U.S. Department
Of Transportation

Federal Railroad Administration

Research Results

RR04-02
January 2004

On-Line High-Speed Rail Defect Detection

SUMMARY

The Federal Railroad Administration's (FRA's) Office of Research and Development sponsored a study for reliable rail defect detection from a moving inspection vehicle. The study examined two promising new methods of ultrasonic testing. The first method employs air-coupled ultrasonic testing for non-contact probing and ease of transducer positioning. It was shown that resonant standing waves could be successfully generated in the rail cross-section to alleviate the challenges associated with the large acoustic impedance mismatch between air and steel. The cross-sectional inspection is particularly well suited for the detection of longitudinal defects. The second method uses structural vibrations of the track for long-range detection of transverse and oblique defects. In the presence of various defect types and sizes, the reflection coefficient spectra of broadband longitudinal, vertical and lateral vibrations were extracted by a joint time-frequency analysis based on the wavelet transform. Post processing of the data by the discrete wavelet transform was also employed to de-noise and compress the ultrasonic signals in both methods. The results were found to be useful for the development of a rail defect detection system based on automatic pattern recognition.

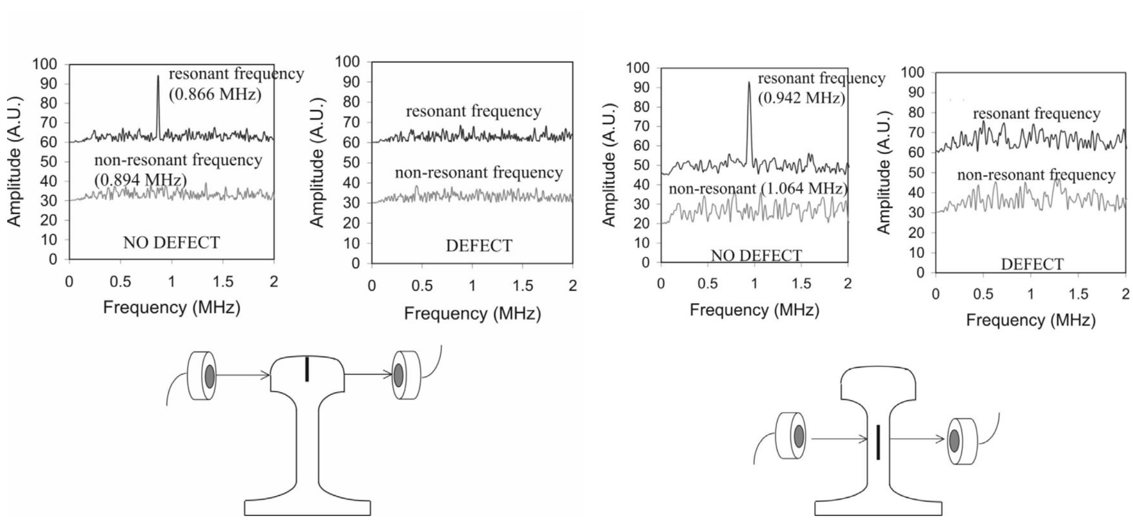

Figure 1: Air-coupled ultrasonic detection of longitudinal cracks in the rail head and web

BACKGROUND

Conventional ultrasonic rail inspection 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, normal incidence for detecting horizontal defects and 70° incidence for detecting transverse cracks. The main disadvantage of these configurations is the contact requirement between the coupling agent and the rail running surface that potentially limits the achievable inspection speed and may suffer from measurement perturbations. Current speeds are thus limited to 10-20 mph in the U.S. Also, due to their size and bulky geometry, fluid-coupled arrangements are not efficient for the inspection of certain areas of the rail such as the head flange. The large sensitivity of fluid-coupled ultrasonic methods to environmental temperature changes can be problematic because rail inspection needs to be performed in a variety of conditions. Finally, shallow horizontal cracks or shelling can block the ultrasonic beams excited from the top of the rail and prevent them from reaching internal defects. In an effort to overcome the limitations of conventional ultrasonic rail inspection in terms of inspection speed and defect detection reliability, two new methods were examined. The first method uses non-contact air-coupled ultrasonic transducers operated in a through-transmission configuration for the detection of longitudinal internal defects. The second method uses guided waves that propagate along, rather than across the rail, for the detection of transverse-type defects at long ranges. Signal processing based on the wavelet transform was employed to improve the performance of the inspection. Tests were performed on 115-lb AREMA rails with defects manufactured in the laboratory. Field tests were also conducted with the assistance of San Diego Trolley, Inc.

REPRESENTATIVE RESULTS

Air-coupled, cross-sectional inspection

It was found that the air-coupled cross-sectional method is effective in generating signals across the rail once resonance frequencies are used in the inspection. Resonance conditions can be established in the rail head and web due to their plate-like geometry and occur every time the width of the test section is equal to an integral number of half the wavelength of the ultrasonic signal. Longitudinal defects were created in test rails by saw cutting to assess the effectiveness of this system for defect detection. Typical results are shown in Figure 1 for the rail head and web. These plots show the amplitude of the Fast-Fourier Transform of the air-coupled signals with and without the defect. Also, the effect of the excitation frequency is shown by presenting the results for a resonance frequency and for a non-resonant frequency. The particular resonant frequencies shown in the figure are 0.866 MHz for the rail head and 0.942 MHz for the rail web. Defect detection was accomplished by observing the disappearance of the signal peaks. Three averages were needed for these results to eliminate the inherent random noise of the air-coupled measurements. The inspection is successful only when resonant frequencies are used, since no peak is present in Figure 1 even in the defect-free rail at the non-resonant frequencies.

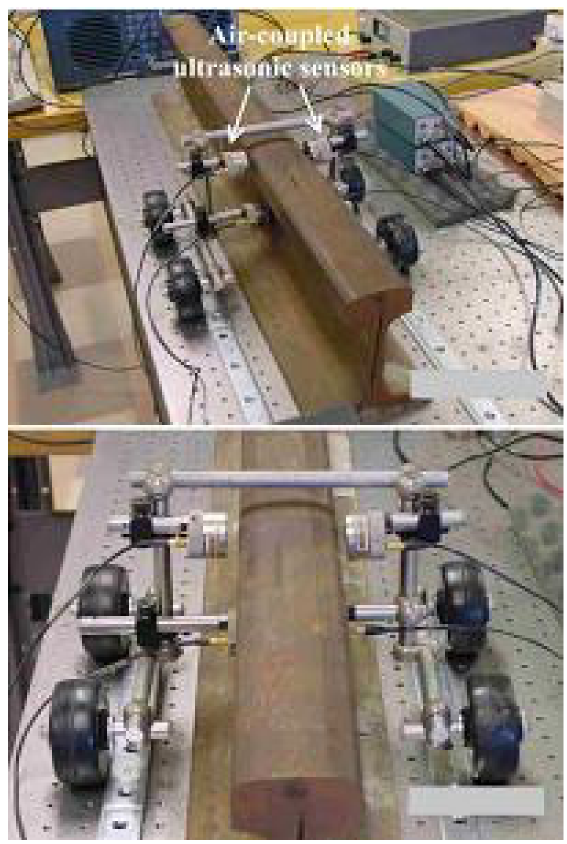

Figure 2: Scanning cart for in-motion air-coupled rail testing

Figure 2 shows a scanning cart that was built at the University of California, San Diego, for in-motion testing of the rail. Four air-coupled transducers, arranged for the inspection of the railhead and web, can be seen in these photos. The cart enabled the researchers to observe changes of the signals in real-time as it passed over a rail segment with defects.

The maximum achievable inspection speed of the air-coupled inspection was found to be lower than that of conventional rail inspection systems due to the need for large excitation energy and signal averaging. However, preliminary results of the application of the Discrete Wavelet Transform processing proved promising to increase inspection speed by de-noising the signals.

Long-range inspection

Research activities on the long-range inspection were first aimed at characterizing the propagation characteristics of longitudinal, vertical and transverse guided waves in rails. The propagation velocity and the attenuation losses were measured by hammer impulse excitation and accelerometer detection. The measurements were performed on 24-foot long sections of rail in the laboratory and subsequently confirmed in the field at the San Ysidro section of the San Diego Trolley near the U.S.-Mexican border. Signal processing based on the Continuous Wavelet Transform was employed to resolve the dispersive and multimode signals so that all the information needed could be extracted in a single hammer strike. The measurements confirmed that guided waves travel at extremely high speeds. The average velocities in the frequency range DC-20 kHz were measured at 4.8 km/s (10,700 mph) for the longitudinal wave, 2.2 km/s (4,900 mph) for the lateral wave, and 2.1 km/s (4,700 mph) for the vertical wave; hence, the potential for extremely high-speed inspections. The attenuation rates were also reasonable, with acoustic losses on the order of 0.5 dB per meter of propagation length.

Three different types of defects were manufactured in the head portion of the test rails, namely a transverse cut, an oblique cut oriented at 20 degrees from the transverse direction and a second oblique cut at 35 degrees from the transverse direction. For each defect type, four different sizes were cut at increments of one quarter of the head cross-sectional area (Figure 3).

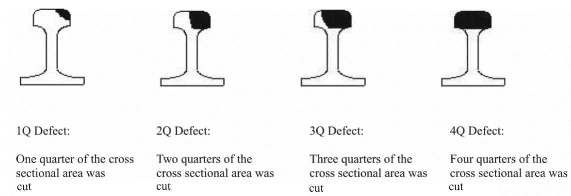

Figure 3: The different sizes of transverse-type defects examined by the long-range inspection method

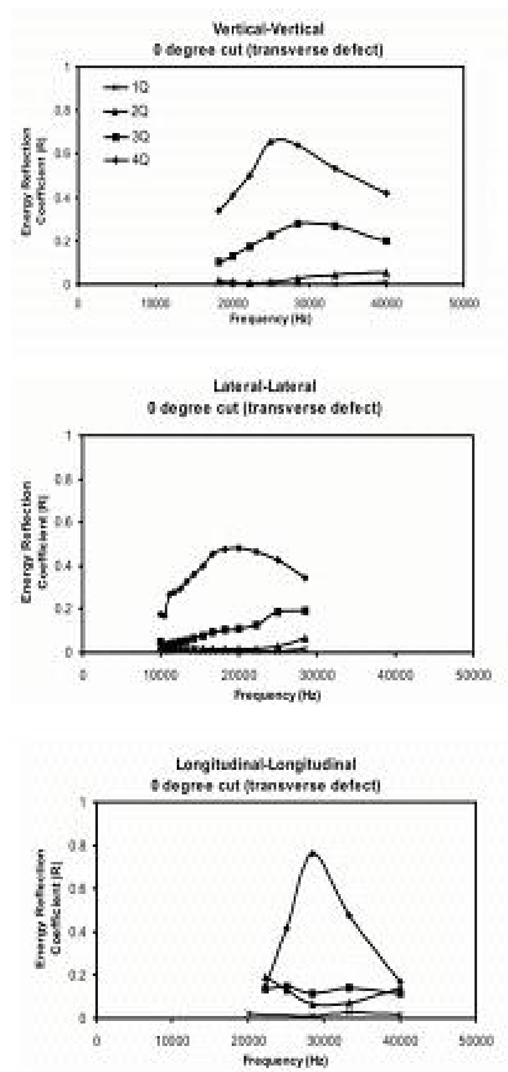

Figure 4: Energy reflection coefficient spectra for the long-range waves in the presence of transverse head cuts of varying sizes.

The interaction of the long-range waves with the defects was studied in terms of reflection coefficients by taking the ratios between the echoes from the defects and the incoming signals. Representative results for the transverse defect orientation are presented in Figure 4 were the four defect depths are indicated by 1Q, 2Q, 3Q and 4Q with 1Q being the smallest and 4Q the largest size. It can be seen that the reflection strength of the waves generally increases with defect size. This result shows promises for quantitative, rather than qualitative, defect detection. Moreover, the vertical and the lateral wave reflections show a more uniform trend with increasing defect size than the longitudinal wave reflection does. The vertical and the lateral waves thus appear more suitable for field applications. Optimum inspection frequencies are found at 25 kHz for the vertical mode and at 15 kHz for the lateral mode. Similar results were obtained for the two oblique cracks where the reflection patterns changed providing a means for defect classification.

CONCLUSIONS

The capabilities of two ultrasonic rail inspection methods were investigated. The air-coupled, cross-sectional method offers ample sensitivity to longitudinal-type defects, with the tradeoff being a limited inspection speed. The long-range method offers practically unlimited speed and adequate sensitivity to transverse-type defects, notoriously among the most dangerous in rail failures. It thus appears that the second method has a higher probability of success for practical field applications.

The long-range method requires additional data to correlate the defect echoes with quantitative defect information, namely defect type, size and location. In Phase II, the defect reflections will be simulated by dynamic finite element packages to build a map of reflection signatures for various defect classes. Automatic pattern recognition algorithms will be implemented in the reflection measurements to provide real-time, quantitative defect detection capabilities. The use of signal processing, and particularly the Discrete Wavelet Transform for signal de-noising and compression, will be considered further to improve the performances of these systems.

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ACKNOWLEDGMENTS

Francesco Lanza di Scalea, Associate Professor, and John McNamara, Ph.D. candidate at UC San Diego, performed this study. Ricardo Medina of San Diego Trolley provided the sections of rail for the laboratory testing and allowed access to the tracks in the field. Mahmood Fateh, FRA Technical Representative, provided support through technical discussions.

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