AUTOMATIC LASER ULTRASONICS FOR RAIL INSPECTION

S. A. Nielsen[1], A. L. Bardenshtein[1], A. M. Thommesen[1], and B. Stenum[2]
[1]Sensor & NDE Innovation Division, FORCE Technology, 2605 Brøndby, Denmark
[2]Optics and Plasma Research Dept., Risø National Laboratory, 4000 Roskilde, DK

Abstract: This paper presents the state of the current activities to develop a high-speed inspection system for evaluating rail defects. Since conventional contact ultrasonic techniques are speed limited, the aim was to build an automatic inspection system, which applies non-contact ultrasonic methods. An automatic Laser Ultrasonic system for Rail Inspection (LURI) has been developed and tested on a railroad line containing man-made structural defects. LURI is mounted on a specially designed railroad vehicle and allows detection of defects on the running surface of the rail, as well as, horizontal and vertical flaws in the railhead. LURI is tested in the field up to 40 km/h (25 mph). In order to support LURI, a battery-operated ultrasonic rail flaw detector based on the P-scan Lite system was developed and tested.

Introduction: Efforts to improve the safety and efficiency of railways have generated new NDT techniques to verify defects in rails. Especially ultrasonic methods have been developed for many years. In these methods ultrasonic beams are sent into the rail and scattered from defects and the rail itself. These measurements can detect the presence of a variety of defects but as the inspection speed increases there are practical problems with the technology. They are concerned with the traditional contact ultrasonic technology employed by the majority of rail flaw detectors [1]. Rail inspection is traditionally based on either rolling-contact or sliding transducers, which require maintaining a liquid-column acoustic contact. Acoustic contact is difficult to maintain during high inspection speeds and may result in loss of data. Furthermore, such transducers can only send and receive ultrasound on the running surface of the rail. This makes contact ultrasonic technology almost blind to critical flaws as transverse and longitudinal vertical cracks in the railhead. Moreover, surface-breaking defects are difficult to find by contact ultrasonic interrogation of a rail.

Laser-based ultrasonics provides a very attractive solution to these problems. Since in this technique, a pulsed laser is used to generate ultrasonic modes in the rail by ablation, and a continuous-wave or a long-pulse laser, coupled to an optical interferometer, is used to detect ultrasound after it has propagated through the material, the following significant advantages are special for the laser-ultrasonic rail inspection system [2]:

- LURI is a non-contact method, where only laser light interacts with the running surface of the rail.
- LURI implies high-speed inspection up to traffic speed, reducing the need for blocking the rail traffic.
- LURI identifies surface breaking defects.
- LURI can detect transverse and longitudinal vertical cracks in the railhead – the most common defects found in rails – by impinging ultrasound from the side rather than from the top of the head.
- LURI reveals smaller defects compared with traditional ultrasonic methods for rail inspection.

- LURI emits three important wave types with their own directivity patterns giving enhanced flaw identification. The wave types are sent and received at once without any changes in transmitter/receiver configurations [2].
- LURI gives a high level of flexibility of the laser beam in terms of distance and side positioning.

In this paper, we describe the LURI system briefly and report results of its field-testing on a railroad line containing man-made structural defects.

The basic principles of LURI: The basic principle of LURI system is shown in Fig. 1. Generation of ultrasound in the rail is performed in the ablation regime by a sufficiently powerful laser. In order to inspect rails during movement with appropriate spatial resolution, the laser operates at sufficiently high repetition rates. Bulk longitudinal waves as well as their surface-skimming mode, bulk shear waves, and surface Rayleigh waves are generated in the rail body as a result of the recoil effect leading into material ablation. The ultrasonic modes are reflected and scattered by the free surface of the rail body and possible flaws i.e. discontinuities in the rail body or breaks of the surface, reach the predetermined receiving point where they are detected by means of a second laser. The detection laser is very stable in frequency and intensity. When the ultrasonic wave reaches the detection laser point it causes a small surface motion in the nanometer range. The motion produces a Doppler frequency shift on the scattered light of the detection laser. The scattered light is coupled into an interferometer, which demodulates the Doppler shifted light into time variation of light intensity. The registered intensity signal represents surface displacement or velocity history and enables rail defect detection in much the same manner as conventional contact or electromagnetic ultrasonic rail flaw detectors.

Since the running surface of the rail is optically rough, the scattered light has a speckle pattern that continuously changes during movement of the detection laser and causes speckle noise. A confocal Fabry–Pérot interferometer (CFPI) was used in this version of LURI to reduce the speckle noise. The CFPI allows significant suppression of a speckle noise pattern by means of active high-pass filtering and implementation of a weighted conjugation optical detection scheme. With this system, stable and reproducible ultrasonic measurements were demonstrated in our laboratory on fast rotating discs at more than 100 km/h (62 mph).

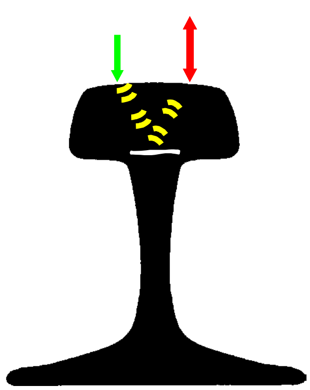

Figure 1. *Basic principle of LURI.*

Inspected rail profile and detectable defects: LURI was developed and tuned to inspect rails of the European profile UIC 60. The dimensions of this profile are: 172 mm in height, 72 mm of running surface width and the weight is 60 kg/m. However, by minor changes of the mechanical design and the ultrasonic data processing software the LURI system can be used with other types of railroad rail profiles. LURI was tested on the following types of structural defect types according to the International Union's of Railways (UIC) convention:

- UIC Code 211 – progressive transverse cracking of the head,
- UIC Code 212 – horizontal cracking of the head,
- UIC Code 213 – longitudinal vertical crack in the rail head,
- UIC Code 221.2 – long groove at the running surface,
- UIC Code 2321 – horizontal cracking at the fillet radius between the web and the head of the rail,
- UIC Code 200 – complete vertical (transverse) rail break.

Description of LURI: The system constructively comprises two subsystems positioned on a railroad car, as shown in Fig. 2.: a control subsystem and an optical subsystem.
The control subsystem is placed inside the car and includes both the generating and detecting laser systems; the CFPI control and power supply units, data acquisition electronics, as well as several computers for system parameter monitoring, ultrasonic signal processing, and defect finding and identification.
The optical subsystem is mounted on a special-purpose, measuring vehicle, which is attached to the bottom of the railroad car. The optical equipment includes the two laser heads, the CFPI with optical detectors, and the auxiliary optics. The optical equipment is mounted on a vibration-insulated platform that is attached to the frame of the mini-car over one of the rails and covered with a dust-tight, moisture-proof shield. The system currently performs one-rail track inspection but may be extended to inspection of both rails. This arrangement of the system allows movement with the speed up to 40 km/h.
The adjustment of the system is carried out by means of a number of electromechanical actuators, which control angular and linear displacements of the platform. The beams of the lasers are directed towards the rail by means of inclined mirrors. The generating beam is focused to a line on the surface of the rail. The proper lengths of the generating beam spot as well as two optimal arrangements of the laser spots, which enable best detection of rail defects, have been found by means of comprehensive computer simulation [3] and numerous laboratory and field experiments [2].

Figure 2. *LURI with optical subsystem.*

Some optimal source-receiver arrangements are schematically shown in the Fig. 3. The arrangement shown in the Fig. 3a is mainly meant for detection of defects UIC codes 2321, 212, and 211, while the arrangement shown in the Fig. 3b allows better disclosure of defects UIC codes 213 and 221.2. Obviously, both of them enable to disclose complete rail break (defect UIC code 200) by many features of the correspondent ultrasonic waveforms.

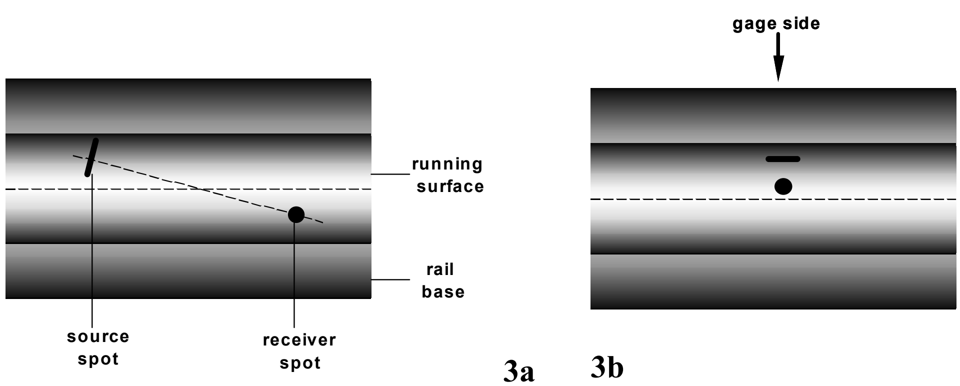

Figure 3. *Two optimized source-receiver arrangements for LURI (view from above, not drawn on a scale).*

Results obtained in the field test: The LURI software provides a variety of displays, ranging from the data acquisition display to advanced displays of the defects finding and identification software showing ultrasonic waveforms (A-scans), as well as ultrasonic images synthesized by straightening A-scans lengthwise a rail (B-scan). The example of such a display is shown in Fig. 4. When the defect is found and identified in some section of the rail, the software displays the correspondent report.

Several series of field tests of the LURI system were carried out at the broad-gauge line at Banedanmark's site near the Storebælt railway tunnel facility in Denmark. A piece of rail profile type UIC 60 was provided with artificial defects imitating the six man-made defects and welded into the railroad line. The railroad car was coupled to a locomotive driving at speeds up to 40 km/h (25 mph). An example the defect finding software, which represents identification of flaw type UIC 213, is shown in Fig. 5.

These field tests, however, clearly revealed that, the region of the railhead currently limits the interrogated volume, and the speed of 40 km/h is the uppermost limit for the rail wagon of the LURI system. There are two main reasons for that. First, the energy and the repetition rate of the generating laser were limited. Second, the mechanical design of the railroad car is currently not robust enough to reach higher inspection speeds.

Nevertheless, these limitations do not seem to be fundamental or intrinsic and can be overcome by further development and investments. Therefore, the work is presently underway on expansion of the interrogated zone down to the rail base and increasing of the inspection speed.

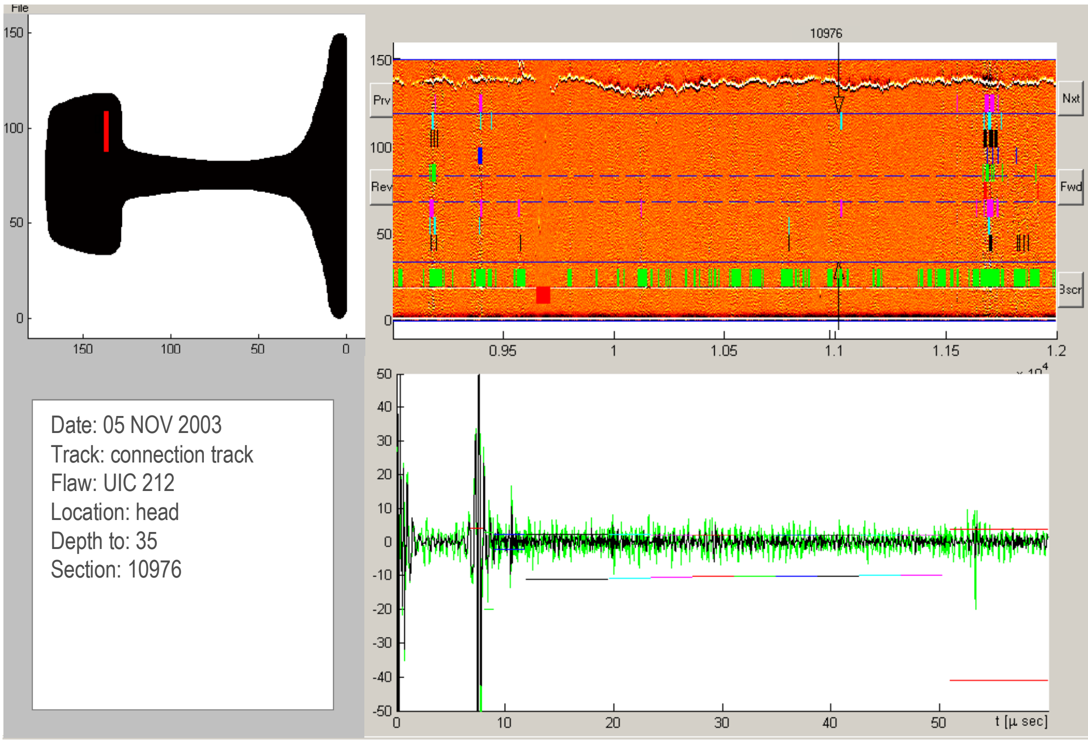

Figure 4. *LURI software. The ultrasonic A-scan and B-scan indicating different ultrasonic signatures with a color code.*

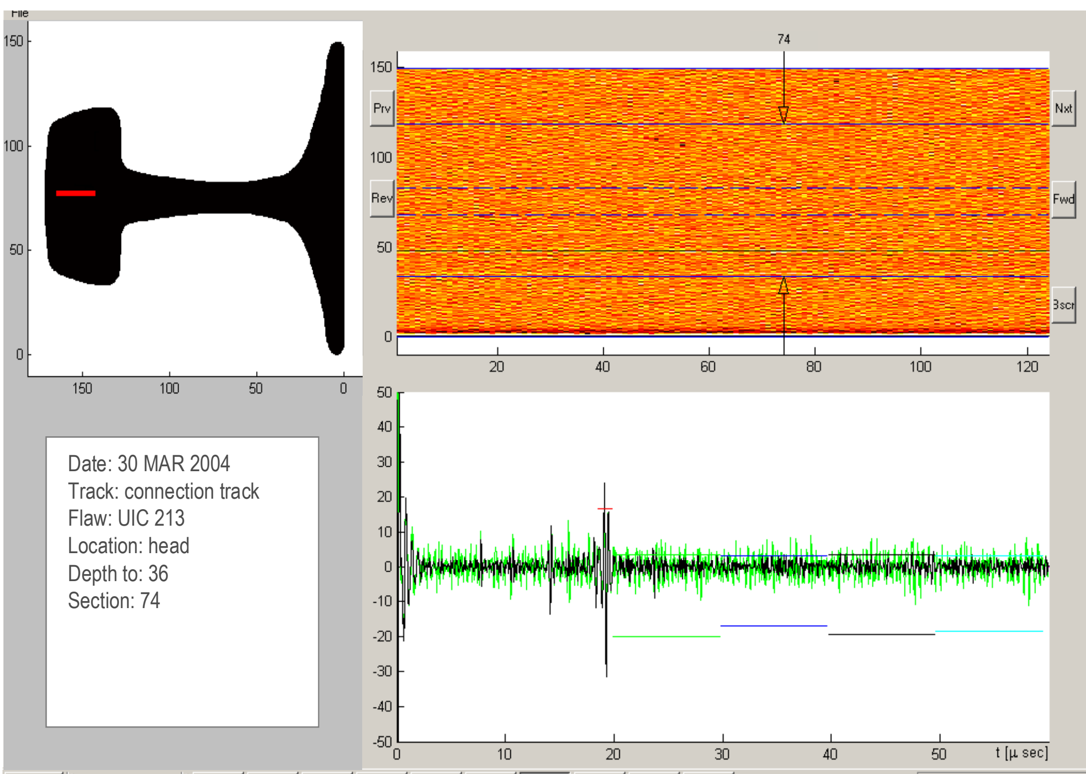

Figure 5. *LURI software. The defect type UIC 213 is identified in one of the rail sections.*

Results obtained with P-scan Lite: A battery-operated system based on contact transducers was additionally developed for rail inspection. The system consists of a standard ultrasonic P-scan Lite [4] system mounted on a flexible rail car. The main advantage of this system is its four channels to acquire ultrasonic data and its relative low weight. Results from a rail piece with small artificial flaws are shown in Fig. 6. Several defects are seen in the figure. The uppermost signal identifies a crack in a bolthole (UIC 235), and below a horizontal flaw (UIC 232) in the web at 85 mm depth is seen clearly. Finally a flaw in the head (UIC 212) at 20 mm depth is displayed by a cross-mark.

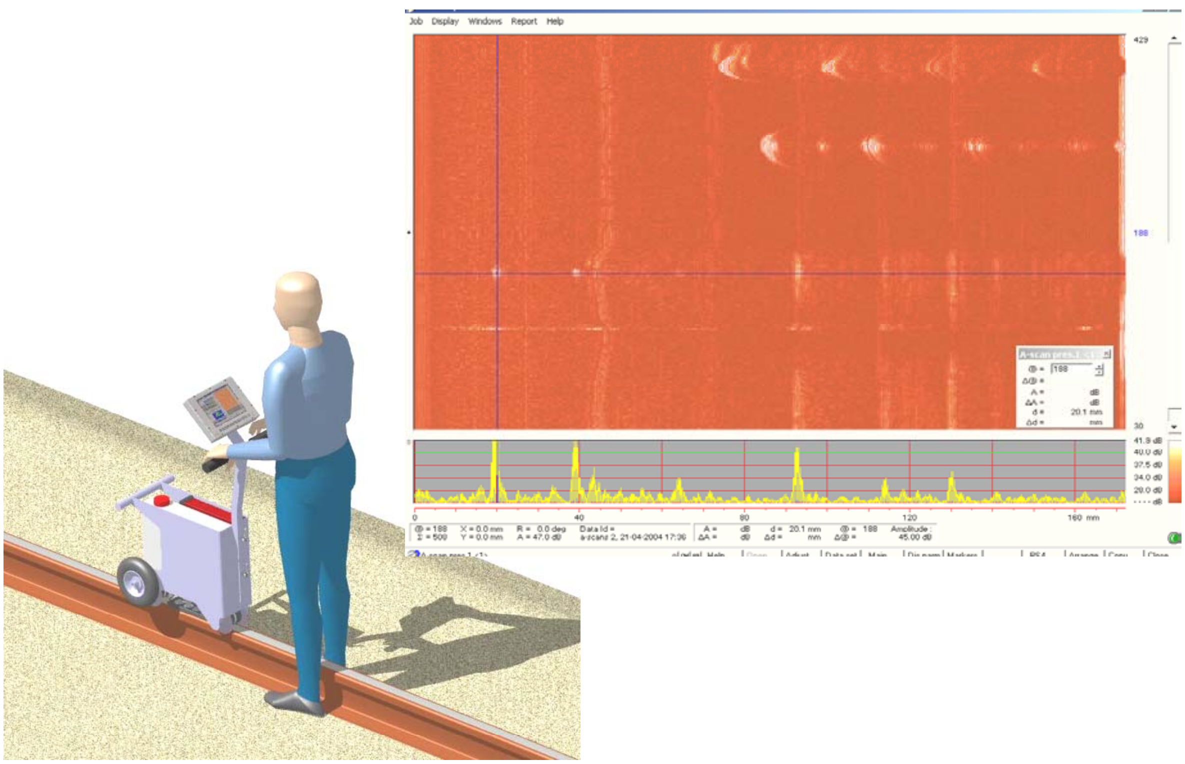

Figure 6. *P-scan Lite for rail inspection.*

Conclusion: An automatic Laser Ultrasonic system for Rail Inspection (LURI) has been developed and tested on a railroad line containing man-made structural defects. LURI is mounted on a specially designed railroad vehicle and allows detection of defects on the running surface of the rail, as well as horizontal and vertical flaws in the railhead. At present, LURI provides rail integrity information up to speed of 40 km/h (25 mph) interrogating both the running surface and the body of the head of the rail. Several critical rail defects were found and identified during the field test of the LURI-system. The results of the test confirm appropriateness of the developed concept of rail flaw detection and open up possibilities for further development.

Acknowledgements: The authors would like to thank Banedanmark for consultations and help in carrying out the field tests of the LURI system.

References:

[1] R. Clark. Rail flaw detection: overview and needs for future developments. *NDT&E International* **37** (2004) 111-118.

[2] S. A. Nielsen, A. L. Bardenshtein, and A. M. Thommesen, B. Stenum. Non-contact ultrasound for industrial process monitoring of moving objects. *Review of Progress in QNDE* (eds. D. O. Thompson and D. E. Chimenti) **23** (2004) 1499-1506.

[3] S. A. Nielsen, and J. S. Hesthaven. A multi-domain Chebyshev collocation method for predicting ultrasonic field parameters in complex material geometries. *Ultrasonics* **40** (2002) 177-180.

[4] S. Neergaard, S. Kohler, and E. T. Bogen. System for advanced automated ultrasonic inspection. *Insight* **41** 11 (1999) 692.