Eurographics Italian Chapter Conference (2007)
Raffaele De Amicis and Giuseppe Conti (Editors)

Dynamic Rail Inspection by Vision System

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Abstract

Current in-field rail track ultrasonic inspection technologies, requiring contact between the probes and the rail surface, show limitations as defect detection is affected by rail surface condition, rail head geometry and defect geometry and orientation. Moreover, inspection speeds are moderate. To improve rail flaw detection, the partnership of the U-Rail project - within the sixth EU framework programme - proposes a new non-contact ultrasonic inspection system, consisting of a pulsed laser and air-coupled transducers. For a proper positioning, the inspection unit includes a laser optic triangulation unit and an automatic positioning system. The first determines the position of the rail, processes the data and drives the positioning system. The U-Rail system allows high speed inspection of the complete rail section. The paper describes the system and results of research activities of two U-Rail partners.

Categories and Subject Descriptors: C.3: Special purpose and application-based systems

1 Introduction

Periodic in-track rail inspections are performed to detect critical defects before they grow enough to cause structural failure. Rail cracks are caused either by manufacturing processes, service-related problems or fatigue. Some of the defects to which the railroad industry addresses its concern, as they are undetectable with current methods, are vertical split head, transverse defects in the head and base defects.

Nondestructive inspection technologies currently used worldwide rely mainly on ultrasonic methods. Detector cars use water filled rubber wheels that contain transmitter-receiver piezoelectric transducers and are kept in continuous rolling contact to the rail surface; otherwise transducers are sledded over the running surface using always water as coupling medium. Due to the rail structure, in motion testing allows to inspect a quarter of the head area and almost the whole web. Altogether the inspected area of the rail is about a third of the entire section.

Even though contact ultrasonic technologies are extensively used and are proved to be reliable, they are not perfect. In fact, train derailments caused by broken rails, which pass inspection, still occur. Defect detectability may be affected by rail surface condition, railhead geometry, defect geometry and orientation, electrical and/or mechanical noise introduced into the transducer, inadequate transducer-to-rail surface coupling.

The goals of rail defect management are to prevent rail flaw related operating accidents and to minimize track maintenance costs. Development and implementation of new or emerging nondestructive testing (NDT) technologies, to inspect rail in track, are expected to advance both goals [Gar. 2002, 2006].

A new non-contact ultrasonic inspection system for rail flaw detection is being developed in the partnership of the U-Rail project within the sixth EU framework programme.

Partners of the U-Rail project are:

- SMEs Proposers: Tecnogamma SpA, Italy, Coordinator; Quantel, France; Jenaer Meβtechnik GmbH, Germany; CM4 Enginyeria S.A., Spain;
- End Users: Eurotunnel, Great Britain/France; Attiko Metro Operation Company S.A. Greece; RATP, France; RFI, Italy;
- RTD Performers: Department of Mechanics, University of Palermo, Italy; Trastec SpA, Italy; University of Liège M&S, Belgium; Enea Uts Mat, Italy.

The non-contact system consists of high power pulsed lasers and air-coupled transducers. To guarantee proper positioning of laser point sources and sensors for best performances, the inspection unit includes a laser optic triangulation unit and an automatic positioning system. The first determines the position of the rail, processes the data and drives the positioning system. The system has the following advantages:

- flexibility to discover cracks;
- inspection of the complete rail section;
- high speed non-contact inspection.

The paper describes the system and results of research activities of two U-RAIL partners.

2 Transducers configuration

As attenuation in air is severe, the distance at which the air-coupled transducer can be placed is limited. The coefficient of attenuation is proportional to the square of the frequency; as a result the intensity is an exponential function of the frequency. This means that at high frequency attenuation is very high and lift-off distances become very small.

Moreover, the transducers must be oriented at the angle θ respect to the normal to the surface, given by the Snell's law ($\theta = \mathrm{sen}^{-1} c/c_w$, with c and c_w velocity in the air and in the steel, respectively) to optimize the detection of the ultrasonic wave.

Studies were performed at the Department of Mechanics (DIMA) of Palermo in order to determine the influence of the air-coupled transducers position. Experiments were carried out varying the lift-off distance from the rail. Figure 1 shows that ultrasonic wave attenuation as function of lift-off distance is approximately 1 dB/mm.

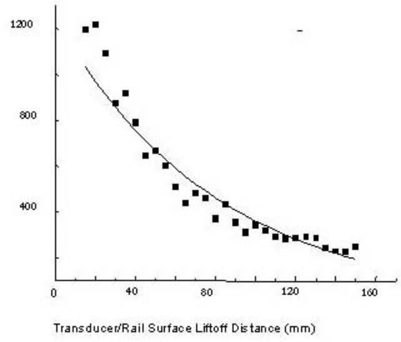

Figure 1: *Signal strength variation of transducer detector as a function of lift-off distance.*

In Figure 2 peak-to-peak wave amplitude is shown as a function of the angle θ between air-coupled transducer and the normal to the sample surface. Maximum amplitude is for $\theta = 6.5^o$. Although proper alignment of the air-coupled transducer is required for maximum signal reception, a $\pm 1.5^o$ misalignment is not critical.

Number of air-coupled transducers and position must be such to guarantee the complete inspection on the whole rail track section [Can. 2003, UIC 712]. Moreover, location of transducers respect to the rail must be such to respect the UIC outline for the vehicle defined in [UIC 505].

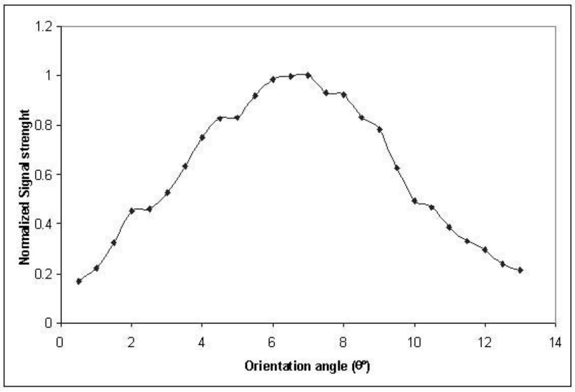

Figure 2: *Signal strength variation of air-coupled transducer detector as a function of inclination to the rail surface normal.*

2.1 Rail head inspection

Defects of interest in the head are in the horizontal, vertical and transverse planes of the rail track. Bulk and surface waves, generated in the rail head using the point source, are acquired by air-coupled transducers in pitch-catch configuration (Figure 3). The area inspected with this configuration is hatched in Figure 4.

Tests were performed at DIMA keeping the sensors at 60 mm lift-off distance to evaluate the maximum distance ***x*** between source/detection points (see Figure 3) for the rail head configuration.

With the above configuration the ultrasonic signal acquired by transducer in position #1 shows clear longitudinal and surface waves (see Figure 5). The attenuation of the longitudinal wave, increasing the source/receiver distance from position 1 to 3, is high but signal to noise ratio is still good (Figure 6).

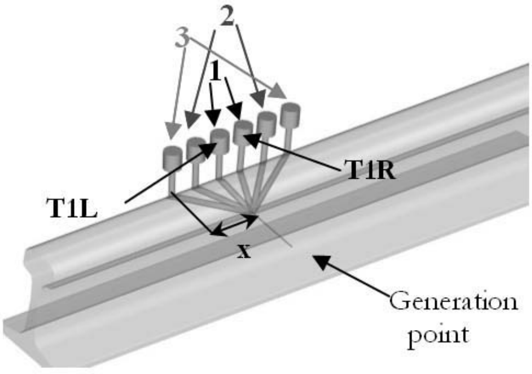

Figure 3: *Configuration for the rail head inspection.*

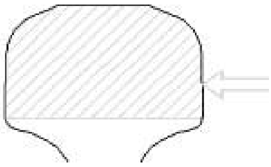

Figure 4: *Inspected area in the rail head is hatched in the oss-section.*

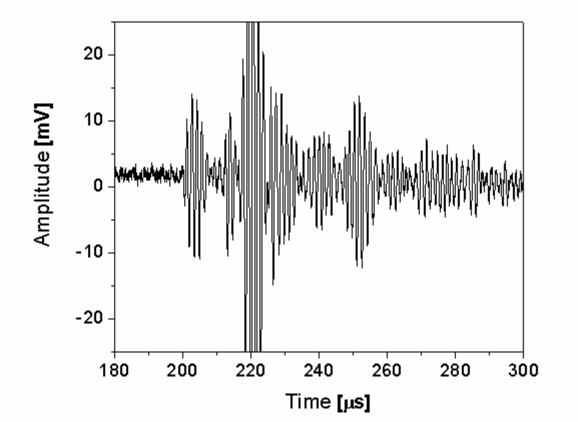

Figure 5: *Signal acquired from the rail head.*

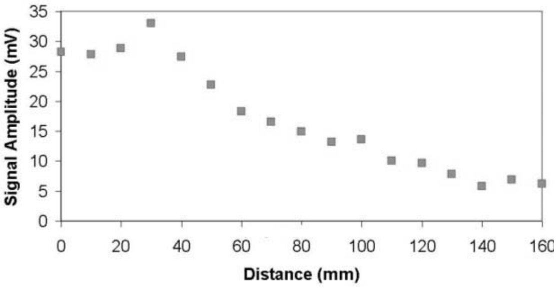

Figure 6: *Distribution of longitudinal wave amplitude as a function of x (lift-off 60 mm).*

2.2 Rail web inspection

Defects of interest in the rail web are in the horizontal and vertical planes of the rail track (such as split and piped web). Bulk waves, generated focusing the laser beam at the bottom of the web, propagate through the web up to the rail head. Best position for the transducer is in pitch-catch configuration above the rail head, centered on the web (Figure 7). The area inspected with this configuration is hatched in Figure 8.

Signal acquired in the web, without defects, shows the package of bulk waves after being reflected more than once along the web walls (Figure 9).

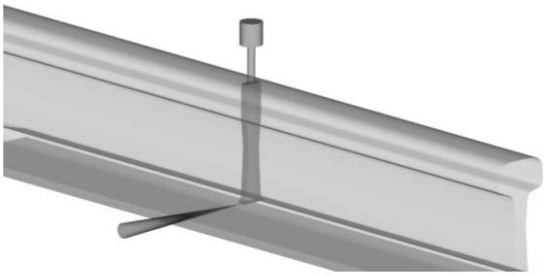

Figure 7: *Configuration for the rail head inspection.*

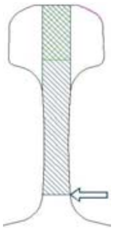

Figure 8: *Inspected area in the rail web is hatched in the cross-section.*

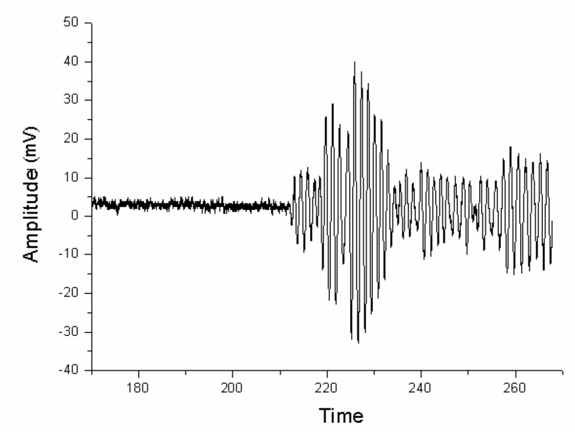

Figure 9: *Signal acquired from the rail web.*

2.3 Rail base inspection

Defects of interest in the rail base are at the outer edges, starting in the transverse plane. Inspection of such area is performed by guided waves generated by a focused laser beam. Signals are acquired through air-coupled transducers located in a symmetric pitch-catch configuration (Figure 10). The area inspected with this configuration is hatched in Figure 11.

Signals acquired in the base by the two transducers show two identical surface waves (Figure 12).

Inspection of rail base with conventional systems is not feasible since with contact transducers the signal can be introduced in the rail only from the top running surface. The use of the laser in the U-Rail system allows to direct the beam to the rail keeping the transducers above the running surface, thus preserving the vehicle outline according to the UIC 505-1 standard.

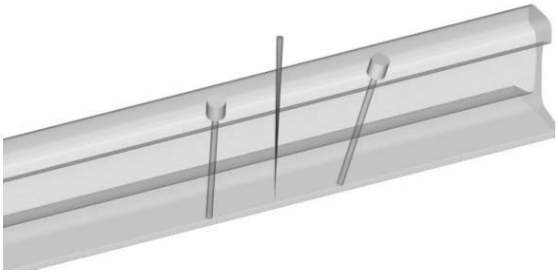

Figure 10: *Configuration for the rail base inspection*

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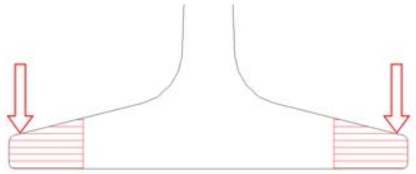

Figure 11: *Inspected area in the rail base is hatched in the cross-section.*

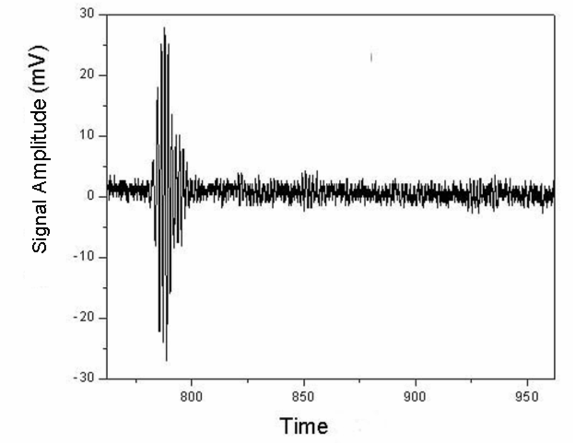

Figure 12: *Signal acquired from the rail base.*

3 The non-contact ultrasonic system

As the inspection unit must chase the rail while inspecting at a certain speed, to guarantee proper positioning of laser point sources and sensors for best performances the ultrasonic inspection unit includes two sub-units that are respectively - the first - a laser optic triangulation unit and - the second one - an automatic positioning system. The first unit determines the position of the rail, processes in real time the data and drives the automatic positioning system.

3.1 Laser optic triangulation unit

The detection of the rail parameters is performed by means of the optical triangulation principle between a laser beam and a digital camera. A scheme of the working principle of optical triangulation applied to the measurement of a point distance is shown in Figure 13. The laser axis is orthogonally projected on the surface to be detected. The D1 distance between the laser origin P1 and the detection point P2 is a constant value determined by the system mechanical design (laser-camera distance).

The inclination of the laser beam A1 is 90° and it is fixed in the system mechanical design. The inclination angle of the camera axis A2 is calculated as proportional function of the data acquired by the optical sensor positioned on P2 point.

As a conclusion the distance *Da* between the laser beam origin point and the point to be detected *Pa* can be easily calculated by the following formula:

$$Da = D1 * \tan (A2)$$

By means of simple geometric calculations it is possible to reconstruct the whole line spanned by the laser beam.

The laser beam is generated from a solid state source and is expanded by a cylindrical lens to obtain a linear source uniformly delivered on the rail. The laser required may have a power of 50 mW at wavelength of 685 nm.

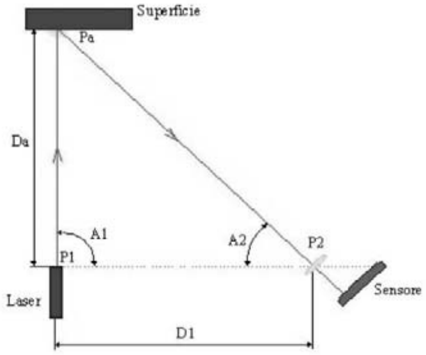

Figure 13: *Scheme of the working principle of optical triangulation.*

A special camera positioned with a known angle detects the reflected laser light. The camera employs a 1024x1024 pixel sensor based on CMOS technology. The sensor integrates a set of 8 A/D converters working in parallel and transfers the out-coming data on a 64 bit~~s~~ parallel bus. Such architecture allows a very high sampling frequency up to 2000 frames/sec. The camera uses a special interferential filter at high selectivity that is able to filter the light into a short wavelength band. It makes the system immune to interference introduced by sunlight or other light sources and allows the apparatus to perform reliably in any light condition without regulation.

Figure 14 shows the components of the rail position measurement system. The measurement unit includes specific electronics that are used to control and to manage image-processing locally. The electronic devices are based on a totally digital technology; specifically FPGA devices at very high integration are used. This configuration allows all the logical functions to be grouped on a single programmable component thus reducing the hardware complexity in favour of system reliability and flexibility. The data detected by the sensors of the cameras are filtered and pre-processed by a DSP integrated on the FPGA device (see Figure 15).

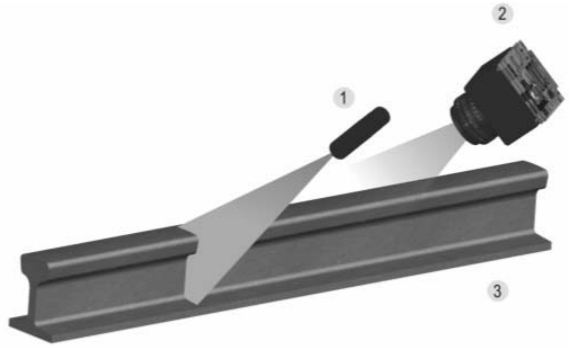

Figure 14: *Components of the rail position measurement system: 1 laser source, 2 detection unit.*

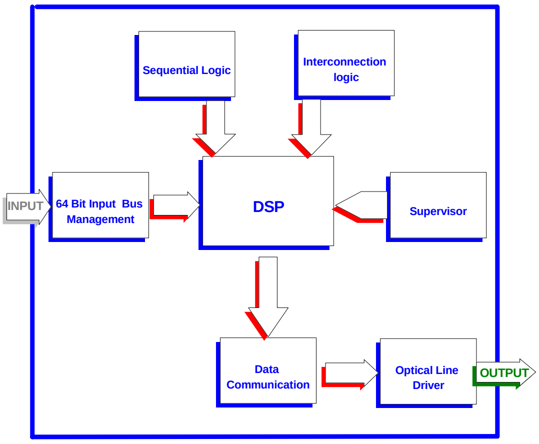

Figure 15: *FPGA Functional Block Diagram.*

Data transfer is carried out with a 64 parallel bus bit from digital camera to the first processing level. Optical fibers are used to create the communication channel between the second and the third processing levels. With this high frequency serial bus it is possible to transmit data to long distance and keep the system practically immune from EMC interferences.

Final data elaboration is made on a dedicated industrial PC. On this PC the complete software elaboration of the system runs to elaborate the information which are coming from the images field and from the kilometric progressive.

This PC extracts from the above information the real profile characteristics of the track and elaborates and correlates all the information that will be prepared for a second station especially designed to perform real time data transmission and archiving data process.

3.2 Laser position measurement system

Laser, digital camera and related electronics are properly positioned inside the inspection case. A glass window is designed in the bottom case for the laser beam and the vision field of the camera. Figures 16 and 17 show respectively the real time acquisition of the rail actual position and the reference points used for positioning.

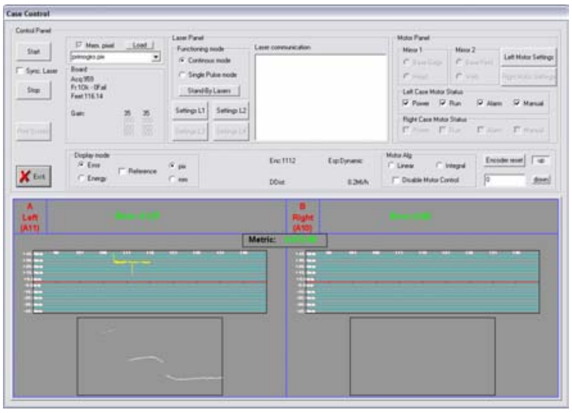

Figure 16: *Real-time acquisition of the actual position of the rail.*

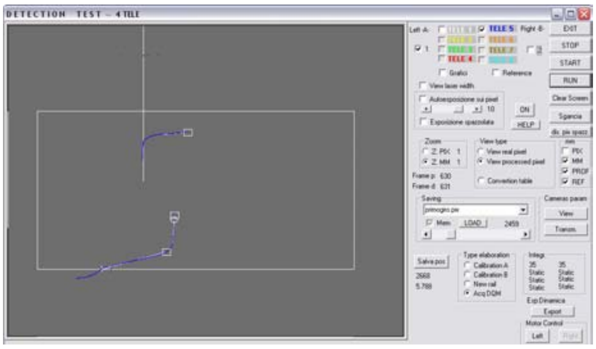

Figure 17: *Reference points in the rail used for positioning.*

3.3 Automatic position system

Once the real-time position of the rail is measured, the software controls the servo-motor of the automatic positioning system. The ac-motor with a servo-controller uses a PID control in order to compensate the position of the detection unit according to movement of the vehicle over the rail and according to the rail gauge variation.

The motion of the inspection unit is performed through linear motion guides with caged ball technology. Advantages of such guides are stable movement, high-speed performance and long-term, maintenance-free, long service life.

4 Conclusions

A new non-contact ultrasonic inspection system for rail flaw detection, that is being developed in the partnership of the project U-Rail within the sixth EU framework programme, is described in the paper. The system consists of pulsed lasers and air-coupled transducers.

The ultrasonic inspection unit includes two sub-units that are respectively - the first - a laser optic triangulation unit and - the second one - an automatic positioning system. The first unit determines the position of the rail, processes in real time the data and drives the automatic positioning system to guarantee proper positioning of laser point sources and sensors for best performances.

It is expected that the new non-contact inspection system will increase flaw detection reliability by providing a more complete inspection of the entire rail section, thereby increasing safety by lowering the risk of service failures.

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