

2015

Assessment of ultrasonic NDT methods for high speed rail inspection

Jianzheng Cheng

Iowa State University and Wuhan Textile University

Leonard J. Bond

Iowa State University, bondlj@iastate.edu

Follow this and additional works at: https://lib.dr.iastate.edu/aere_conf



Part of the [Mechanics of Materials Commons](#), and the [Structures and Materials Commons](#)

The complete bibliographic information for this item can be found at https://lib.dr.iastate.edu/aere_conf/71. For information on how to cite this item, please visit <http://lib.dr.iastate.edu/howtocite.html>.

This Conference Proceeding is brought to you for free and open access by the Aerospace Engineering at Iowa State University Digital Repository. It has been accepted for inclusion in Aerospace Engineering Conference Papers, Presentations and Posters by an authorized administrator of Iowa State University Digital Repository. For more information, please contact digirep@iastate.edu.

Assessment of ultrasonic NDT methods for high speed rail inspection

Abstract

This article reviews some new ultrasonic rail inspection methods emerging in recent years. It focuses on the state of the art for guided wave technologies and their potential use for used for rail inspection. It considers ultrasound transduction options including EMATs, air coupled, pulsed laser and wheel probe guided wave methods. It compares performances in terms of frequency ranges, energy delivered, ultrasonic wave modes excited, sensitivity, potential speeds of inspection, inspection regions, transducer angle and positioning. The advantages and disadvantages of each transduction modality for possible use in high speed railway are discussed. It is concluded that an EMAT and laser method, or their combination has the potential to provide a new tool for higher speed rail in-service inspection.

Keywords

Lasers, Ultrasonics, Educational assessment, Waveguides, Ultrasound

Disciplines

Mechanics of Materials | Structures and Materials

Comments

This proceeding may be downloaded for personal use only. Any other use requires prior permission of the author and AIP Publishing. This proceeding appeared in Cheng, Jianzheng, and Leonard J. Bond. "Assessment of ultrasonic NDT methods for high speed rail inspection." *AIP Conference Proceedings* 1650, no. 1 (2015): 605-614. DOI: [10.1063/1.4914660](https://doi.org/10.1063/1.4914660). Posted with permission.

Assessment of ultrasonic NDT methods for high speed rail inspection

Cite as: AIP Conference Proceedings **1650**, 605 (2015); <https://doi.org/10.1063/1.4914660>
Published Online: 02 April 2015

Jianzheng Cheng, and Leonard J. Bond



View Online



Export Citation

ARTICLES YOU MAY BE INTERESTED IN

[NDT of railway components using induction thermography](#)

AIP Conference Proceedings **1706**, 150001 (2016); <https://doi.org/10.1063/1.4940613>

[Signal processing for non-destructive testing of railway tracks](#)

AIP Conference Proceedings **1949**, 030005 (2018); <https://doi.org/10.1063/1.5031528>

[Groundwork for Rail Flaw Detection Using Ultrasonic Phased Array Inspection](#)

AIP Conference Proceedings **657**, 799 (2003); <https://doi.org/10.1063/1.1570217>

Lock-in Amplifiers
up to 600 MHz



Assessment of Ultrasonic NDT Methods for High Speed Rail Inspection

Jianzheng Cheng^{1, 2, b)} and Leonard J. Bond^{1, a)}

¹Center for Nondestructive Evaluation, Iowa State University, Ames, IA 50011

²College of Electronic and Electricity Engineering, Wuhan Textile University, Wuhan 430200, China

^{a)}Corresponding author: bondlj@iastate.edu

^{b)}jzcheng67@hotmail.com

Abstract. This article reviews some new ultrasonic rail inspection methods emerging in recent years. It focuses on the state of the art for guided wave technologies and their potential use for rail inspection. It considers ultrasound transduction options including EMATs, air coupled, pulsed laser and wheel probe guided wave methods. It compares performances in terms of frequency ranges, energy delivered, ultrasonic wave modes excited, sensitivity, potential speeds of inspection, inspection regions, transducer angle and positioning. The advantages and disadvantages of each transduction modality for possible use in high speed railway are discussed. It is concluded that an EMAT and laser method, or their combination has the potential to provide a new tool for higher speed rail in-service inspection.

INTRODUCTION

For about 160 years, steel rails have been at the heart of the world's railroads. The rails operate in a harsh environment and failure can lead to catastrophic loss of life and significant costs for operators. An overview of the various types of rail defects, as well as inspection technologies was provided by Cannon et al. [1]. The subject of rail defects and inspection is also considered by all rail operators, and every rail system operator makes reference to rail defect handbooks and manuals [e.g., 2,3].

Operation of trains on rails can introduce several forms of stress and the loads experienced can cause fatigue and growth of defects [1, 2, 3]. With increased use of high speed trains and a desire to improve safety, particularly with hazardous material transport, rapid and effective detection of defects in rail is an increasingly important issue. This need has been highlighted by several major derailments of trains which have occurred in recent years.

Inspection is a critical aspect of the operation of a rail network. The various NDT technologies currently employed are summarized in Table 1 [4-5]. Rails are commonly examined visually and also using ultrasonics for detection of internal defects, especially in the rail head and web areas. Ultrasonic testing commonly uses piezoelectric transducers that are coupled to the rails with fluid-filled wheels or sleds. In this kind of system, several ultrasonic transducers are located at the top of the rail head inside a fluid-filled wheel. They can be oriented at 0° from the surface of the rail head to detect horizontal cracks and at 70° to detect many types of transverse cracks. Such inspections have been implemented using hand-pushed carts and in vehicle based systems. These methods do have several drawbacks [6-9], most significantly the limited inspection speeds. Typical operational speeds are between 40 and 70 km/h, and a new generation of units is seeking to operate at speeds up to 100 km/h. However average operating speeds are often much lower, especially in North America, where, when an indication is detected, there is a requirement for immediate manual verification of defects and potential repair or removal is undertaken. In these circumstances average speeds may be as low as 15 km/h [1]. Placing vehicles operating at low speeds onto track will cause an unavoidable disruption of the normal train timetable, particularly when high speed trains are being used.

From a technical perspective, there are further challenges faced by the ultrasonic NDT testing and these include issues relating to shallow crack shadowing, where small shallow cracks can cast a "shadow," or dead zone, that potentially limits detection of more severe cracks by reflecting the ultrasonic beams, hence preventing the detection of deeper defects. There is also the challenge of an automated system which gives a "false" call, where there is a report that of defect, which proves not to be there when a hand inspection for defect verification is performed.

Historically, a lot of work has been performed to investigate and improve traditional ultrasonic rail inspections, such as using neural networks to improve identification of defects [10], and using ultrasonic phased arrays to improve the flaw imaging [8]. However, the improvements made to conventional ultrasonic methods cannot overcome their inherent shortcomings, which include limits to inspection speeds, shallow crack

shadowing, and false calls. In order to overcome these limitations various new methods have been investigated, including using ultrasonic surface and guided wave. These approaches have shown some promise [9, 11-13]. Guided and surface waves can be set to propagate along rather than across the rail, and are thus ideal for detecting critical transverse defects. In addition, guided waves are less sensitive to surface shelling because they can run underneath these discontinuities. Finally, guided waves propagate at the speed of sound in steel (typically more than 3,000 m/sec) and thus offer the potential for extremely high inspection speeds. The major challenge then becomes providing systems with the sensors and electronics needed for transmission and reception for the ultrasonic waves that also provide both adequate sensitivity and transduction speed.

There are several technologies that can be used to transmit and receive ultrasonic waves, and these include: EMATs for the guided wave methods [9], air-coupled, including with a resonant methods [11], combined air-coupled and a pulsed laser methods [12], and wheel probes (single element or phased array) for guided wave methods [13]. A schematic of the different methods is shown in Fig. 1.

TABLE 1. Summary of NDT technologies [after INNTRACK (2008) (4,5)].

NDT Technique	Systems Available	Defects Detected	Performance
Ultrasonics	Manual and high-speed systems (up to ~70 km/h)	Surface defects, rail head internal defects, rail web and base defects	Reliable manual inspection but can miss rail foot defects. At high speed can miss surface defects smaller <4mm as well as internal defects, particularly at the rail base.
Magnetic Flux Leakage	High-speed systems (up to 35 km/h)	Surface defects and near surface internal rail head defects	Reliable in detecting surface defects and shallow internal rail head defects although cannot detect cracks smaller than <4 mm. MFL performance deteriorates at high speeds.
Pulsed Eddy Current (including Field Gradient Imaging)	Manual and high-speed systems (up to 70 km/h)	Surface and near-surface internal defects	Reliable in detecting surface breaking defects. Adversely affected by grinding marks and lift-off variations.
Automated Visual Inspection	Manual and high-speed systems (up to 320 km/h)	Surface breaking defects, rail head profile, corrugation, missing parts	Reliable in detecting corrugation, rail head profile missing parts and defective ballast at high speeds. Cannot reliably detect surface breaking defects at speeds > 4 km/h. Cannot assess the rail for internal defects.
Radiography	Manual systems for static tests	Welds and known defects	Reliable in detecting internal defects in welds difficult to inspect by other means. Can miss certain transverse defects.
Electromagnetic Acoustic Transducers	Low speed hi-rail vehicle (<10 km/h)	Surface defects, rail head, web and base internal defects	Reliable for surface and internal defects. Can miss rail base defects. Adversely affected by lift-off variations.
Long Range Ultrasonics	Manual systems and low-speed hi-rail vehicle systems (<10 km/h)	Surface defects, rail head internal defects, rail web and base defects	Reliable in detecting large transverse defects (>5% of the overall cross-section).
Laser Ultrasonics	Manual and low-speed hi-rail vehicle systems (<15 km/h)	Rail head, web and base defects	Reliable in detecting internal defects. Can be affected by lift-off variations of the sensors, difficult to deploy at high speeds.
Alternating Current Field (ACF) Measurements	Manual systems (hi-speed system under development)	Surface breaking defects	Reliable in detecting and quantifying surface breaking defects. Cannot detect sub-surface defects. Very good tolerance to lift-off variations.
Multifrequency Eddy Current Sensors	Manual system, static and slow speed	Surface and near surface defects	Limited experiments conducted. Has potential to reliably quantify defects detected.

This paper reviews the state of the art for guided wave technologies used for rail inspection. It considers them as options and with the capabilities of the various transduction modalities including EMAT's, air coupled, pulsed laser, and wheel probe, all for guided wave methods. It compares performances in terms of frequency ranges, energy delivered, ultrasonic wave modes excited, sensitivity, potential speeds of inspections, inspection regions, positioning and transducer angle. The advantages and disadvantages of each transduction modality are considered in the context of possible use in NDT vehicles for applications to high speed railway networks and

higher speed inspection are reviewed.

Comparisons of Different Transduction Modalities

A major challenge for rail inspection is to provide transduction modalities that can be used with the inspection unit traveling at or near permissible speeds for trains on a given track. Goals have been set to achieve 100km/h (or even higher). To achieve such speeds, with guided waves induced in the rail, attention has turned to look at non-contact methods.

Energy Transduction

Ultrasonic inspection requires coupling of the energy into a part to cause elastic waves in the rail. This can be achieved in several ways. One approach, which has been applied in several industries including pipeline in-service inspection units and this is a wheel probe [14], as shown in Fig 1. The wheel typically uses a transducer which can be a single element, multiple elements or a phased array, mounted near the axle and incorporating a soft polymer or oil filled soft tire. In some implementations a fluid jet is used to provide a water film to improve wheel/part coupling. These transducers can generate various wave modes in a rail, including guided waves. With such a wheel probe, guided waves may be produced by selecting the appropriate angles of incidence and frequencies for excitation and propagation along the rail. With a stationary transducer, waves are produced that propagate along the rail covering a few meters from each inspection position. With a rolling probe, it is possible to perform pulse-echo inspections. There are issues with regard to maintaining coupling, particularly at higher inspection speeds, which has caused researchers to look at the feasibility of employing other non-contact transduction methods [9, 11-12].

An electromagnetic acoustic transducer (EMAT), generates ultrasound in an electrically conducting or magnetic sample using the Lorentz force or a magneto-elastic mechanism [15], is shown in Fig 1. The EMAT is a non-contacting device, but it must be placed close to the rail and it interacts with the metal, to generate ultrasonic waves, through the electromagnetic coupling. When generating guided waves in a rail, the operating frequency and wavelength are set by a combination of the excitation electronics and the physical geometry of the permanent magnet or a meander-line coil. A powerful tone-burst of current with fixed frequency is used to excite the EMAT and to produce a guided ultrasonic or other wave in the part.

With air-coupled ultrasonics, a transducer is used to excite a compression wave in the air which then impinges on and couples energy into the rail [11]. The applied acoustic wave field generates the ultrasonic waves, as shown in Fig 1. Air-coupled ultrasonics has the benefit that it can be set well above the part being inspected. Recent advances in both electronics and the transducers, including new acoustic matching layers, have provided technology with larger dynamic range, and when used with metals, much improved signal to noise ratio. These advances have now made air-coupled methods potentially attractive for rail inspection.

Laser based ultrasonics provides both standoff generation and detection [16], as shown in Fig 1. A pulsed laser is used to form an ultrasonic source on the part surface. When a laser is focused onto the surface of an elastic solid, there is rapid local heating and some of the energy will be transferred into an elastic stress wave. This wave will then propagate into the part as an elastic wave. The nature of the ultrasonic waves can be controlled by the geometry of laser beam and part material properties. Such units can provide high frequency broadband ultrasonic signals. Laser systems can also be used to measure surface displacements and act as detectors.

Frequencies and Ultrasonic Wave Modes

In an example of the wheel probe guided wave method, a local immersion probe operated in pulse-echo mode was used that consisted of an 8 element transducer array (65 mm wide, center frequency 250 kHz) angled at 30° in a casing filled with water [13,17]. The array elements were effectively all connected together such that the array acted like a wide monolithic probe to allow the excitation and reception of waves nearly across the full width of the railhead. The excitation signal was a 5 cycle Hanning windowed tone burst with a center frequency of 200 kHz, at which there exists a suitable surface wave mode with a sufficient penetration depth.

An EMAT can be used to produce both surface (Rayleigh) and guided waves in rail. These waves

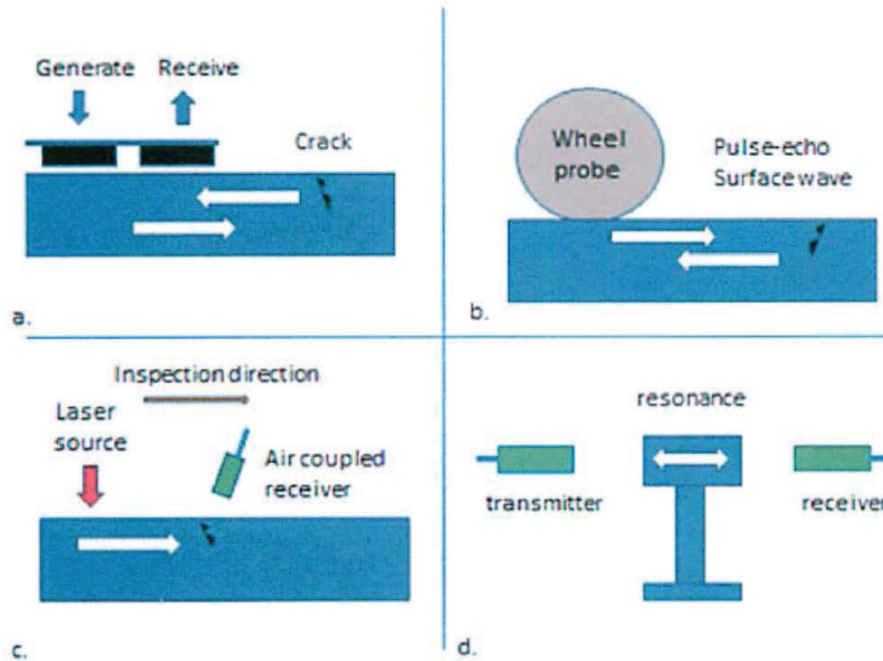


FIGURE 1. Schematic diagrams for different transduction methods: (a) EMAT guided wave method [after 9], (b) wheel probe [after 13], (c) air-coupled pulsed laser method [after 12] and (d) air-coupled resonant method [after 11]

propagate along and near the surface of the rail, and with Rayleigh waves they are penetrating to about 1.5 wavelengths into the part, which would be 18 mm at 250 kHz. Reflection (pulse-echo) and transmission inspections can be performed. A ‘pitch-catch’ low frequency ultrasonic guided wave technique has been used to detect and size transverse cracks in the rail head [9, 15, 18-20]. The frequency range used is between 50 and 600 kHz, and using an FFT, the amplitude data is measured at 400 kHz. In reflection, the ultrasonic response is proportional to defect size, which for a transverse crack is its cross-sectional area. With pulses in transmission, crack depth can be estimated by comparing the surface wave, at a particular frequency, that has passed underneath the crack with that which propagates through a defect-free region.

For air-coupled inspection using ultrasonic bulk waves, a pitch-catch resonant method has been used [11]. For the rail head in through-transmission, the resonant frequency is 866 kHz, for the rail web, the resonant frequency is 942 kHz and for the head flange the frequency is 943 kHz. In pulse-echo, 800 kHz is used vertically for the head [11]. Air-coupled ultrasound is also being investigated for both detection and reception in pulse-echo and transmission.

To overcome the issues relating to the relatively long pulse propagation speed in air, laser generation and reception, and laser-air-coupled hybrid rail inspection systems are being considered. For example a pulsed Nd:YAG laser operating at 1,064 nm with a pulse duration of 8 nsec has been used to deliver a 40 mm-long line beam through conventional optics onto the rail head [12,21-22]. The line source is known to effectively generate directional and broadband ultrasonic guided waves propagating perpendicular to the source. This source can effectively generate frequencies as high as a few tens of megahertz. The air-coupled transducers with broadband response from DC to 2MHz range are used to detect the waves. Signal analysis indicates that most of the energy is in the 100 to 700 kHz range, with a dominant frequency around 200 kHz, in which specific frequencies of 210 kHz, 425 kHz and 600 kHz were used to find the crack depths. Data show 5 mm and 7 mm deep cracks reflect energy mostly at 200 kHz. The smallest 1 mm crack reflects energy primarily at 600 kHz. It is expected that smaller flaws are sensitive to higher frequencies.

Receiver Sensitivities

The various transduction modalities have different conversion efficiencies and detection sensitivities [23-25]. In the 0.5-1.5 MHz frequency band, the absolute limit of a non-contact receiver in air can approach approximately $10^{-17} \text{ m}/\sqrt{\text{Hz}}$. However, all of the practical non-contact transducers are significantly less

sensitive than a piezoelectric transducer. For example, a 100mW laser interferometer can achieve only $10^{-15} \text{ m}/\sqrt{\text{Hz}}$, while a practical EMAT can achieve only $10^{-14} \text{ m}/\sqrt{\text{Hz}}$. On the other hand, an ideal air coupled transducer, assuming perfect acoustic matching to the air, can achieve approximately $10^{-16} \text{ m}/\sqrt{\text{Hz}}$. In the case of a piezoelectric transducer, which exhibits one-way losses of approximately 40 dB, the above limit would be $10^{-14} \text{ m}/\sqrt{\text{Hz}}$. However, a much better performance can be expected for a capacitive transducer with a very thin membrane.

Inspection Speed and Limitation

Existing rail testing trains typically achieve inspection speeds between 40 and 100 km/h. However, as the speed increases, the system's sensitivity and resolution deteriorates significantly [4]. Such degradation of performance and desire to achieve higher operational speeds is driving the need to look at alternate inspection approaches, such as through the use of guided waves.

Surface and guided waves in rail steels propagate at about 3,000 m/s. If one considers the current manual methods employing a wheel probe and a guided wave method theoretically, inspection speed is determined by the pulse repetition rate and the distance along the rail covered by one inspection or that covered by the propagation of wave in a particular time. For a 100 Hz pulse repetition rate and 1 m inspection zone length, the speed of movement for the inspection head could potentially reach 100 m/s, which is 360 km/h. Because the velocity of surface waves ($c \sim 3000 \text{ m/s}$, 10,800 km/h) is much greater than the speed of the trains (less than 400 km/h), the effect of a train's motion during is no longer the limiting factor in an inspection.

There are several options for implementation guided waves. A wheel-probe based guided wave method has been developed by Cawley at Imperial College London, and the transducers can potentially be deployed with the inspection units already deployed and using current inspection methods [26]. Its speed of inspection for such a system should be able to reach that of the current in-service conventional ultrasonic rail testing system, which operates at up to 70km/h.

With an EMAT system, the speed of the guided waves is clearly also much greater than that of the train. It then becomes a matter of considering the velocity of propagation of the EMAT along the rail and the separation of the EMAT's, which constrain the transmission inspection range/volume, and the pulse repetition frequency of the inspection system. With a two-EMAT system set axially linearly along the part and an inspection zone between the two, the pitch-catch measurement enables rapid detection of the deepest, potentially most serious transverse cracks. Advances in data acquisition and analysis allow extremely fast processing and defect characterization of the data in the transmitted signals, again potentially enabling increases in the vehicle speed during testing. The potential vehicle speed improvement is achieved through moving the analysis from software to field-programmable gated array (FPGA)-based hardware systems. Current systems detect signals and perform an Fast Fourier Transform (FFT) and changes in the detected signal amplitude and frequency content are used to characterize defects. The speed limitations are determined by the repetition rate of the pulse (PR) and the distance between the transmitting EMATs and the receiving EMATs (d). The vehicle speed can then be estimated using the relationship: $v = PR \times d$. For example, with a pulse repetition rate of 50 Hz and a train travelling at 200 km/h, the minimum separation of the EMATs must be approximately 1.1 m [15].

For air-coupled ultrasonics, a potential resonant measurement vehicle inspection speed along the rail is limited by the generation pulse repetition rate and the number of averages needed for improvement of SNR. [11] The well known relationship between the duty cycle (DC), the length of the generation tone-burst (T) and the pulse repetition rate (PR) can be written as $DC(\%) = T(us) \times PR(Hz) \times 10^{-4}$. From this relationship, if the number of cycles (C) in the tone-burst which is introduced, an expression for the maximum measurement rate (MR) corresponding to a given number of signals averaged (A) with a 1% duty cycle the limits can be written as:

$$PR(Hz) = \frac{DC(\%)}{T(us)} \times 10^4 = \frac{DC(\%)}{C/f(MHz)} \times 10^4$$

$$MR(Hz) = \frac{PR(Hz)}{A} = \frac{DC(\%) \times f(MHz)}{A \times C} \times 10^4$$

where f is the frequency of the tone burst. The equation above represents an ideal case assuming that processing for the signal averaging and quantification of the measurement parameters is performed in real time. It is important to note that while the inspection speed benefits from a low number of averages and a low number of cycles in the tone burst, the SNR for air-coupled ultrasonic measurements is improved with averaging and longer pulse length.

Assume that the inspection is implemented with a single pair of transmitting and receiving transducers with a diameter aperture D . The maximum measurement rate can be translated into the limits for inspection vehicle speed, and assuming that the inspection gage length for each measurement is D (the diameter of the air-coupled transducer active area), and its footprint on the rail and (v) is the velocity for the inspection system traveling above the rail:

$$v_{inspection} = MR(Hz) \times D(mm)$$

For the example of a system where the parameter $A = 3$, $C = 40$, $f = 0.866$ MHz, $DC = 1\%$, $D = 10$ mm, air-coupled testing can be achieved at maximum measurement rate MR of 72 Hz and maximum inspection speed, v , of 2.6 km/h. With no averaging, speeds can reach 7.8 km/h for rail head resonant inspection, 11.3 km/h for the rail web and head flange resonant inspection, and 9.6 km/h for the head flange pitch-catch inspection [11].

For air-coupled ultrasonics using transducers set above a rail with a lift-off distance for the transmitter and the receiver on the order of 15 mm, and the maximum thickness of rail was 67 mm, the time for sound traveling from the transmitter to the receiver was

$$t = \frac{15mm}{0.34mm/us} \times 2 + \frac{67mm}{6mm/us} = 99.4us \ll 1/72Hz \times 10^6$$

When based on a 1 % duty cycle the limit for the pulser gated amplifier indicate that the maximum inspection speeds achievable by air-coupled experimental configurations are within the speed range of conventional rail testing cars, assuming a lock-in amplification is used. The speed limit results from the number of signal averages and length of the generation tone-burst required to yield a consistent measurement parameter. It can be expected that narrowband, rather than broadband, air-coupled transducers (such as piezoelectric-composite devices) tuned at a resonant frequency would further increase the achievable inspection speed by improving the sensitivity of the measurements. Transducer arrays, rather than a single transmitter-receiver pair, could be used to facilitate increased inspection speeds. In such measurements there are geometric constraints. There is limited tolerance of the measurements to transducer misalignments, so stability of the measurement system must be taken into account for field implementation of the technique.

In principal, air-coupled ultrasonics could be used to generate guided waves in a configuration similar to that used with a wheel transducer. However, air-steel coupling is found to give relatively poor signal to noise. To overcome this limitation and yet still provide non-contact inspection, a laser-air-coupled hybrid rail inspection method using guided and/or surface waves has been considered [12, 21-22]. Such a system is potentially able to achieve inspection speeds higher than conventional ultrasonic methods requiring contact with the rail. The actual speed limitations for this non-contact approach are set by the repetition rate of the laser employed and the distance between the air-coupled sensors [12]. With a 20 Hz repetition rate for the laser and 400 mm for the distance between the air-coupled sensors, in a geometry as shown in Figure 2, the inspection speed can be calculated to be:

$$v = PR_{laser} \times d = 20Hz \times 400mm = 8m/s = 28.8km/h$$

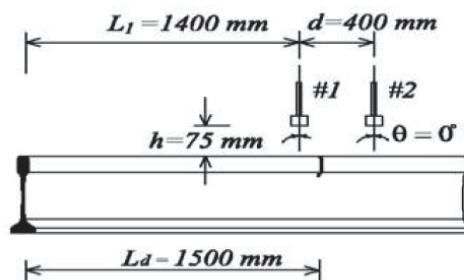


FIGURE 2. Inspection configuration for a laser-air-coupled rail inspection system [21].

In this laser-air-coupled hybrid rail inspection system [21], in order to effectively remove the noise and

make signal identification possible, the signal was reconstructed by the digital wavelet transformation (DWT) processing with a threshold set at 40% of maximum coefficient amplitude. When the system performance was reviewed it was seen that the speed of inspection was limited by the time required for signal processing.

The laser-air-coupled hybrid rail inspection system is reported to have performed well at up to the 14.5 km/h permitted on the Herzog test track, although with a decreased position resolution at higher speeds. Tests at speeds up to 24 km/h have been reported to have been performed in the field, although higher speeds are possible. Although there would appear to be potential for modifications to the system hardware that could be made to achieve robust performance at higher speeds, the maximum speed potentially achievable reported with the current design [21] is on the order of 64 km/h.

Positioning and Angle

Each implementation requires a fixture and transducers set at specific angles. In wheel probe guided wave method, the probe was angled at 30° to the rail in a casing filled with water and contacting samples with a 60 mm wide and 25 mm long contact patch that matched the impedance of water [26].

In the EMAT system, the transmitter and the receiver are held a fixed separation and kept at a fixed lift-off by the use of a trolley. A separation of 150 mm and a lift-off of 1.5 mm have been chosen for the experiments reported in the literature [9]. For online testing applications, the separation of the EMATs may potentially be increased to enable faster scanning speeds, however the signal amplitude will be reduced.

In the air-coupled resonant ultrasonic method, the transducers are placed on an axis perpendicular to the side surfaces of the rail and the lift-off distance for the transmitter and the receiver were of the order of 15 mm throughout the measurements. When compared to optimal alignment conditions for 15 mm lift-off distances, misalignment angles, for either the transmitter or the receiver, of up to three degrees resulted in a 70% reduction in the signal strength detected [11].

In the laser-air-coupled hybrid rail inspection system, the air-coupled transducers were oriented at 0°, 6.3°, and -6.3° per the Snell’s law of refraction with a 50.8 mm to 76.2 mm lift-off distance from the top of the rail head, satisfying the recommended clearance envelope for rail inspection systems claiming “non-contact” performance. However the signal-noise ratio for high-frequency waves was significantly reduced due to losses during propagation in air [12, 21].

Inspection Regions

For the wheel probe surface wave method, the depth of inspection is at least 1.5 wavelengths (18 mm at 250 kHz) with the pulse-echo mode [13], the laser-air-coupled hybrid method inspects 2-10 mm [21-22] and the EMAT method inspection depth is 2-15 mm with pitch-catch mode [9].

In the air-coupled ultrasonic resonant method, inspection regions are the rail head, head flange, and rail web with ultrasonic bulk waves, which are similar to those regions inspected with conventional ultrasonic NDT. With the EMAT, the wheel probe surface wave and laser-air-coupled hybrid method, the goal for the studies was to provide more reliable defect detection in the rail head, including detection of internal transverse head defects under shelling and vertical split heads. It has been found that in the work reported to date that due to the different intensity and bandwidth of the excited signals used in the three methods, the reported inspection regions are not identical, which limits direct comparisons.

Demonstrated Probability of Detection (POD)

There is limited data available on the performance of the various NDE modalities for inspections on rail. An example of the reported POD for current manual NDT is shown in Fig 3. [3, 27].

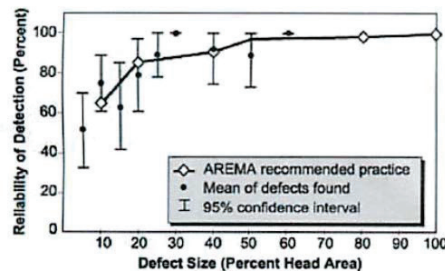


FIGURE 3. POD for manual inspection [AREMA (27)].

When the probability of detection (POD) for the various modalities for higher speed guided wave inspection are considered, very limited data are available. For the laser-air-coupled hybrid rail inspection system, in dry conditions POD is reported to reach 61.5% for defects in the form of surface cut's, larger than 2% of the head area, and 92.3% for internal defect; in wet conditions, POD was reported to reach 90% for surface cut defects more than 2% head area and 92.3% for internal defect [21-22]. The data as obtained was reported for field tested at speeds of up to 15 km/h. The test track included three different sizes of internal head defects (3.5%, 35%, and 12% head area), two sizes of transverse surface head cuts (2% and 5% head area), and one oblique surface head cut (3.5% head area). The results of the tests were reported to indicate a high POD for all defects present, ranging from a 75% to 100% success (POD) rate over 24 runs conducted with varying environmental conditions, including with wind and rain [21-22]. These POD data are summarized in Table 2.

For the EMAT and wheel probe guided wave methods, no detailed data for PODs was found to have been reported, but images of some defects were found to have been presented in several papers [9, 13, 15, 17, 19]. Based on review of the data in the images for the defects, it is probable that a POD of about 70% was be achievable for significant indications.

TABLE 2. POD of Pulsed Laser Method [21-22].

Artificial Defect	Dry Conditions	Wet Conditions	Most Sensitive Parameter
Surface cut 1 (~5% H.A.)	61.5% (over 13 tests)	90% (over 10 tests)	High freq. sensor pair 1
Surface cut 2 (~2% H.A.)	61.5% (over 13 tests)	90% (over 10 tests)	High freq. sensor pair 1
Internal defect 1 (80% H.A.)	92.3% (over 13 tests)	100% (over 10 tests)	Low freq. sensor pair 1
Internal defect 2 (10% H.A.)	76.9% (over 13 tests)	100% (over 10 tests)	High freq. sensor pair 2
Oblique surf cut 1 (~3.5% H.A.)	33.3% (over 3 tests)	50% (over 4 tests)	High freq. sensor pair 1
Internal defect 3 (40% H.A.)	7.7% (over 13 tests)	10% (over 10 tests)	Low freq. sensor pair 2
Oblique surf cut 2 (~3.5% H.A.)	100% (over 3 tests)	50% (over 4 tests)	High freq. sensor pair 1

Advantages and Disadvantages of Various Inspection Modalities

The wheel probe guided wave method is the closest to current capabilities and can be easily incorporated into reconfigured conventional ultrasonic testing systems. Issues relating to mechanical robustness and ensuring coupling remain the same as for existing equipment. In terms of deployment, it has the advantage of relatively low cost/investment for a modified system, but it still has the drawback of low inspection speed.

The EMAT based method has the advantage of being relatively insensitive to misalignment and surface profile when compared with contact transducers. EMAT's can work at standoffs of a few millimeters and it requires no physical couplant, but the standoff distance reduces signal strength. If the standoff is too small there is the risk of impacts between sensors and perturbations on the rail surface. Changes in detected amplitude due to changes in standoff can be compensated for in signal processing applied to the spectrum of received signal. The bandwidth of guided waves generated by EMATs can also be controlled.

The air-coupled resonant method has the advantages of eliminating the requirement for contact conditions. It has ease of positioning and flexibility for the operating parameters. The severe challenges associated with air-coupled resonant and direct coupling in or out of ultrasonic energy for rail testing include the acoustic signal losses (attenuation) in air and, more importantly, the large acoustic impedance mismatch between air and steel, which results in small signal amplitude and very low signal to noise ratio.

The hybrid laser-air-coupled rail inspection system, with an optically generated line source perpendicular to the rail axis, is less impacted by surface profile. Another advantage is that controllable laser pulse intensity can produce high intensity ultrasound with controlled frequency content that is capable of penetrating the rail surface. One significant disadvantage is the low laser pulse repetition rate which has the effect of limiting the inspection speed. There are also issues relating to the source bandwidth, and receiver sensitivity that both contribute to the low signal to noise ratio.

CONCLUSIONS

NDT as applied to rails is critical for safety. As the use of high speed trains increases, there is an urgent need to provide both higher speed and more sensitive inspection capabilities. Detection of transverse defects in rail remains a challenge.

Ultrasonic guided wave methods have been identified as a potentially promising approach to meet high speed inspection needs. Such waves propagate along rather than across the rail, and are thus suited for detecting critical transverse defects. In addition, these waves are less sensitive to surface shelling because they can run underneath these discontinuities. Finally, guided waves propagate at the speed of sound in steel (~3,000m/s) and thus offer the potential of extremely high inspection speeds. In reviewing implementations of guided wave inspection, (i) EMAT, and (ii) laser ultrasound, and (iii) laser/air-coupled these modalities seem to have the potential to provide the required rail in-service inspection needed in the future.

ACKNOWLEDGEMENTS

Jianzheng Cheng is supported by a fellowship funded by the China Scholarship Council (Research on Method of Defect Detection in Rail with Ultrasonic Guided Wave, Grant No [2011] 5025) and National Natural Science Foundation of China (Research on Method of Defect Detection in Rail with Ultrasonic Guided Wave, Grant No 11174230) and performed while he was a visiting scientist at the Center for NDE, Iowa State University.

REFERENCES

1. D. F. Cannon, K-O. Edel, Grassie, S. L. and K. Sawley, "Rail Defects: An Overview," *Fatigue Fract. Engng. Mater. Struct.*, **26**, pp. 865-887 (2003).
2. FRA (2011) Track Inspector Rail Defect Reference Manual, Federal Railroad Administration, Office of Railroad Safety, (August 2011).
3. NSW (2012) Rail Defects Handbook, TMC 226, Version 1.2, NSW Transport RailCorp.
4. INNTRACK, "Rail Inspection Technologies," D4.4.1, University of Birmingham, Project #TIPS-CT-2006-031415, (2008).
5. M. Ph Papaalias, C. Roberts, and C. L. Davis, "A Review on Non-Destructive Evaluation of Rails: State-of-the-Art and Future Development", *Proc. Inst. Mech. Eng., Part F: Journal of Rail and Rapid Transit*, **222**, pp. 367-384 (2008).
6. G. Zumpano and M. Meo, "A New Damage Detection Technique Based On Wave Propagation For Rails," *Int. J. Solids and Structures*, **43**, pp. 1023-104, (2006).
7. R. Clark, "Rail Flaw Detection: Overview and Needs for Future Developments," *NDT&E International*, **37**, pp. 111-118 (2004).
8. D. Utrata and R. Clark, Groundwork For Rail Flaw Detection Using Ultrasonic Phased Array Inspection, in *Review of Progress in Quantitative Nondestructive Evaluation*, **22**, **657**, edited by D. O. Thompson and D. E. Chimenti, American Institute of Physics, Melville, NY, 2003, pp. 799-805.
9. R. S. Edwards, Y. Fan, M. Papaalias, S. Dixon, C. L. Davis, and C. Roberts, "Ultrasonic Detection Of Surface-Breaking Railhead Defects," in *Review of Progress in Quantitative Nondestructive Evaluation*, **27**, **975**, edited by D. O. Thompson and D. E. Chimenti, American Institute of Physics, Melville, NY, 2008, pp. 602-609.
10. Jung-Huai Chou and R. Clark, "Application Of Neural Networks To The Inspection Railroad Rail", in *Review of Progress in Quantitative Nondestructive Evaluation*, **18**, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York, 1999, pp. 2121-2128.
11. John McNamara and Francesco Lanza di Scalea, "Advances in Health Monitoring of Railroad Tracks, Smart Nondestructive Evaluation For Health Monitoring Of Structural And Biological Systems", *Proceedings of SPIE* **4702**, 2002, pp. 250-261.
12. F. Lanza di Scalea, P. Rizzo, S. Coccia, I. Bartoli, and M. Fateh, "Laser-Air-Coupled Hybrid Noncontact System for Defect Detection in Rail Tracks," *J. Transportation Research Board*, **1943**, 2006, pp. 57-64.
13. D. Hesse and P. Cawley, "Excitation Of Surface Wave Modes In Rails And Their Application For Defect Detection", in *Review of Progress in Quantitative Nondestructive Evaluation*, **25**, **820**, edited by D. O. Thompson and D. E. Chimenti, American Institute of Physics, Melville, NY, 2006, pp. 1593-1600.
14. D. Ensminger and L. J. Bond, "Ultrasonics, Chapter 8", CRC Press, Boca Raton, 2011.
15. R. S. Edwards, S. Dixon, and X. Jian., "Characterization Of Defects in The Railhead Using Ultrasonic

- Surface Waves,” *NDT&E International* **39**, 2006, pp. 468-475.
16. C. B. Scruby and L. E. Drain, “Laser Ultrasonics Techniques and Applications, Taylor and Francis, New York, 1990.
 17. D. Hesse and P. Cawley, “A Single Probe Spatial Averaging Technique for Guided Waves and Its Application to Surface Wave Rail Inspection,” *IEEE Trans. on UFFC*, **54**, 2007, pp. 2344-2356.
 18. S. B. Palmer, S. Dixon, R. S. Edwards, and Xiaoming Jian, “Transverse And Longitudinal Crack Detection In The Head Of Rail Tracks Using Rayleigh Wave-Like Wideband Guided Ultrasonic Waves,” in *Nondestructive Evaluation And Health Monitoring Of Aerospace Materials, Composites, And Civil Infrastructure IV*, Proc. of SPIE, **5767**, 2005, pp. 70-80.
 19. Y. Fan, S. Dixon, R. S. Edwards, and X. Jian, “Ultrasonic Surface Wave Propagation And Interaction With Surface Defects On Rail Track Head,” *NDT&E International* **40**, 2007, pp. 471-477.
 20. S. Dixon, R. S. Edwards, and X. Jian, “Detection And Depth Gauging Of Transverse Cracks In The Rail Head,” *Ironmaking and Steelmaking*, **32**, (5), 2005, pp. 376-378.
 21. S. Coccia, I. Bartoli, R. Phillips, P. Rizzo, S. Salamone, and F. Lanza di Scalea, “On-line High-speed Rail Defect Detection – Part II,” Technical Report No. SRP-10/03, Federal Railroad Administration, University of California, San Diego, 2010.
 22. F. Lanza di Scalea, I. Bartoli, P. Rizzo, and J. McNamara, “On-line High-speed Rail Defect Detection,” Technical Report DOT/FRA/ORD-04/16, Department of Transportation/Federal Railroad Administration, 2004.
 23. J.D.N. Cheeke, “Fundamentals and applications of ultrasonic waves, 2nd Edition,” CRC Press, Table 20.1, (2012)
 24. W. A. Grandia, and C. M. Fortunko, “NDE Applications of Air-Coupled Ultrasonic Transducers,” in *Proceedings, 1995 IEEE Ultrasonics Symposium*, (IEEE, New York), pp. 697-709.
 25. E. S. Boltz, C. M. Fortunko, M. A. Hamstad, and M. C. Renken, “Absolute Sensitivity of Air, Light and Direct-Coupled Wideband Acoustic Emission Transducers,” in *Review of Progress in Quantitative Nondestructive Evaluation*, **14**, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York, 1995, pp. 967-974.
 26. D. Hesse and P. Cawley, “Detection of Critical Defects in Rails Using Ultrasonic Surface Waves,” in *Review of Progress in Quantitative Nondestructive Evaluation*, **26**, **894**, edited by D. O. Thompson and D. E. Chimenti, American Institute of Physics, Melville, NY, 2007, pp. 1413-1420.
 27. AREMA (2001) American Railway Engineering and Maintenance-of-Way Association Manual for Railway Engineering, Vol. 1 (Track), Section 4.6.