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Chapter

Contemporary Inspection and Monitoring for High-Speed Rail System

Lu Zhou, Xiao-Zhou Liu and Yi-Qing Ni

Abstract

Non-destructive testing (NDT) techniques have been explored and extensively utilised to help maintaining safety operation and improving ride comfort of the rail system. As an ascension of NDT techniques, the structural health monitoring (SHM) brings a new era of real-time condition assessment of rail system without interrupting train service, which is significantly meaningful to high-speed rail (HSR). This chapter first gives a review of NDT techniques of wheels and rails, followed by the recent applications of SHM on HSR enabled by a combination of advanced sensing technologies using optical fibre, piezoelectric and other smart sensors for on-board and online monitoring of the railway system from vehicles to rail infrastructure. An introduction of research frontier and development direction of SHM on HSR is provided subsequently concerning both sensing accuracy and efficiency, through cutting-edge data-driven analytic studies embracing such as wireless sensing and compressive sensing, which answer for the big data's call brought by the new age of this transport.

Keywords: non-destructive testing, structural health monitoring, defect detection, fibre Bragg grating, high-speed rail, sensing technology

1. Introduction

The past decade has witnessed the most prosperous blooming of HSR, marking a splendid new age of this fast-developing transportation, which subtly alters people's travelling habit with great convenience and ride comfort. Hidden behind the high-quality ride service provided by HSR is the tremendous effort and huge budget spent on the inspection and maintenance work, which is more challenging with increasing speed and capacity.

With long-term numerous cycles of loading and unloading, both rail tracks and train wheels are suffering from vibrations and stresses caused by wheel/rail interactions, leading to fatigue, wear, plastic deformation, cracks and other deteriorations. The wheel/rail interactions are intense with average contact stresses over 1000 MPa under normal operating conditions, and this number can go much higher upon specific situations (wheel flange/rail edge contact while train turning, poor conforming wheel and rail profiles, etc.) [1]. Moreover, to author's knowledge with recent research work on contact mechanics using NDT approaches, machine element contacts including wheel/rail contacts are essentially contacts between the

asperities due to surface roughness of the contact bodies, and the asperity contacts indicate hyper-stress concentration beyond 4000 MPa at the contacting peaks [2]. Under such high stresses, components of the rail system are deteriorating rapidly in various forms and the deteriorated structures create a worse operating environment, adding the occurrences of failures. A typical failure is rolling contact fatigue (RCF) causing a series of subsequent rail defects (squats, transverse cracks, spalling and gauge corner cracks).

The rail also takes up impact load from running trains intermittently due to wheel defects, rail irregularities or at certain areas rail turnouts, rail joints, etc. The intense vibrations caused by wheel/rail interactions and impacts are transmitted bidirectionally from the wheel/rail interface up to the coach and down to the rail slab simultaneously. In terms of HSR, to meet the high standard requirements of smooth operation under high speed, the components utilised are different from those in conventional rail lines. For example, the rail tracks are strengthened with high resistance to wear, and multi-layer concrete forms up the rail slab with CA mortar layer serving as the damping instead of traditional ballast. These measures add ride comfort in HSR operation, but make the system more 'brittle' with reduced capability in vibration absorption, hence add the risks of cracks in the rail system. A recent example is the giant crack (44 cm long) found in an operating Japan Shinkansen bullet train in December 2017, causing interruption of service and great social panic [3]. Similar cases can be highly possible on ballastless rail tracks leading to more catastrophic consequences, calling for more reliable and thorough inspection actions.

NDT techniques have long been used for inspection in rail system since the 1920s. With integrated ultrasonic probes or eddy current sensors, the NDT systems are able to check surface and internal defects along the rail in either contact or non-contact manner. The NDT inspection is conducted through manual inspection device or inspection vehicle. Conventional inspection vehicles are normally attached to a traction locomotive to carry out inspection. In the age of HSR, many countries have developed high-speed comprehensive inspection vehicles (CIVs) for the more complicated inspection tasks, such as the 'East-i' CIV in Japan, the 'IRIS320' CIV in France, and the 'No. 0' CIV in China, etc. Inspection content of the high-speed CIVs covers from geometry data of rail infrastructure to dynamic behaviours of trains. Despite of the wide range of data types, the NDT techniques require interruption of train service to conduct the inspection. To provide early alarming in prevention of further consequences in terms of accidents similar to the Japan Shinkansen case, continuous real-time information of in-service rail system is highly desired, which puts forward the introduction of online monitoring to this area. Since wheel/rail interaction is the core part of the rail system, this chapter mainly focuses on the inspection and monitoring methods of wheel and rail defects.

2. Typical defects of wheels and rails

2.1 Wheel out-of-roundness (OOR)

Various types of wheel OOR/defects occur on HSR in-service, which influence operational safety and give rise to high maintenance cost. These defects take on many patterns, such as flats, eccentricities, polygons, corrugations on block-braked wheel treads, missing pieces of tread material owing contact to fatigue cracking and other random irregularities [1, 4]. Generally, they can be categorised into two major types: local defects and periodic OOR all around the wheel. The former can cause severe repeated wheel-rail impacts, while the latter leads to abnormal vibrations of vehicle-track system at certain frequencies [5].

2.1.1 Wheel local defects

There are two major causes behind initiation and development of wheel tread local defects: thermal cracking and rolling contact fatigue (RCF) [6]. Several factors, such as speed, axle load, wheel-rail adhesion, wheel material and braking conditions, also have some effects on deterioration rates of wheel tread [7]. In HSR operation, wheel wear rate can increase quickly due to the high operation speed, high stiffness track, wide wheel-rail impact frequency, intense vibrations and high speed flow [5, 7, 8]. Wheel defects can cause abnormal vibrations and have the potential to impose damage to both track and vehicle components such as sleepers, rails, wheelsets and bearings, increase the likelihood of derailment and deteriorate operational safety and comfort owing to high vibration amplitudes [1, 9]. Previous research found that the load history of axle bearing and bogie frame may fluctuate due to the influence of wheel roughness and lead to fatigue cracks [10]. Wheel defects also result in an increase in the noise both inside and outside the train [11, 12] which can be annoying for both passengers on the train and residents along the rail line [5]. For high-speed trains, the high-magnitude impact loads generated by a defective wheel can excite various vibration modes for the wheelsets and thereby contribute to abnormal increases in the stress states of wheel axle under high-speed conditions [13].

2.1.2 Wheel polygonisation

The studies of wheel polygonisation were stated some three decades ago when some of polygonal wheels were detected on high-speed trains (ICE, Germany). Wheel polygonisation with one, three and four harmonics around circumference has been found on disc-braked wheels in ICE, in which the third harmonic dominated for solid steel wheels, while the second harmonic was common for rubber sprung wheels [5]. The research on high-order polygonisation (15–25 orders) had not been carried out until recent years, when new problems and challenges in HSR operation were raised. For HSR, there is an increasing demand for relative studies on this problem because it is reported that high-order polygonisation with very small radial deviation (< 0.05 mm, or <20 dB re 1 μm) can cause abnormal vibration and even failures to the bogie components. The influences of polygonal wheels on track structure and vehicle components are studied by [13, 14]. It is revealed that: (1) the wheel-rail impact normal force increases with the deepening of the wheel polygonal wear; (2) the amplitude of the normal force fluctuation depends mainly on the wavelength and depth of the wheel polygonal wear on the wheel running surface; and (3) the stress load cycles induced by wheel polygonisation can considerably increase the propagations of the initial crack in the wheel axle.

2.2 Rail defects

2.2.1 Common defects caused by inappropriate manufacturing and use

As per increasing of demand for HSR, rail defects have become a critical challenge in operation because an incident could cause more losses when trains run at higher speed. Many researchers have proposed classification methods for typical types of rail cracks derived from different propagation orientations of rail defects [15, 16]. The most common rail defects are caused by inappropriate manufacturing and inappropriate use of rails, and they mainly include transverse defects (TD), detail fractures (DF) and split heads. TD (**Figure 1a**) is one of the most critical type

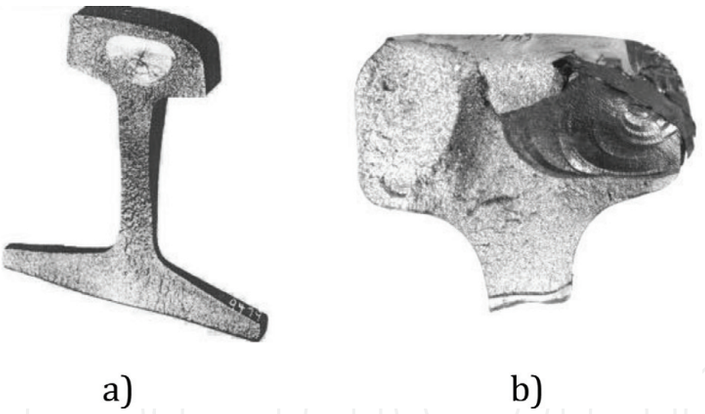


Figure 1.
Transverse defect and detail fracture [15]. (a) Transverse defect. (b) Detail fracture.

of cracks that appear in railheads propagating along lateral direction. DF (**Figure 1b**) has an origination point and grows radially from the origination point. These types of defects are caused by inappropriate use such as excessive stress concentrations. The vertical split heads (VSH) (**Figure 2a**), which usually originate from manufacturing anomalies, cause the second most train derailments (after TD).

2.2.2 Rolling contact failure (RCF)

RCF has become a significant economic and safety challenge for HSR and metro lines. Fatigue fracture occurs as a result of a periodic loading applied to the materials which exceeds its fatigue limit. Normally, it will lie between 35 and 60% of the tensile strength of rail [17]. Once a fatigue crack has initiated, it will spawn with every period of loading. At the beginning, it is very gentle and then quicker until a critical size is achieved [18]. Typical RCF originating at rail surface includes head checks, surface gauge corner head checks and squats. The cracks generate as the rails experience huge impacts from the wheels [19, 20] and the fatigue damage results from the normal and shearing stresses of the wheel-rail interaction [21]. A micro-crack may induce surface spalling effect when it propagates from the railhead to inner parts of the rail. In addition, RCF can cause corrugation and bolt hole cracks on the rails, significantly influencing track structure. Generally, there are six classes of corrugation: short-pitch corrugation, light rail corrugation, corrugation on sleepers, contact fatigue corrugation, rutting and roaring rails and heavy haul corrugation [22].

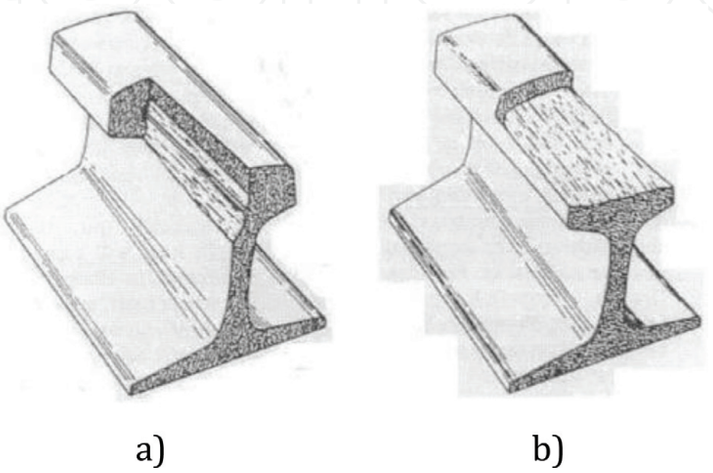


Figure 2.
Split head [16]. (a) Vertical split head. (b) Horizontal split head.

3. Wheel roughness measurement and defect detection

The most effective and common strategy to control the wheel defects is wheel re-profiling [5] which can eliminate local defects and polygonisation and reduce the resulting noise and vibration [4]. In modern HSR wheel maintenance, many modern depots are equipped with a wheel re-profiling facility known as a wheel lathe and the wheelsets are not necessary to be disassembled during re-profiling. However, the wheel re-profiling always follows a time or mileage-base schedule per earlier experience or supplier's specification. Consequently, it can decrease the wheel diameter and thereby shorten the service lives of the healthy wheels which are scheduled to be re-profiled. Therefore, there is a large economic incentive for adopting condition-based maintenance (CBM) scheme based on advanced NDT and SHM techniques, to reduce maintenance costs of wheelsets and efficiently preventing the hazards imposed by wheel defects. There are two main types of CBM approaches: in-service (online) condition monitoring and in-depot (offline) inspection [23]. The former one provides real-time condition information for maintenance planning, while the latter approach, normally done at a fixed interval, can offer accurate measurement for condition assessment of vehicle components.

3.1 Wheel roughness measurement/in-depot (offline) wheel inspection

Wheel tread roughness measurement (in-depot inspection) is a direct way of collecting wheel condition information for maintenance, monitoring profiles in conjunction with wear problems. With wheel roughness measurement data, the wheel re-profiling strategy can be optimised using data-driven wear model [24]. The NDT technologies employed by roughness measurement include linear variable differential transformer (LVDT), the mechanical displacement probe, the rotation sensor, electromagnetic acoustic transducer (EMAT) [25], laser-ultrasonics [26], laser-air hybrid ultrasonic technique (LAHUT) [27] and other novel NDT techniques [28–30]. Some even allow the trains run at a low speed during inspection [30]. However, for measurement methods using ultrasound pulse-echo technique, it is sometimes difficult to detect wheel flats because they usually have smooth edges that do not generate echoes [31]. There are now many commercial devices that allow the measurement to be done in depot with high efficiency, such as ØDS measurement instrument, Miniprof, MÜLLER-BBM, etc.

3.2 Online wheel condition monitoring and defect detection

Existing online wheel condition monitoring systems mainly include trackside wheel impact load detector (WILD), force gauges installed on sleeper pads, distributed sensors based on Brillouin optical time domain analysis (BOTDA), accelerometer-based trackside detector, acoustic detectors, laser- and video camera-based detectors, etc.

3.2.1 Trackside WILD and wheel: rail interaction detector

By deploying strain gauges and accelerometers on the rail, it is possible to measure wheel-rail contact force or rail acceleration response when a train passes over the instrumented rail section. These devices report impact as either a force at the wheel-rail contact interface or a relative measure of the defect [10]. The most common WILD is composed of a series of strain gauge load circuits mounted on the

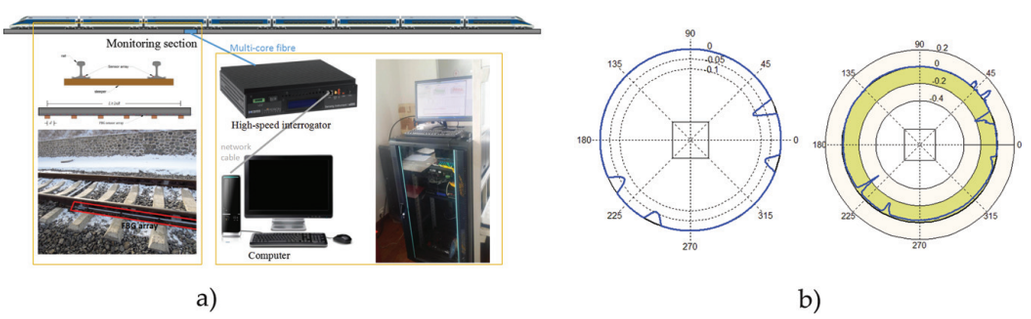
neutral axis of the rail between two adjacent fasteners in several consecutive sleeper bays to quantify the wheel-rail interaction force.

Johansson and Nielsen [1] made use of this set-up to build a detector on the rail web in nine consecutive sleeper bays. Nielsen and Oscarsson [32] used both rail web and rail foot strain gauges to measure the wheel impact load and rail bending moment. Stratman et al. [33] proposes new criteria for removal of wheels with high likelihood of failure, based on two real-time SHM trends that were developed using data collected from in-service trains. Filograno et al. [34] developed an FBG-based sensing system comprising FBG strain gauges mounted at both rail web and rail foot enables train identification, axle counting, speed and acceleration detection, wheel imperfections monitoring and dynamic load calculation. They have expanded the application of this system in the Madrid-Barcelona HSR line [34]. An FBG-based wheel imperfection detection system that can provide in-service measurement of wheel condition was developed by The Hong Kong Polytechnic. It offers a comprehensive health monitoring scheme for vehicle and track in the entire railway network of Hong Kong [35]. A monitoring system has been proposed with FBG sensors implemented on rail tracks to detect wheel local defects such as wheel flats and polygonisation [36]. The impacts of wheel/rail interactions caused by wheel local defects are reflected as subtle anomalies in response to signals collected by FBG sensors, and the deployed system is shown in **Figure 3a**. The detecting results match well with those from offline inspection (**Figure 3b**).

In addition to the strain gauge-based detector, there are other methods for online wheel load measurement to assess the condition of passing wheels, such as force gauges installed on sleeper pads, distributed sensors based on Brillouin optical time domain analysis (BOTDA), etc. Besides, there are also some commercial WILDs, such as WheelChex® system, GOTCHA system (optic fibre-based wheel-flat detection and axle load measurement system), and MULTIRAIL WheelScan.

3.2.2 Trackside rail acceleration and noise detector

Accelerometer-based systems can provide 100% coverage of the circumference of a wheel of any size in defect detection [10]. Skarlatos et al. [37] used two B&K accelerometers placed on the rail foot to pick up the rail vibration signals for diagnosis of wheel defects. Belotti et al. [38] used four consecutive accelerometers and an inductive axle-counter block which help to discriminate the response corresponding to each wheel. Seco et al. [39] proposed a trackside detector which has eight accelerometers installed on both bend zone and straight zone. However, the acceleration data are difficult to convert to wheel-rail impact load, which is widely used as wheel local defect indicator [5]. This is mainly because the measured acceleration signal could not directly refer to the excitation of each wheels, and



a) b)

Figure 3.
High-speed train wheel defect detection using online FBG-based system [36]. (a) System configuration. (b) Detection results (left—online detection; right—offline inspection).

sometimes an additional axle counter is needed [23]. Furthermore, their performance might be limited by their repeatability and by the analysis applied to the accelerations acquired.

The commonly used noise detector is called trackside acoustic array detectors (TAADs), which make use of arrays of high-fidelity microphones to listen to the audible noises produced by the passing trains [40]. There are also some commercially available systems, such as trackside acoustic detection system (TADSTM) and the RailBAMTM [41, 42]. However, these systems are specialised in wheel bearing fault diagnosis rather than wheel tread defect detection. For the slight flat defect of high-speed train wheel (flat depth < 0.5 mm), this method may not be applicable because when the train runs at high speed (>200 km/h), the prediction accuracy can be limited [11].

3.2.3 Detection methods based on laser and video cameras

There are various types of wheel roughness monitoring systems based on laser and video cameras. Some typical or well-known detectors include wheel profile detectors (WPDs), MBV-systems, wheel profile measurement system (WPMS) and those based on light illumination devices, light-sensing devices, charge-coupled device (CCD) camera, and laser displacement sensors (LDSs).

WPDs are based on a combination of lasers and video cameras to automatically measure the wheel profile while train is in motion [40]. These data acquired from WPDs include wheel profile and wear, wheel diameter, height and thickness of the flange, back-to-back distance and wheel inclination. A prototype of a condition monitoring system called MBV-systems is presented by Lagnebäck [43] for measuring the profile of the wheels with a laser and a camera. An automatic WPMS based on laser and high-speed camera was installed on an iron ore line in Sweden in 2011 and can measure the wheel profile for speeds up to 140 km/h [44]. This system, which is in a CBM manner, has been attracting more and more interest from maintenance engineers in the Swedish railway sector. Zhang et al. [45] presented an online non-contact method for measuring a wheelset's geometric parameters based on the opto-electronic measuring technique. The system contains a charge-coupled device (CCD) camera with a selected optical lens and a frame grabber, which was used to capture the image of the light profile of the wheelset illuminated by a linear laser. Besides, there are some newly designed laser-based online detectors, which are immune to vibration and on-site noise, easy to calibrate, with high efficiency of data acquisition and with high accuracy of positioning [46, 47].

4. Rail defect detection and monitoring techniques

Manual inspection method is still widely used in most routine track inspections until today since it can directly figure out rail defects. However, it needs experienced workers and involves significant human input and judgement [48]. Therefore, NDT&E techniques, which enable rail inspection in an automated manner, are in need. NDT techniques were advocated for rail inspection as early as the 1920s [49]. Ultrasonic testing (UT) emerged in the 1960s became dominant in rail inspection [10, 50]. With the development of UT, European countries and Japan have released a variety of forms of ultrasonic rail flaw detection equipment, such as portable types, hand-push types, road and rail dual-use vehicles and specialised rail-testing trains [28]. While being extensively utilised, both the magnetic induction testing and conventional UT methods are not suitable for all defect scenarios; for

example, they offer poor sensitivity to defects located in the rail web and rail foot [51]. A wide variety of inspection techniques are under research and development with the target to enhance the detection capability.

4.1 Advanced UT techniques

To enhance accuracy, speed and detection rate in rail defect detection, many research efforts have been made to improve the detection methods and develop advanced UT techniques. The novel techniques include laser ultrasonic testing (LUT), phased array ultrasonic testing (PAUT), electromagnetic acoustic testing or electromagnetic acoustic transducer (EMAT), guided wave testing (GWT) and acoustic emission testing (AET).

4.1.1 Laser ultrasonic testing (LUT)

Compared with traditional piezoelectric UT, LUT has its own merits such as non-contact and no coupling agent. The laser device can be located relatively far away from the rail with optic-fibre used as transmission media. This enables the establishment of trackside monitoring system. Besides, with good interference immunisation, laser can be used in measurement in adverse environment or high temperature. Pulsating laser works on solid surface and produces longitudinal wave, lateral wave and surface wave simultaneously. As a result, it can be applied to detect not only surface defects but also internal defects. Yet certain problems exist in LUT, such as low efficiency of light-sound energy transformation, weak ultrasonic signal and high cost of detection equipment.

Nielsen et al. [52] developed an automatic LUT-based system for rail inspection, named LURI, which was tested on a railroad line containing man-made structural defects. This system can detect defects on the running surface of the rail, as well as horizontal and vertical flaws in the railhead. Kenderian et al. [53] developed the first non-contact testing system based on laser-air hybrid ultrasonic technique for rail defect inspection. The system can detect VSH defects and thermal fatigue cracks with a success rate of nearly 100%, and rail web defects with a rate of approximately 90%. Lanza et al. [54] developed a laser/air-coupled rail defect detection system, which can accurately locate rail transverse cracks by using laser emission and ultrasonic wave for detection.

4.1.2 Phased array ultrasonic testing (PAUT)

PAUT, developed from the research on phased array radar, can detect cracks in different directions, depth and locations conveniently. Utrata and Clark [55] present groundwork of PAUT methods, which provided useful information and evidences for the positioning of phased array (PA) probes in rail flaw detection. PAUT is now widely applied in rail defect detection, covering railhead, rail web, rail base and weld areas. Institutes that carry out research on PAUT for rail defect detection include: Transportation Technology Centre Inc. (TCCI), Lowa State University, University of Warwick, University of Birmingham in UK, TWI Company and Socomate in France, etc.

Wooh and Wang [56] developed a hybrid array transducer which is an assembly of a linear phase and a static array and can accurately assess real defects in rail specimens. Speno International Company [57] developed an ultrasonic rail testing equipment based on multi-element phased array technology and the equipment was installed on a trial inspection car which can achieve a speed of 80 km/h and a sampling rate of 6 kHz when detecting rail defects. TTCI [58] developed an

Omni-scan PAUT system which was applied in on-site detection of TDs. Field test of the system was conducted on the Facility for Accelerated Service Testing (FAST) of TTCI.

4.1.3 Electromagnetic acoustic testing (EMAT)

EMAT, as a kind of excitation and detection technique of propagating ultrasonic wave, can provide detection of defects located in subsurface area of railhead. Thus, a promising method appears to be electromagnetic-acoustic method which is realised by EMAT transducers. Both transverse and longitudinal cracks in railhead can be detected by using EMATs, as shown in **Figure 4** [59]. University of Warwick and University of Birmingham [60] developed a railway surface-detect inspection technique based on EMAT equipped with two EMAT converters, one for emitting surface Rayleigh waves and the other for receiving surface propagating Rayleigh waves. It is found that this technique can improve the inspection rate of horizontal and vertical defects on the railheads, compared with piezoelectric transducers. University of Warwick [61] designed a lab-based laser-EMAT system to investigate the ultrasonic surface wave's generation, propagation and interaction on the railhead with a Michelson interferometer measuring the out-of-plane displacement. The Rayleigh-like wave generated by EMAT can flood the whole curve makes it capable to detect the gauge corner cracking.

4.1.4 Guided wave testing (GWT)

GWT techniques have been widely investigated over the past decades because of the potential for long-range interrogation and detecting vertical-transverse defects under shelling and weld defects [62, 63]. They are ideal in SHM applications that can benefit from built-in transduction, moderately large inspection ranges and high sensitivity to small flaws. In rail applications, since ultrasonic guided wave can propagate through the discontinuous defects on rail surface, the screening effect of lateral cracks distributed underneath produced by surface detachment can be minimised.

Rose et al. [63] developed a GWT inspection system with non-contact air-coupled and EMATs to transmit and receive guided waves for the detection of transverse defects under shelling. Wilcox et al. [64] developed a GWT system with a dry-coupled piezoelectric transducer array to detect smooth transverse-vertical defects and alumino-thermic welds, but this system requires interruption of the operation of trains. Lanza et al. [54] developed a GWT system using a pulsed laser

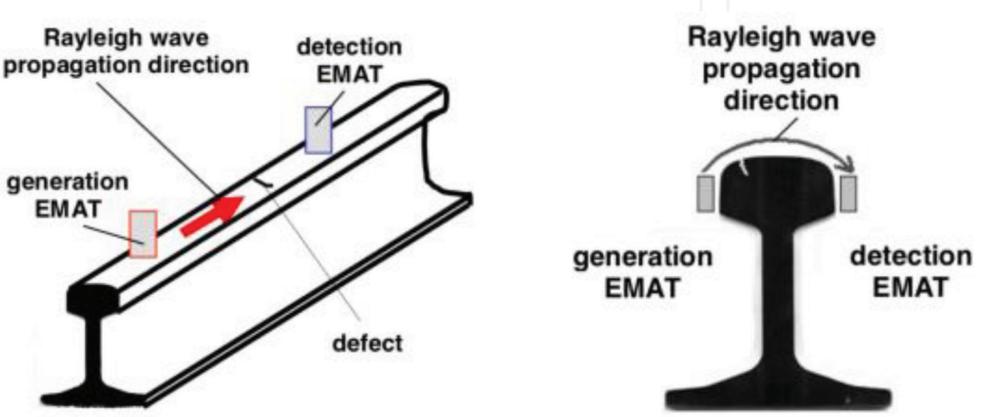


Figure 4.
Rail cracks detection using EMAT [59].

to generate ultrasonic guided waves and air-coupled transducers to sense the guided waves for the detection of vertical cracks hidden below horizontal cracks. Park et al. [65] proposed a built-in active sensing system consisting of two piezoelectric patches in conjunction with both impedance and guided wave propagation methods for rail defect detection. Marine Technology Association of South Africa and Council of Scientific and Industrial Research [66] jointly developed solar power GWT detection system (**Figure 5**). The coverage of the single system for rail defect detection is up to 2 km. Imperial College London and Guided Ultrasonics Ltd. cooperatively developed a G-shaped scanning ultrasonic rail track detection device, which can inspect vertically distributed defects and alumino-thermic weld joint [67], as shown in **Figure 6**. It can effectively inspect 18-mm-deep defects under rail crossing nose.

4.1.5 Acoustic emission testing (AET)

Different from common ultrasonic inspection, acoustic emission (AE) is instantaneous elastic waves by quick release of localised energy in solid materials under external applied loads. AE events can be captured by the piezoelectric sensors, generated elastic waves along all directions. Many sensors can be utilised to document arrival time of the signals and the variation of frequency during the crack initiation process. Hence, the nature of cracks can be determined. Through experimental study, AE has been proven a feasible solution in defecting rail detection, especially in rotating machinery [68]. A simplified analytical model, which separates defects caused by AE activities from background noise, was proposed by Thakkar et al. [48]. They also investigated the physical interaction between AE and axial load, speed, as well as traction through experiment. It is found that AE signal can be used for analysing the defects on the surface of the rail under normal operating speed.

The application of AET on rail defect detection is rarely reported. Previous research [69] shows that the benefit of AET may be limited due to imperfection of materials, which can produce different nature of signal source. Besides, the installation of the sensor may also affect the AE signal generation. It may also be affected by wheel and track defect for any misalignment [48]. Another concern of AET is signal processing for those AE waves that have similar amplitude with that of background noise produced by the rolling wheel [18]. Advanced data learning and

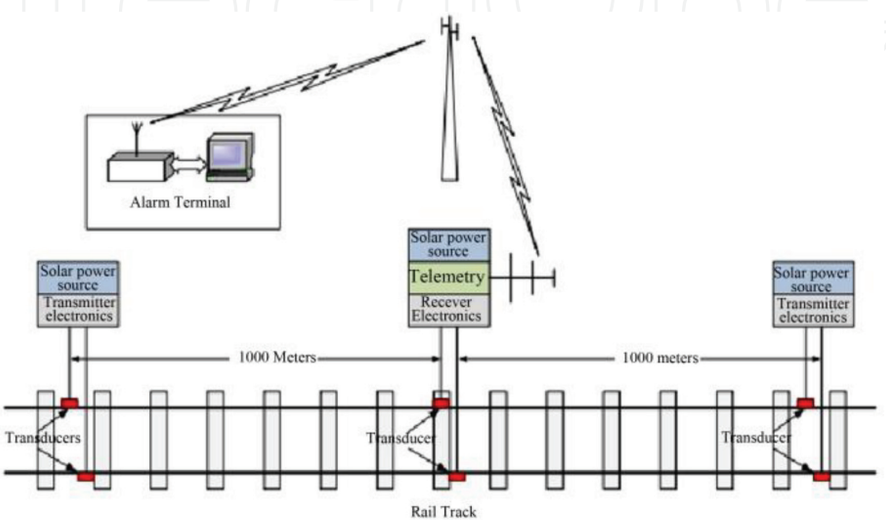


Figure 5.
Monitoring system on freight line in South Africa [66].

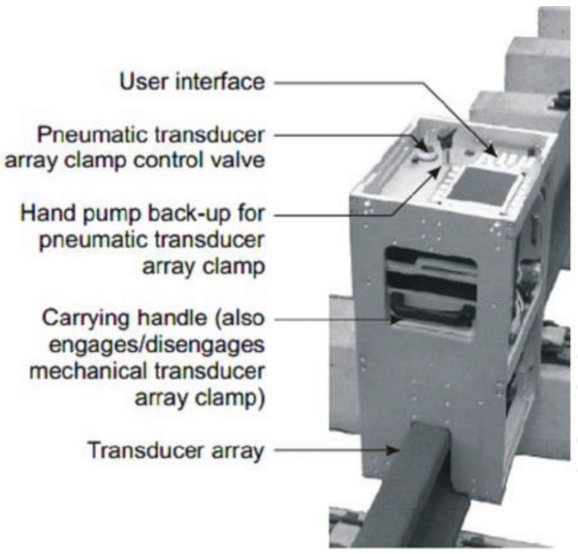


Figure 6.
G-type scan guided wave in inspection device in UK [67].

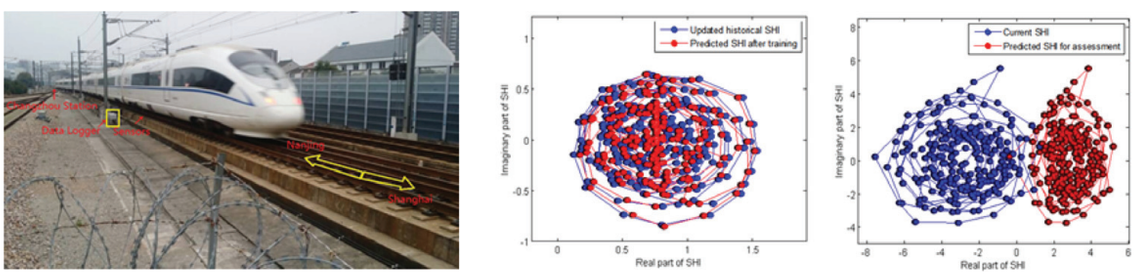


Figure 7.
(Left) Online HSR turnout condition monitoring system; (right) defect diagnosis method with model updating approach [70].

updating methods have been investigated dealing with great uncertainties arisen from the online monitoring data for more accurate and efficient damage diagnosis. AE method incorporating Bayesian framework is utilised in an online rail turnout crack monitoring system developed by CNERC-Rail [70]. The method is able to detect defects without training data of damaged rail structure and the monitoring systems have been implemented on Shanghai-Nanjing HSR lines, as shown in left panel of **Figure 7**. The rail turnout conditions are indicated in a probabilistic manner through a structure health index (SHI), as shown in right panel of **Figure 7**.

4.2 Other NDT techniques applied in rail defect detection

4.2.1 Magnetic particle testing

Magnetic particle testing [71] can be used easily to detect the specimen surface defects. But, the result is very sensitive to the specimen surface condition. If the specimen surface is coated or wet, the reliability of the detect result will decrease a lot. Therefore, removing the coating materials and surface drying are necessary before testing.

4.2.2 Eddy current testing

Eddy current testing is very simple and easy to detect surface and shallow internal cracks [28]. Eddy current sensors have been mounted on the bogie of track

inspection cars and equipped in roller-guided trolleys for mobile inspection of rails [28]. They are able to detect surface and near-surface defects in the railhead but fail to locate internal defects.

4.2.3 Alternating current field measurement (ACFM)

The alternating current field measurement (ACFM) technique is an electromagnetic inspection method that uses hand-held probes, and computerised control, data acquisition and computational models. ACFM is more efficient than conventional inspection methods due to a reduced need for surface preparation and an ability to work through surface coatings. ACFM also has an added benefit that it is not only capable of detecting flaws but can also detect size defects for length and depth [72]. In 2000, TSC with the support of Bombardier Transportation began the development of an advanced ACFM system for application in the rail industry. Following the experimental work on the train axles, it became evident that an ACFM system could be deployed to detect RCF cracking on rails. This led to the development of a pedestrian-operated ACFM walking stick [73]. The inspection of the railhead is carried out by sequentially scanning across the group of sensors enabling the uninterrupted inspection of the rail. The system can detect and size gauge corner cracks and head checks smaller than 2 mm in depth. However, the ACFM sensors cannot quantify squats accurately and are unable to detect short-wave corrugation and wheelburns.

4.3 FBG-based online monitoring of HSR

In recent years, optic fibre sensors have been advocated for application to rail infrastructure monitoring. The FBG sensors have merits of being immune to electromagnetic interference (EMI) and no power supply is needed on-site. A monitoring system based on the FBG technology has been developed and installed on an operating rail line in Hong Kong for real-time and continuous detection of rail strain and temperature, rail breaks, axle counting, wheel imperfection assessment and dynamic loading identification [35]. Wang et al. [74] proposed a rail performance monitoring and safety warning system and implemented this system on a rail line by deploying FBG sensors in the rail web and at the expansion joints between supporting concrete slabs. Yoon et al. [75] proposed a distributed fibre sensory system based on Brillouin scattering and a correlation domain analysis technique for longitudinal strain monitoring of rails. Ni et al. developed a deformation monitoring system for an in-service HSR tunnel using an FBG-based monitoring system [76]. An array of FBG bending gauges was deployed at the rail slab of a segment inside the tunnel. Upon occurrences of deformation, there would be relative rotation between two adjacent bending gauges. Phase shift of the FBG sensors caused by the relative rotations was recorded, and the deformation can then be derived, resulting in a profile of the deforming rail slab, and the deformation of the tunnel can be inferred.

FBG sensors for detecting acousto-ultrasonic signals have been studied since the mid-1990s [77]. The conventional interrogation technique for FBGs as sensing elements utilises their spectral encoding and decoding capabilities for the measurand; however, the spectral decoding capability cannot be used to detect high-frequency signals (e.g., acoustic and ultrasonic waves) due to the low wavelength scanning speed. Appropriate demodulation techniques capable of high-sensitivity detection of high-frequency waves are necessary to develop acousto-ultrasonic FBG sensors. There are two main approaches to detecting acoustic and ultrasonic waves with FBGs: the first one uses a narrowband light source to

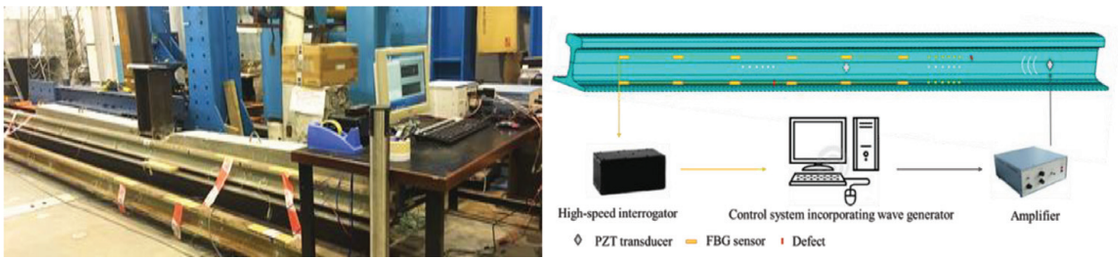


Figure 8.
Schematic set-up of the FBG-PZT monitoring system [79].

illuminate the FBGs and demodulate the power intensity variation when the waves impinge on the FBGs, while the second one uses a broadband light source and an optic filter. Minardo et al. [78] conducted a numerical investigation on the response of FBGs subjected to longitudinal ultrasonic waves. Ni et al. [79] have developed a hybrid monitoring system using FBG sensors to interrogate ultrasound signals emitted by PZT sensors (**Figure 8**). The hybrid system has been verified in lab and a test line in mainland China.

5. Outlooks of SHM on HSR

With embedded hybrid monitoring systems of FBG and PZT sensors, the SHM techniques have shown their promising prospect in HSR, enabling real-time monitoring of structural conditions of in-service trains and rail infrastructure. To realise large-scale utilisation on numerous HSR lines worldwide, practical solutions ought to be achieved concerning both economic and efficient aspects, answering for the need of early warning and quick decision-making upon emergencies in high-speed operation and guiding the potential development direction of SHM applications on HSR in the coming decades.

Wireless sensing network (WSN) provides a cost-effective approach eliminating wires and enabling remote sensing, which largely enhances the practical applicability of SHM [80, 81]. A wireless-based system was designed to monitor the performance of rail vehicles by Nejikovsky and Keller [82]. The communication in the WSN system can be made through satellite and Ethernet, while data are uploaded onto cloud for storage and transmission to control room far away from site; system data transmission plan can be found in the aforementioned railway tunnel deformation project [76]. Particularly, in terms of near-field communication, radio frequency identification (RFID) has been proposed as a competitive candidate [83], which provides a new thinking on emerging RFID modules in normal sensors. The passive RFID sensors embedded in the HSR structures need no wired power supply and can be activated by passing trains, sending structural condition information.

Continuous online monitoring of HSR over multiple HSR lines puts forward the difficulty in storage and analysis with massive data collected. The authors' team has long been dedicated to damage diagnosis and prognosis of HSR based on monitoring data with updating and learning methods. Facing the data amount issue, compressive sensing, which is able to sample data at sub-Nyquist sampling rate while maintaining almost all the original information, is being actively investigated to streamline the axle box acceleration data from an operating high-speed train and has successfully verified the feasibility of sub-Nyquist data acquisition in HSR online monitoring [84, 85]. This is of great significance to wireless sensing and RFID where transmitted data amount is limited.

6. Conclusions

Various sensing technologies have long been benefiting rail industries with systematic and reliable inspection and monitoring. In turn, the vigorous development of HSR has been pushing research in sensing technologies with flourishing state-of-the-art deliverables coming out. The HSR is expanding worldwide, satisfying people's growing demands in travelling with ease and comfort, and bringing heavier inspection and maintenance tasks. In response to the expanding HSR network, conventional offline inspection will still be the primary approach taking up most of the work, and online SHM will be a powerful supporting tool playing a more important role and reflecting real-time states of the operation HSR systems. The use of sensors will be less solitary and separated but more in a combined manner containing multi-disciplinary subjects from mechanical engineering, civil engineering, electrical engineering to computer science, mathematics, etc. Moreover, the requirements to contemporary sensing go beyond fundamental functions of accuracy and reliability to flexibility, portability and environment-friendly. Taking advance of nature of railway, the SHM applications on HSR can do more than environment-friendly. The concept proposed by the authors, a high-speed train with embedded sensing systems can be treated as an integrated moving sensor, capable of gathering information not restricted to structural conditions, but air conditions inside and outside the car body concerning surrounding environment and people's health. Having accomplished multiple SHM projects on HSR lines, we are initiating just calling a start, and in the near future, the encounter of sensing technologies and HSR will continuously foster reciprocal developments, paving a high-speed path to structural well-being, sustainable environment and social health.

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