in particular, by tapholes. In order to further reduce inspection costs, only one transducer system is applied at a time and the wheel set is inspected in two steps. In the first step, the left wheel is tested. After placing the transducer system on the wheel, the first rotation of the wheel set is used to wet the surfaces to achieve optimal coupling conditions. The actual inspection requires only one more revolution of the wheel.

The ultrasonic data are acquired within a short time and, after completion, the inspection results are presented. Extensive automation of the data evaluation process and a concise display of the processed ultrasonic data (Figure 6) assist the operator in assessing the inspection results and determining their acceptability.

In the second step of the inspection, initiated by the examiner, the transducer assembly is lifted off the wheel that has been tested, and, after a swivel through 180 degrees, the transducer system is positioned on the right wheel to complete the inspection of the wheel set.

The inspection of an entire wheel set, including data display, takes approximately five minutes. Additional data analysis and result evaluation involves only a few more minutes for the skilled, experienced operator.

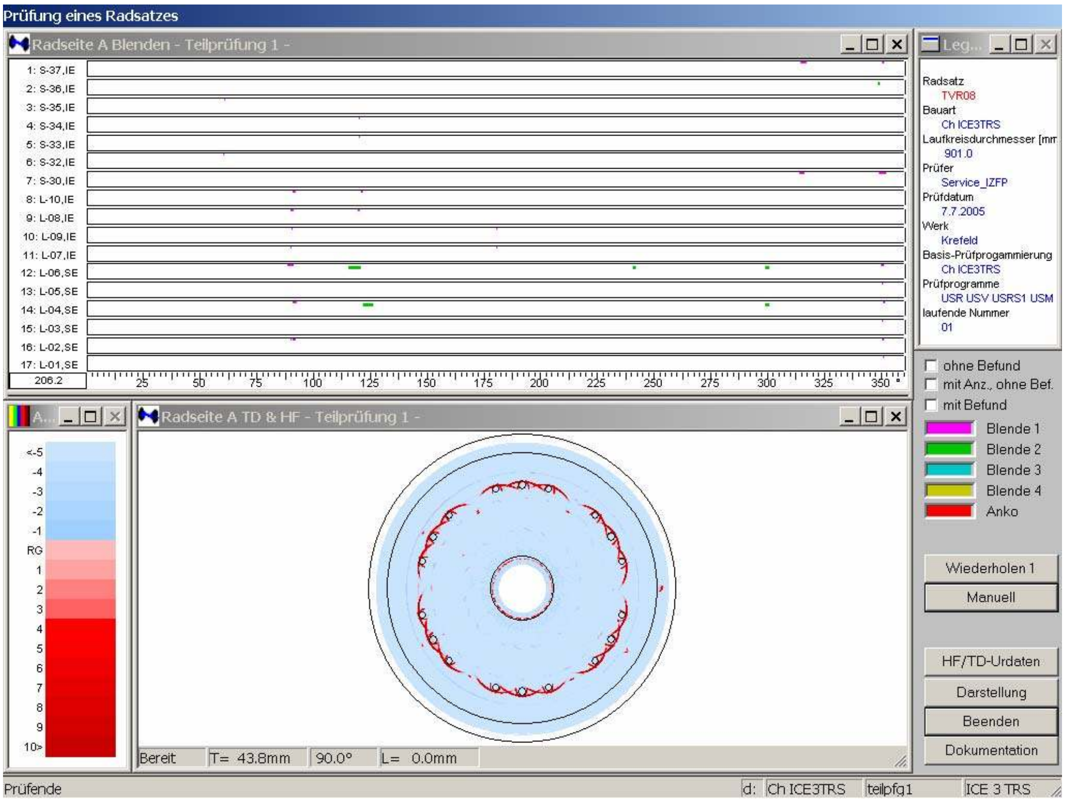

Figure 6: Result Display after Wheel Rim and Disk Inspection of an ICE 3 Drive Wheel

2.2 Combined Testing Station for Wheels and Axles of Freight Cars

The Süddeutsche Rail Service GmbH, Kaiserslautern (SRS) performs refurbishment, reconditioning, repair and maintenance on a variety of rail equipment components of freight cars. The reconditioning of wheel sets is an important task within the overhaul process. Following inspection on arrival and measurement of residual stresses in the wheel rim, using a stress measurement system provided by the IZFP [5], the wheel sets are re-profiled on a metalworking lathe. Subsequently, wheel rims and axle are inspected for flaws and discontinuities using a testing system supplied by the IZFP and the TEG (Figure 7).

Ultrasonic techniques are used to inspect the wheel rims for cracking and volumetric flaws. The running surface is tested for surface cracking by eddy-current techniques. Twelve ultrasonic transducers and four eddy-current sensors are used for the inspection of each wheel.

The axles of freight cars are usually solid and are ultrasonically inspected for transverse cracking in the wheel seats, journal, dust-guard seat, and all areas with cross-sectional variations. In order to cover all these areas, a large number of different incidence angles are required. To reduce the overall time for axle inspection, a phased array system provided by GE Inspection Technologies is used [6]. The incidence angles are electronically varied from 25° to 75°. For the ultrasonic inspection one phased array search unit with fourteen active elements is positioned on each side of the axle body.

Figure 7: Combined Testing Station for Wheels and Solid Axles at the SRS Maintenance Facility

To reduce overall costs and space requirements, a wheel set testing station has been implemented for the first time that permits the combination of ultrasonic and eddy-current techniques for the inspection of wheel rims and the ultrasonic testing of solid axles using phased array technology. The inspection station was installed and commissioned at the SRS plant in the autumn of 2004.

The entire system is controlled from a centralized host computer; all functions for wheel rim and solid axle inspections are integrated into a higher order test program. The entire inspection process is fully automated. The ultrasonic transducers and eddy-current sensors required for the inspection of the wheel rim are positioned onto the tread and onto the back face of the rim. The phased array search units are placed onto a defined area of the axle body, which was shot blasted prior to the inspection (Figure 8). The axial position of the phased array transducer varies depending on the type and design of the axle to be inspected.

Two 16-channel ultrasonic front-end modules and one 8-channel eddy-current front-end are applied for the examination of the wheel rims. They are installed in close proximity to the transducer carrier, in other words close to the ultrasonic transducers and eddy-current sensors.

The test data are digitally transferred to the host computer. Networking technology provides for all data transfer and data communication with the host computer. The COMPAS system, operating the phased array search units, is also linked to the host computer for data transfer and communication.

During wheel rim inspection, test data are automatically processed and analyzed. The inspection results are available shortly after all data have been processed. Ultrasonic and/or eddy-current indications that reach or exceed the reporting threshold can be assessed by the examiner while data acquisition for the axle is still underway. The images resulting from the axle inspection require visual evaluation by qualified inspection personnel, because geometric indications from cross-sectional variations and inner bearing races are usually present and do not permit automated analysis. However, a custom-tailored evaluation program, part of the COMPAS software package, aids the examiner in the data evaluation process.

Figure 8: View of Probe System Carriers for Testing the Wheels and Solid Axle

Indications reaching or exceeding the reporting threshold can be analyzed using a manual inspection mode by rotating the wheel set into the position where the indication is visible in the A-scan presentation. Information presented in the A-scan provides valuable assumptions of cause and origin and, in combination with a visual examination of the area in question, permits the accurate assessment of the indication.

Wheel sets free of reportable indications are forwarded to additional service jobs, including dimensional control in a measurement station designed and delivered by the Fraunhofer Institute for Factory Operation and Automation [7].

2.3 Underfloor Testing of ICE Wheels

Underfloor testing systems are applied at DB maintenance facilities to inspect wheel sets of ICE high-speed trains by ultrasound with the wheel sets installed at the train. The first generation of Underfloor Testing Systems (UFPE) resulted from cooperation between DB, BAM (Bundesanstalt für Materialforschung und -prüfung), IZFP, and TEG, and is currently in use at several DB facilities [3]. For testing, the wheel set is lifted from the rail head and rotated by an appropriate mechanical device. Both drive wheel sets and running wheel sets can be inspected.

With the objectives of reducing testing time, minimizing handling efforts, and improving reliability and simplicity of maintenance, a new concept for underfloor testing was developed. This concept includes the application of IZFP's front-end electronics in close proximity to the transducer assembly as depicted in Figure 9, with transfer of the ultrasonic data over wireless LAN to the host computer placed besides the maintenance track (Figure 10). Thus noise- and failure-prone cable connections are avoided. Since after completion of an inspection the testing equipment has to be moved to the next wheel set to be inspected, time to set up the inspection system is reduced since no cables have to be handled.

In its essential features the software applied for data acquisition, data display and evaluation is the same which is used for testing of disassembled ICE wheel sets (see section 2.1).

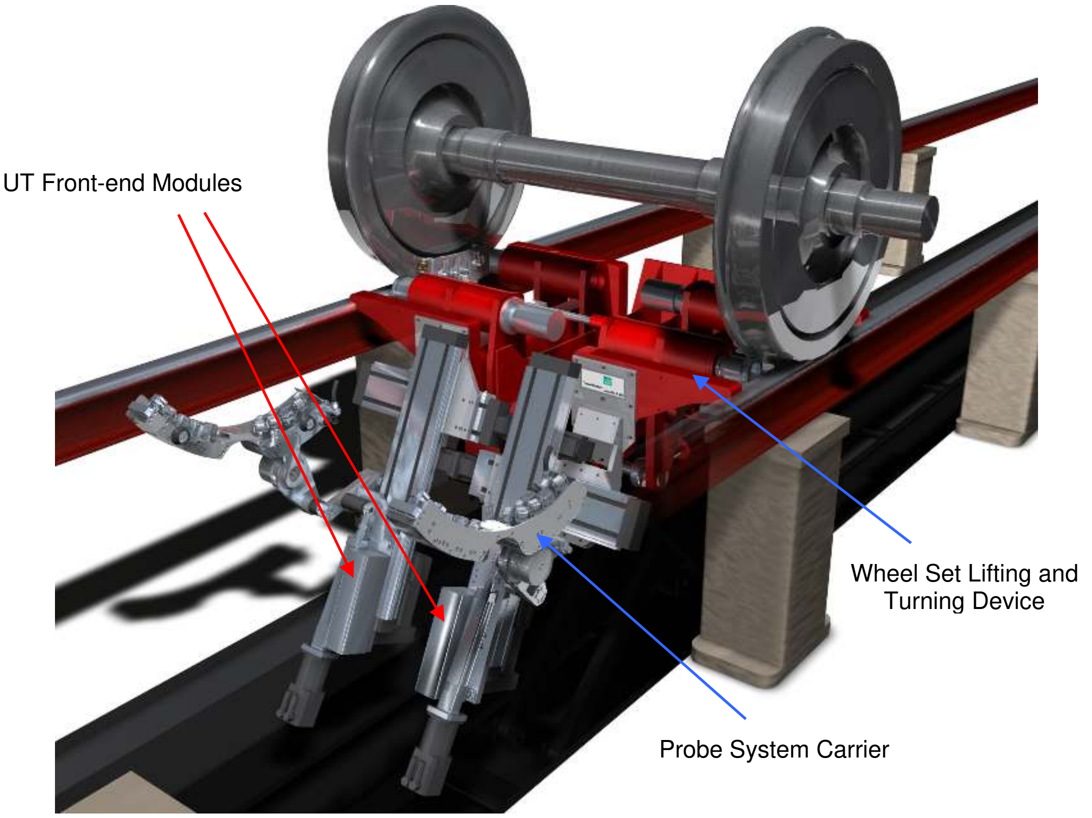

Figure 9: UFPE System Components with Probe System Carrier in Basic Position

3. Conclusion

The AURA systems delivered to DB and SRS demonstrate that inspection systems can be custom-tailored to specific applications for wheel set maintenance and service facilities by utilizing innovative handling technology and state-of-the-art test electronics in combination with high-level miniaturization and modular design.

The high-level availability of AURA inspection systems is supported through remote service and diagnostics via ISDN or Internet communication and periodical maintenance.

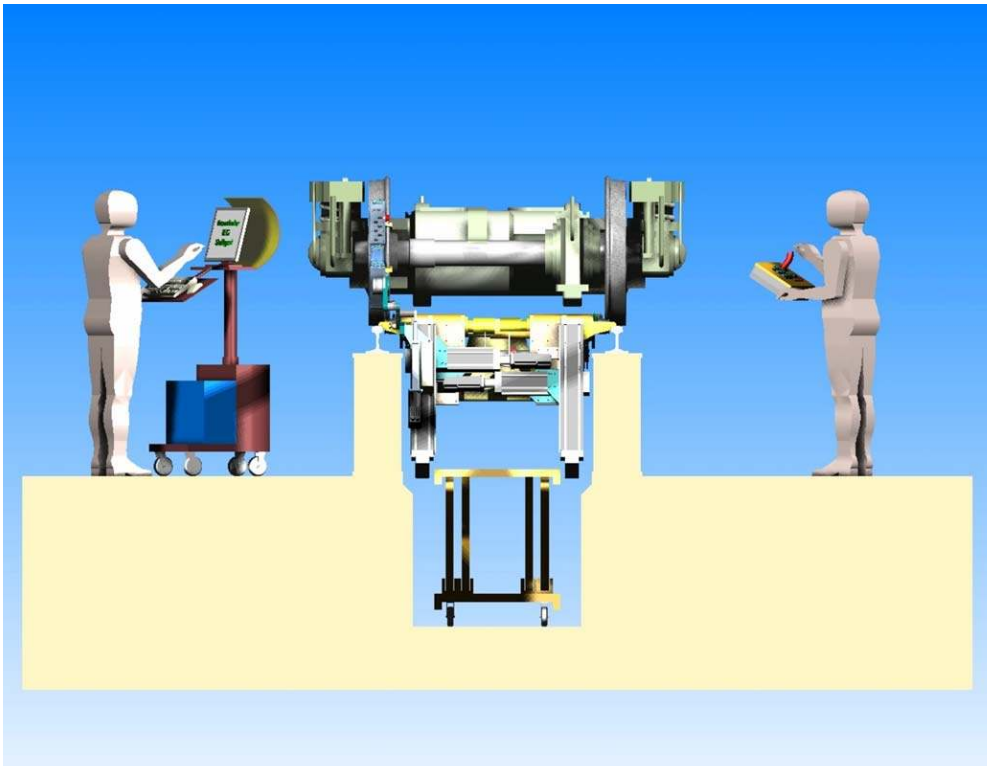

Figure 10: Wireless Operation and Data Transfer as a Part of the New Concept for Underfloor Testing

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