Predictive Maintenance employing Non-intrusive Inspection & Data Analysis

D2.1
Assessment report on suitable methods for structural integrity inspection of embedded girder rails

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Reviewed: Y

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Instrument: Small or medium-scale focused research project
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1. EXECUTIVE SUMMARY

This deliverable summarises the state-of-the-art techniques available for rail inspection. Within WP2 a technique has to be selected which is effective for testing embedded girder rails on site. The information contained in this deliverable about recent inspection techniques is mainly extracted from following recent documents and sources:

- EC project INTERAIL kick-off meeting notes, October 2009;
- 14th AAR Research Review, Improved Rail Flaw Inspection, Pueblo 2009 (Appendix A);
- Conference proceedings CM2009, Rail Restoration Lifetime on High Speed Line, September 2009 (Appendix B);
- EC project INNOTRACK deliverable D4.4.1 on Rail Inspection Technologies, November 2008;
- EC project WIDEM deliverable D6.1 on Development of Compensated Resonance Inspection Prototype for Wheelset, January 2005 (Appendix C).

The types of defects to be considered are defined by the urban rail operators. Most common defects in embedded girder rail for tram in order of importance are:

- Electrolytic corrosion of web and/or foot.
- Cracks in deposit welded rail repairs in curves leading to loosening of the welded repair. Welded repairs are in the active surface of the railhead and in the guiding rail part.
- Cracks leading to broken rail, mainly close to rail connection welds (about 10 cm from weld location).
- Cracks under railhead surface, leading to shelling.

The specific inspection difficulties related with embedded girder rails are:

- The rail web and rail foot are not accessible (visual inspection and surface contact with sensors is not possible).
- The rail web is not situated under the railhead and the railhead has a complex geometry making conventional ultrasonic testing impossible.

It is concluded from this state-of-the-art review that no existing inspection technique is suited to inspect the embedded girder rails for the type of defects to be considered. A new inspection technique based upon high frequency excitation in a large frequency band (50 kHz – 150 kHz) with analysis of the broad band reflected wave patterns will be developed and tested.
2. INTRODUCTION

2.1 OBJECTIVES OF THE DELIVERABLES
(with reference to the Technical Annex)

This deliverable is a first step (state-of-the-art review) in the process of selection, development and validation of a suitable inspection method for the assessment of the structural integrity of embedded rails. The general objectives of WP 2 are:

1. To select a suitable method for the inspection of the internal integrity of embedded girder (grooved) rails.
2. To develop the selected method for the inspection of the internal integrity of embedded girder rails: this includes data acquisition method (sensor), data analysis method and diagnostic method.
3. To validate the developed suitable method for the inspection of the internal integrity of embedded girder rail: this includes the building of a prototype, the mounting on a trolley and the on site validation of the technique.

2.2 INPUTS (contributions from beneficiaries, other deliverables....)

- EC project INTERAIL kick-off meeting notes, October 2009;
- 14th AAR Research Review, Improved Rail Flaw Inspection, Pueblo 2009 (Appendix A);
- Conference proceedings CM2009, Rail Restoration Lifetime on High Speed Line, September 2009 (Appendix B);
- EC project INNOTRACK deliverable D4.4.1 on Rail Inspection Technologies, November 2008;
- EC project WIDEM deliverable D6.1 on Development of Compensated Resonance Inspection Prototype for Wheelset, January 2005 (Appendix C).

2.3 MAIN RESULTS

An inventory has been made of the most common current non-destructive on site inspection methods and techniques for rails. The types of defects to be considered have been identified.

It is concluded from this state-of-the-art review that no existing inspection technique is suited to inspect the embedded girder rails for the type of defects to be considered. A new inspection technique based upon high frequency excitation in a large frequency band (50 kHz – 150 kHz) with analysis of the broad band reflected wave patterns will be developed and tested.

2.4 POSSIBLE LINKS OF RESULTS WITH OTHER DELIVERABLES

D2.1 gives the necessary input to all other deliverables within WP2.
3. MOST COMMON CURRENT NON-DESTRUCTIVE ON-SITE INSPECTION METHODS FOR RAILS

3.1 RAIL INSPECTION USING ULTRASONICS

During the inspection of vignol (or T) rails using conventional ultrasonic probes a beam of ultrasonic energy is transmitted into the rail. The reflected or scattered energy of the transmitted beam is then detected using a collection of transducers. The amplitude of any reflections together with when they occur in time can provide valuable information about the integrity of the rail. Since defects are not totally predictable, the energy is transmitted at several different incident angles in order to maximise the Probability of Detection (PoD) of any detrimental defects present in the rail. The refracted angles generally used are 0, 37 or 45 and 70°. In addition, transducers are also positioned to look across the railhead for longitudinal defects such as vertical split heads and shear defects.

At STIB, this ultrasonic testing is carried out at least once a year using the RATP test train (Eurailtest services). Sliding plate sleds are used to couple the piezoelectric transducers to the rail. The presence of detected anomalies by the test train is confirmed through the deployment of portable ultrasonic inspection units, which perform a local analysis.

After this local inspection, the anomalies are basically categorised into 4 classes: urgent replacement required, non-urgent replacement required, further observation required, non-relevant anomaly (most common case).

Train speed in the STIB network is limited to 45 km/h; a 90-95% success rate of defect identification is anticipated.

In general, problems encountered by the ultrasonic test trains include:

- Very cold weather where ice interferes with testing by providing an intervening interface.
- Leaf mould, which drastically affects sensitivity of the probes.
- Sandite can be problematic as it provides an intervening interface.
- Heavily applied lubrication can affect results up to 100m from a trackside lubrication unit, which also produces an intervening interface.
- Identification of vertical/transverse defects can be problematic.

Magnetic Flux Leakage (MFL) testing is usually employed in certain inspection trains for the detection of near-surface defects as complementary technique to ultrasonic testing. The use of this technique is restricted at speeds below 35 km/h as its performance deteriorates significantly at higher speeds.

More recently, hybrid systems based on the simultaneous use of pulsed eddy current (EC) sensors and conventional ultrasonic testing probes have been introduced in Germany.
Netherlands and elsewhere for the high-speed inspection of rail tracks. Pulsed EC sensors have a superior performance in comparison to ultrasonic testing probes when inspecting for near-surface or surface-breaking defects, such as Rolling Contact Fatigue (RCF), spalls and shelling. Pulsed eddy current sensors seem to offer a better proposition than MFL probes as they are more sensitive to near-surface and surface defects and can operate at significantly higher speeds (inspection speeds of up to 100 km/h are possible).

3.2 RAIL INSPECTION USING MAGNETIC FLUX LEAKAGE

Magnetic flux leakage method (MFL) is broadly used for NDE of structural components. In MFL, permanent magnets or DC electromagnets are used to generate a strong magnetic field in order to magnetise the ferromagnetic specimen under inspection to saturation. The magnetic flux lines are coupled into specimen using metal ‘brushes’ or air coupling. If there are any anomalies or inclusions, the magnetic flux lines will leak outside of the specimen close to the anomalies and the sensor or sensor array will detect the leakage magnetic field, which conceives information relating to anomalies or inclusions such as corruptions and cracks.

According to the distribution of magnetic flux lines coupled into the specimen, MFL systems that comprise magnetiser and sensors or sensor array are categorised into two types:

1. circumferential MFL excelling in detection and sizing of longitudinal defects.
2. axial MFL that is able to volumetric or metal-loss defects with a significant circumferential extent or width.

Both methods suffer from the probe velocity effect on MFL signals.

It has been reported that velocity effects for circumferential MFL are more significant than for axial MFL and the speed at which probe velocity influences the circumferential MFL is much lower than that for axial MFL.

In rail inspection using MFL, search coils fixed at a constant distance from the rail, are used to detect any changes in the magnetic field that is generated by a DC electromagnet around the rail. In the areas where a near-surface or surface transverse defect is present in the rail, ferromagnetic steel will not support magnetic flux and some of the flux is forced out of the part. The sensing coil detects a change in the magnetic field and the defect indication is recorded.

Unfortunately, transverse fissures are not the only types of defects found in rail. Other manufacturing and service-related defects that can occur include inclusions, seams, shelling, and corrosion. Fatigue cracks can initiate from these defects, as well as normal features of the rail such as boltholes. If these defects go undetected, they can lead to railhead and web separations. Many of these defects are not detectable with the flux leakage method because the flaws run parallel to the magnetic flux lines or the flaws are too far away from the sensing coils to detect. The maximum speed achieved for the combined ultrasonic/MFL system is typically 35 km/h.
3.3 Rail inspection using pulsed eddy currents

For several years, application of eddy current technology was limited for inspection of individual rail welds.

More recently, eddy current systems were developed to perform inspections on rails at speeds of a few metres per minute in order to detect cracks due to Rolling Contact Fatigue. The sensor is pushed by the operator along the railhead who looks for changes in the signal caused by the presence of RCF cracks.

As mentioned earlier, standard ultrasonic sensors have poor detection ability when surface-breaking or near-surface defects are involved. An eddy current sensor has a far better ability in detecting this type of defects. Nearly all relevant surface or near surface defects can be detected using eddy current inspection.

Nonetheless, attention needs to be given to lift-off variations during eddy current inspection. Table 1 provides an overview of the detect-ability of eddy current sensors.

<table>
<thead>
<tr>
<th>Category</th>
<th>Detectability</th>
<th>Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head Checking</td>
<td>Very good</td>
<td>Quantity, location, depth</td>
</tr>
<tr>
<td>Indentures</td>
<td>Very good</td>
<td>Quantity, location, period</td>
</tr>
<tr>
<td>Wheel-burns</td>
<td>Very good</td>
<td>Location, extent</td>
</tr>
<tr>
<td>Grinding marks</td>
<td>Very good</td>
<td>Quantity, location, period</td>
</tr>
<tr>
<td>Rail joints</td>
<td>Very good</td>
<td>Location, kind</td>
</tr>
<tr>
<td>Squats</td>
<td>Good</td>
<td>Quantity, location</td>
</tr>
<tr>
<td>Short/long pitch corrugation</td>
<td>Good</td>
<td>Location, period</td>
</tr>
<tr>
<td>Welds</td>
<td>Good</td>
<td>Location, Kind, Lack of fusion</td>
</tr>
</tbody>
</table>

Table 1 – Capability of eddy-current sensors in detecting various surface defects

It is very important to guide the eddy current probes so that the signals are not influenced and the sensitivity does not fluctuate due to lift-off from the test surface. The rail inspection test situation is especially complex, since the probe has to be positioned at an angle relative to the guiding surface.

* Extract from ref. [4], table 1, p. 14
3.4 RAIL INSPECTION USING ALTERNATING CURRENT FIELD MEASUREMENT

Alternating Current Field Measurement (ACFM) is an electromagnetic inspection method, which is now widely accepted as an alternative to magnetic particle inspection in the Oil and Gas Industry, both above and below water. Although developed and patented by TSC Inspection systems initially for routine inspection of structural welds, the technology has been improved further to cover broader applications across a range of industries. Increases in inspection speeds (from a few centimetres per minute to a few metres per minute), application to non-planar crack morphologies and extension of sizing models to accommodate different crack types have all been achieved.

The technique is based on the principle that an alternating current (AC) can be induced to flow in a thin skin near the surface of any conductor. By introducing a remote uniform current into an area of the component under test, when there are no defects present the electrical current will be undisturbed. If a crack is present, the uniform current is disturbed and the current flows around the ends and down the faces of the crack.

Because the current is an alternating current it flows in a thin skin close to the surface and is unaffected by the overall geometry of the component.

In contrast to eddy current sensors that are required to be placed at a close (<2 mm) and constant distance from the inspected surface, a maximum operating lift-off of 5 mm is possible without significant loss of signal when using ACFM probes. This is due to the fact that the signal strength diminishes with the square of lift-off, not with its cube which is the case for eddy current sensors. This enables the ACFM technique to cope with much greater lift-off and thicker non-conductive coatings. For larger threshold defects a higher operational lift-off (>5 mm) is possible.

ACFM probes are available as standard pencil probes and multi-element array probes. These probes can be customised to optimise inspection of particular structural components and maximise the Probability of Detection (PoD) of critical-sized defects. ACFM pencil probes can detect surface-breaking defects in any orientation. Nonetheless, in order to size defects, they need to lie between 0°-30° and 60°-90° to the direction of travel of the probe. This drawback is overcome in ACFM arrays by incorporating various field inducers in order to allow a field to be introduced within the inspected surface in other orientations. This is particularly useful in situations where the crack orientation is unknown or variable. In this case, additional sensors, are also incorporated in order to take full advantage of the additional input field directions.

A pedestrian-operated ACFM walking stick has been developed, a totally self contained device and capable of 8-hour long independent operation. The incorporated ACFM array has been shaped to conform to the shape of the head of the rail. This allows the application of the ACFM system in both new and worn rails. The inspection across the railhead is carried out by sequentially scanning across the group of sensors enabling the uninterrupted inspection of the rail. Based on the data acquired through extensive metallographic work on rails with RCF cracking, a customised software package incorporating the appropriate defect sizing algorithms
has been developed in order to enable the automated sizing of the RCF cracks that are detected with the walking stick. By increasing sampling rates to 50 kHz the walking stick system achieved scanning speeds of 0.75 m/s (approximately 2 - 3 km of rail can be inspected within an hour). It should be stressed that sufficient data must be collected to not only detect a defect but also to determine its severity. Further experiments are currently under way in an effort to develop a high-speed ACFM sensing system for the detection and quantification of RCF in rails in collaboration with the University of Birmingham within the EC INTERAIL project.

Only surface defects can be detected with ACFM with a crack size of 10 mm by 1 mm and higher.

3.5 Rail inspection using laser ultrasonic

Laser ultrasonic testing combines the sensitivity of ultrasonic inspection with the flexibility of optical systems in dealing with complex inspection problems. It works well in the testing of metals, composite materials, ceramics, and liquids. Its remote nature allows the rapid inspection of curved surfaces on fixed or moving parts. It can measure parts in hostile environments or at temperatures well above those that can be tolerated using existing techniques. Its accuracy and flexibility have made it an attractive new option in the non-destructive testing market.

Laser-based ultrasonic is a remote implementation of conventional ultrasonic inspection systems that normally use contact transducers or immersion systems. Laser ultrasonic systems operate by first generating ultrasound in a sample using a pulsed laser. When the laser pulse strikes the sample, ultrasonic waves are generated through a thermo-elastic process or by ablation. The full complement of waves (compression, shear, surface, and plate) can be generated with lasers. When this ultrasonic wave reaches the surface of the sample, the resulting surface displacement is measured with the laser ultrasonic receiver based on an adaptive interferometer.

Transportation Technology Centre Inc. (TTCI) together with Tecnogamma in the U.S. developed the first laser ultrasonic system for rail inspection. Preliminary tests showed that the developed laser ultrasonic system can be used to inspect the entire rail section including rail head, web and base. The system is loaded on a hi-rail vehicle (shown in attached video) and can currently operate at speeds up to 32 km/h. The optimum inspection speed however has been found to be between 8 km/h and 15 km/h.

It was found that ultrasound generation using laser impact line increases sensitivity and optimises the signal reception. However, the rate of detection still seems not satisfactory and the cost of the system is very high. Since this is a new method, more information is provided in appendix A.

3.6 Rail inspection using ultrasonic phased arrays

Ultrasonic phased arrays are a novel technique for non-destructive evaluation of structural components.

Instead of a single transducer and beam, phased arrays use multiple ultrasonic elements and electronic time delays to create beams by constructive and destructive interference. As such, phased arrays offer significant technical advantages for weld testing over conventional ultrasonic.
The phased array beams can be steered, scanned, swept and focused electronically. Beam steering permits the selected beam angles to be optimised ultrasonically by orienting them perpendicular to the predicted discontinuities, for example lack of fusion in automated welds.

More recently, SNCF in collaboration CEA developed a phased array system to inspect arc welding repairs. This system has been recently used to inspect several hundred of arc welding repairs on the SNCF’s high-speed lines network. This is reported in appendix B.

### 3.7 Rail Inspection Using Long Range Ultrasonic Testing

Long-range ultrasonic testing is a technique based on transmitting ultrasound as volumetric waves along a structure such as a rail. Long-range ultrasonic testing may employ a range of wave modes Lamb, Plate, Rayleigh, but has become commonly known as the Guided Wave technique.

Transducers are designed and placed so that the appropriate wave modes can be excited and transmitted in the structure. Reflections from fixed reference points, such as girth welds, can be detected as well as changes in cross sectional areas, such as cracks or corrosion. These reflections are recorded and analysed to produce information on the probability, approximate size and location of the reflections. This analysis requires suitable software in addition to trained and experienced personnel.

Long-Range Ultrasonic can be effective over distances up to 180 m from the sensor array. However, various factors can significantly attenuate the signal to an extent that in some cases, the effective distance may only be a few metres. The wave mode and frequency selected determines the most effective inspection range.

The techniques are generally sensitive to change in the cross-sectional area of the component. As such, a 5% change in the cross-sectional area of the inspected structure is needed in order to produce an interpretable response indication.

A commercial guided waves hi-rail vehicle, known as Prism, has been produced by Wavesinsolids LLC in the U.S. Typically a single frequency wave of 40 kHz is used which is responsible for the lack in detection performance of the system.

### 3.8 Other Inspection Methods

Some other NDE techniques that are currently under investigation for inspection of rails include Electromagnetic Acoustic Transducers (EMATs) and visual high-speed cameras.
### 3.9 SUMMARY OF NDT TECHNIQUES FOR THE RAIL (TABLE 2†)

<table>
<thead>
<tr>
<th>NDT Technique</th>
<th>Systems Available</th>
<th>Defects Detected</th>
<th>Performance</th>
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<tr>
<td>Ultrasonics</td>
<td>Manual and high-speed systems (up to 70 km/h)</td>
<td>Surface defects, rail head internal defects, rail web and foot defects</td>
<td>Reliable manual inspection but can miss rail foot defects. At high speed can miss surface defects smaller &lt;4mm as well as internal defects particularly at the rail foot</td>
</tr>
<tr>
<td>Magnetic Flux Leakage</td>
<td>High-speed systems (up to 35 km/h)</td>
<td>Surface defects and near surface internal rail head defects</td>
<td>Reliable in detecting surface defects and shallow internal rail head defects although cannot detect cracks smaller than &lt;4mm. MFL performance deteriorates at higher speeds</td>
</tr>
<tr>
<td>Pulsed Eddy Current</td>
<td>Manual and high-speed systems (up to 70 km/h)</td>
<td>Surface and near-surface internal defects</td>
<td>Reliable in detecting surface breaking defects. Adversely affected by grinding marks and lift-off variations</td>
</tr>
<tr>
<td>Automated Visual Inspection</td>
<td>Manual and high speed systems (up to 320 km/h)</td>
<td>Surface breaking defects, rail head profile, corrugation, missing parts, defective ballast</td>
<td>Reliable in detecting corrugation, rail head profile missing parts and defective ballast at high speeds. Cannot reliably detect surface breaking defects at speeds &gt;4 km/h. Cannot assess the rail for internal defects</td>
</tr>
<tr>
<td>Electromagnetic Acoustic Transducers</td>
<td>Low speed hi-rail vehicle (&lt;10km/h)</td>
<td>Surface defects, rail head, web and foot internal defects</td>
<td>Reliable for surface and internal defects. Can miss rail foot defects. Adversely affected by lift-off variations</td>
</tr>
<tr>
<td>Long range Ultrasonic Testing</td>
<td>Manual systems and low-speed hi-rail vehicle systems (&lt;10 km/h)</td>
<td>Surface defects, rail head internal defects, rail web and foot defects</td>
<td>Reliable in detecting large transverse defects (&gt;5% of the overall cross-section)</td>
</tr>
<tr>
<td>Laser Ultrasonic Testing</td>
<td>Manual and low-speed hi-rail vehicle systems (&lt;15 km/h)</td>
<td>Rail head, web and foot defects</td>
<td>Reliable in detecting internal defects. Can be affected by lift-off variations of the sensors, difficult to deploy at high speeds</td>
</tr>
</tbody>
</table>

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Table 3‡ – Summary of NDT techniques for the rail

‡ Extract from ref [4], table 2; p.23
‡ Extract from ref [4], table 2; p.23
None of the available techniques or techniques under investigation is suited for the detection of the identified defect types in embedded girder rail.
4. PROPOSED HIGH FREQUENCY EXCITATION AND SENSOR
TECHNIQUE

Figure 1

The proposed technology has been developed and validated for the inspection of cracks in wheel set axles. In general, there is a correlation between the vibration spectra of parts made by a controlled process. These spectra depend on the product’s dimensions and material properties. By measuring and comparing these spectra, one is able to separate defective items from good items.

With a simple and single impact, the structure that needs inspection is excited dynamically. The whole structure receives the excitation and starts to vibrate in return and waves are generated and returned. The returned vibration spectrum is measured up to 150 kHz. A large number of spectral peaks are automatically selected and analysed.
Analysis of these peaks is done with a customised combination of statistical criteria such as Percentage of Common Peaks (PCP), Least Square Coefficient (LSQ) and Spectral Cross Correlation (SCC)…

Based on a number of selected criteria, good items are distinguished from defective items by comparing the measurement spectra and analysis results with a database, containing reference values. As not only defects but also temperature variations and size variations influence the vibration response spectrum, an identification procedure has to be set-up for these effects.

The impact excitation to the whole structure can be given by e.g. a miniscule hammer. High frequency vibration response is measured by a dedicated sensor. Unlike a microphone this sensor has to be not sensitive to environmental noise and has to be able to measure vibration spectra up to 150 kHz (with a flat response). The technology makes the inspection fast and inexpensive.

Appendix C gives more details about the high frequency defect detection method.

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§ Extract from ref. [5], p.55, figure 4.45
5. REFERENCES

[1] EC project INTERAIL kick-off meeting notes, October 2009
[4] EC project INNOTRACK deliverable D4.4.1 on Rail Inspection Technologies, November 2008
[5] EC project WIDEM deliverable D6.1 on Development of Compensated Resonance Inspection Prototype for Wheelset, January 2005
APPENDIX A

This appendix consists of:

- the presentation of 14th AAR Research Review, *Improved Rail Flaw Inspection*, Pueblo 2009;
- the video 2008 u-rail video.mpg.
Improved Rail Flaw Inspection

Greg Garcia and Bill Larson
SRI Project: Improved Rail Flaw Inspection

Priority Technology Road Map (TRM) Direction:

- Onboard & in-track condition monitoring and reduced track-caused derailments:
- Objective: improve reliability of rail inspection
  - Reduce broken rail derailments
  - Inspect the entire rail cross section

Other TRM Impacts:

- Increased rail life
- Reduced in-service failures
- Decreased maintenance costs
- Increased axle loads
- Zero reactive maintenance
Major Tasks in 2008:

- Redesign, development, commissioning, and revenue service implementation of laser-based ultrasonic technology for rail inspection (URail)
SRI 7A Improved Rail Flaw Inspection

Flaw Simulations Show:

♦ Non inspectable areas using conventional UT when scanning from the top of the railhead

♦ Sound path influenced by rail wear, rail surface damage, and orientation of flaw

♦ It is expected that detection capability would increase if rail was inspected from locations other than just the top of the railhead
SRI 7A Improved Rail Flaw Inspection

Transverse Defect Showing UT Effects from Shelling

Without Shell Flaw Detected

With Shell Flaw Not Detected
Laser-Based Rail Flaw Inspection

URail
Improved Rail Flaw Inspection

Laser Based Ultrasonic Inspection:
- A prototype, single-rail, inspection system redesigned
- Tests show system is capable of inspecting the entire rail section
- Apr 2007-Mar 2008: Production of new prototype
- Apr-Oct 2008: System qualification at TTC

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Improved Rail Flaw Inspection

URail Inspection Box

- Profile System
- Head Sensors
- Sensor Assembly for Base Field
- Base Field Laser Collimator
- Web Sensors
- Head Laser Collimator
- Sensor Assembly for Base Gage
- Base Gage Laser Collimator
- Web Laser Collimator

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Improved Rail Flaw Inspection

System Description (Inspection Box)

- Real time adjustment of laser sources and sensors providing compensation for geometrical changes in the rail section
- Profile system - based on triangulation between laser beam and digital camera

- Laser source position is adjusted by rotation of the collimators
- Sensor mounts slide laterally with respect to the rail
System Description Railhead Inspection

Pitch-Catch Configuration

No-defect

Internal defect

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System Description — Rail Web Inspection

Pitch-Catch Configuration

No-defect

Internal defect
System Description — Rail Base Inspection

Pitch-Catch Configuration

No-defect

Surface defect
### RDTF Evaluation Results

<table>
<thead>
<tr>
<th>Flaw Type</th>
<th>Flaw Size</th>
<th>AREMA Category I Reliability Ratio</th>
<th>Current RDTF Reliability Ratio</th>
<th>Current URail Reliability Ratio</th>
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<tr>
<td>TD</td>
<td>5-10%</td>
<td>65%</td>
<td>68%</td>
<td>67-100%</td>
</tr>
<tr>
<td>TD</td>
<td>10-20%</td>
<td>85%</td>
<td>76%</td>
<td>67-100%</td>
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<td>90%</td>
<td>91%</td>
<td>75-100%</td>
</tr>
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<td>41-80%</td>
<td>98%</td>
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<td>75-100%</td>
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<td>HSH</td>
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<td>95%</td>
<td>No Data</td>
<td>80-100%</td>
</tr>
<tr>
<td>VSH</td>
<td>4-36 in.</td>
<td>95%</td>
<td>67%</td>
<td>80-100%</td>
</tr>
<tr>
<td>Split Web</td>
<td>2-4 in.</td>
<td>95%</td>
<td>No data</td>
<td>25-100%</td>
</tr>
<tr>
<td>Base</td>
<td>1 inch</td>
<td>Not addressed</td>
<td>No data</td>
<td>20-100% (0.25”)</td>
</tr>
</tbody>
</table>

Note: Flaw sizes shown in the table, other than transverse defects, represent the minimum size of flaw required to be detected by the FRA Track Safety Standards Part 213.113 Defective Rails Subpart D Remedial Action Table. The reliability ratios are compared to those listed in the AREMA “Recommended Minimum Performance Guideline for Rail Testing.”
Improved Rail Flaw Inspection

Test Results

- Technology is able to detect defects in railhead, web, and base
- Defect detection at RDTF 20-100%
- High number of false calls
- Areas of improvements identified
- Work underway to identify and address problem areas
TAG Recommendations

♦ Implementation Time Line:
  • Conduct a complete review of the system
    ▲ Transducers
      — January through February 2009
    ▲ Electronics enhancement
      — January through March 2009
    ▲ Data and software
      — December 2008 through April 2009
    ▲ Implementation
      — February through April 2009
  • Perform field evaluations
    — April through May 2009
  • Go – no go decision
    — June 2009
  • Begin development of a production system (2009-2010)
RAIL RESTORATION LIFETIME ON HIGH SPEED LINE

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ABSTRACT

Electric arc welding process has been widely used by SNCF (French national railways) to repair rails which presents damage on running surface. Depending on the depth of the defect, rails can be more or less ground and weld beads are deposited on one or more layers (2 to 15 mm) to restore the rail to its initial profile. In-track observations show that this kind of restoration has a limited lifetime on high speed lines. Indeed, lots of rails are removed due to development of cracks in welding repair. Moreover this cause of removal has been increasing since the late 90s.

SNCF, on behalf of RFF (French network owner), has initiated a study to improve knowledge about this phenomenon. This study is based on the idea that welding repair behaviour cannot be explained without considering its metallurgical quality. One of the main reasons of cracks development on welds is the presence of small gas inclusions spread among the whole repair, which could then cause crack initiation under mechanical stress. Until now, destructive methods were used to determine quantity and size information about porosities in welds. SNCF asked the CEA to develop a non-destructive testing method to check weld integrity. CEA was also asked to develop a specific instrumentation to detect, locate and classify by size gas inclusions bigger than 0.3 mm in the whole repair.

The principle of the method is based on the use of an ultrasonic contact phased-array transducer associated with a specific processing. The transducer is articulated to conform as much as possible to the nominal rail section. The use of a phased-array probe allows limitation of mechanical displacements to only one axis, along the longitudinal plane of the rail. Inspection in the plane perpendicular to the axis of the rail is performed through electronic commutation and beam steering. The data analysis is done using CIVA software. A processing based on ultrasonic field computation was developed. The method was experimentally tested on real repairs in laboratory conditions. A prototype was then designed and realised to carry out the method on rail track. This device performs two functions:
- Inspection of a repair without any operator intervention thanks to an automatic displacement of the transducer.
- Transportation of the system between two repairs.

The system is autonomous; it has its own power generator and water supply for ultrasonic coupling.

A test campaign was achieved by SNCF on the railway network during which nearly 400 repairs were inspected. Once relationship between integrity and lifetime is established, new porosity thresholds should be considered.

This paper describes the method as well as the instrumentation designed for this study. Experimental results including ultrasonic images and associated analysis are shown. A first assessment of the general health of the repair from the high-speed lines is done.

1 INTRODUCTION

SNCF (French national railways) widely proceeds to restoration on rails which running table is damaged. Arc welding technique is used to deposit metal in layers on the surface of the rail. The depth of such repairs is between 2 and 15 mm and the length is less than 500 mm. Unfortunately, lifetime of such restorations can be limited, particularly on high speed lines, due to cracks development in the deposit metal. As a consequence, rails are removed, and this cause of removal has been increasing since the late 90s.

A study was initiated by SNCF to improve the understanding of crack initiation and growth behaviour.

One of the main reasons of cracks development is the presence of small gas inclusions in the restoration, which could cause crack initiation under mechanical stress.

SNCF asked the CEA to develop a non-destructive testing method and its associated instrumentation to detect and characterize gas inclusions equal or bigger than 300 μm embedded in restorations.

The first part of this paper describes the method of inspection, the instrumentation and the method of analysis specifically developed for this application. The second part presents an inspection campaign carried out by SNCF on high speed line restorations.
2 INSPECTION METHOD

2.2 Principle of the method

The method of inspection is based on a UT-phased array technique. A linear phased array, including 128 active elements individually driven, was designed for this application. This technique offers the advantage of inspecting the whole restoration with only one mechanical displacement, along the rail axis. The scanning in the perpendicular plane is achieved by an electronic commutation combined with several delay laws defined by CIVA-Software

This specific UT-phased array is shown in Figure 2. The shape of the probe is cylindrically curved to focus naturally the ultrasonic beam in the cross section of the rail; focusing in the incident plane is done by applying electronic delay laws. Some head rails can present a profile different from the nominal one. Considering these cases, the contact between the wedge and the surface of the rail is improved thanks to a central articulation which provides a partial flexibility to the probe.

The system is mainly made up of the UT-phased array, a Pulser/Receiver (M2M system), a motorized linear guide and a generator. The ultrasonic coupling between the probe and the rail is ensured by a film of water.

2.3 Example of result

Figure 4 to Figure 6 show an example of inspection obtained on track with the prototype. These three figures illustrate the possibility to represent data in various views as C-scan (top view), B-scan along the rail axis and B-scan in the plane perpendicular to the rail. One can observe that gas inclusions are detected in the whole volume of the repair. On Figure 5, alignment of several defects marks the boundary between restoration and base metal. Moreover, a difference of structural noise between the HAZ (heat-affected zone) and the base metal allows separating the limit between both areas.

Figure 1. Illustration of the method of inspection

Figure 2. UT-Phased array probe

Figure 3. Prototype of inspection on track

Figure 4. Example of inspection on track – Top view (C-scan)

Figure 5. Example of inspection on track – Cross-section view // to the running edge (B-scan)
3 ANALYSIS METHOD

Data analysis aims at characterizing gas inclusions in terms of size, position and number. This analysis is achieved using several tools already available in CIVA-software or specifically developed in the framework of this study.

3.1 Analysis tools

3.1.1 Equalization

Gas inclusion sizing is based on their reflected amplitude; which is supposed to increase according to the size of the defect assuming that the geometry of the flaw is approximately spherical. The link between size and amplitude can be calibrated using defects with known dimensions.

This method can be used if the amplitude variations due to the size of the defects can be separated from the amplitude variations caused by the field effects. We use a data-processing technique to compensate for the latter. First a DAC (Depth Amplitude Compensation) is applied to each shoot in order to compensate for the variations of sensitivity in depth. A second step takes into account the variations of sensitivity between all shots. The processing then consists in performing normalization between the shots.

Principle of the processing:
Considering the number of shots and the geometry of the rail, it is impossible to determine a DAC and a normalization procedure from experimental results. For this reason, simulation was used.

The principle of the method to define the DAC curve is as follow: for each shot, we simulate the ultrasonic field along the ultrasonic path. We obtain amplitude versus time curve that allows determining the associated DAC. Figure 7 shows three examples of field computation (curves) along the main path of the beam (line).

In addition, variations of sensitivity between shots are automatically calculated. It is thus possible to deduce the normalization factor to apply for each shot.

Figure 7. Example of field simulated with CIVA

Figure 8 shows an acquisition before and after applying data processing. Before processing, there is a 6 dB difference in amplitude between the holes located at 9 and 12 mm in depth. Using the processing, this difference is lowered to about 1 dB.

3.1.2 Sizing method

The sizing method aims at sorting inclusions in size categories. The connection between amplitude and defect size can be determined using equalization processing and spherical defects of known size. In that way, experiments were carried out on a mock-up that contains calibrated hemispherical bottom holes (HBH). Figure 9 shows a mock-up containing three HBH; 0.3, 0.6 and 0.9 mm in diameter. This mock-up was used to adjust detection threshold for the inspection of the area under the running band. The echodynamic curve shows the amplitude of the echoes during the mechanical scanning.
Amplitude values are reported in the table 1.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>∅0.3</th>
<th>∅0.6</th>
<th>∅0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>-6 dB</td>
<td>-2 dB</td>
<td>0 dB</td>
</tr>
</tbody>
</table>

Table 1. Amplitude / Size connection

From this acquisition, two thresholds are defined at -2 dB and -6 dB allowing defects to be sorted in three categories:

- Amplitude ≥ -2 dB for defects bigger or equal to 0.6 mm,
- -6 dB ≤ Amplitude < -2 dB for defects of size ranging from 0.3 to 0.5 mm,
- Amplitude < -6 dB for defects strictly smaller than 0.3 mm.

These values were validated by Radiographic Testing on real repairs including gas inclusions. Moreover, several simulation and experimental acquisitions were done to confirm the validity of these thresholds on worn rails.

3.1.2 Segmentation

The “Segmentation” tool of CIVA Software provides information such as the number of defects, the position for each one, their maximum amplitude and it makes also possible to classify the defects according to these criteria. The principle of segmentation is based on the search for coherences between consecutive signals of the same acquisition to gather them into segments (2D) then into groups (3D). Each group corresponds finally to a defect in the repair (Figure 10).

3.2 Automation tools

A new automation module was specifically developed to make the analysis of inspection easier. This module automatically performs the processing described above and provides a report containing the number of inclusions, their position and their amplitude which can be connected to the size. Moreover, this automation module can be carried out by a non-specialist operator.

4 TEST CAMPAGNE ON TRACKS AND FIRST ANALYSIS

4.1 On track tests

There is no national register of all restoration carried-out on track. There is only local information about the working area but not a precise location.

That is why it was decided to determine an area where it is known that rail restoration has been realised (1 or 2 kilometres area) and find precise location directly on track. Each rail restoration found has been inspected with the prototype.

In order to have a representative sample of network, 38 areas of high speed lines have been inspected. One night of inspection per area (tracks are available only by night on high speed lines) was organised, so the whole campaign represents 38 nights between June and September 2008.

One night represents 5 hours of work, conducted in according with this process:

- prototype set up,
- first acquisition for signal checking,
- rail restoration searching,
  for each rail restoration:
- realisation date on hallmark is noted
- rail repair is carried-out as described above
- last acquisition to check that there is no drift of signal.

Nine rail restorations were inspected on average per night, so around 370 results.

Figure 10: Procedure of segmentation

Figure 11: On track inspection

4.2 First analysis

A first laboratory study was realised in 2000 on ten samples of broken and non broken rails, to understand crack initiation and development on rail restoration. It concludes that cracks seem to initiate on internal small porosities, more often located at the rail metal/deposit metal limit, and progress from depth to surface.

The localisation of porosities has a metallurgic explanation: welding operation involves fusion of the
surface of the rail, and apparition of gas. UT observations show this alignment of gas inclusion.

![Figure 12](image)

**Figure 12. Line of inclusions**

The first part of the analysis consists in validating the hypothesis of crack initiation and development cycle (from depth to surface). For that, recorded data of rail presenting crack will be analysed to confirm location of crack initiation (surface or not).

To make a statistic analysis of recorded data, we have to propose a representative parameter of rail damage. Thanks to conclusions of a laboratory study, we can consider that there is a link between location of inclusions and risk of crack initiation. That’s why the first criterion of the analysis is the position of the porosity in the deposit.

For each recorded file, two kind of information are considered:

- Depth of the deposit: It is possible to estimate the depth thanks to the visibly limit of rail metal/deposit metal by UT.

![Figure 13](image)

**Figure 13: Limit of metals**

It is important to note that metal deposit thickness depends on age of restoration. Indeed, metal is removed by wear and grinding, especially on high speed line. After some years, metal deposit is totally removed. A first analysis made on the 370 restorations inspected during the campaign shows that only 20% are deeper than 5 mm.

- Location of the porosities. As for depth, it is important to take into account rail age. Indeed, with metal removed relative position of inclusions from surface changes. Inclusions, located in-depth at the realisation of rail restoration, are closer to surface after some years.

The aim of statistic analysis is to try to determine an area in the depth of deposit metal, where inclusion progress as crack, maybe due to special solicitations. Then, two kind of standard rail restoration evolution can be defined:

- There is no porosities apparition during welding process: with time, metal is removed by wear or grinding and deposit metal disappears,
- There is porosities apparition during welding process: metal is removed by wear or grinding and porosities climb up to the surface; cracks are initiated from porosities when they are at a well defined depth.

The analysis of old rail restoration already on track could be very interesting. Indeed, two categories can be determined:

- rail restoration where metal deposit near to elimination by wear ; the process of welding can be consider as well-done
- rail restoration presenting porosities, the associated question is : is there any chance that a crack could initiate on one of these porosities?

A third fictive category is rail restoration where there was crack development and rail break, and which are not yet on track.

With this statistic analysis, we could estimate:

- Location of inclusions in the metal deposit where risk of crack development exists

![Figure 14](image)

**Figure 14: Risk area for crack initiation**

- risk of damage of rail restoration with initial metallurgic quality

![Figure 15](image)

**Figure 15: Risk of crack initiation**
This analyse will aim at establishing a correlation between lifetime restoration and probabilities of crack initiation.

4 CONCLUSIONS

Operations of restoration are widely made on rail presenting damaged running band. Several layers of weld metal are deposited by arc-welding technique. Unfortunately, this kind of restoration can have limited lifetime, particularly on high speed lines, due to cracks initiation in welding layers. One of the main reasons of cracks development on welds is the presence of small gas inclusions spread among the whole repair, which could then cause crack initiation under mechanical stress.

SNCF asked CEA to develop a non-destructive method and an associated instrumentation to detect gas inclusions in restorations; this method is based on UT-phased array technique. An analysis method was also developed to characterize inclusions in terms of quantity, position and size.

The developed method of inspection has then been carried out by SNCF on high speed lines, and a total of around 370 restorations were inspected. Statistical analysis realized on these acquisitions will aim at assessing the general health of restorations, and enhancing the understanding of the crack initiation mechanism.

8 REFERENCES


3. EN 15594: 2006: Railways applications – Track – Restoration of rails by electric arc welding, European Standard
Project no. TST-CT-2005-516196

Project acronym “WIDEM”

Project title “Wheelset integrated design and effective maintenance”

Sixth Framework Programme

Priority 6

Sustainable Development, Global Change & Ecosystem

D6.1 – Development of compensated resonance inspection prototype for wheelsets

Due date of deliverable: 30/06/08
Actual submission date: 30/06/08

Start date of project: 01/01/2005
Duration: 42 months

D2S International

Revision [1]
Index

D6.1.1  *Report on compensated resonance inspection method*  pag. 3
D6.1.1  Report on compensated resonance inspection method

Prepared by :
Ward Verhelst

D2S International

Date : 30/06/2008
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1 INTRODUCTION

This report summarizes the work done by D2S International in the WIDEM project, WP6.1, namely: soft and hardware development of a compensated resonance inspection prototype for wheelsets.

It includes:

- development of hardware (electronics design);
- development of a software/hardware user interface adapted to the specific needs for measurements on axles and wheelsets on site;
- development of algorithms to separate damaged from good axles/wheels.

The system can be used not only on axles and wheels but also on other objects. Initially, since no wheels with known cracks/defects were available, the software was tested on railway axles. In a later validation phase, the technique is tested on axles mounted in complete wheelsets.

Due to the large amount of measurement data, post processing data and software, only the most relevant figures and analyses are shown.

This report is completed by the presentations given by D2S on several meetings during the project (06M, 12M and 18M meetings).
2  **PRINCIPLE**

When an object is impacted, it will start vibrating at its resonance frequencies.

These frequencies depend on:
- stiffness of the material;
- mass (or density) of the object.

A defect reduces the stiffness and lowers the resonance frequency.

The shift in the resonance frequency is related to the size of the defect.

Normal production variations also cause shifts in frequency. These shifts have the potential to mask defects. The compensation technique is based on the separation of resonance peaks:
- constant separation within a subset – acceptable;
- change in separation within a subset – defect.

This principle, largely used in various industrial sectors, will be implemented to investigate material integrity of railway wheelsets.

This method is based on artificial excitation of the whole wheelset and on evaluating a large set of data: resonance frequencies and associated modal damping in a well-defined high frequency band (10 - 150 kHz or higher).

A prototype of the compensated resonance inspection system will be developed and tested at Lucchini workshop downstream of the production process.

Compensation techniques are used to eliminate the effects of production variations and wear. A pattern recognition algorithm will be used to compute the compensating relationship based on the statistics of a training set of good and bad parts (with known cracks). This means also that extensive learning measurements will be carried out on ‘good’ Lucchini wheelsets and on wheelsets with several types of known artificial defects. Work will consist of data gathering, resonance selection, development of a sorting module and validation.
3 DEVELOPMENT OF THE COMPENSATED RESONANCE INSPECTION SYSTEM

3.1 HOW TO USE/DEFINITION OF PHASES

The system should be small, easy transportable, user friendly and controlled and linked by a (portable) computer. One operator should be able to perform and process measurements. The goal is that after each measurement the system tells the user if the Device under Test has possible defects and should be inspected further in detail or not.

The system is used in four well-defined phases.

3.1.1 Phase 1: Build up experience

Build up excitation/response experience on the samples/parts to be included in the system. The result of this phase will be:

- definition of type of sensor;
- definition of type of excitation;
- definition of the number and type of measurements on one sample.

This first phase is the most critical and takes most of the set-up time. A number of “GOOD” and “BAD” samples have to be tested in detail: Impulse response measurements in several frequency ranges, various types of suspension of the samples, modal analysis in order to understand the vibrational behaviour of the samples.

3.1.2 Phase 2: Training of the software

Acquiring data on “GOOD” and “BAD” samples based on the results of Phase 1. The results of this phase will be a general database where all measurement data is stored and linked with serial number, type, … This data will be stored as “training data”.

3.1.3 Phase 3: Processing of “training data”

A. The training data will be first subdivided into similar blocks based on dimensional variations. This subdivision can be made by software that makes a first analysis on the measurement data or by information given by the provider of samples (e.g. similar parts, but slightly different dimensions).

B. Each subdivision of data will be analyzed more profoundly by several algorithms and links between the results of these algorithms and the presence of known defects will be made. For each algorithm, an “acceptable” zone will be defined and stored.
3.1.4 Phase 4: Production/Control Phase

- Each new sample to be tested will be measured as described in Phase 1 and results will be entered into the database.
- A first subdivision is made based on possible dimension variation (equal to Phase 3A).
- Several algorithms are applied on measurement data and a decision will be made (GOOD/BAD) based on results of phase 3B.

Every new measured sample without defects can be included into the database with “GOOD” samples. In that case, the probability of detection of “BAD” samples will increase.
3.2 HARDWARE

A robust, easy to use system is developed.

Figure 3.1

3.2.1 Specifications

- power supply 110/220 Volts - 50/60 Hz;
- providing power for several types of sensors (piezoelectric, ICP powered sensors as accelerometers microphones and external sensors (voltage input, …);
- control of acquisition start by external Normally Open contact (ex. foot switch);
- high frequency range (0 – 200 kHz);
- possibility to include the system in an automatic control system (future development).

3.2.2 Hardware Block scheme

Following figure shows schematically the hardware/software blocks in the developed system.
Various types of sensors can be used with the system. Each type of sensor requires a specific power and signal conditioning. The hardware detects automatically the type of sensor that is connected.

The resulting measurement signal is then connected to an amplification circuit which is capable of amplifying the incoming signal with a user selectable gain in a frequency zone DC-200 kHz. An external voltage signal (max. ±10 Volt) coming from other systems can also be amplified and used.

Then, data is acquired by an analog/digital converter card and further processed by software routines. The results of these software routines are stored and further used in post processing routines.

All settings and controls necessary for data acquisition: selection of type of sensor, state of the sensor (for ICP sensors), applied gain, frequency range, … can be made by the software pop-up menus.
3.2.2.1 Sensors types

Following types of sensors and inputs can be used, depending on the application.

- **ICP**: Internally Amplified Sensors - low impedance, piezoelectric force, acceleration and (sound) pressure type sensors with built-in integrated circuits (ICP® is registered trademark of PCB Group, which uniquely identifies PCB’s sensors, which incorporate built-in electronics).
- In-house developed piezo-sensor: the same measurement principle as ICP but more efficient in high frequency ranges.
- Voltage input: also an external voltage signals (max. ±10 Volt) coming from other systems can be acquired, amplified and used with the system.

3.2.2.2 Sensor power + signal conditioning

<table>
<thead>
<tr>
<th></th>
<th>Power: 24 volts/2 mA</th>
<th>Connector BNC</th>
<th>Bias voltage control to check cable connection automatic by software</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In house developed piezo-sensor</td>
<td>Lemo 4 pins connector</td>
<td>+ 12/-12 Volt power supply</td>
<td></td>
</tr>
<tr>
<td>External input</td>
<td>Max +10/-10 Volt</td>
<td>BNC connector</td>
<td></td>
</tr>
<tr>
<td>Output signal</td>
<td>BNC connector</td>
<td>In case recordings on a DAT-recorder or other devices are to be made an output BNC connector is foreseen: the amplified signal, the same as the signal that is going into the A/D converter.</td>
<td></td>
</tr>
</tbody>
</table>

3.2.2.3 Amplification

An instrumentation quality amplifier is foreseen with a user selectable gain of 20/40 or 60 dB for ICP sensors and a fix gain of 50 dB for the in-house developed piezo-sensor in a frequency zone DC- 200 kHz.

In future versions a user selectable high pass filter (0, 10, 100 and 1000 Hz) will be introduced in order to filter out the low frequencies generated by hand movements, positioning of the probe/sensors, …

3.2.2.4 Analog/Digital conversion

The analog/digital conversion is made by means of a National Instruments DAQCard-AI-16E-4 PCMCIA card. The big advantage of this device is the high sample rate (500 kHz) combined with the small size and direct connection into a PCMCIA slot of a portable computer.

The relative low resolution (12 bit A/D conversion) is sufficient because of the high gain on the analog signal before doing the A/D conversion.
3.3 **SOFTWARE DEVELOPMENT**

The software is developed in MATLAB code. The standard Matlab code uses three extra Matlab toolboxes: signal processing, data acquisition and the Matlab Compiler to generate a stand alone version.

A user interface was written in order to perform the measurements by using only the mouse, keyboard for typing in some comments and a foot switch to start acquisition.

3.3.1 **The user interface**

The user interface is necessary to set the hardware in a condition needed to perform measurements for a typical test object and sensor. Different settings are to be selected. The complete set-up of the system can be stored for later use. When the system is started it will always start in the configuration that was used before the last shutdown.

![User interface layout of the measurement system](image)

*Figure 3.3*  
User interface layout of the measurement system
Above, in figure 3.3, we see the user interface in its first version. The user has the possibility to:

- **Read a set-up file**: this set-up file stores following settings, which can be adjusted:
  - type of sensor (piezo-ICP-external);
  - gain (x1 x10 x100);
  - number of averages;
  - bandwidth 0 – 20 kHz up to 0 – 200 kHz;
  - signal input range 0.1 V to 10 V;

- **load or store set-up file + text comment on site**;

- **start measurement**:
  - wait for impulse;
  - confirmation if OK with beep;
  - pedal to hold system when changing sensor position;

- **visual check of**:
  - time signal after each average;
  - frequency spectrum;
  - peak values – damping (if applied);

- **store measurement data**.

Some special user-friendly features are foreseen:

- high tone beep after an good acquisition of data;
- low tone beep while waiting for foot pedal switch;
- double low tone beep when all averages are acquired;
- colour indication to check the ICP sensor connection (GREEN/OK, YELLOW/cable loose, RED/cable short circuit);
- automatic red coloured indication and stop of the actual set of acquisitions when an overload of the A/D converter is detected;
- overrule current settings and restart the measurement by using CTRL-C.

The selection of a hardware high pass filter was recently included.
3.3.2 **Post processing software**

The separation of cracked/faulty test objects can be made only by the use of (post processing) software. Depending on the phase (see §3.1) the user is in (build up experience, training, processing, production/control, ...), this detection will be made after post processing was done, or during measurements.

All algorithms necessary for detection of cracks can be applied in selectable frequency ranges. These ranges vary depending on the type of test object and the algorithm in question.

The user cannot only change these frequency ranges but also several other parameters in the software. The selection of these parameters is crucial in the detection of faults. For railway axles this selection is made in Phase 1 (see §3.1.1) during the set-up of the system.

This software was developed during the WIDEM project and was modified several times following experience with available test objects. Several algorithms were written and applied on the available test objects. We give a brief description of the written algorithms, however not all were giving usable results.

3.3.2.1 **Conversion from time to frequency domain**

Standard Fourier analysis is used to convert the sampled data from time domain to frequency domain. Data is acquired with a fix sample frequency of 500 kHz. Because an impulse excitation is used, a trigger level at 5% of the maximum input voltage is used to start acquisition of data.

The acquired signal length (T) is always 1 second, in order to achieve a fix frequency resolution of 1 Hz (1/T (s)). In case a limited bandwidth is needed, a data reduction is done by down sampling, using a decimate function: resample data at a lower rate after low pass filtering (eighth order Chebyshev Type I low pass filter).

During the measurements, the time data (amplitude as function of time) after each excitation is displayed, while spectral averaging is used to eliminate spectral noise in the frequency response. Finally time data, as well as frequency response is stored together with other set-up data.

3.3.2.2 **Peak detection on the frequency response**

Depending on two parameters that are changeable, the user can decide which peaks are included in the analysis. These two parameters are:

1. **TRESHOLD**: Amplitude of the peak in dB (to exclude non significant peaks);
2. **LEVEL DROP**: Min. Level drop at both sides of the peak in dB to be selected.

All the selected peaks are stored together in a matrix together with the specific measurement or set of measurements. This matrix is used later for further processing.

Following figures are giving some examples:
Figure 3.4
Response spectrum (blue) measured on a railway wheel with selected peaks (black)

Figure 3.5
Response spectrum (blue) measured on a railway wheel with selected peaks (black), zoomed to illustrate the amount of peaks in a 10-30 kHz band
3.3.2.3 Estimation of damping

Before calculating the damping, a spline interpolation of original spectrum curve is done in order to have a more correct damping estimation. An interpolation with a factor 100 was applied (resolution = 1 Hz ⇔ resolution= 0.01 Hz).

Following formulas are used to calculate the damping:

\[
Q = \frac{F_d}{d_F}
\]

\[
\xi = \frac{1}{2Q} \times 100
\]

With 
- \(F_d\) resonance frequency [Hz]
- \(d_F\) width of the peak at -3 dB below the peak level [Hz]
- \(Q\) Quality factor
- \(\xi\) damping [%]

Figure 3.5

Zoom around a resonance peak: original curve (resolution=1 Hz) in blue a spline interpolation (resolution= 0.01 Hz) in red

According to the above formulas and graphs the damping is automatically calculated for every peak that was put into the peak matrix.

3.3.2.4 Spectral cross correlation

Since amplitude is used to calculate the spectral cross correlation we have to keep attention that excitation – which is not controlled and influenced by the operator- is done in the same point, with the same intensity on all specimens of one family of samples.

The spectral cross correlation between two spectra is defined by:

\[
SCC = \frac{\sum_{i=1}^{N} [A_1(i) \times A_2(i)]}{\left( \sum_{i=1}^{N} [A_1(i)]^2 \times \sum_{i=1}^{N} [A_2(i)]^2 \right)^{0.5}}
\]

With \(A1\) spectral amplitude spectrum 1
A2 spectral amplitude spectrum 2
i spectral line
N number of lines in the spectrum

Figure 3.6
Left: Individual SCC, Right: Global SCC

The above figure 3.6 shows an example of the SCC calculated for nine axles. The Individual SCC was calculated for each axle combined with each other axle, as shown in the left graph. Multiplying all the calculated values per axle reduces data en leaves one single value/axle: the Global SCC (right graph). In this example, axles A13 and A16 are separated from the rest due to the difference in geometry. The same principle is used for finding cracks or faults.

3.3.2.5 Least square coefficient

The least square coefficient is based on resonance modal values: the found resonance frequencies are plot versus mode numbers in a selectable frequency band. An example is shown in Figure 3.7 (brown curve).

We have performed three steps:

1. linear least squares fit to frequency-mode number pairs (red curve)
2. sum of the squares of the deviation (blue curve) of the actual numbers from the least square fit

This leads to one single value per frequency band were we do the analysis.
Figure 3.7
Data needed for estimation of the Least square coefficient (LSC) in a 50-70 kHz band

3. find a frequency zone where this parameter is sensitive to cracks. An example is shown in the following figure 3.8.

Figure 3.8
Visual presentation of the estimation of the Least Square Coefficient (LSC) in ten 40 kHz wide bands, for good and cracked axles

The axles indicated with the RED line (A1 till A5, A8 and A16) are not cracked. It is clear the LSC shows a completely different behaviour in certain frequency zones: good axles have High values in the 35-75 kHz band while cracked axles have Low values.
3.3.2.6 Percentage of common peaks (PCP)

PCP is calculated using the following formula:

\[
PCP = \frac{\text{number of common peaks of one axle}}{\text{total number of different peaks of all uncracked axles}} \times 100\% 
\]

If an axle is damaged, his peaks will shift down (see later). This will result in a number of peaks that is completely different from peaks that were found on good axles, so this will result in a lower percentage of PCP. PCP can be calculated in different frequency bands to look for the most sensitive area, as done for LSC.

3.3.2.7 Peak relations

**Shift of frequency ratio & differences**

1. Simple - shift due to: production variation:
   - dimensions;
   - cracks.

2. Relation between 2 peaks:

   \[
   FD = (A \cdot f_1 + B) + W
   \]

   with:
   - FD: diagnostic resonance
   - F1: base resonance
   - W: width accept window
   - A & B: constants to be determined

   This was checked in detail on axles before and after the cracks but no usable results were found.

3.3.2.8 Cepstrum analysis

This analysis is used for many years to detect cracks in wheels. It was now tested on axles to see if cracks can be found. However, the crack reflection effect is too small compared with diameter alterations that generate much more important reflections.

This was checked in detail on small axles with a saw cut were it was measurable. No usable differences were found on real axles between before and after cracking.
4 APPLICATION OF HARD-AND SOFTWARE ON TEST SAMPLES

4.1 SUMMARY OF TESTS

Table 4.1 shows when, where, and what kind of activity was performed chronologically during the WIDEM project in order to test, refine and validate the developed hard- and software.

For each location we will briefly illustrate by means of pictures and measurement results what was done and how it was used in the development. No intermediate results of the algorithms will be given.
<table>
<thead>
<tr>
<th>date</th>
<th>LOCATION</th>
<th>test objects</th>
<th>type of measurements/equipment</th>
<th>description</th>
<th>ongoing simultaneously performed activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/04/2005</td>
<td>Mechelen</td>
<td>Wheelsets with no defects</td>
<td>impulse response /Prototype high frequency response analyzer</td>
<td>gathering of data for development of electronics hardware +sensor /excitation definition</td>
<td>adaptation of usability of hardware/software in the field, User interface</td>
</tr>
<tr>
<td></td>
<td>Belgium</td>
<td></td>
<td></td>
<td></td>
<td>sensor checks</td>
</tr>
<tr>
<td>19/05/2005</td>
<td>Gentbrugge</td>
<td>Wheelsets with no defects</td>
<td>impulse response /Prototype high frequency response analyzer</td>
<td>gathering of data for development of electronics hardware +sensor /excitation definition</td>
<td>filtering /amplification</td>
</tr>
<tr>
<td></td>
<td>Belgium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20/09/2005</td>
<td>Darmstadt</td>
<td>Axles 2 similar without cracks, 8 similar with cracks</td>
<td>impulse response /Prototype high frequency response analyzer + modal analysis with SIGLAB 12 channel system</td>
<td>gathering of data for development of electronics hardware +sensor /excitation definition + relation between peaks in frequency response an modal behavior of axles</td>
<td>foots which testing</td>
</tr>
<tr>
<td></td>
<td>Germany</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>Location</td>
<td>Axle Condition</td>
<td>Test Procedure</td>
<td>Data Collection</td>
<td>Test Start</td>
</tr>
<tr>
<td>------------</td>
<td>--------------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
<td>------------</td>
</tr>
<tr>
<td>14/11/2005</td>
<td>Lovere, Italy</td>
<td>7 un-cracked, 1 cracked</td>
<td>impulse response + modal analysis with SIGLAB 12 channel system</td>
<td>gathering of data for development of electronics hardware + sensor/excitation definition + relation between peaks in frequency response and modal behavior of axles</td>
<td>start testing of first algorithms</td>
</tr>
<tr>
<td>Date</td>
<td>Location</td>
<td>Location/Manufacturer</td>
<td>Details</td>
<td>Activities</td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>-------------------</td>
<td>-----------------------</td>
<td>--------------------------------------------------------------------------</td>
<td>-------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>3/02/2006</td>
<td>Cambridge, UK</td>
<td>TWI</td>
<td>Used Axles, 1 uncracked, 3 cracked</td>
<td>impulse response with refined hardware for high frequency response analyzer</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>gathering data for software/algorithm s refining</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>algorithm verification/ refining</td>
<td></td>
</tr>
<tr>
<td>23/03/2006</td>
<td>Cambridge, UK</td>
<td>TWI</td>
<td>Used Axles, 4 cracked</td>
<td>definitive version of high frequency response analyzer</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td>gathering data for software/algorithm s refining</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>algorithm verification/ refining</td>
<td></td>
</tr>
<tr>
<td>3/05/2006</td>
<td>Lovere, Italy</td>
<td>Lucchini</td>
<td>Axles for test bench same as on 14/11/2005 but now 8 cracked</td>
<td>impulse response with refined hardware for high frequency response analyzer</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td>gathering data for software/algorithm s refining</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>algorithm verification/ refining</td>
<td></td>
</tr>
<tr>
<td>16/01/2007</td>
<td>Lovere, Italy</td>
<td>Lucchini</td>
<td>mounted wheelsets (11 pieces)</td>
<td>impulse response with refined hardware for high frequency response analyzer</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>gathering data for software/algorithm s validation, will be repeated on a cracked axle that will be mounted again in the same kind of wheelset configuration</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>algorithm verification/ refining, final validation</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1 Activities on development of the system
4.2 DETAILED DESCRIPTION OF TESTS

In the next chapter, a brief description of the performed activities is given in chronological order. Presentation of results is limited to the most essential plots.

4.2.1 NMBS Belgium (Mechelen, Gentbrugge) - Wheelsets with no defects

4.2.1.1 Test samples

Nine complete wheelsets NMBS:
- Mechelen;
- Gentbrugge;

consisting of:
- axle;
- wheel 1;
- wheel 2.

⇒ No bearings, break disks: as simple as possible
⇒ Lifetime wheelsets: 7 - 10 years

Figure 4.1
Measurement set-up + wheelsets
4.2.1.2 \textbf{Performed measurements}

Measurement of eight response spectra on each wheelset.

Figure 4.2 shows schematically the response/excitation points where impulse response was measured.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure42}
\caption{Measurement points on wheelsets at NMBS}
\end{figure}

Detailed photographs of the measurement points: probe/excitation hammer are shown in Figure 4.3.
Measurements on wheelsets, positioning of sensors and excitation

We used as:

- **sensor** ⇒ In house developed piezo-sensor:
  - high frequency range (>150 kHz);
  - manual positioning (sensitive to low frequency hand movements);

- **impulse excitation** ⇒ 2 mm bearing ball:
  - short impulse time ⇒ high frequency excitation (>100 kHz).
4.2.1.3 Results

Typical frequency responses on a wheelset (0 - 100 kHz).

Figure 4.4
Typical frequency response on a wheel

Typical frequency response on an axle mounted in a wheelset (0-100 kHz)

Figure 4.5
Typical frequency response on an axle mounted in a wheelset
Comparison of different wheelset (without defect)

In total, seven measured frequency responses are compared in different frequency zones. Results are very similar, but when zoomed, we see big shifts in certain peaks. This is caused by variation of dimension of these wheelsets. It gives a good idea what to expect on real, used wheelsets.

**Figure 4.6**

Typical frequency response in overlay on 7 wheels, mounted in a wheelset

### 4.2.1.4 Conclusions

- Hardware/first version of user interface is usable, but refining is required (foot switch, filtering, noise, ...).
- Real wheelset without defects shows already significant frequency shifts due to dimension variation.
- On this first measurement data a number of algorithms could be tested for the first time: e.g. Peak find, modal damping calculation.
4.2.2 LBF Darmstadt Germany – solid axles with defects(8)/without(2)

4.2.2.1 Test samples
Solid axles, two without cracks and eight with cracks were available.
But these two groups are unfortunately not with equal dimensions, so difficult to use in a statistical approach. Therefore, it was decided to concentrate on the frequency responses and modal behaviour of these solid railway axles.

4.2.2.2 Performed measurements
Two types of measurements were performed:
1. Measurement of response spectra on each axle: excitation in one axle end, four directions, pick-up signal same point & direction.

![Figure 4.7](image-url)  
Response/Excitation directions on axle end at LBF

2. Modal analysis: sixteen sections, four points/section, two directions in order to identify bending modes, torsion modes up to 3.5 kHz.
4.2.2.3 Results

*Typical Frequency responses*

Figure 4.8

Typical frequency response at LBF

Figure 4.9

Typical frequency responses zoomed (1800 - 3500 Hz) at LBF
**Modal analysis**

The results of this analysis can learn us where and how to excite and measure the axle, and also get an idea of the importance of certain peaks in the frequency response. Next photo shows the measurement set-up (simul. four response points in two directions acquired with SIGLAB 12 channels acquisition system)
Next figures 4.12 till 4.21 show the mode shapes, together with the frequency responses. Bending and torsion modes are clearly defined, and sometimes very close coupled (see mode shape at 812 and 862 Hz).

Figure 4.12
Mode shapes at 162 Hz of a solid axle at LBF

Figure 4.13
Mode shapes at 450 Hz of a solid axle at LBF
Figure 4.14

Figure 4.15
4.2.2.4 Conclusions

- Ten axles were tested.
- Frequency responses on all, and modal analysis on one axles were performed.
- An idea about mode shapes and the related peak importance in frequency response was formed.
- Hardware/interface is easy to use.
- Algorithms could be tested on these measurement data.
- Unable to differentiate between good and cracked axles because of different geometries.
4.2.3 LUCCHINI VISIT1 Lovere Italy - 9 Hollow Axles for test bench, 1 cracked

4.2.3.1 Test samples
Hollow axles, designed for the Lucchini test bench were available. There are two types (different geometry $\varnothing \Delta = 7.5$ mm).
- type 1: seven axles (serial numbers: E0401348XX, XX=01, 02, 03, 05, 06, 08):
  - one cracked;
  - six good: cracks will be initiated on test bench later on: will be used for further analysis.
- type 2: two axles (serial numbers: E0401349XX, XX=03, 06):
  - 1 cracked;
  - 1 good.

4.2.3.2 Performed measurements
All these axles will be cracked in the Lucchini test bench later on, so they were all measured. On one axle a modal analysis was performed.
- Measurement of response spectra on each axle: excitation in two axle ends, three directions, pick-up signal same point & direction.

![Response/Excitation directions on axle end at Lucchini](image)

- Modal analysis: eleven sections, four points/section, two directions in order to identify bending modes, torsion modes up to 3.5 kHz.
4.2.3.3 Results

*Typical Frequency responses*

Figure 4.23
Typical frequency response on axles mounted in straps

Figure 4.24
Typical frequency response (zoomed 1770 - 1840 Hz) on all axles mounted in straps
Modal analysis
The results of this analysis can learn us where and how to excite and measure the axle, and also get an idea of the importance of certain peaks in the frequency response. Next figures show the mode shapes, together with the frequency responses. Bending and torsion modes are clearly defined, and sometimes very close coupled.
Figure 4.27

Detailed analysis in one section: bending mode at 175 Hz

Figure 4.28

Detailed analysis in one section: to identify the breathing mode: large peak at 7640 Hz

Verification of influence of excitation on response (red curve: excitation in tangential direction, black curve: excitation in radial direction). This can lead to the conclusion that tangential measurement results in much more peaks (that can be influenced by the crack!!).
Figure 4.29
Influence on excitation point on number of peaks: (red curve: tangential direction, black curve: radial direction)

*Complete axle (1 radial response/section) in order to identify ONLY the bending modes*

Figure 4.30
Modal analysis to identify bending modes
Figure 4.31
Modal analysis: first bending at 169 Hz

Figure 4.32
Modal analysis: fifth bending at 1780 Hz
4.2.3.4 Conclusions

- Nine axles were tested.
- Frequency responses on all, and modal analysis on one axle were performed.
- An idea about mode shapes and the related peak importance in frequency response was formed.
- Hardware/interface is easy to use.
- Algorithms could be tested on these measurement data.
- First try to differentiate between good and cracked axles by the use of some algorithms.
- Wait for end of fatigue testing at Lucchini to measure other cracked axles and refine algorithms
4.2.4 TWI Cambridge UK- 3 Hollow Axles for test bench, 1 cracked

4.2.4.1 Test samples

TWI “real axles”:

On 03-02-2006: one uncracked two cracked  
Bending fatigue ↓ ↓
On 23-03-2006: one cracked two cracked re-measured

Now we can compare one identical axle before & after generation of cracks and also check the influence of time, temperature, stability of measurement system on a measurement.

Photo 4.33  
Measurement set-up at TWI
4.2.4.2 Performed measurements
Measurement of response spectra on each axle: excitation in one axle end, three directions, pick-up signal same point & direction.

![Measurement set-up](image)

Figure 4.34 Measurement set-up

4.2.4.3 Results
For the first time we are able to determine the influence of a crack on the shift of the peaks, because the same axle could be measured before and after the crack was applied.

*Typical Frequency responses*

![Typical frequency response on one axle mounted in straps](image)

Figure 4.35 Typical frequency response on one axle mounted in straps
Figure 4.36
Typical frequency response: the same axle before (blue) and after (green) the presence of a crack, zoomed in on one peak at 930 Hz.

Figure 4.37
Typical frequency response: the same axle before (blue) and after (green) the presence of a crack, zoomed in on three peaks in a (7500 -10000 Hz) band.

The same cracked axle measured two times in a 50 days interval (see Figure 4.38) results in a (0 - 30000 Hz) band. Very similar results: the variation in resonance frequencies is <0.04% due to temperature, measurement system instability, …
4.2.4.4 Conclusions

- Frequency responses on 3 axles were measured.
- Hardware/interface is stable and easy to use.
- Algorithms could be tested on these measurement data.
- First try to differentiate between good and cracked axles by the use of some algorithms.
- Very good repeatability of measurements.
- A shift down due to the presence of a crack at all resonance peaks was seen. This shift was confirmed in a very wide frequency band and is constant with a level of 0.2% downwards (example: 20 Hz @ 9 kHz - 90 Hz @ 38 kHz, ...).
4.2.5  LUCCHINI VISIT2 Lovere Italy- 9 Hollow Axles for test bench, 8 cracked

4.2.5.1 Test samples
On 03-05-2006, eight newly cracked axles are available. Now we have a database of seven un-cracked axles, ten cracked axles = seventeen axles hollow axles, designed for the Lucchini test bench.

4.2.5.2 Performed measurements
All the cracked axles will be re-measured the same way as done at the first measurement session at Lucchini.

- Measurement of response spectra on each axle: excitation in two axle ends, three directions, pick-up signal same point & direction.

Figure 4.39
Measurement directions at Lucchini
4.2.5.3 Results

Typical Frequency responses

Figure 4.40
The same axle, zoomed around 840 Hz before and after the presence of a crack

Figure 4.41
The same axle, zoomed in the band (8000-9400 Hz) before and after the presence of a crack
Comparison of peaks

On the next figure we visualize the peaks found by the peak find criterion for all the axles measured at Lucchini: with and without cracks. In the legend, the axles who are cracked are indicated with C: e.g. CA1 = axle A1, with crack. A zoom shows very clearly that ALL cracked axles show the same shift down in frequency. This confirms the results found at TWI in §4.2.4.

Figure 4.42
Peaks found by the peak find algorithm

4.2.5.4 Conclusions

- Frequency responses on all axles were measured.
- Hardware/interface is stable and easy to use.
- Algorithms can be tested in detail on these measurement data.
- Very good repeatability of measurements.
- Again a shift down due to the presence of a crack at all resonance peaks was seen. This shift was confirmed in a very wide frequency band and is constant with a level of 0.2% downwards, as seen on the TWI axles.
4.3 Processing of Algorithms on Lucchini Axles

All the algorithms, seven in total, were tested on the database of seventeen Lucchini axles.

Finally four were held because of the good results:

- Peak detection;
- Spectral Cross Correlation (SCC);
- Least Square Coefficient (LSQ);
- Percentage of Common Peaks (PCP).

The results of these algorithms on the Lucchini axles is shown in following figure 4.43 and explained in §4.3.1 till 4.3.4.

Figure 4.43
Summary of processing results on Lucchini axles
4.3.1 **Peak detection**

A level drop of 10 dB and a threshold of 20 dB results in a good peak database to do further analyses. The next figure shows some zooms and visualize the shift down of cracked axles.

![Figure 4.44](image)

4.3.2 **Spectral Cross Correlation (SCC)**

The two upper plots of figure 4.43 show the calculated SCC, at the left side the results for all axles with respect to six axles of the same dimensions, without cracks, at the right side, the global cross correlation by multiplying all the calculated values per axle. This reduces data en leaves one single value/axle.

On this figure we see immediate that the three lowest values are found for axles A13 A16 and CA16, who have other dimensions than the not-cracked axles.

So the SCC can be used for exclude large dimension variations or to separate very large cracks.
4.3.3 **Percentage of common peaks (PCP)**

The lower left plot of figure 4.41 shows the calculated PCP. Only peaks in a frequency zone from 16 to 60 kHz were used for the calculation of this parameter. Again, we see immediately that the lowest values are found for the cracked axles and for axles who have other dimensions than the not-cracked axles. The shift down of frequencies due to the crack is responsible for this good result.

4.3.4 **Least square coefficient (LSC)**

As explained in §3.3.2.5, we have first looked for the most sensitive zone. The software has routines that do this automatically. The LSC in the 16 to 56 kHz band was very sensitive to the presence of cracks. In that band, the cracked axles have high values.

4.3.5 **3D-presentation of results**

When the results of the three last algorithms (LSC, SCC and PCP) are visualized in a 3D presentation, we see very clearly that all not cracks axles can be separated from the cracked or those with other dimensions.
5 **FINAL VALIDATION**

As proposed by D2S on the 24M meeting, Lucchini has provided the possibility to measure on new axles who are mounted in wheelsets (CISALPINO), ready for delivery.

One of these axles will be send to TWI were a crack will be induced by simple bending fatigue. This axle will be mounted again in the same type of wheelsets and will then be measured again, the same way the others.

Then the algorithms will be used to separate the cracked axle.

5.1 **TEST SAMPLES**

In total twelve wheelsets are measured.

Axles A1 till A10 thane serial numbers as N0600870-37XX, XX = between 68 and 91.

Axles A11 and A12 have serial numbers as N0601193-4023, …
5.2 **PERFORMED MEASUREMENTS**

Measurement of response spectra on each axle: excitation in one axle ends, three directions, pick-up signal same point & direction, + a supplementary point in the middle of an axle, in between two break disks.

![Measurement diagram](image)

**Figure 5.2**

Measurement directions at Lucchini

5.3 **RESULTS**

All the measured axles are shown in figure 5.3 for the complete frequency range (0 - 200 kHz).

![Frequency response chart](image)

**Figure 5.3**

Typical frequency response measured in the middle of the axle
The compensated resonance technique has been implemented and validated on railway axles. It is shown that when properly applied (measurements in high frequency range) and when properly analysed (use of appropriate criteria), the technique is capable of identifying defective axles without any difficulty.

A further validation on axles mounted in a complete wheelset is in progress.