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A review of health and operation monitoring technologies for trains

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Abstract. Railway transport of goods and passengers is effective in terms of energy conservation and travel time savings. Safety and ride quality have become important issues as train speeds have increased. Due to increased speeds, minor damage to railway structures and abnormal interactions between trains and structures have given rise to increasingly serious accidents. Therefore, structural health and operational conditions must be monitored continuously in all service environments. Currently, various health and operation management systems are being developed and these are reducing both maintenance frequency and costs associated with disassembly. In this review, major damage and malfunctions and their locations are first analyzed based on numerous references. Then advanced train health and operation management technologies are classified into wayside detection methods and advanced integrated sensor methods and their operating principle and functions are reviewed and analyzed.

Keywords: trains, damage; wayside detection method; integrated sensing method; integrated health and operation monitoring.

1. Introduction

Among different modes of transportation, railway transportation offers excellent energy conservation, environmental protection and reduced travel time (Soejima 2003, Kim 2005). Invariably, this mode of transportation plays a major role not only in the transportation of goods, but also of passengers. Both passenger and freight trains are usually made up of two main modules: the carbody and the bogie. Fig. 1 shows the typical components that make up the carbody shell and Fig. 2 shows the common components of the bogie, as well as the elements of a wheel profile.

In the past, although stainless steel was widely used to build the carbody's sturdy structure, lightweight Al-alloy is now being used to streamline traveling speeds and payload capacities, especially for the passenger cars of high speed trains such as the ICE (Germany), the ETR 450 (Italy), and the Talgo (Spain) (Galganski 1993). Hitachi (Japan) has adopted a double-skin (Al-alloy hollow extrusion) for the carbody of the Shinkansen 700 series. This structure improves the soundproof characteristics of the carbody, as it allows the inside of the double-skin truss to be filled with a foam vibration isolator, which helps to reduce the transmission of noise and vibrations through the roof and sides (Matsumoto *et al*. 1999).

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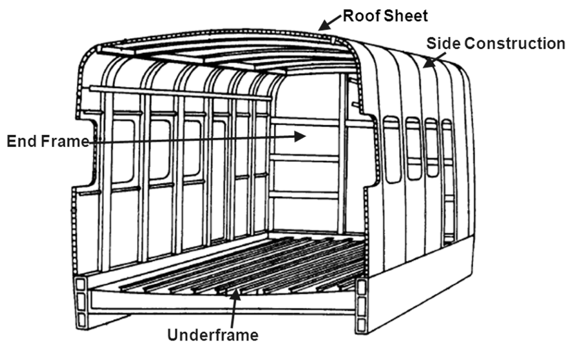

Fig. 1 Components of the carbody shell

The bogie is a system that is connected to the carbody through the body bolster. Its purpose is to ensure the safe carriage of cars along the railway and to create comfortable riding conditions for passengers by absorbing the vibrations that are generated by track irregularities (Okamoto 1998). The essential components of the bogie are:

(a) bogie frames (side frames)
(b) wheelsets (wheels, axle, journal)
(c) elastic suspension
(d) carbody to bogie connection (bolster)
(e) brakes

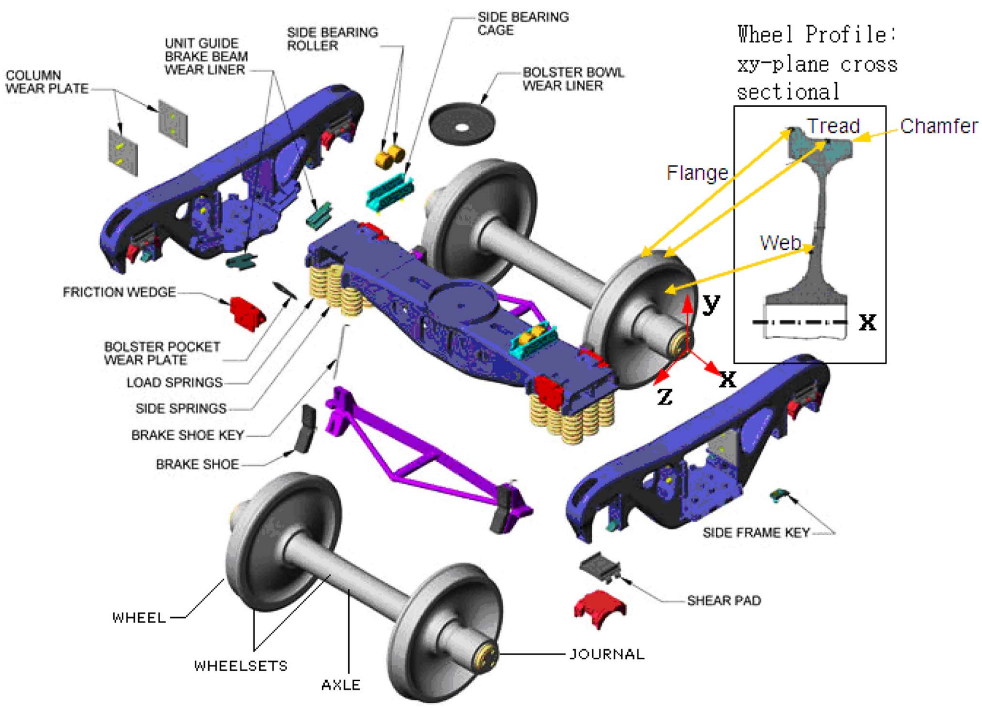

Fig. 2 Components of the bogie and the elements of a wheel profile (Standard Car Truck Company 2008)

The configuration of the bogie with the incorporation of these components is shown in Fig. 2. The wheelsets, elastic suspension, bolster and brakes are connected to the two side frames. In general, the wheelsets have two common features: a rigid connection between the wheels through the axle and the cross-sectional profile of the wheel rolling surface, known as the wheel profile (Orlova and Boronenko 2006). Fig. 2 shows the cross sectional view of the wheel profile which consists of four elements: the flange, tread, chamfer and web.

2. Structural damage

All train vehicles must comply with technical standards (Kawasaki *et al.* 2008) that ensure a safe ride for passengers. However, the mechanical properties of trains deteriorate over time due to exposure to environmental influences such as humidity, temperature, and ultraviolet radiation (Shin and Hahn 2005). As time passes, reduction of structural strength and stiffness can result in the degradation of a train's structural performance. Furthermore, the train is a complex dynamic system (Wickens 2006). Just as damage includes changes to the material and/or geometric properties of systems, boundary conditions, and system connectivity, dynamic events in the train can affect the system's performance (Farrar and Sohn 2000), which can prompt chain reaction failures due to the mechanical interactions within each component, such as plastic deformation or local failure. Thus, without frequent, planned maintenance, damage to train structures could ultimately result in derailment.

Fig. 3 depicts a database, established by the Federal Railroad Administration (FRA), showing degradation/damage to mechanical parts that caused accidents/incidents from the years 2004 to 2007 in the United States (Federal Railroad Administration Office of Safety Analysis 2008). This database reveals that mechanical parts can be separated into three groups in terms of contributions to train accidents. Wheelsets (wheel, axles and journal bearings) comprised the largest group, with a 44.7% contribution in terms of total accidents caused. The second largest group included the brakes, coupler and body, with a 36.7% contribution, followed by a rate of 18.6% for the group including the pantograph, underframe and door. This analysis underscores the increasing need for wheelset damage detection techniques.

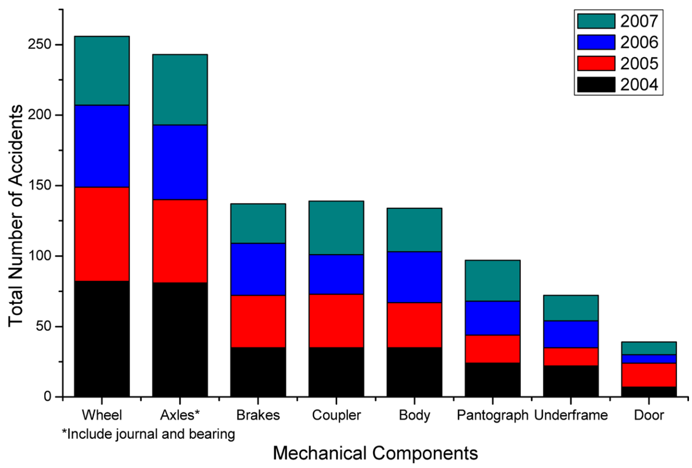

Fig. 3 Train accidents caused by mechanical components for the years 2004 and 2007 (U.S.) (Federal Railroad Administration Office of Safety Analysis 2008)

Table 1 Classification scheme for wheelset damage (Olofsson and Lewis 2006, Mutton 2001, Lewis *et al*. 2004, Howard 1994, NTN Bearing Corporation of America 2008, Barden Precision Bearings 2008, The Timken Company 2008).

Components	Damage
Wheel	Wear, slit flat, build-up tread, rolling contact fatigues (spalling, shelling), breaks, cracks, plastic deformation
Bearing	Wear, spun cone, corrosion, flaking, spalling, brinelling, peeling, smearing, chipping
Axle	Cracks, corrosion
Axle box	Crack

The causes of wheelset defects are summarized in Table 1. In previous studies (Olofsson and Lewis 2006, Mutton 2001, Lewis *et al.* 2004), rolling contact fatigue was classified into two categories: subsurface-initiated defects, also termed shelling, and surface-initiated cracks, also known as spalling. Shelling and spalling are induced by wheel-rail contact conditions and wheel sliding, respectively, due to malfunctions of the braking system.

In a train system, the wheel-rail contact is a complex and open system with no protection against dust, rain, sand, or even ballast stones, all of which can seriously affect the contact conditions and the forces transmitted through contact (Ayasse and Chollet 2006). The contact conditions at the wheel-rail contact are of primary concern to railway engineers because the contact zone always experiences high concentrated stresses due to heavy vehicle loads. These stresses also occur because of the dynamic responses induced by track and wheel irregularities (Olofsson and Lewis 2006) that change the wheel profile in terms of tread shelling (Fig. 4). Wheel tread shelling is generated due to the excessive normal contact and shear stress that cause fatigue cracks to initiate and grow below the tread surface, which eventually leads to pieces cracking off of the wheel tread while in service (Thanh 2003, Zakharov and Goryacheva 2005, Nielsen and Johansson 2000, Lonsdale 2008).

Malfunctions in the brake system, such as a release handbrake failure or a brake control valve failure, are the main causes of wheel tread spall (Fig. 4) generation (Lonsdale 2008). Malfunctions in the system cause wheel sliding, in which the wheel is locked up by the brake shoes and a wheel flat is generated on the wheel tread as the wheel slides continuously on the rail (Thanh 2003, Kilian 2002, Jergéus 1998). Subsequently, surface cracks are initiated on the surface of the wheel tread when brittle martensite is formed around the flat, where the sliding causes the temperature to rise, followed by rapid cooling into the adjacent material when the wheel starts rolling again (Jergéus 1998, Ahlström and Karlsson 1999, Ekberg and Kabo 2005, Ekberg and Sotkovszki 2001, Snyder *et al.* 2003).

Fig. 4 Wheel tread (a) spalling and (b) shelling (Zakharov and Goryacheva 2005)

In terms of chain reaction failure, these wheel flat and out-of-round wheels caused by rolling contact fatigues lead to high impact forces between the wheel and rail, which can cause secondary damage to the wheelset components (Jergéus 1998) and increase the incidence of hot boxes, burned-off journals, broken wheels, and rail fractures (Snyder *et al.* 2003). These failures may be very costly both in terms of economic losses and human injuries, as well as influencing the reliability of train operations if no immediate action is taken.

In general, bearing failures are due to wheel impacts that shorten the life-cycle of the bearing by generating vibrations on the surface contact between the bearing roller and axle journal. In addition, various adverse conditions may cause a bearing to fail prematurely. Gerdun *et al*. (2007) stated that bearing damage occurs due to:

(a) Improper lubrication
(b) Excessive load
(c) Excessive rotation speed
(d) Inadequate mechanical properties
(e) Insufficient operating clearance
(f) Radial stress caused by an external heat source
(g) Obstructed run due to the breaking of the cage
(h) Initial damage of the bearing

Choe *et al*. (2008) reported that bearing damage mechanisms could be classified into two types: brinelling and spalling. Brinelling consists of one or more indentations distributed over the entire raceway circumference that is subjected to static overloading (Howard 1994). Each indentation acts as a small fatigue site, producing sharp impacts with the passage of the rolling element, eventually leading to the development of spalling at the indentation sites as the bearing continues to operate (Howard 1994). Under normal loading conditions, the bearing will form minute cracks due to material fatigue after a certain duration of usage. With an increase in size during cyclic loading, the cracks progress to the surface and are manifested as spalling in the contact areas (Howard 1994, Holm-Hansen and Gao 2000). In previous studies (Howard 1994, NTN Bearing Corporation of America 2008, Barden Precision Bearings 2008, The Timken Company 2008), bearing defects are summarized, as shown in Table 1. Fig. 5 shows the defects of taper roller bearings.

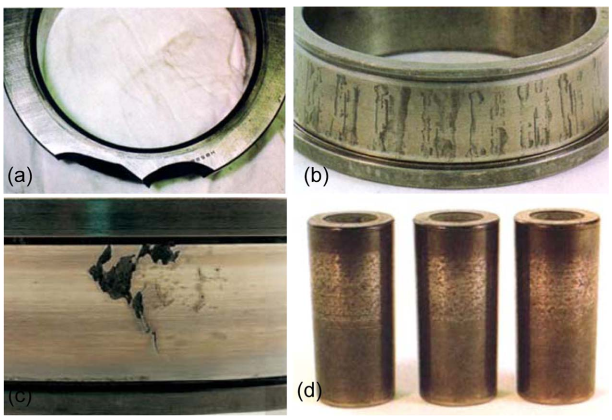

Fig. 5 Taper roller bearing defects: (a) chipping of cone back face rib (inner ring), (b) rusting of raceway surface, (c) spalling and (d) indentations of rolling contact surfaces (temper color at two ends) (NTN Bearing Corporation of America 2008, The Timken Company 2008)

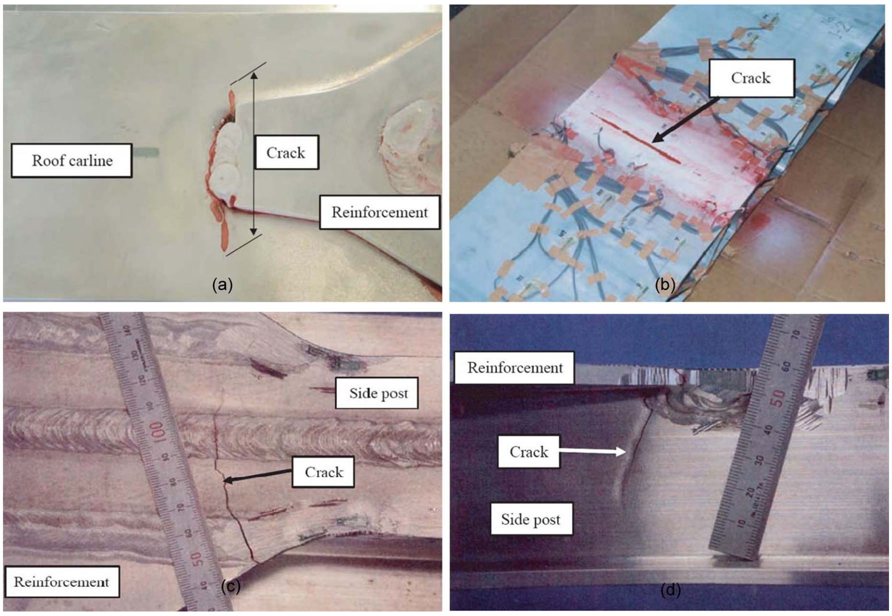

Fig. 6 Carbody defects: (a) crack initiation site on reinforced welded roof carline joint, (b) crack initiation on welded joints of an Al-alloy hollow extrusion, (c) surface view and (d) section view of crack initiation sites on reinforced welded side post joints (Yagi *et al*. 2007)

In general, bearing defects are associated with the speed of the train (Gerdun *et al.* 2007, Stubbe 2008), wheel impact, and poor lubricant handling (Gerdun *et al.* 2007, Fitch 2008, General Training Pty Ltd. 2008). Wheel impact can result in a loose fit bearing inner raceway. Consequently, it causes wear on the inner raceway circumference and can lead to a spun cone. In addition, wear on the race/roller cage and solid surface can also be caused by poor lubricant handling, excessive lubrication, or a lack of lubrication (Fitch 2008, General Training Pty Ltd. 2008). It is imperative that lubricant is clean, as it will help to prolong the bearing life cycle. If the lubricant is contaminated with water, this may lead to a water-etched surface. Furthermore, as water is added to the bearing, rust can form inside the bearing roller or raceway. Subsequently, the wear will be magnified due to the fatigue on the contact surface between the roller and raceway, until the roller is broken.

Typically, fatigue in the carbody shell results from changes in the internal and external differential pressure on an airtight structural vehicle as trains pass each other in tunnels (Takeichi *et al.* 1997, Hanni *et al.* 1994, Yagi *et al.* 2007). The fatigue strength of the joint between the cantrail and roof sheet and the joint between the side post and side sill were evaluated in a laboratory test using strain gauges (Yagi *et al*. 2007). In this test, the crack initiation sites were determined (Fig. 6). Using the conventional penetration method, crack initiations were observed at the hollow extrusion welded joints, the reinforced welded roof carline joint and the welded side post joints.

3. Hot spots

Many monitoring systems have been introduced for structural damage identification. Therefore, the trustworthy acquisition of data is imperative so as to optimize the accuracy level of structural

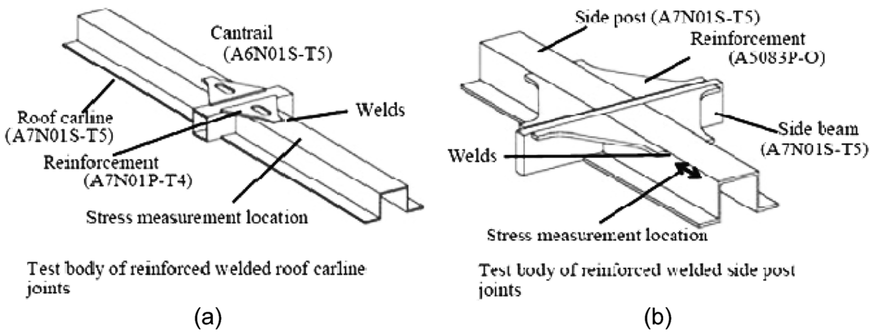

Fig. 7 Stress measurement locations for (a) reinforced welded roof carline joints and (b) reinforced welded side post joints (Yagi *et al.* 2007)

damage analysis. Inevitably, sensors must be installed at appropriate locations to enhance the accuracy of data acquisition and to reduce the necessary number of installed sensors in the monitoring system. These factors help to reduce costs and data processing time. Hot spots are analyzed below by reviewing structural damages tested by conventional methods. These hot spots need to be monitored by integrated sensors using an integrated health and usage monitoring approach.

3.1 Joints of the carbody

In a laboratory test (Yagi *et al.* 2007), reinforced welded roof carline joints and welded side post joints were identified as sites that experience high stress concentration. Fig. 7 shows the strain measurement locations where the strain gauges were placed for the fatigue strength test.

3.2 Carbody and underframe

It is important for operators to monitor the dynamic performance and operation of trains. The monitoring system should accurately report the health trends of train structures. This can be achieved by placing accelerometers and strain gauges on the carbody and underframe.

In previous studies (Andersson and Stow 2006, Tyrell *et al.* 2000), accelerometers and the linear variable differential transducers (LVDTs) were installed on the carbody and underframe, as shown in Fig. 8. These sensors were used to measure the imparted force on the wall, the elastic vibration motions of the carbody, and the gross motion of the car and bogie, including the longitudinal, vertical, and lateral accelerations and displacements.

Fig. 9 shows an array of high-elongation strain gauges that were installed on the lift cant rail, draft and center sills, and side sills for train crashworthiness testing (Tyrell *et al.* 2000). For this arrangement, the sensors help measure the relative loads carried by the longitudinal structural members and determine the mode of crush of the carbody.

3.3 Axle

In nondestructive testing experiments (Zerbst *et al.* 2005, Ares *et al.* 2006, Rudlin *et al.* 2006a, b), the gear seat, wheel seat and brake seat were identified as hot spots where cracks were initiated, as shown in Fig. 10.

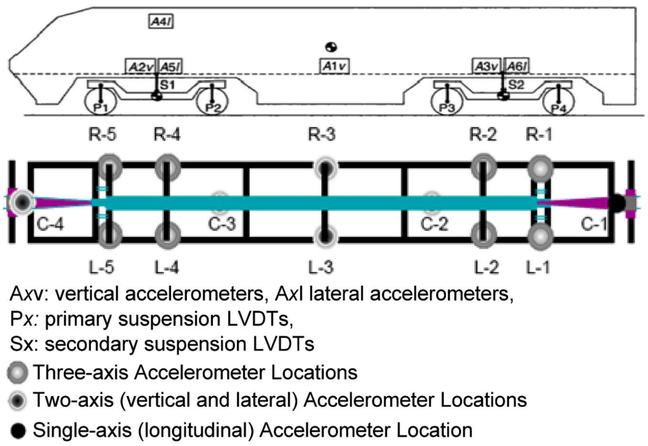

Fig. 8 Placement of accelerometers and LVDTs on the carbody and underframe (Andersson and Stow 2006, Tyrell *et al*. 2000)

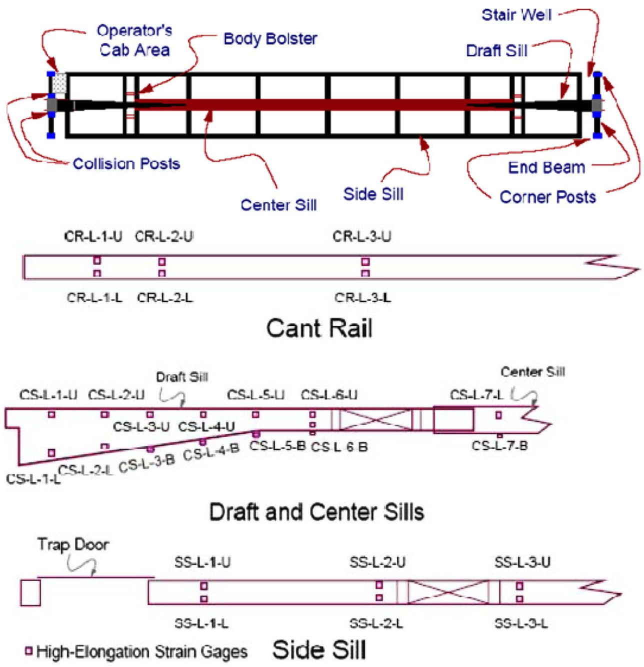

Fig. 9 Placement of strain gauges on the underframe (Tyrell *et al*. 2000)

4. Health and operation management

The optimization of traveling speeds and train safety are the major focus areas for railway network owners and researchers (Soejima 2003, Tomii 1999). Inevitably, excessive train speeds lead to motion sickness due to vibration (Krylov 2001, Suzuki *et al*. 2005), structural defects in the bearings (Gerdun *et al*. 2007, Stubbe 2008), and other problems. Hence, the adoption of reliable health and operation monitoring techniques is necessary to ensure the structural health of trains.

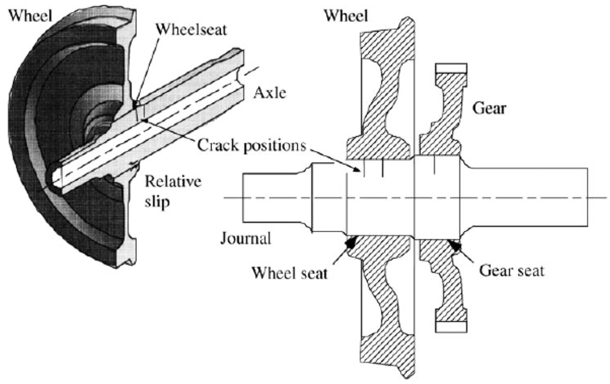

Fig. 10 Typical positions of crack initiation for a railway axle (Zerbst *et al*. 2005)

Health and operation management systems are being applied to related structures such as transportation vehicles, buildings, power plant structures and infrastructures, incorporated with a sensor network to continuously monitor the health of the structure in real-time (Worden and Dulieu-Barton 2004, Ciang *et al*. 2008, Rafiquzzaman and Yokoyama 2006). Furthermore, in recent years, health and operation management systems have not only been used for structural integrity diagnosis, but also in conjunction with damage prognoses. The damage prognoses attempt to forecast system performance by measuring the current state of the system, estimating the future loading environments for the system, and then predicting the remaining useful life of the system through both simulation and past experience (Farrar and Lieven 2007). Health and operation management systems coupled with damage prognoses and integrated sensor networks (Balageas 2008, Achenbach 2009, Tessler 2007) have the distinct advantage of being able to provide better planned maintenance schedules and are able to optimize structural health life cycles into the train operation monitoring systems.

4.1 Wayside detection-based health and operation management

Wayside detection methods can be considered as integrated health and operation management methods because trains run along fixed rails. These techniques are used to detect specific faults on rolling stock by interrogating sensors placed along the sides of tracks and to monitor critical parameters that relate to the condition of in-service railway vehicles. Information on vehicle condition and performance is recorded and sent to operators through the railway's computer network.

In general, wayside detection is employed to monitor the health of bogies and wheelsets. Various methods of detection can be classified as follows.

4.1.1 Wheel impact monitors

Wheel impact monitors are used to identify bad wheels by identifying the high-impact loads that are induced by wheel surface defects such as flat spots, chipped-off tread surfaces, or spalling on the wheel-rail contact. Electrical strain gauges, mounted to the rail's web and foot, were used in wheel impact monitors to quantify the load applied to the rail head using a mathematical relationship between the applied load and the deflection of the foot of the rail (Stratman *et al*. 2007). In some studies, accelerometers were also used to quantify the wheel surface conditions. Bladon *et al.* (2004)

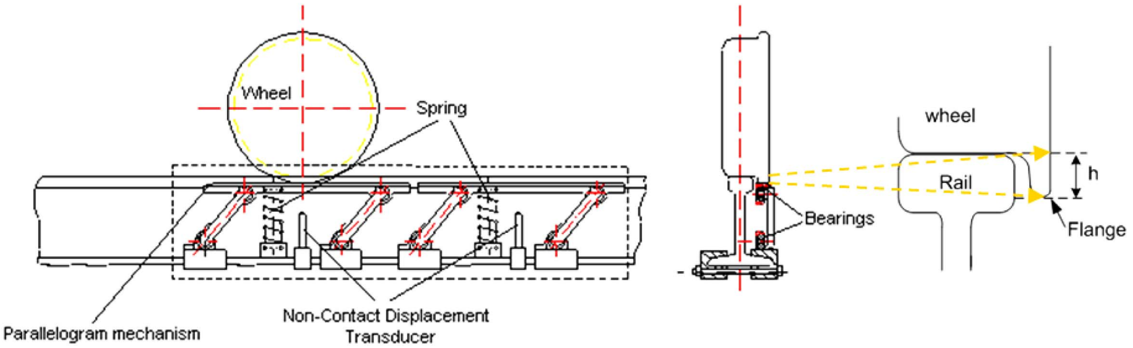

Fig. 11 Schematic illustration measuring the wheel flat and abrasion (Feng *et al*. 2000)

reported that properly configured accelerometers had superior sensitivity, and that the impact data detected was independent of sprung mass or electromagnetic influence.

4.1.2 Wheel profile detectors

There are two methods to inspect changes of wheel profiles (Feng *et al*. 2000, Lagnebäck 2007), based on (a) mechanical indications and (b) laser scanning images, and the setup configurations are shown in Figs. 11 and 12, respectively. The working principle of a mechanical indication is to determine the height of the wheel flange (Fig. 11), *h*, relative to the rail head when the flange rolls through on a plate. Throughout the detection process, the system provides an indication of both the radial profile of the wheel and the amount of wear.

Fig. 12 shows one of the commercial products for wheel profile detection that makes non-contact measurements (Lagnebäck 2007) based on laser scanning images. The system schematic is shown on the right-hand side of Fig. 12. Based on this schematic, the activation of the laser scanning process is dependent on wheel sensors. The lasers start scanning once the wheel sensors detect the passing wheels, at which point images are captured by the cameras and sent to the computer to determine the wheel profile. Using the captured images, the system is able to provide measurements such as rim thickness, hollow wear, and flange height (Gallon and Wilson 2008).

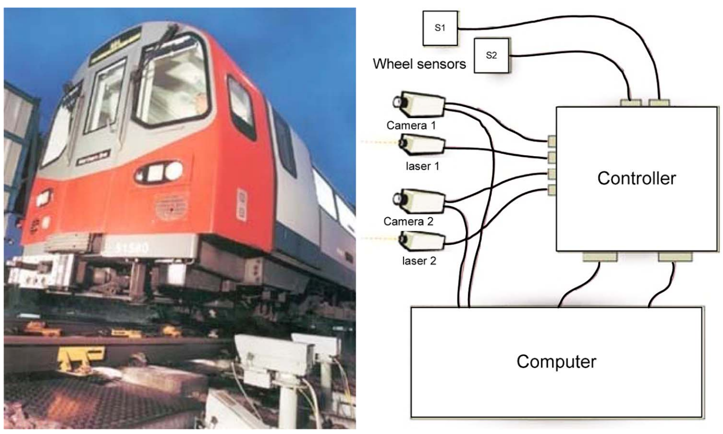

Fig. 12 View vehicle inspection system mounted at rail level and the system schematic (Gallon and Wilson 2008)

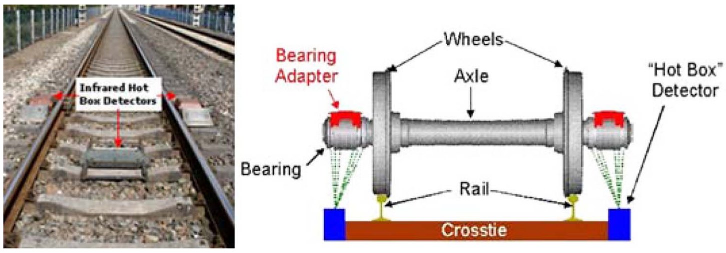

Fig. 13 HTK-499 infrared hot box detection system (Harbin VEIC Technology Co. Ltd 2008, Southern 2007)

4.1.3 Weight detector

Basically, weight in motion devices are designed to capture and record axle weights and gross vehicle weights as they drive over a sensor. The system configuration is similar to the wheel impact detection in that the strain gauges are mounted on the rail's web to detect the axle load. The measurement of the axle load is made by measuring the bending of the rail web or foot using the strain gauge sensors (Barke and Chiu 2005). However, the weight detectors can be replaced by wheel impact monitoring systems due to their capability for determining the static axle load and dynamic wheel load (Barke and Chiu 2005).

4.1.4 Hot box detector

Hot box detectors are mounted on the two side rails, as shown in Fig. 13, to detect the heat emitted by a vibrating bearing if the inner raceway is loosely fitted or defective. In the early years, thermoresistors were used to detect the heat emitted from the journal bearings. Due to their low detection accuracy, thermoresistors have been replaced by pyroelectronic sensors (Barke and Chiu 2005). In Fig. 13, the hot box detectors were positioned so as to aim at the inboard side of the journal bearings when the train passed through, and the middle inboard, which was mounted on the sleepers, was used to detect hot axles of high-speed and quasi-high-speed trains (Harbin VEIC Technology Co. Ltd. 2008). However, the detectors were unable to detect all bearing failures due to the quick burn-off mechanism (Lagnebäck 2007, Steets and Tse 1998). The technology used in the hot box detection application has evolved to include an advanced high-speed photon scanner. This rapid response system made it possible to detect bearing temperatures on high-speed trains (Barke and Chiu 2005).

4.1.5 Sliding wheel detector

A sliding wheel is normally caused by a malfunction in the brake control valve where the wheel locks up and the heat becomes concentrated at the interface between the wheel and the rail. When this happens, an infrared line scan camera is used to capture the heat image so as to detect the heat distribution on the wheel (Barke and Chiu 2005, Steets and Tse 1998). The captured heat image will show an even heat distribution on a wheel if the brake retardation is normal. In contrast, the heat image will show an uneven heat distribution on a wheel if the brake is malfunctioning. Hence, the system is not only able to detect wheel slides, but also able to detect a brake system failure. For the alternative method, a mechanical roller is used. The roller is mounted on the rail and it rotates as it contacts the flange of each passing wheel. The directions of roller rotation are the indication showing the occurrence of the wheel slide. When the direction of rotation is the same as the

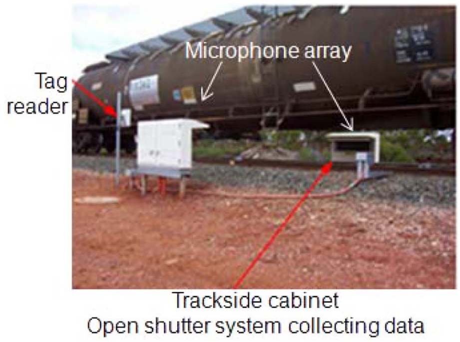

Fig. 14 Acoustic bearing defect detection device (Southern 2007, Trackside Intelligence Pty. Ltd. 2008)

Fig. 15 T/BOGI installation side tracks (Lagnebäck 2007)

traveling direction of the train, it will indicate the occurrence of a wheel slide (Barke and Chiu 2005, Steets and Tse 1998).

4.1.6 Acoustic bearing defect detectors

An acoustic bearing defect detector that analyzes the vibrations of bearing defects is being developed by installing microphone arrays next to the track. Fig. 14 shows the commercial product, RailBAM. Before the train passes by the RailBAM, the shutter of the trackside cabinet will automatically open to let the microphone arrays record the acoustic signature of the bearings (Southern 2007, Trackside Intelligence Pty. Ltd. 2008). Choe *et al*. (2008) proposed using neural network algorithms to enhance both bearing defect detection and damage type recognition.

4.1.7 Skew bogies and hunting vehicle detectors

Truck hunting is characterized by rapid sustained side-to-side motion of the trucks in a car, and this imposes excessive lateral forces on the track structure. In the past, lateral strain gauges were usually mounted on the rail and the truck motion was monitored. Due to the advancement of computer and laser technologies, truck hunting can be detected using lasers (Steets and Tse 1998) to measure the angle of attack and to track the position of a wheelset at different locations along the rail (Fig. 15). It is then possible to infer the hunting behavior of the bogie.

4.1.8 Wheel imperfection detectors based on fiber Bragg gratings

In recent years, Hong Kong Polytechnic University and Kowloon-Canton Railway Corporation proposed a Smart Railway Sensor Network to improve both the operational and safety characteristics of the railroad by incorporating an optical sensor network (Tam *et al*. 2005) (Fig. 16).

In this scheme, fiber Bragg grating (FBG) sensor arrays are installed on railway rails, high voltage lines, rolling stock, escalators, and other parts to collect the massive signals through the use of wavelength-division-multiplexing (WDM) techniques. The sites and control center are interconnected through the fiber optic network to allow massive signals to be transmitted at high speed and low loss rates. In addition to the optical fiber, lasers/LEDs are also used as a transmission link between trains and platform detectors through the free spaces.

FBG is basically capable of measuring strain and temperature by detecting change in Bragg wavelength. Therefore, conventional electrical strain gauges can be replaced by the FBG sensors for

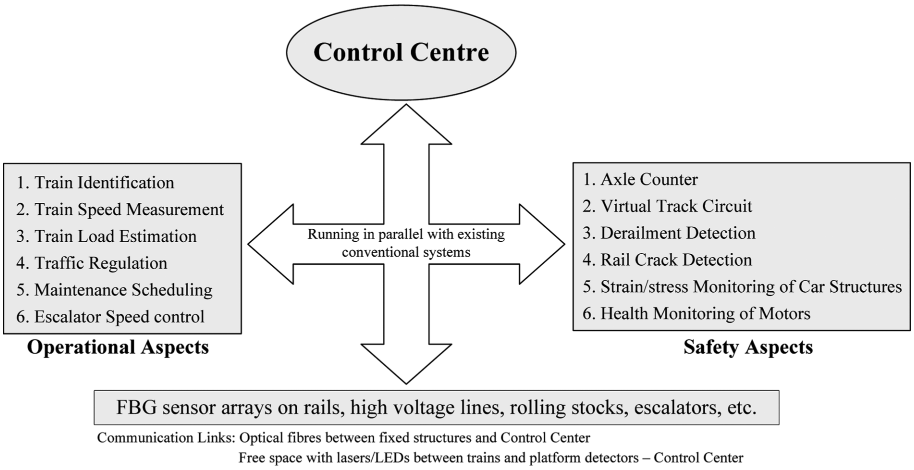

Fig. 16 Proposed Smart Railway Sensor Network (Tam *et al*. 2005)

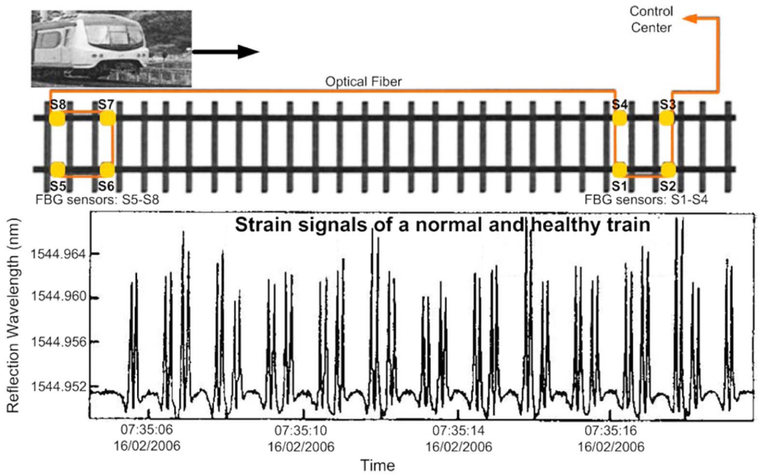

Fig. 17 FBG sensor setup configuration and acquired strain signals (Ho *et al*. 2006)

collecting strain measurements as a means of wayside detection, e.g., wheel impact detectors and train operation parameter detectors. Fig. 17 shows the FBG sensor setup configuration mounted on the rail at two different locations (Tam *et al*. 2005, Ho *et al*. 2006). When a normal, healthy train passed through the FBG sensors (S5-S8) to sensors further down the track (S1-S4), the strain measurements were interrogated and the strain signals (Fig. 17) were sent to the control center for analysis by way of the optical network.

The acquired strain signals can be used to detect wheel imperfections (e.g., wheel out-of-roundness) that lead to wheel damage. When the wheel exhibits out-of-roundness, it strikes the rail and creates noise-like vibrations as the train passes. The vibrations from the impact force affect the acquired strain signals (Fig. 18). The strain signals of defective wheels are distinctly different from the strain signals of a healthy train (Fig. 17). Thus, wheel imperfections can be recognized or tracked using only signal processing techniques that detect anomalous high frequency vibration noise.

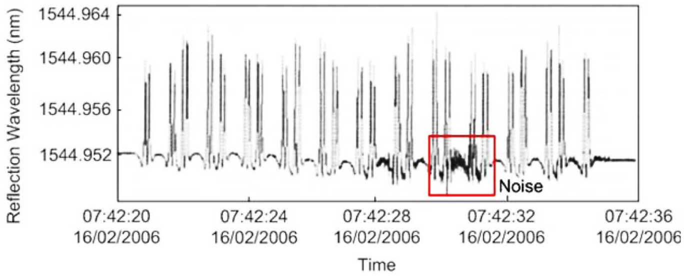

Fig. 18 Strain signals of a train with defective wheels (Ho *et al*. 2006)

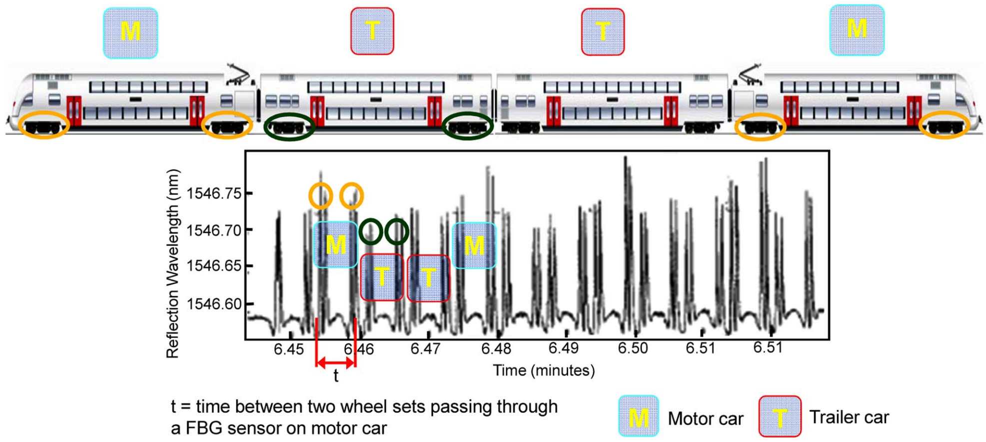

Fig. 19 Relationship between types of cars and reflection wavelength (Tam *et al*. 2005)

4.1.9 Train operation parameter detectors based on fiber Bragg gratings

From the perspective of train operation, the strain signals of the train can be used to differentiate the types of cars as either motor cars or trailer cars. The shifts of reflection wavelength are correlated with strains created by motor and trailer cars. In Fig. 19, the heavier motor car generated higher wavelength shifts than the lighter trailer car. In addition, the number of axles can be counted, as the generated strain signals are discrete when each wheelset passes through the FBG sensors. The time difference between two consecutive wheelsets passing through a FBG sensor on motor car can also be determined easily (Fig. 19). Once the distance and time difference between two consecutive wheelsets are determined, the average velocity of the motor car can be calculated. Based on a calibration approach using the measured average velocity and FBG wavelength shift, the weights of the cars can be estimated.

4.1.10 Laser ultrasonic technique

Recently, a prototype wayside automated axle crack detection method based on a laser air-coupled hybrid ultrasonic technique (LAHUT) was developed by the Transportation Technology Center, Inc. (TTCI) (Morgan *et al*. 2006), which is able to detect surface-breaking fatigue cracks in railroad axles while in motion. The system schematic diagram and configuration setup are shown in Fig. 20, where the laser power supply, laser head, and beam-steering mirror are placed alongside the railroad tracks and the optics and air-coupled receivers are placed between the rails. The working principle is that the axle rolls through the inspection station and a single laser pulse is output by the high

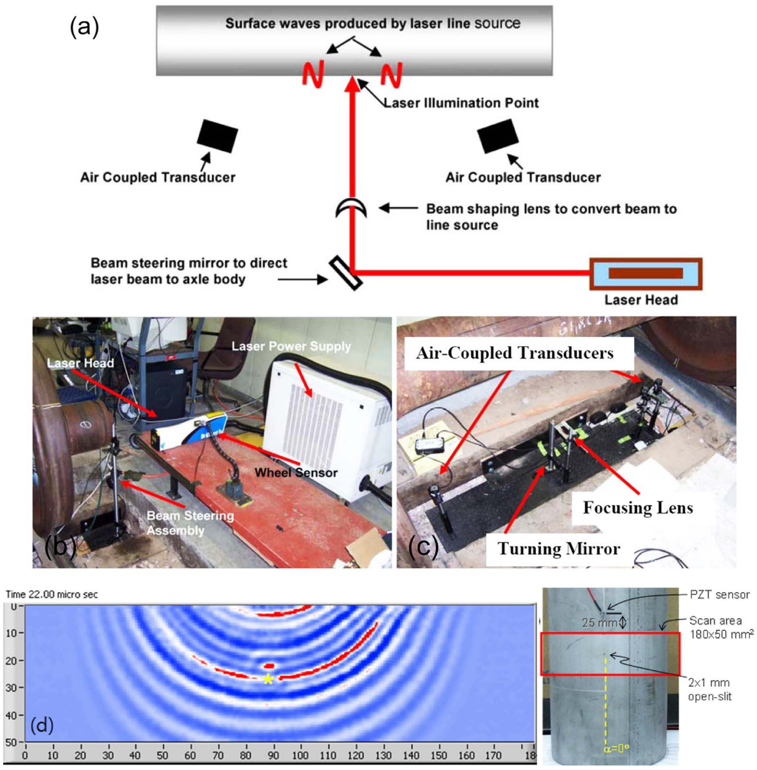

Fig. 20 (a) Schematic for laser air-coupled hybrid ultrasonic technique, (b) laser and beam steering assembly, (c) optics and transducers in crib (Morgan *et al*. 2006) and (d) crack evaluation in a curved structure using laser ultrasonic propagation imaging technology (Chia *et al*. 2009)

energy laser, after which the reflected sound waves are monitored by air-coupled receivers. In laboratory experiments, results demonstrated the viability of the system to detect flaws in the axle body, both statically and dynamically, by distinguishing the difference between the ultrasonic waves of non-cracked and cracked conditions. However, the system has yet to be implemented due to the need for further design considerations on the transducer type and placement, data acquisition and processing, axle position sensors, and environmental protection and system operation (Morgan *et al*. 2006). Instead of the temporal comparison between measurement results under non-cracked and cracked conditions, advanced spatial referencing method, called ultrasonic propagation imaging was also developed (Chia *et al*. 2009).

4.2 Integrated sensor-based health and operation management

In recent years, on-board sensors and FBG-based transducers have been actively developed to provide a broad applications range with the implementation of integrated sensor-based health and operation management. The implementation of FBG-based accelerometers (Mita and Yokoi 2000), tilt angle (Guan *et al*. 2004), strain, and temperature sensors on train wagons using one interrogator has been proposed (Tam 2008, Tam *et al*. 2009). In a similar approach, usage of on-board electronic sensors has been proposed for freight cars (Sneed and Smith 1998, Donelson III *et al*. 2005), and

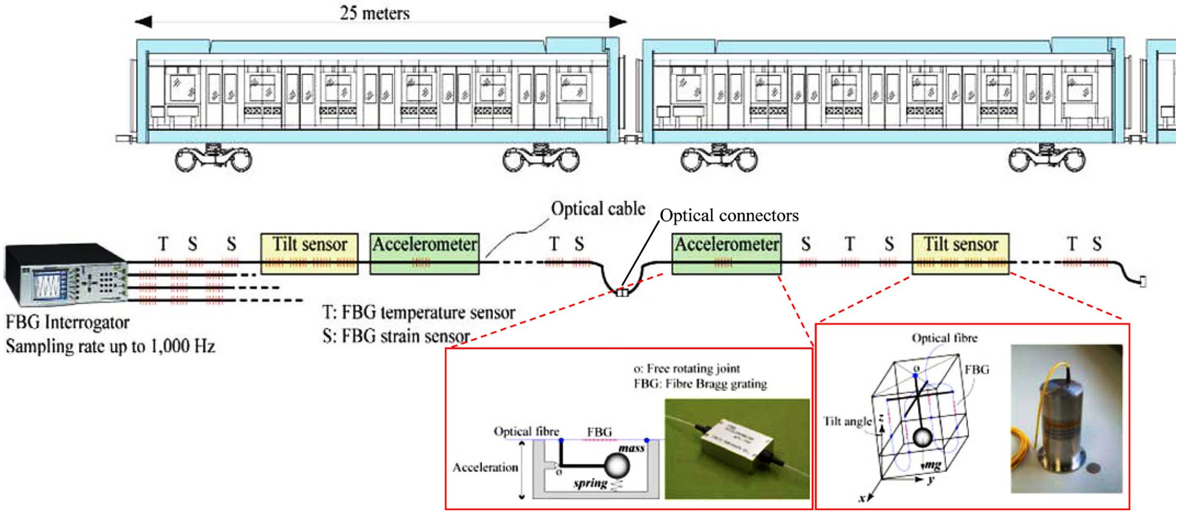

Fig. 21 Multi-functionality of FBG arrays for the measurement of temperature, strain, tilt angle and acceleration of train wagons (Tam 2008, Tam *et al*. 2009, Mita and Yokoi 2000, Guan *et al*. 2004)

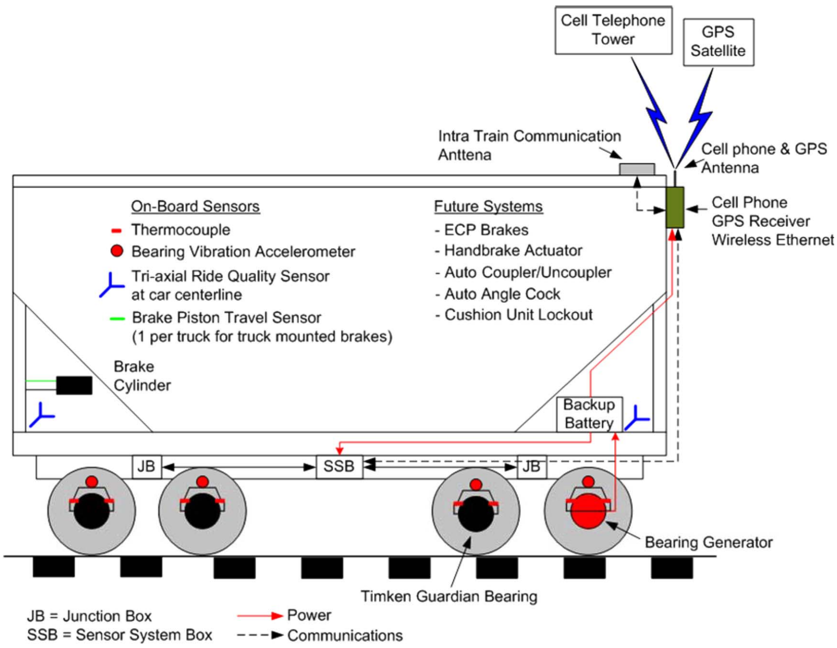

Fig. 22 On-board sensors and communication systems (Donelson III *et al*. 2005)

Figs. 21 and 22 depicts the system schematic configuration.

4.2.1 On-board railroad bearing defect detection and monitoring

4.2.1.1 Integrated accelerometers

The Association of American Railroads (AAR) and the FRA have developed on-board real-time railroad bearing defect detection and monitoring technology using accelerometers (Sneed and Smith

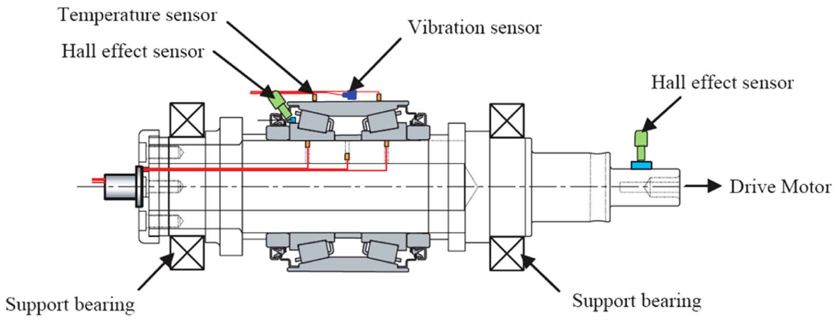

Fig. 23 Sensor setup configuration on a bearing (Nagatomo and Toth 2006)

1998, Donelson III *et al*. 2005). The accelerometers were mounted on the bearing (Fig. 22) to acquire the bearing's vibration level, which is important information to detect bearing damage, wheel defects, and derailments by identifying their signal characteristics respectively. As previously reported (Sneed and Smith 1998), the spun cone defects in a bearing have been identified based on the distinct spectra acquired by the accelerometers. In a laboratory test (Nagatomo and Toth 2006), an accelerometer attached to the sleeve jacket of an exterior surface cup (Fig. 23) was used to understand the relationship between cone creep and bearing damage by monitoring the vibration signal trend in a cartridge tapered roller bearing. The sensor showed that the vibration signal increased sharply at the point of incipient thermal failure, when the cone motion rate climbed rapidly approximately to 23 rpm and the bearing temperature showed a remarkable variation of approximately 150 ºC above ambient temperature, causing rapid oxidation and deterioration, and viscosity loss of the grease, eventually leading to the development of spalling at the cup and roller.

4.2.1.2 Integrated temperature sensors

Bearing damage is closely associated with a rapid temperature rise. Therefore, temperature sensors were used to monitor change in bearing temperature (Sneed and Smith 1998, Donelson III *et al*. 2005, Nagatomo and Toth 2006). In one study, the thermocouples were attached directly to the outer casing of each test bearing to determine the temperature trend with respect to increased speed (Sneed and Smith 1998). The temperature of the bearing outer race increases by 0.52 ºC per additional km/h of speed. However, the thermocouple used in one study (Donelson III *et al*. 2005) (Fig. 22) worked well initially, but over time, the sensors began to fail and damage due to static electricity occurred, especially in the bearing. In a laboratory test (Nagatomo and Toth 2006), five resistance temperature detector (RTD) temperature sensors were installed on a test bearing as shown in Fig. 23. The temperature sensors monitored temperature at the exterior surface cup, cone bore, axle, as well as ambient temperature. The sensors successfully detected a connection between increased bearing temperature and internal damage deterioration such as grease oxidation and bearing misalignment. It is inferred that on-board integrated temperature monitoring systems (i.e., a fiber optic temperature network) can be developed to monitor the change in bearing temperature and to detect a rapid temperature rise that gives rise to a bearing burning-off.

4.2.2 Hunting vehicle detectors

On-board tri-axial accelerometers were used to detect low frequency hunting motion, impacts delivered by the track, and shocks delivered during the coupling, acceleration, and braking

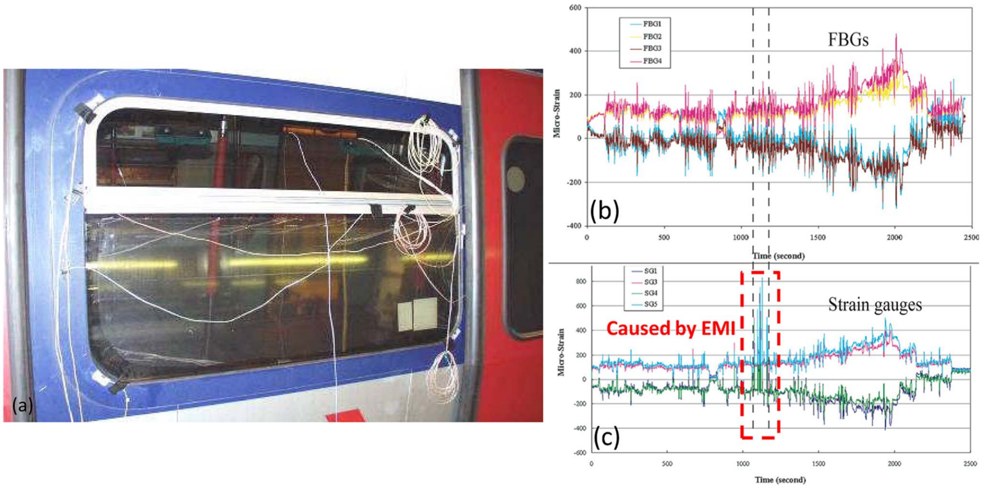

Fig. 24 (a) FBG sensors and strain gauges mounted on a train car; the results of dynamic load test using (b) FBG sensors and (c) electrical strain gauges (ESGs) (Tam *et al*. 2009)

operations by measuring the lateral, vertical, and longitudinal vibration at the bolsters on each end of the car, respectively, as depicted in Fig. 22 (Donelson III *et al*. 2005).

4.2.3 FBG sensors for assessing structural integrity of carbody shells

Fig. 24(a) shows a series of FBG sensor arrays with different wavelengths that was installed on a trailer car and a motor car of a train to replace electrical strain gauges to measure the strain of the carbody shells. For the trailer car, three FBG sensors were positioned at the corners of the window frame, as shown in Fig. 24, with one at the bottom steel bar, while the other two were at the top surface of the car. For the motor car, four FBGs were installed at the four corners of a window frame. The other two were located at the top surface and the bottom steel bar, respectively. The results (Fig. 24(b)) from the FBG sensors agreed well with the electrical strain gauge, mounted in close proximity to the FBG sensor. However, the strain signals that were obtained from the electrical strain gauges at 1100 seconds were contaminated by an electromagnetic field, which was due to the change of phase in the high-voltage electrical overhead line cable (Tam 2008, Tam *et al*. 2009). In contrast, due to electromagnetic interference immunity, the strain signals that were obtained from the FBG sensors did not show any electromagnetic interference.

4.2.4 Dynamic strain monitoring of weld joints

FBG sensors were also installed in the underframes of trains for monitoring vibrations in critical locations, such as weld joints, cross beams and sole bars, as shown in Fig. 25 (Tam *et al*. 2009). By measuring vibration signals with FBG sensors, the equivalent fatigue index was obtained (Tam *et al*. 2009) that can be used as reference for the prediction of the train life expectancy. Fig. 26 shows typical strain detected by the FBG sensors at different locations, and the frequency spectrum of the vibrations could be analyzed and checked for any conspicuous signatures close to the resonance frequency of the train body.

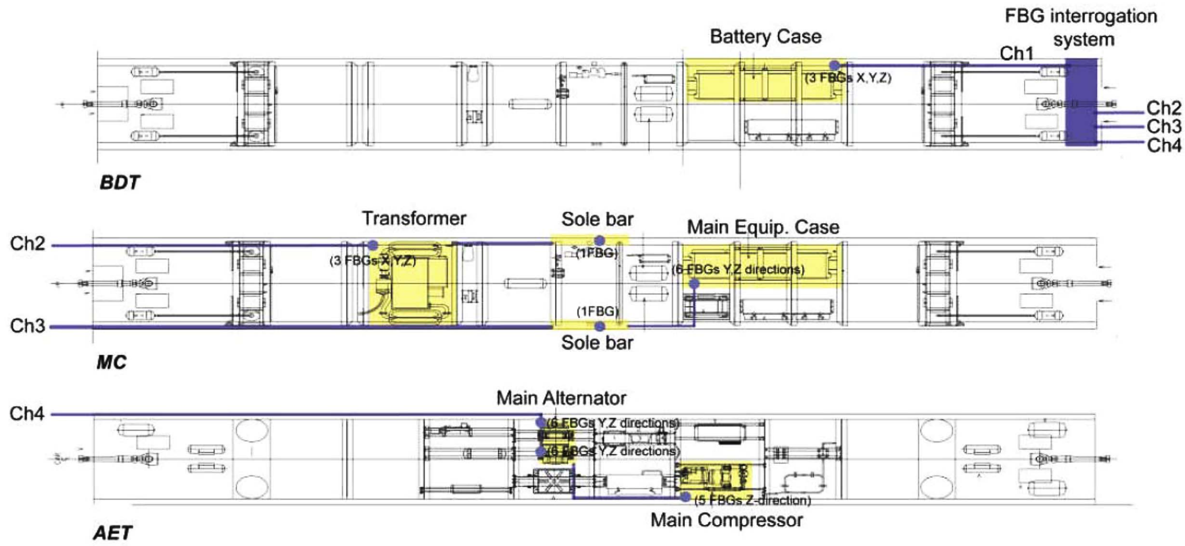

Fig. 25 Locations of weld joints where FBG sensors are installed for monitoring dynamic strains of critical parts: BDT = Battery Trailer, MC = Motor Car, AET = Auxiliary Equipment Trailer (Tam *et al*. 2009)

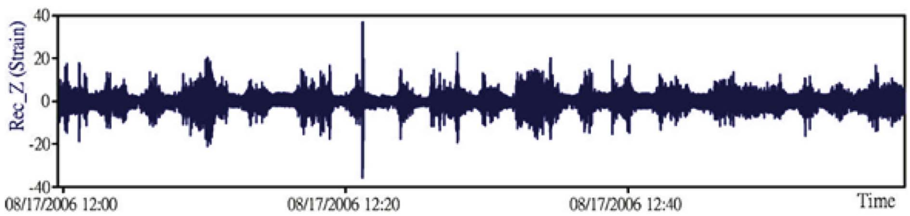

Fig. 26 Dynamic strain measured with FBG strain sensors epoxy-bonded to weld joints (Tam *et al*. 2009)

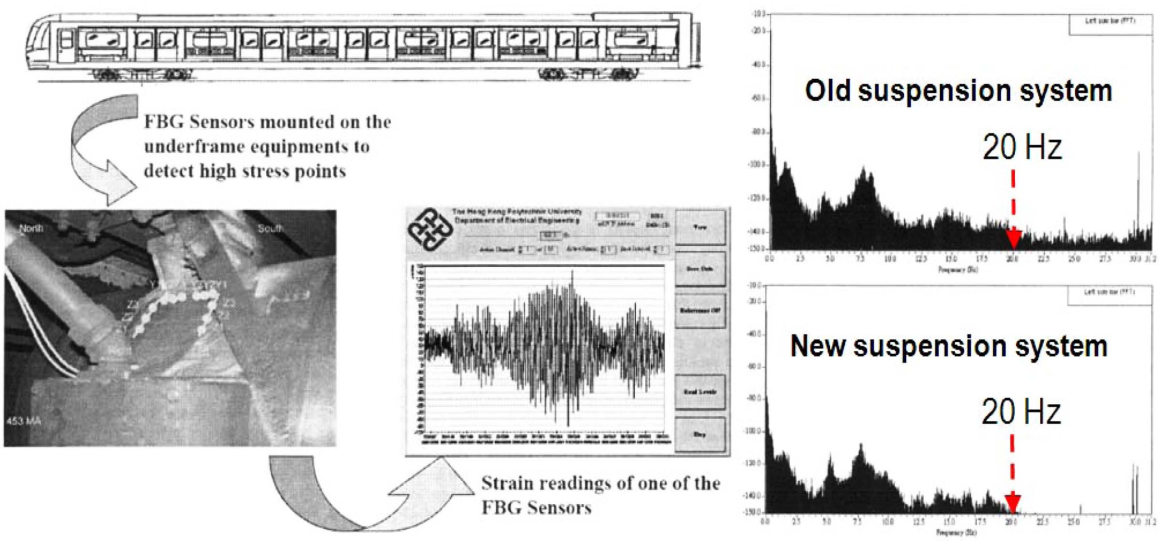

Fig. 27 Aging analysis using FBG sensors mounted on old and new suspension systems (Ho *et al*. 2006)

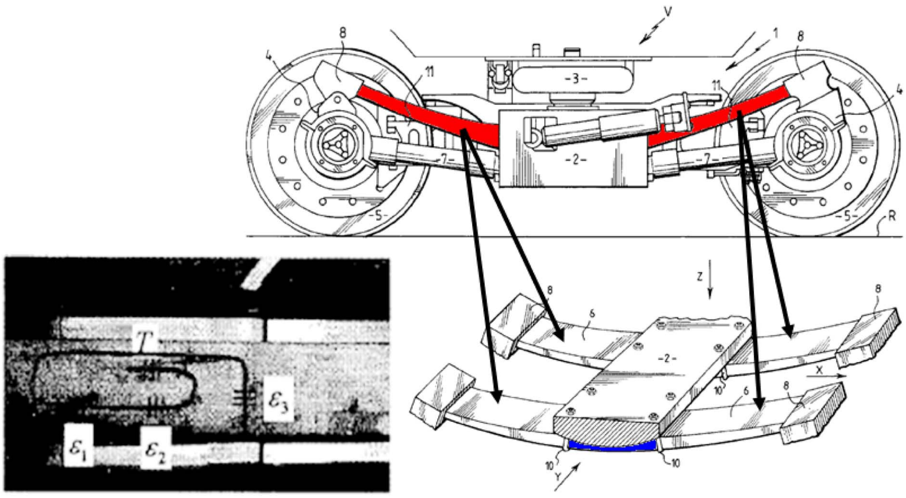

Fig. 28 Bogie spring blade with embedded FBG sensors (Maurin *et al*. 2002, Landrot 2002)

4.2.5 Suspension aging monitoring

Due to their small size, FBG sensors are easily mounted on the underframe to evaluate aging suspensions. In Fig. 27 (Ho *et al*. 2006), the frequency spectrums of strain signals were collected for an old used suspension and a newly replaced suspension system. Our results showed that the frequency spectra of the two suspension systems were significantly different. For the old suspension system, signals above 20 Hz were generated, but not for the newly replaced suspension system. Thus, the suspension aging monitoring system can easily distinguish suspension aging using spectrum analysis techniques.

4.2.6 FBG sensors embeded in a composite spring blade

Alstom Transport (France) has developed a glass fiber reinforced plastic spring blade (Maurin *et al*. 2002) (Fig. 28). They have integrated four FBG sensors into the mid-spring blade, which is shaded in Fig. 28. The mid-spring blade was determined to be the site experiencing the highest stress concentration and thus three FBG sensors were embedded to measure the strain and the fourth was used for temperature measurement.

4.2.7 Railway overhead line temperature monitoring

FBG sensors were also used for railway overhead line monitoring (Fig. 29) to measure temperature on the railway overhead lines. The purpose of this monitoring is to prevent thermal overheating of the overhead contact line to the point where it will degrade parts of the catenary construction and may lead to the malfunction of a passing train pantograph (Bosselmann 2005).

4.2.8 Others

The use of composites for the train carbody is continuously being tested. Integrated health and operation management is being proposed to assess the reliability of new materials. The direct application of integrated health and operation management to train carbodies has not been accomplished, although an aircraft fuselage (Airbus 340) may be considered as a similar reference structure (Camerlingo *et al*. 2006), in which FBG sensors were used to acquire the strain signals in

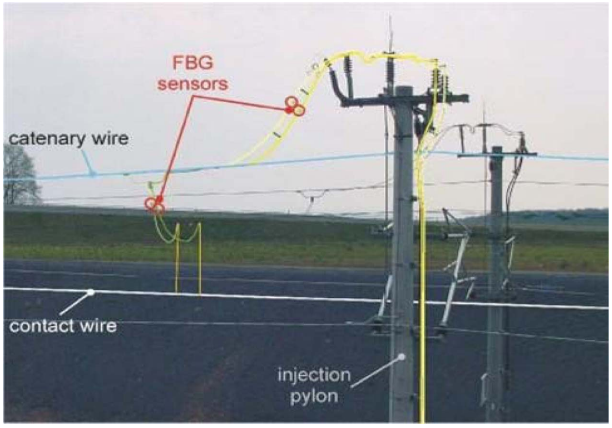

Fig. 29 Arrangement of FBG sensors for railway overhead line monitoring (Bosselmann 2005)

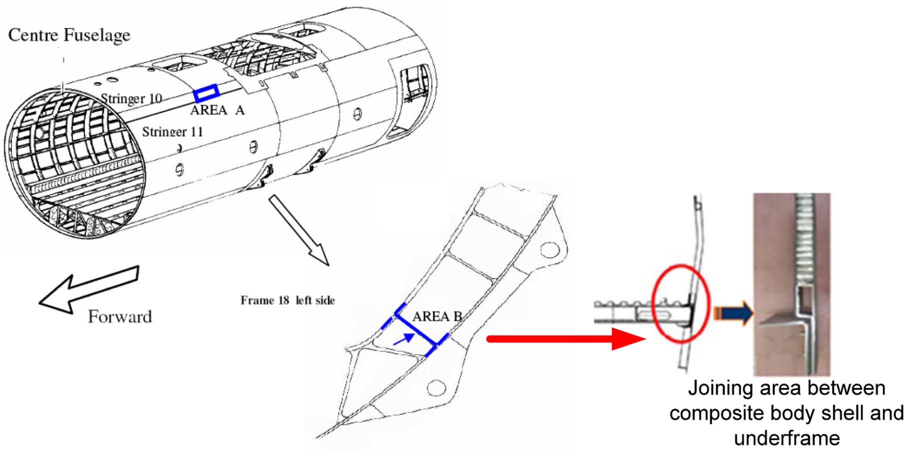

Fig. 30 FBG sensors installed in fuselage and stringers to measure aircraft load (Camerlingo *et al*. 2006)

the stringer (area A) and the lug connected with the sandwich-like structure (area B) (Camerlingo *et al*. 2006). This suggests the feasibility of integrated FBG sensors at train carbody joints between the side sill and the side frame (right side in Fig. 30) for obtaining not only strain but also acoustic emission (AE) signals for structural health monitoring.

As for fiber optic AE sensing, a simultaneous multipoint AE sensing system using modified FBG sensor heads (fiber acoustic wave grating sensors, FAWGSs) and a narrowband tuneable laser has been developed (Lee *et al*. 2008). The results (Fig. 31(d)) show the AE waves detected in the vibrating composite plate by simultaneously operating FAWGSs during all events. This evidence supports the feasibility of the system as an *in situ* integrated health management system for the composite train carbody.

5. Conclusions

To inform systematically the health and operation monitoring technologies for trains, their

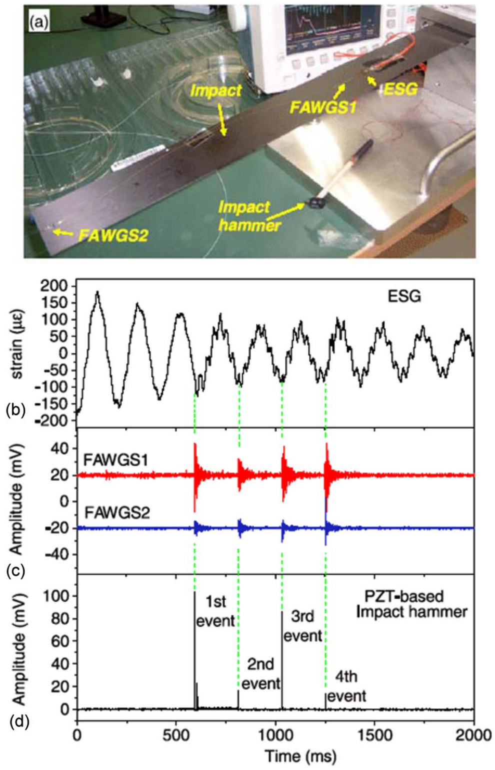

Fig. 31 Impact event detection in the vibrating composite plate: (a) experimental setup, (b) strain history during the free vibration measured with the ESG, (c) impact waves detected by FAWGSs and (d) impact events detected by an impact hammer with a PZT (Lee *et al*. 2008)

structure and damage types were summarized and then the sensing locations to detect such damages were analyzed based on the literatures related to the conventional tests. Then the health and operation monitoring technologies are classified into wayside detection and integrated sensing methods which covers on-service and challenging technologies.

A review of train structures and damage has shown that wheelsets incur damage at relatively high frequency due to high loads from the carbody and high stress concentration at wheel-rail contact points. In addition, a train is a multi-body dynamic system; thus, one component defect may lead to another and eventually result in system failure. Therefore, hot spots on the components of the carbody and underframe were also analyzed.

In terms of health and operation monitoring systems, wayside detection methods mostly monitored structures using non-contact or indirect inspection, in which all detection devices were installed along the side track or the rail. The results obtained by non-contact hot box detection, acoustic bearing defect detection, and laser ultrasonic methods were proximate in predicting the current state of the structures. In addition, fiber optic and electrical strain gauge sensors were also used for in-contact health and operation monitoring such as wheel imperfection detection, or wheel impact analysis and train operations, where the sensors were mounted on the rail to acquire the strain signals. On-board real-time bearing defect detection systems have recently been developed (by the AAR and FRA), in which accelerometers and thermocouples were mounted on the bearing.

With the advancement of optical fiber sensing systems, many research teams have demonstrated the feasibility of implementing optical fiber technology into railway structures. In our review, strain signals obtained from the carbody shell indicated that FBG strain sensors were immune to electromagnetic interference. Invariably, thermocouple damage due to static electricity in the bearing could be solved with the FBG temperature sensor. Promising results have been obtained using fiber optic sensors; structural integrity assessment of carbody shells and weld joints based on strain monitoring, aging identification of a suspension system based on spectral analysis of measured strain, strain and temperature monitoring in a bogie spring blade, and temperature monitoring in railway overhead lines.

With the advantages of small size, accessibility and integration capabilities, FBG sensors could easily replace massive strain gauges and accelerometers for the *in situ* monitoring of dynamic train performance and the global and local damage to train structures using the integrated optical network for simultaneous multipoint strain, temperature, AE sensing, and so on. In particular, since the fiber optic sensors and optical non-contact sensors are not affected by a high electromagnetic environment and can provides longer lifetime than the target structure, they will be useful tools to innovate train structural health and operational management strategy. Therefore, we carefully conclude that development of enabling technologies for safety of the present and next high-speed trains should be focused on on-board fiber optic health and operation monitoring systems and automatic non-contact automatic optical inspection systems.

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