TECHNOLOGY DIGEST

TD-16-030
©JULY 2016

TIMELY TECHNOLOGY TRANSFER

The work described in this document was performed by Transportation Technology Center, Inc.,
a wholly owned subsidiary of the Association of American Railroads.

High-Speed Rail Flaw Detection Using Phased Array Ultrasonics

Matthew Witte and Anish Poudel

Summary

Transportation Technology Center, Inc. (TTCI) has developed a phased array rail inspection prototype technology for detecting rail defects in track. Preliminary results demonstrate that the phased array flaw detection technology is outperforming conventional ultrasonic (UT) inspection under controlled testing on known defects at the Rail Defect Test Facility (RDTF) at Transportation Technology Center in Pueblo, CO. This *Technology Digest* describes the fundamentals of the phased array technology and demonstrates the capability to detect flaws in a controlled environment. Future work will show how phased array rail flaw detection compares to conventional UT inspection in the service environment. This work was performed under the Association of American Railroads' Strategic Research Initiative to improve detection of rail flaws/defects. This patented technology is available under non-exclusive, royalty free licenses for developers interested in commercial deployment in North America.

Conventional UT detector cars use piezoelectric transducers housed in roller search units that run atop the railhead. These systems have fixed angle probes. Fixed angle inspection cannot scan the entire section of the railhead, and it cannot dynamically compensate for rail wear. Fixed angle probes are set to inspect a specific volume of rail material and they must be physically reoriented by the operator to maintain aim as the inspection vehicle traverses worn rail. These shortcomings can be corrected by using phased array ultrasonic inspection technology.

The TTCI phased array prototype has the ability to scan the entire railhead section. In addition, this prototype can steer and focus the inspection beam without reorienting the probes. This allows it to compensate dynamically for profile wear without operator input. TTCI's patented phased array prototype operates in two independent inspection modes: high speed mode and high resolution mode. The high speed inspection mode mimics conventional UT inspection by inspecting the rail length at discrete angles. The high resolution mode replaces manual hand scanning for defect verification at specific locations. In the high resolution mode, the probes sweep through a continuum of angles and create a very detailed picture of the rail condition at that location. Similar to conventional ultrasonic inspection, however, this technology cannot inspect the rail base flanges.

Please contact **Matthew Witte (719) 584-0503** with questions or concerns regarding this *Technology Digest.* E-mail: Matt_Witte@ttci.aar.com.

BACKGROUND

Rail breaks due to internal anomalies are a leading cause of track-related derailments in North America. The railroad industry relies on an ultrasonic nondestructive evaluation (NDE) method to detect and characterize defects before they cause a rail break. Conventional ultrasonic inspection has proven effective at finding most rail flaws (about 90 percent), but inherent limitations leave some flaws (about 10 percent) undetected during periodic inspection. Phased array ultrasonic inspection overcomes some of those limitations.

Ultrasonic rail flaw detection is an NDE technique for detecting and characterizing defects inside the rail material. Piezoelectric transducers housed in roller search units (RSUs) of the detector cars generate/emit ultrasonic waves in the rail. The transducers listen for reflected energy (i.e., an echo). Reflections occur at internal discontinuities and the surfaces of the rail. The amount of reflected sound energy is displayed on a time chart, which provides the inspector information about the features that reflect the sound. A trained operator learns to discern the difference between defects and normal features such as bolt holes and welds.

Several factors limit the detection capability of conventional ultrasonic systems. Foremost is the directionality of the ultrasonic beam. Ultrasonic waves are direction-specific, which works both for and against the inspection objectives. The benefit is that measurements are accurate in a given direction; the drawback is that the directions must be selected and controlled. As a result, there is no broad coverage from a conventional, single-crystal probe. Conventional ultrasonic inspection systems use several probes pointed in specific directions to inspect certain volumes of the rail material. The inspection angles are pre-determined and fixed by the hardware; this inherently limits the area of the head that gets inspected. Only "high likelihood" areas are inspected for defects. In itself, this limitation is overcome by adding more RSUs and more probes to the inspection truck.

Steering of the inspection beam on curve-worn rail also presents a challenge. When ultrasonic waves travel from one medium to another (water-filled RSU to the metal of the rail), the transmitted waves are refracted, which means their direction changes. The refraction angle is governed by the physical properties of the water and steel, which usually do not change, and also by the geometry of the interface, which is a function of rail shape. As such, the direction of the ultrasonic wave within the material will be different on a worn rail than on a new rail. As a result, flaws may be missed during dynamic testing on worn rail because the wrong volume of material is inspected.

Phased array ultrasonic inspection can overcome these drawbacks. The multiple elements (transducers) in a single housing have the capability to send an array of sound in a wide range of angles. This is based on the wave physics principle of phasing, i.e., by pulsing (firing) the elements in different delay sequences (phasing), the ultrasonic beam can be electronically controlled to effectively steer and focus the sound beam. This allows not only multiple angles to be inspected by a single probe, it also allows for correction of the inspection angles caused by refraction at the wear surface. The result is more consistent inspection of the target volumes in the railhead and web. Figure 1 shows the basic working principle of the phased array ultrasonic probe.

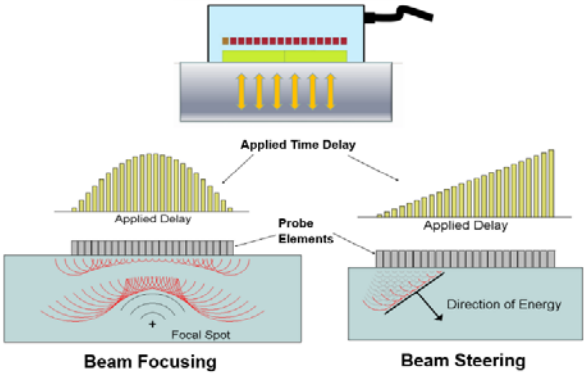

Figure 1. Basic Working Principle of Phased Array Ultrasonics

INTRODUCTION

In support of the AAR's Strategic Research Initiative to improve detection of rail flaws/defects in revenue service, TTCI has produced a phased array rail inspection prototype. This prototype is meant to demonstrate improved detection capabilities over conventional ultrasonic testing (UT) for inspecting railroad rail. TTCI undertook this development in partnership with EWI of Columbus, Ohio, a world leader in materials joining and nondestructive testing. The team designed and optimized the rail flaw detection prototype to detect flaws at 20 mph. The optimization was performed based on the performance and cost of commercially available technology. An optimal probe arrangement was selected based on the results of modeling and laboratory testing. Lab tests were performed on rail samples with artificial defects installed at various locations and orientations. These samples were tested in an immersion tank to validate the models and to determine which focal laws provided the best overall detection capability in actual conditions. The resulting set of focal laws was applied to the phased array prototype vehicle and tested on track at the Transportation Technology Center, Pueblo, CO.

CONFIGURATION OF THE TTCI PROTOTYPE

The probe configuration on the TTCI prototype is optimized for inspection of the head and web at 20 mph. The limitation is based on the size and speed of commercially available phased array hardware. The probes consist of three 125-element matrix phased array (MPA) probes (field, center, and gage side), and one 54-element linear phased array (LPA) probe. Figure 2 shows the probe configuration within the RSU.

This configuration provides a total of 429 crystal elements for inspecting the rail. In phased array ultrasonics, two parameters are required for focusing and steering ultrasonic beams: time delay and apodization (gain) for each element of the array. These sets of delays and gains are grouped into a single law and are referred to as "focal laws." The calculation of time delay and gain for each individual element can be a complicated process; therefore, commercial software was used to determine focal laws. Since the matrix probes can inspect at angles side-to-side as well as longitudinally in the rail, there is substantial overlap of the areas that these probes can inspect. Redundancy adds confidence to the detection event; hence, when multiple probes have an indication at the same location, it increases confidence in the detection event and reduces the likelihood of false alarm.

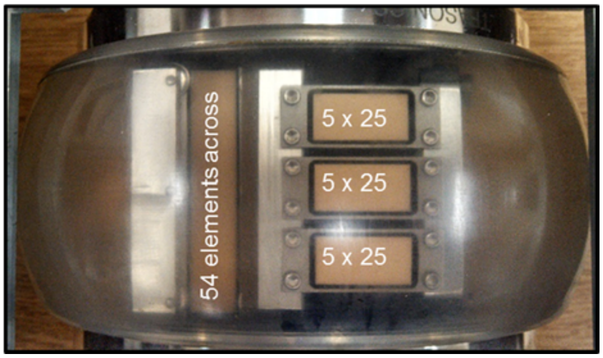

Figure 2. Phased Array Probes Configured Inside the RSU

THE TTCI TEST TRUCK

Figure 3 shows the TTCI phased array prototype which is based on a conventional rail inspection platform. The vehicle and carriage were carried over from a truck donated by Union Pacific Railroad.

Figure 3. TTCI Hy-Rail inspection Vehicle

The RSU containing the phased array probes fits in place of a conventional RSU on the vehicle carriage. Figure 4 shows the phased array RSU in inspection position.

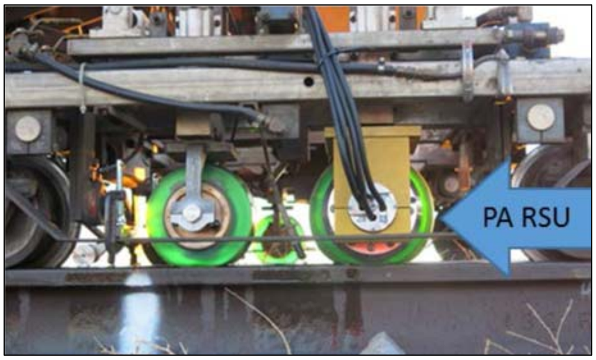

Figure 4. Phased Array RSU in Inspection Position

TTCI selected commercially available instruments to drive the phased array probes. The equipment selected was compact and configurable. One 128-channel instrument was required for each 125-element matrix probe. One 64-channel instrument was required for each linear probe. These instruments were networked with standard network cabling. A signal from the vehicle encoder was fed into the master instrument, which triggered other instruments at precise intervals. Specially designed electronics and precise timing prevent cross talk between the probes.

TESTING

TTCI tested the prototype at the Rail Defect Test Facility (RDTF). The RDTF has known rail flaws of various types and sizes. Initial testing was performed at low speeds. A first objective was to characterize defect signatures. Not all indications are from defects, e.g., bolt holes and some welds have distinct ultrasonic signatures that must be distinguished from defects and from bolt holes and welds with defects. Features such as profile wear compensation and higher speeds were added as testing progressed.

PROFILE WEAR COMPENSATION

Ultrasonic inspection of rail must address the challenge of varying profile. The patented TTCI approach does not need to reproduce the rail profile. Instead, water path depth is measured using the probes. Figure 5 illustrates the concept.

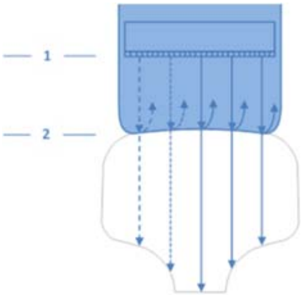

Figure 5. Water Path Depth Measured with the LPA

An angle representing the profile wear is estimated from the water path distance measurements. Finally, the focal law for each probe is corrected based on the wear angle. An option in the phased array instruments allows real-time updating of the focal law without interrupting data capture. Figure 6 illustrates the focal law correction based on wear angle.

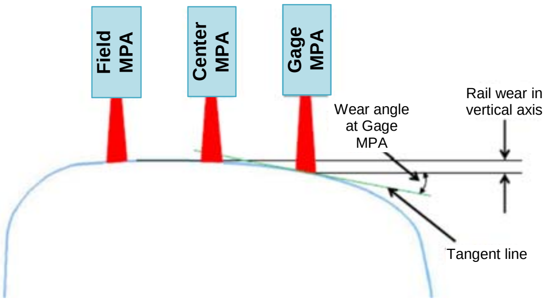

Figure 6. Focal Law Correction Based on Wear Angle

An open loop control structure permits instantaneous updating. A lookup table, populated with a series of compensated focal laws, is referenced in real time. The result is real-time wear compensation without compromising inspection speed.

RESULTS

TTCI performed a side-by-side detection comparison between its conventional UT inspection truck and the phased array prototype. This initial test, run on the evaluation section of the RDTF, was performed at low speed and before the profile compensation feature was active on the phased array system. Table 1 shows the results of this comparison.

Table 1. Initial Low-Speed Detection Comparison

Flaw Type	Total	Phased Array %	Conventional %
Base	26	0	0
Web	11	100	0
Weld	4	100	100
Detail Fracture	16	81	100
Vertical Split Head	2	100	50
Bolt Hole Crack	1	100	0
Transverse Fissure	3	100	100
TD Under Shell	6	83	0

The detail fractures that the phased array truck missed in this test are on heavily curve-worn rail and this test was run before the profile wear compensation feature was active. All other defect types on nominal condition rail are detected as well or better than with conventional inspection. Of notable improvement is the detection of vertical split head and transverse defect (TD) under shell. The TD under shell defect type is problematic for conventional inspection. The phased array prototype detected five of the six defects of this type on the RDTF.

Conventional inspection systems generally detect bolt hole cracks well, but the bolt hole crack on the RDTF is oriented at the top of the hole and is particularly small (Figure 7). TTCI's conventional inspection truck did not detect it. This defect was clearly detected by the center MPA.

The system is performing as expected at higher speeds. Figure 8 shows a B-scan with the indications of the TD under shell at 15 mph. This defect, and the normal TD, are detected by multiple probes, giving high confidence in the detection.

Signal strength is good at the higher speed and indications are similar to the 5 mph data. The indications are clear, confirming that the signal to noise ratio is adequate at the higher speed. Finally, the redundant indications bring confidence to the detection events. Additional work is underway to show the results for the other defect types at speed.

Figure 7. Bolt Hole Crack Defect on the RDTF

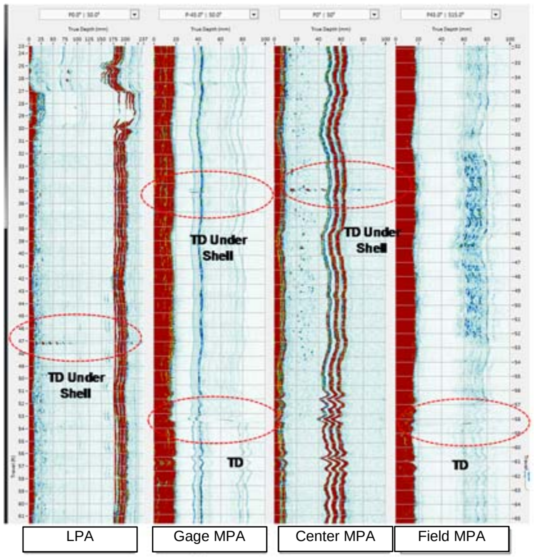

Figure 8. Detection of TD Under Shell at 15 mph

CONCLUSIONS

TTCI has demonstrated the application of phased array technology to rail inspection. The high speed mode has been demonstrated at 5 mph and shows promising results at 15 mph. Demonstration of the system at 20 mph is underway. The system shows equivalent or superior detection capability for all flaw types tested on the RDTF. This includes the ability to detect transverse defects under shelling, to detect vertical split head, and to reliably detect bolt hole cracks that may go undetected by conventional inspection.

NEXT STEPS

TTCI is refining the prototype to improve the user interface for testing at the higher speeds. Future work will report on the results at the 20 mph goal speed and with comparison to state of the art conventional inspection in side by side testing.