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Of Transportation

**Federal Railroad
Administration**

Research
Results

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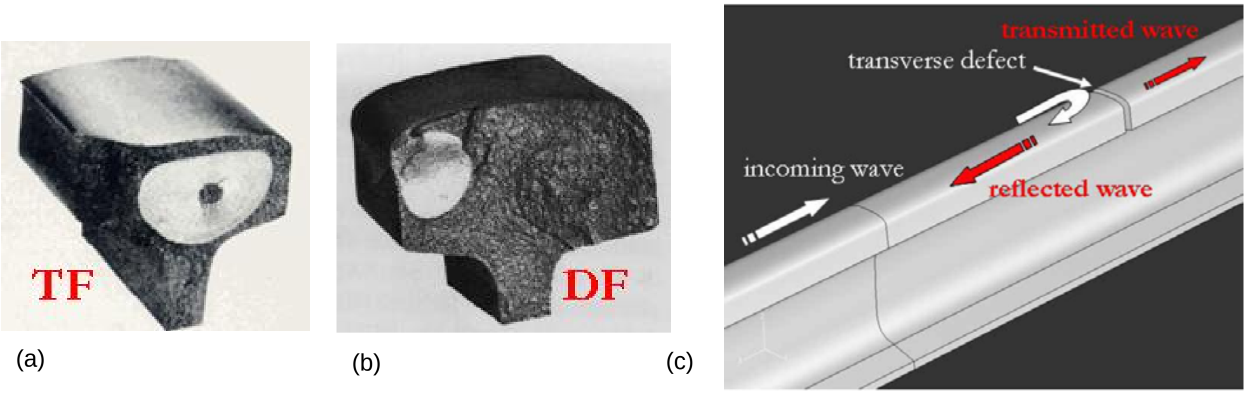
On-line High-speed Rail Defect Detection – Phase III

SUMMARY

The Federal Railroad Administration (FRA) Office of Research and Development's Track and Structures Program sponsored a study for developing and testing a rail defect detection system based on ultrasonic guided waves and non-contact probing. Current rail defect detection systems based on ultrasonic testing have limitations in terms of reliability of defect detection, inspection speed, and other drawbacks associated with the requirement for contact between the ultrasonic probes and the rail surface. More importantly, conventional ultrasonic testing of rails has serious difficulties detecting internal defects in the presence of surface shelling. The rail defect detection technique that is being funded is based on fundamentally new concepts in that 1) uses ultrasonic waves traveling along, rather than across the rail running direction, 2) uses non-contact means of generating and detecting the ultrasonic waves in the rail, and 3) uses advanced signal processing algorithms to de-noise the measurements and extract robust defect-sensitive information. A prototype is being assembled based on this technology and plans are in place to install and test the prototype in the FRA Research Car.



(a) (b) (c)

Figure 1. (a) Transverse fissure; (b) Detail Fracture; (c) Ultrasonic guided wave detection of transverse defects ("reflection" and "transmission" modes).

BACKGROUND

Conventional ultrasonic rail inspection, that is the common approach taken by railroad maintenance personnel for defect detection, uses piezoelectric transducers that are coupled to the top of the rail with ultrasonic wheels or sleds filled with water or other fluids. The transducers are typically operated in a pulse-echo mode with two orientations, namely 0° (normal) incidence for detecting horizontal cracks and 70° incidence for detecting transverse cracks. The most concerning drawback of this method is the fact that horizontal shallow cracks (shelling) can mask the internal transverse defects. This limitation was the most likely cause of a train derailment in Superior, WI in June 1992, where an entire town had to be evacuated as a result of hazardous material spillage. Other limitations of conventional rail defect detection are the limited area of rail inspected at once and the limited inspection speed resulting from the contact requirements.

The system under investigation, based on ultrasonic guided waves, non-contact sensors and advanced signal processing algorithms, has the potential to increase the reliability of defect detection in rails and the inspection speed. The technology is particularly suitable for detecting transverse-type defects (TDs). During the decade 1992-2002, TDs were responsible for $162M in associated damage costs in the US and 2,782 derailments according to FRA Safety Statistics Data (FRA 2002). The TDs targeted by the inspection include Transverse Fissures initiating in a location internal to the railhead, and Detail Fractures initiating at the head surface as Rolling Contact Fatigue defects (Figure 1a and 1b). The project is currently in its third year and present activities are being conducted to assemble an inspection prototype and subsequently install and test it in the FRA Research Car.

ELEMENTS OF THE RAIL DEFECT DETECTION SYSTEM

The system under development uses an Nd:YAG pulsed laser (1064 nm, 10 nsec pulse duration) focused to an illumination line source on the top of the rail head to generate ultrasonic waves in the DC-2MHz frequency range (Figure 2a). The line source forces the waves to propagate along the rail running direction while insonifying the entire section of the railhead. Hence the waves are "guided" by the geometry of the rail head. This wave propagation direction is particularly suitable to detect TDs, which generate large reflections (Figure 1c). Micro-machined, capacitive air-coupled sensors are used to detect the ultrasonic waves propagating in the rail (Figure 2a).

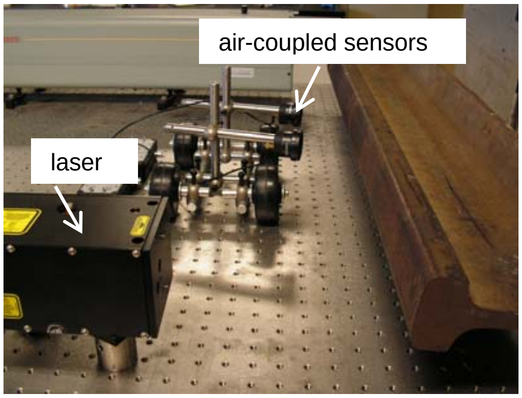


Figure 2a. The prototype non-contact rail defect detection system: Laser and air-coupled sensors.

These devices offer a wide response bandwidth (DC-2MHz) with large sensitivities. A 40 kHz high-pass filter is generally used to limit the influence of ambient vibrations and other sources of noise in the field. The air-coupled sensors can be positioned as far away as 3 inches from the top of the rail head thus satisfying the clearance envelope that is generally recommended for rail inspection systems claiming "non-contact" capabilities.

Defects can be detected by monitoring the presence of a reflection or echo of the ultrasonic wave ("reflection" mode) or by monitoring an attenuation of the ultrasonic wave as it travels past the flaw ("transmission" mode). The two modes require different orientation angles of the air-coupled sensors and different positions of these sensors relative to the laser source. Extensive numerical (finite element analyses) and experimental studies have been conducted to examine both of these defect detection modes. As a result of these studies, the "transmission" mode has been selected for configuring the prototype system. A pair of air-coupled sensors is oriented at 6° from the normal to the rail surface towards the laser source. The distance between the two sensors, in combination with the laser repetition rate, controls the achievable inspection speed.

According to the "transmission" mode, defects are detected when the ratio between the ultrasonic measurements of the two sensors decreases from the "no defect" value of unity as a result of the ultrasonic attenuation past the flaw. Defects can also be sized based on the value of this ratio.

A sophisticated software program has been programmed to achieve all of the tasks required by the inspection, including control of the laser firing, synchronization of the sensor measurements with the laser, processing of the measurements by de-noising algorithms, computation of the Damage Index, and display of an indication of a defect and its size. The program is based on National Instruments PXI© technology running under LabVIEW (Figure 2b).

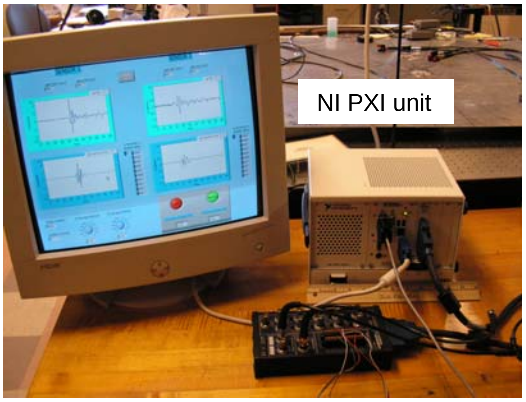
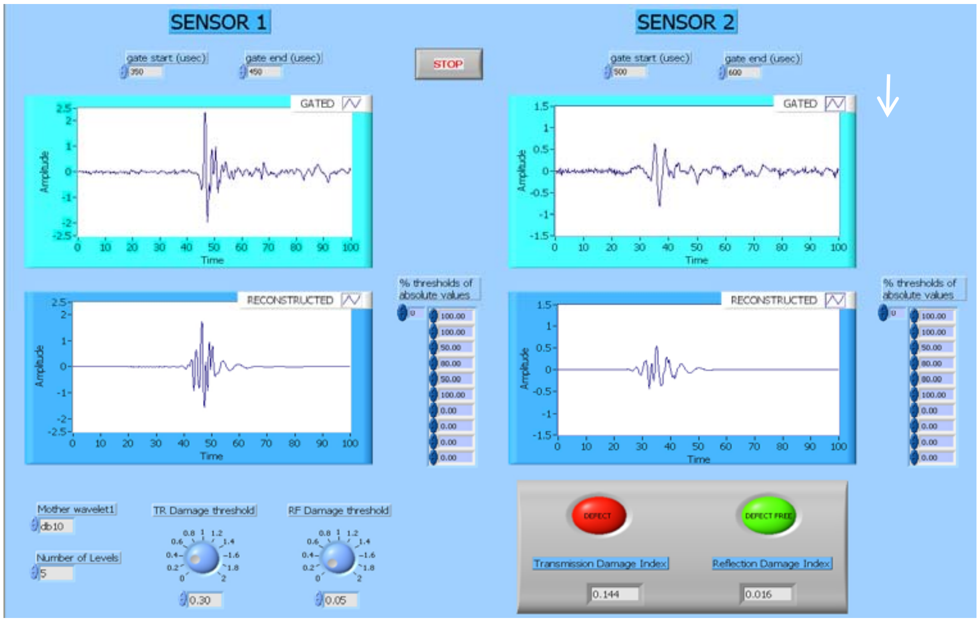


Figure 2b. The prototype non-contact rail defect detection system: Data control and display.



SENSOR 1: gate start (usec) 350, gate end (usec) 450

SENSOR 2: gate start (usec) 500, gate end (usec) 600

Mother wavelet1 db10

Number of Levels 5

TR Damage threshold 0.30

RF Damage threshold 0.05

Transmission Damage Index 0.144

Reflection Damage Index 0.016

Figure 3. User front panel for the signal detection portion of the inspection software showing the detection of a transverse head crack in the "transmission" mode.

An intermediate version of the user interface for the signal detection part of the program is presented in Figure 3. The traces measured by the two sensors are shown, along with their de-noised versions after Discrete Wavelet Transform processing. Two Damage Indexes (D.I.s) based on the "reflection" and on the "transmission" modes are shown in the lower-right portion of the screen. This measurement, taken in the laboratory, refers to an instance where a transverse head crack was positioned between the two sensors, hence the "transmission" D.I. correctly alarms of its presence.

LABORATORY TESTS AND RESULTS

Surface-breaking cracks were simulated in a section of rail by narrow notches that were machined at depths (*s* in Figure 4a) ranging from a minimum of 0.5 mm to a maximum of 8.5 mm, all corresponding to a cross-sectional area reduction of the rail head (% H.A. reduction) below 20%.

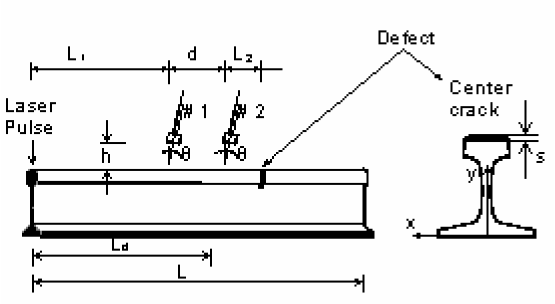


Figure 4a. Schematic of rail tested with crack defect.

The ultrasonic signals from the sensors were acquired at a 5 MHz sampling rate from ten laser pulse generations at each damage condition. The general approach for the quantitative defect detection starts with a Discrete Wavelet Analysis for de-noising the signals and extracting the damage-sensitive features, followed by an Artificial Neural Network (ANN) algorithm for classifying the damage size (Lanza di Scalea et al. 2005). The D.I. is then calculated taking the ratio between features of the signal detected by the further sensor #2, F_{sens2}, over the same features from the closer sensor #1, F_{sens1} ,

$$\text{Damage Index} = \frac{F_{\text{sens2}}}{F_{\text{sens1}}} \qquad (1)$$

In the “transmission” mode the D.I. is expected to drop in the presence of a crack due to the reduction in ultrasonic energy transmitted through the discontinuity. The features of variance, RMS, peak amplitude and peak-to-peak amplitude of the threshold wavelet coefficient vectors were computed.

Figure 4b shows the D.I. from equation (1) using the variance feature. The mean value of ten measurements is plotted as a function of the crack depth and the extension of the vertical line is equal to 2 standard deviations.

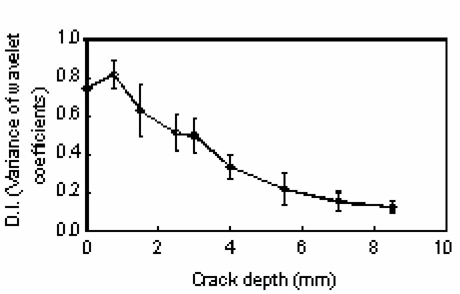


Figure 4b. Damage Index vs. crack depth.

As expected the D.I. monotonically decreases with increasing defect size. This suggests the potential for sizing the crack. The defect sizes were further subdivided into three classes (Classes 1, 2 and 3), corresponding to % H.A. reduction in the ranges 0% - 1.1% (the pristine condition), 1.5% - 9.9%, and 10% - 20%. Each class was coded with a 2-digit binary number. A feed-forward, back propagation ANN with three layers was employed. Five of ten acquisitions for each damage condition were used as training data while the remaining data were used as testing data.

Figures 5a and 5b illustrate, respectively, representative classification results of the laboratory tests and a comparison with the A.R.E.M.A. recommendations for rail inspection reliability of transverse defects.

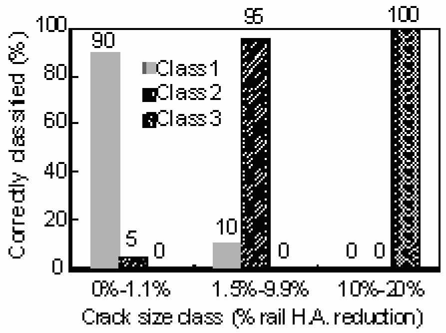


Figure 5a. Defect classification performance as a function of crack size classes

A parametric analysis identified the following four features providing the best classification performance: the variance, the RMS, the peak amplitude of the wavelet coefficient vectors and the area below the FFT spectrum of the reconstructions. Classes 1, 2 and 3 were properly classified in the 90%, 95% and 100% of the cases, respectively. Thus all defects larger that 10% H.A. reductions were properly classified.

The setup gave a total of 10% false positives and only a total of 5% false negatives.

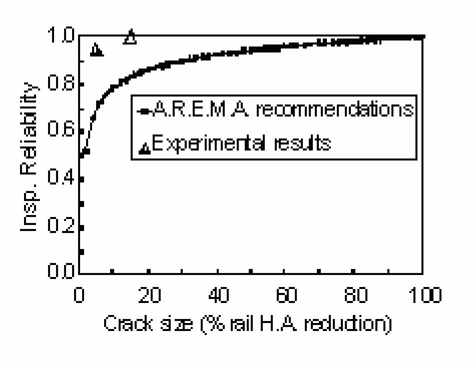


Figure 5b. Inspection reliability of proposed defect detection method compared to A.R.E.M.A. standards.

CONCLUSIONS

A rail defect detection system based on ultrasonic guided waves, non-contact probing and advanced signal processing is under development. The system has the potential for detecting transverse defects in spite of the presence of surface shelling thus increasing the reliability of defect detection over conventional rail defect detection systems. In addition, the system can in principle achieve inspection speeds higher than those achievable by conventional rail defect detection systems. Promising results have been obtained in laboratory tests on simulated transverse cracks in the rail head extending below 20% H.A. Preparations are underway for field testing of the system.

ACKNOWLEDGMENTS

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