Automated Ultrasound-based Inspection of Rails: Review

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Abstract

The main aim of the report is to review recent progress in the utilisation of ultrasound-based automated inspection systems for rails of railway tracks and to provide a basis for further research in the field of railway track inspection. This paper reviews the ultrasound technologies currently employed in the automated inspection of railway tracks, along with examples of recent field applications. The main research areas that this review focuses on are firstly, the utilisation of ultrasound inspection for rail tracks; secondly, the different automated ultrasound techniques, and, finally, the special features of the ultrasound inspection of railway tracks. In addition, there is a review of the most recent ultrasound-based systems, and future techniques that have not yet been automated or used in routine inspection.

Keywords: Automated inspection, Ultrasound, Track inspection, Nondestructive testing

1. Introduction

Non-destructive testing (NDT) or non-destructive evaluation (NDE) is characterised as the examination of an object without affecting the future usefulness of the inspected component [1]. The inspection of railway tracks is important in order to find defects before they reach critical size and cause failure in the railway track structure [2]. The trend is to combine the NDT of the railway track with preventative maintenance procedures (like rail head grinding) to optimise the compromise between maintenance cost and reliability [2].

Many different NDT methods are utilised for railway track condition monitoring. Contact ultrasonic testing belongs to the first methods utilised for railway tracks along with magnetic induction method [3]. Nowadays and probably even more so in the future, railway track NDT is being combined with measurement systems consisting of many different methods, completing the information gained about the defects and increasing the probability of defect detection [4]. At present, rail inspection vehicles may incorporate many inspection methods, i.e. ultrasonic testing facilities [3], the induction method [3], (pulsed) eddy current testing [2,5,6] and/or image processing technology for visual testing of sectional wear measurement, and rail corrugation measurement using lasers [2]. The target of one example project was to develop a measurement system combining ultrasound, alternating current field measurement (ACFM) and artificial vision [7]. Inspection systems can be integrated with grinding test trains [5]. In addition, the trend in rail flaw detection is towards improving the efficiency of measurements whilst minimising track time for maintenance, as Clark [3] suggests. Automatic inspection systems that are able to detect rail defects will increase the ability of inspection and reduce the measurement time, allowing more accurate and frequent maintenance work [8].

Various mechanisms are responsible for the different defect types that appear in rails of railway tracks. Commonly, ultrasound inspection is used for finding internal defects that are formed during the cyclic loading of rails [4]. Ultrasound inspection is capable of searching for the inner defects that lie under the surface. The inspection uses a beam of ultrasonic energy that penetrates the inspected component via a probe and a couplant in between. Ultrasound energy is reflected back or scattered from boundaries with different acoustic emissions. The received signals are col-
lected with receiver transducers and studied in order to find possible defects [9]. The cyclic loading of rails causes wear and wear-related changes and therefore the rails are inspected periodically to ensure that no possible flaws and defects compromise the traffic. Certain regulations for track maintenance exist and, for example, in the United States, inspection for rail flaws is carried out at intervals based on the track class and annual tonnage [10]. Ultrasound inspection for rails of railway tracks can be carried out manually with hand-held devices or with fixtures moved by an operator that slide on top of the rail, or with automated ultrasound test fixtures towed by hi-rail inspection vehicles or inspection trains. Some railway track inspection techniques can be installed on commercial trains, but at the current state of inspection method development, ultrasound inspection is still unsuitable for commercial trains [11].

The German Institute for Standardization (DIN) has recently published a draft standard “DIN EN 16729-1 Railway Applications - Infrastructure - NDT On Rails In Track - Part 1: Requirements For Ultrasonic Inspection And Evaluation Principles” of ultrasonic inspection for railways [12]. The draft specifies reference reflectors on the test track for ultrasound inspection to produce comparable results with regard to location, type and size of reference reflectors.

This paper reviews the technologies currently employed along with examples of recent field applications. The main aim of this report is to review the recent progress in the utilisation of automated techniques and to provide a basis for further research. The concept of the ultrasound inspection method for railway tracks will be presented in Section 2, the ultrasound equipment and units for automated inspection in Section 3, rail defects and the probability of their detection and special features of the ultrasound inspection of railway tracks in Section 4, future inspection systems for railway track inspection in Section 5 and other ultrasound-based inspection systems for railway track inspection in Section 6. Conclusions are presented in Section 7. This review was carried out in liaison with the Life Cycle Cost Efficient Track research programme (TERA) implemented in co-operation with the Finnish Transport Agency and Tampere University of Technology (Finland). The research programme comprises ten sub-areas, one of which is research on track rail life cycle. At the moment, research activity on rails is concentrated on the verification of rolling contact fatigue and surface defects in Finnish rails, as well as suitable analysis methods for rail inspection.

2. Basic Principle of Ultrasound Measurements for Railway Tracks

Ultrasound inspection is based on sound waves, or vibrations, created by a piezoelectric crystal in the probe, that propagate in solids, liquids and gases, at a frequency above the range of human hearing, normally above 20 kHz. Sound waves can propagate in different forms, of which the most generally used in inspections are longitudinal (compression) or transverse (shear) waves. The difference between these waves is the particle motion in relation to the sound wave direction [9]. In addition, surface waves and Lamb waves can be used in some special cases in the inspection of thin structures. Sound waves travel with different velocity depending on the material. The factors affecting this are density and the elasticity of the material. In addition, different waveforms have different speeds in the material; a transverse wave travels at almost half of the speed compared to a longitudinal wave [9]. Different materials have different acoustic impedance values, meaning that the ultrasound energy is refracted from the boundary between different media [9]. The discontinuities act as a reflector to the ultrasonic waves, resulting in a portion of the wave being reflected back to the receiver. These echoes are studied in order to find defects. In cases when there are no other reflectors, the reflection comes back to the receiver from the back wall of the inspected component. If the back wall echo is missing, it might be caused by defects masking it and in this case also there might be a potential defect in the structure [13].

The most common method for ultrasound inspection is called the pulse-echo method. The same transducer sends and receives the pulses which are studied; for example the amplitude and the time that the ultrasound beams travels inside the inspected component. There exist different probe configurations for the measurements. A normal beam probe transmits ultrasound wave that is directed straight to the face of the transducer. Probes can be aligned with wedges in different angles as a function of the inspected component surface. These probes are called angle probes [1,9,14].

Generally, NDT techniques are used to locate flaws, to size them and to characterise material conditions. A basic flaw detection procedure is applied: firstly, the defects need to be detected, secondly, the dimensions can be determined and, finally, the evaluation of the defects based on the acceptance criteria must be performed. Usually, the ultrasound systems use a threshold level in a gate to record the ultrasound response in cases where the reflection is above this level [12].

The preferred system for data presentation of ultrasound
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inspection results, i.e. flaw indications, from rails has been the B-scan [3,15,16]. The B-scan based test system provides an image of a defect in the perpendicular direction of the rail. It gives the cross-sectional display of the time-of-flight data from the surface of the rail to the bottom of the rail [9]. Heckel et al. [5] reported the use of a Glassy-Rail-diagram for interpreting results given by multiple ultrasound probes which gives a side view of the rail. The colours of the Glassy-Rail-diagram represent the amplitude of the reflected signals and the diagram gives a fixed resolution independent of the inspection speed [5].

An automated railway track inspection with ultrasound is carried out simultaneously with multiple ultrasound probes to gain maximum inspection volume and to maximise the probability of detecting defects [2]. The ultrasound probes are generally located in rotating wheels or in sliding shoes/runners also called a sliding plate sled [3,13]. A schematic presentation of these is shown in Fig. 1.

2.1 Roller search units (RSU)

Rotating wheels are also called roller search units (RSU) and are a fluid-filled wheel housing the ultrasound probes for rail inspection [3,6,17]. The RSU wheel membrane can be composed for instance of flexible polyurethane [18] or a pliable urethane membrane [18]. The elastic shell of the wheel adapts to the surface of the rail and enables a constant contact during the inspection. The filling material of the wheel is a solution that permits efficient sound energy transfer into the rail track steel [18]. The wheels of the RSU (with a diameter of e.g. 170 mm [19]) are installed in a carriage with rail position sensors [19].

2.2 Sliding plate sled

The sliding shoes, sliding plate sled or slide probes have ultrasound probes mounted in a fixture that ensures direct contact of the probe to the rail surface [4,5,16,20,21]. The probes can be either in direct contact to the surface [5] or there may be a belt between the probe and the surface [21]. The belt system protects the probe unit from mechanical shocks and against damage caused by bad track conditions [21]. In the studies made by Heckel et al. [5], the sliding plate sled contained ten ultrasonic probes per rail, which were inserted into their positions by springs with calibrated tension.

Differentially oriented ultrasound beams created with angle probes can be used for searching different regions of the inspected rail. Usually, a combination of probes emitting waves from different angles is used, and the measurement is repeated along the length of the rail as the inspection instrument moves along. Normally, the probes are operated in the pulse-echo mode. Also, the transmitter-receiver mode with one sending and one collecting probe can be used for rail head defect inspection [5]. The probes can be aligned in the longitudinal axis of the rail and multiple probes may also be located next to each other to provide better coverage [6,22]. Probes can be aligned to point forward and backward on the rail [5,22]. Generally, there is a normal probe for searching the full railway track depth, rail head and horizontal foot defects, [3,5,6,7,18,22] and several angle beam probes pointing forward and backward for detection of web and foot defects. Probes with angles 35° [3,5,7,18], 37° [6,22], 42° [22], 55° [5] and 70° [3,5,6,7,22,28,29] are reported to be used. An angle beam probe of 70 degrees can be utilised for transverse defect detection [18] or welding crack studies [19].

2.3 Couplants

The basic ultrasound inspection always requires a couplant between the sensor and the inspected component [23] to couple the piezoelectric transducers to the rail and to ensure a sufficiently high energy transfer and signal-to-noise ratio [24]. Normally, water, oil or a gel is applied between the probe and the inspected component. In automated ultrasound inspection for railway tracks, a water-based couplant is injected between the probe and track in all the studied configurations. For example, for the RSU inspection unit, a mixture of water and propylene glycol (40%) is used [18] by sparking it before the RSU moves. This blend offers quite a similar sound velocity to the membrane of the RSU wheel and the possibility to use it at different temperatures [18]. For the sliding plate sled installation, water is sprayed constantly below the sensors. To verify the contact between the ultrasound probes and rail, a coupling check between the rail and sliding plate sled can be done with one normal probe [5].

The main benefits of the RSU-based unit are the robustness of the system and its ability to adapt to the rail

![Fig. 1 Schematic presentation of rotating wheel and sliding plate sled with multiple ultrasound probes.](image_url)
geometry [3]. One limitation that has been recognised is the centrifugal force of water inside the RSU wheel, which distorts the wheel membrane when using too high measurement speeds and may cause premature failure of the wheel [21]. The different installation set-ups of the RSU and sliding plate sled also affect the measurements. Generally, the sliding plate sled ultrasound probes are in closer contact to the rail with flexible mounting [13]. However, the RSU wheel probes can be adapted better to rail profile wear [2] and irregular rail shape [13].

3. Manual Inspection and Automated Inspection: Ultrasonic Equipment and units for Automated Inspection

Ultrasonic testing is conventionally performed from the top of the rail head in a pulse-echo configuration. It includes various ultrasonic probes for different kinds of defects and defect orientations. Manual ultrasound inspections are carried out with portable rail detector units or portable rail inspection units [2], which employ the RSUs or sliding plate sleds in a rail testing trolley [25] that is pushed forward on the railway tracks. Manual measurements can be performed on only one rail or both rails with a special fixture [26]. In addition, there is a tandem technique, which utilises two angle beam probes for transmission and receiver that are moved simultaneously [25]. Manual inspections take much more time than automated ones and usually there is only a limited period of time to carry out the measurements due to rail traffic. Thus, automated inspections have replaced manual measurements.

The ultrasound unit, composed either of RSUs or a sliding plate sled, can be installed in a number of vehicle platforms or trains. The automated inspection of rail is done by integrating an ultrasound module into a hi-rail vehicle [27], a bogey that is attached to a hi-rail vehicle [28] or an inspection train [4,18]. Track inspection trains [6] are also called ultrasonic measuring cars [29], inspection vehicles [30], test carriages [31], instrumented carriages [3] or inspection trains with integrated inspection systems [2,18,32,34].

Generally, defects that are first found by automated inspection are subsequently studied by manual ultrasound inspection [34,35]. Each defect is tagged with GPS coordinates, time stamps, kilometre markers and additional event markers in real time for follow-up inspection [5]. Manual ultrasound testing is carried out to confirm the defect and to determine its size and position. Further analysis of the defect is greatly affected by the operator’s judgment and level of experience [36]. Two existing techniques are the so-called “non-stop” method [15] and “stop and verify/confirm” technique. The “stop and verify/confirm” technique is used, for example in Northern America [3,30,36] where two units carry out the inspection. The first does the automated inspection, while the second one stops to carry out manual verification of any flaws found. The second unit, the chase car, carries the hand-held ultrasonic test equipment to verify and size the suspected defect [31]. The maximum testing speed of the “non-stop” method has been reported to be 48 km/h in order for the ultrasound beam to investigate the entire rail [15].

3.1 Measurement intervals

Railway track endurance is facing new challenges due to the high-speed and high axle load vehicles operating on the track material [37]. The railway tracks are inspected periodically to ensure that any possible flaws and defects do not compromise the traffic. The periodical inspections are important in order to find flaws that have grown from a non-detectable size to critical size [30]. Certain regulations for track maintenance exist and, for example, in the United States inspection for rail flaws is carried out at intervals based on the track class and annual tonnage of accumulated traffic carried by railway tracks [10]. This is because heavy axle load operation accelerates and increases track degradation and thus leads to the need for track maintenance [10]. For example, the Australian Rail Track Corporation’s guidelines for ultrasound inspection state that continuous ultrasonic testing should be carried out at intervals of 15 million gross tons (MGT) of axle loading passing over a rail [31].

3.2 Calibration

Calibration of the ultrasound units is an important step in the whole inspection. Probes can be calibrated with special standardized calibration blocks. For railway track inspection systems, simulated reflectors can be manufactured to represent real rail defects. Ultrasonic reference reflectors on the test track can be used to determine the inspection system’s ability to detect defects from railway tracks [12]. For the test track, multiple simulated reflectors are manufactured in different areas of the rail head, web and foot [12]. The test track is studied and reported at the same inspection speed as the one used when taking measurements. Reference reflectors need to be detected at defined ultrasound probe angles [12]. For defect threshold verification, a calibration railway track with drilled flat bottomed holes of different diameters [12,35] or a test block with drilled holes and welds [5] can be utilised. Also, some calibration tools can be used for verifying the probe fixture position. Heckel et al. [5] reported that the probe adjustment for a sliding plate sled ultrasound fix-
ure is carried out with a special calibration device to achieve a gap of 0.2 mm between the rail head and the probe shoe in order to keep the abrasion minimal and the coupling optimal. Simulation studies made by Cygan et al. [16] showed that the centring of the probe to the rail is important in order to maximise acoustic field attenuation in the railway track.

3.3 Data processing of ultrasound inspection

The automated inspection is carried out with a certain repetition rate of the beam dispatch of the order of a few kHz. Due to the high inspection speed, the large amounts of incoming measurement data present challenges for the evaluation and reviewing of all the collected data at once [5]. Additionally, all data have to be processed in real time for online monitoring. The recognition of the potential defects from the large amount of data gathered is crucial [13]. Evaluation of the measurement data by the operator can be done with automated classification algorithms which allow preselection of the data displayed [5]. Post-processing of the data can use for instance algorithms based on neural networks [5,30] and fuzzy logic [5]. Also, wavelet decomposition has been utilised to separate the defect echo from noise [16]. The different flaws are identified from the ultrasonic reflection patterns for each different flaw. Ultrasonic reflections can be divided into reflections coming from the head, web, base and potential defects [13]. The identified rail defects are evaluated based on a series of defect categories. In the Australian Rail Track Corporation’s guidelines, the response codes define the appropriate response that needs to be applied to the railway track [30]. It has been reported that some algorithms have been used to remove the false crack signals coming from grease spots, rail gaps and rust [21]. In addition, some recognition patterns have been utilised to identify rail ends and bolt holes, for example [13]. The development of faster computer processors will allow faster signal processing and the utilisation of faster software for adaptive recognition of defects [21].

4. Rail Defects and Probability of Detection, Special Features of Ultrasound Inspection of Railway Tracks

4.1 Rail defects

There are different defect types in rails, originating from various mechanisms. The most common flaws are found in the rail head due to the cyclic loading of rails caused by changes related to wear and wear [38]. Multiple transducers need to be employed to cover the rail head area [2]. Reiff and Garcia sum up three general causes for the failure to detect defects during inspection as follows: 1) flaw size being too small, 2) flaws located in areas that were not included in the inspection, or 3) surface conditions masking the signal and compromising the detection of the flaw [30]. The physical limitations of the ultrasound method itself pose some restrictions, such as flaws in the first few millimetres of the rail head or surface-breaking flaws being poorly detected due to the dead zone of normal probes [4,13]. In addition, certain types of rail head flaws are difficult to detect because of their shape or because their orientation is not optimal in relation to the ultrasound beam [3]. The defect must be oriented at 90 degrees to one of the search beams utilised in order to be found in the inspection [13]. Many difficulties have been observed, as in the detection of transverse fissures with a volume that is only 5% of the rail head volume [39]. Ultrasound beam simulation has been used to model the beam [16] for defect searching with real 3D models of the defects [7,39]. The simulation verified the difficulty to detect transverse fissures; they are observable with a 70 degree angle beam only if their orientation is between 5 - 37 degrees to the centreline of the railway track [39]. The detection threshold for small flaws can be difficult to achieve, for instance, in old, less clean steel rails with inclusions masking the ultrasound beams [13].

The overall sensitivity of the inspection system depends on the quality of the rail surface quality [5]. For example, uneven rail surfaces due to shelling, pitting or worn rail profiles can reduce the quality of the interface between the ultrasonic probe wheels and the rail surface [30]. Horizontal surface cracks such as shelling and heavy head checking [40], corrosion [40] and surface initiated rolling contact fatigue (RCF) damage [30,34,41,42] can prevent the ultrasonic beams from reaching the internal defects and resulting in false negative indications, missing the flaws located beneath them. Furthermore, there are some common rail conditions that can mask flaws or impede defect detection. For example, excessive rail lubrication [10,43], leaf mould [4], grease and dirt [31] and weather conditions like ice [43] may cause problems in probe contact.

The probability of detection (POD) for different sizes of defects has been studied with ultrasonic reference reflectors manufactured for a test railway track [30]. The probability of detecting a defect increases as the defect size percentage of the head area increases. If the defect is 5% of the head area, the mean value of probability of detection is 50% [30]. Another problem with the automated system was the false negative defects that could not be verified as flaws with manual inspection [44]. One study concluded that non-stop inspection achieved a result of 85...
% verified defects of all suspected defects reported [15].

The ultrasound inspection measurement parameters affect the theoretical observation of defects. While using higher frequencies, the probability of observing smaller flaws increases but the absorption of the ultrasound energy to the inspected component also increases [9].

4.2 Measurement speed

Generally, the detectability of defects decreases when the measurement speed increases. With higher speeds, the lateral resolution for finding defects decreases [5]. The automated inspection testing speed for inspection vehicles is between 40km/h and 100km/h. However, as the speed increases, the sensitivity and resolution of the system deteriorate significantly [2]. Heckel et al. concluded that a measurement speed of 60 km/h is close to the physical limits for ultrasonic testing, as the maximum pulse repetition rate is limited by the sound velocity in the rail [5]. Aharoni and Glinkman also came to the same conclusion about the maximum measurement speed, putting it at 58 km/h [20]. Aharoni and Glinkman [20] also concluded that the maximal scan speed for the RSU is approximately half of that for the slide probe, due to the wheel medium causing a delay in the ultrasound beam.

Some real time algorithms have been utilized to increase the pulse repetition rate [5]. Other issues affecting the measurement speed are the surface quality of the rail, which limits the speed, and probe wear must also be taken into consideration [5].

5. Future Inspection Methods

Research on using ultrasonic phased arrays in railway track inspection is currently ongoing in different universities [2,7]. The phased array ultrasound method uses an array of transducers operating with different timing to generate an ultrasound wave front. Comparing the phased array to a single-element transducer allows many inspections to be made from one location without changing the angle or moving the probe. The main benefits of using a phased array system are sectoral scanning, showing the discontinuities at appropriate angles, and increased coverage to raise the probability of detection [43].

No practical systems utilising the ultrasonic phased array method have been developed for automated high-speed rail inspection so far, due to the difficulties arising from the large amount of data requiring analysis [43]. The maximum inspection speed currently achievable with the ultrasonic phased array method is approximately 5 km/h [2]. Manual phased arrays are used, for example, in the validation and verification of the defects detected by ultrasonic high speed systems [7] and during the inspection of welds in railway tracks [45]. Aoki et al. [34] have developed a method with two-phased array probes to inspect the transverse cracks in the presence of horizontal cracking from the underside of the rail head. This method uses two-phased array probes beneath both sides of the rail crown, which can be moved automatically [42]. The research on this promising method is still ongoing [34].

The next step in phased array inspection is the ultrasonic tomography inspection technique. The automated 3-D imaging of rail defects has been studied by Phillips et al. [36] to obtain more accurate information on flaw size, shape and orientation. In the ultrasonic tomography technique, a few ultrasound elements transmit with diverging beams, whereas in the phased array technique all the phased array elements transmit with a time delay [36]. Divergent beams will increase the inspection volume compared to the phased array technique [36].

6. Other Ultrasound-based Inspection Systems for Railway Track Inspection

Generally speaking, the automated inspection carried out with RSUs or sliding plate sleds with conventional ultrasound probes are capable of finding only certain types of defects. Transverse defects in the head cannot usually be detected by the normal pulse echo ultrasound method [46]. They also have the limitations which were discussed earlier, i.e. the need for coupling. Thus, other ultrasound-based inspection systems are also presented here briefly, including laser ultrasonic inspection, guided wave inspection and electromagnetic acoustic transducers, or EMATs. These methods are still under development and no commercially available automated inspection systems are available yet. The new techniques have demonstrated successful application in the laboratory but their utilization in practice appears to be problematic [40].

6.1 Laser ultrasonic, pulsed laser ultrasonic, laser-based ultrasonic

The laser ultrasonic method is a non-contact inspection method in which the ultrasound wave is generated by a high energy pulsed laser. The method uses air-coupled transducers for wave monitoring [47-49]. Cerniglia et al. [48] concluded that the system is capable of detecting defects in the head, web and base of the railway track. Field tests have been carried out at up to 40 km/h but, according to Nielsen et al. [50], this is the maximum measurement speed with their inspection system.
**6.2 Guided wave inspection**

Guided wave inspection utilises low-frequency waves in the region of 10-100 kHz, which travel in the longitudinal direction of the railway track and bounce back from a transverse defect. Guided waves propagate along the rail and thus are ideal for detecting transverse defects[51]. Rose et al.[52] presented different combinations of guided wave inspection of railway tracks which could have potential. Guided wave inspection can be carried out, for example, with fixed sensors on rails in places like switches where the probability for defect detection is high and the use of other conventional NDT methods is restricted. This has been demonstrated by Loveday et al.[53]. The system could be installed on a rail inspection vehicle where the ultrasonic transducers are mounted on both ends of the inspection vehicle to induce the guided wave energy on one end and receive from the other end. One possibility is also to use sensors on a train.[52]

**6.3 Electromagnetic acoustic transducers, EMATs**

Non-contact electromagnetic acoustic transducers, or EMATs, generate and detect ultrasound in electrically conducting or magnetic materials. An EMAT does not need a coupling between the railway track and the probe but a lift-off of up to 10 mm is reported by Petcher et al. in the case of railway track inspection[54]. The studies of Petcher et al.[54] utilised a pitch-catch configuration for EMATs, creating guided surface waves. The benefit of EMATs is that they operate without a coupling[43], however, there are still problems if the lift-off is too big[46]. Utilisation of EMATs for railway track inspection has also been introduced in the studies of Rose et al.[55]. As Petcher et al. conclude, the EMAT still requires development before it is suitable for use in a commercial environment[54].

**7. Conclusions**

This study reviewed the recent progress in the inspection of rails of railway tracks using ultrasound-based methods. The paper reviews the technologies currently employed along with examples of recent field applications. The current automated inspection systems include many different methods along with ultrasound inspection. The two most common automated methods are either to install the ultrasound probes inside a fluid-filled wheel, or roller search unit, or attach them to a sliding plate sled. However, there are more restrictions on measurement speed in the case of a fluid filled roller search unit. In addition, several studies have concluded that the top measurement speed will be around 60 km/h, due to the physical limitations of ultrasound travelling in railway track steel. Calibration of the ultrasound units is an important step in the whole inspection. Simulated reflectors can be manufactured to represent real rail defects which can be used to determine the inspection system’s ability to detect defects. Some new studies have been made in the utilisation of phased array ultrasound measurement and computed tomography in the detection of defects. However, these methods need further development before they can become commercial automated systems with widely acceptance in railway track inspection protocols.

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