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Structural Health Monitoring for Trains: A review of damage detection methods

정시옌* 이정율**† 김정석*** 윤혁진***

Chong, See-Yenn Lee, Jung-Ryul Kim, Jung-Seok Yoon, Hyuk-Jin

ABSTRACT

Among all transportations, railway transports have been promisingly offering excellent energy conservation and travelling time. Inevitably, they become a main role in not only transport goods but also passengers. With leap in development of technology, trains have tremendously enhanced their services in terms of speed, accessibility and comfort. However, the safety and ride quality have become a main issue as the train speed increased. The higher speeds have led the structural dynamics and health must be monitored from time to time to ensure that they are in good condition to provide reliable ride. Among all monitoring systems, the structural health monitoring (SHM) systems are imperative important due to its capability of in-situ monitoring and inherently reduce the maintenance frequencies and the huge associated cost. In this paper, SHM systems and the related non-destructive test and evaluation methods were discussed. The types of damages related to train vehicles as well as the damage hot spots are also included in this paper.

1. Introduction

From the past decades, railway transports are one of the most used means for goods and passengers transportation. It is because they have been promisingly offering excellent in terms of safety, energy conservation, environmental protection, and travelling time [1, 2].

With leap of technology development, trains' services have been continuing enhance the speed, accessibility, comfort, and safety. Inevitably, many types of trains have developed like high-speed trains (HST), Maglev trains, commuter trains and rapid transit trains, respective on the services that they provide.

The optimization of travelling speeds and safety of trains are commonly focused by railway network owners and researchers [1, 3]. Reference 4 stated that the increasing of speeds will induce the increasing of the train derailment too. Thus, the higher speeds have caused the structural dynamics and health must be monitored from time to time to ensure that they are in good condition to provide reliable ride. Among all monitoring systems, the structural health monitoring (SHM) systems are imperative due to its capability of in-situ monitoring and inherently reduce the maintenance frequencies and the huge associated cost.

* 비회원, 전북대학교 항공우주공학과, 대학원생
**† 책임저자 : 비회원, 전북대학교 항공우주공학과, 교수
E-mail : leejrr@chonbuk.ac.kr
TEL : (063)270-4637 FAX : (063)270-2472
*** 정회원, 한국철도기술연구원, 연구원

In this paper, SHM systems and the related non-destructive test and evaluation methods were discussed. The types of damages related to train vehicles as well as the damage hot spots are also included in this paper.

2. Train Structure

Train is a series of rail vehicles that generally constitute of locomotives and cars or wagons. The locomotive is a powered vehicle, used to haul a train of unpowered cars to either conveyance passengers or freight and as an example high-speed train configuration is showed in Figure 1.

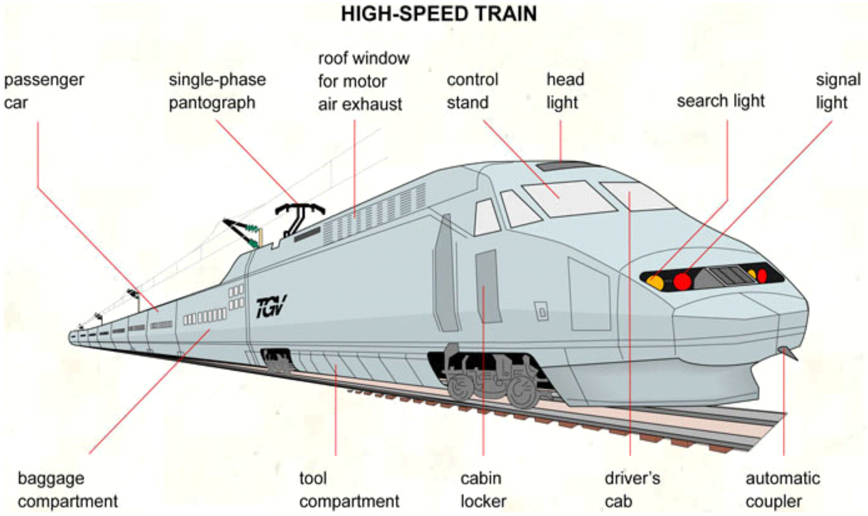


Figure 1 High-speed train configuration [5].

Generally, a train structure is built up by two main modules, carbody and bogie, as shown in Figure 2 and 3 respectively. Both of them are connected together through bolsters.

2.1 Carbody Structure

Carbody is a structure that constructed by:

1. Cab
2. Frames - side frame, end frame and underframe
3. Roof
4. Floor

The sturdy structure of carbody is built to protect the passengers and goods which hazardous or poisonous in case of an accident. In the past, the material that wide spread used was stainless steel to build carbody shells. However, due to its heavyweight, the lightweight aluminium was introduced later and used to streamline the traveling speeds and payload capacities. The carbody shells of 700 series Shinkansen (Japan) as shown in Figure 2 was used double-skin structure (aluminium-hollow extrusion). It has enhanced the comfort ride and the safety of passengers by reducing the noise and vibration level [6, 7], and the number of parts and welding length [6].

Carbody is mounted on the underframe which is connected together with bogies through the body bolsters. Figure 3 shows the topside and underside views of underframe and the parts names. Commonly, underframe is designed to protect the crews and passengers when come to crash especially at end sill by absorbing crash energy at the two end of carbody [8].

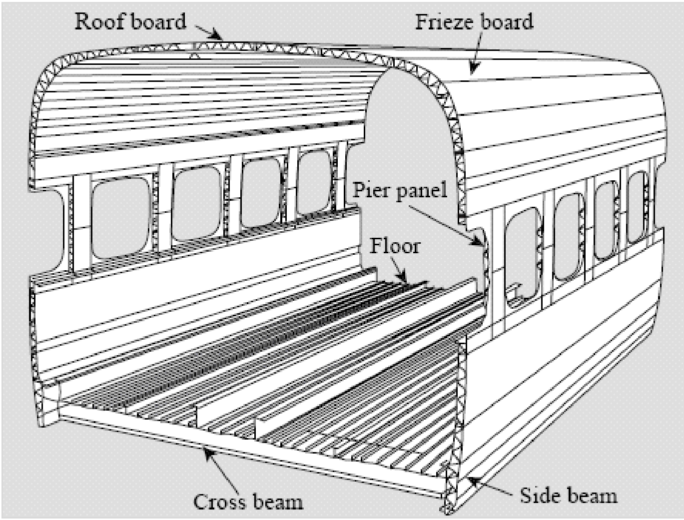


Figure 2 The carbody structure of 700 Series Shinkensan (Japan) [6].

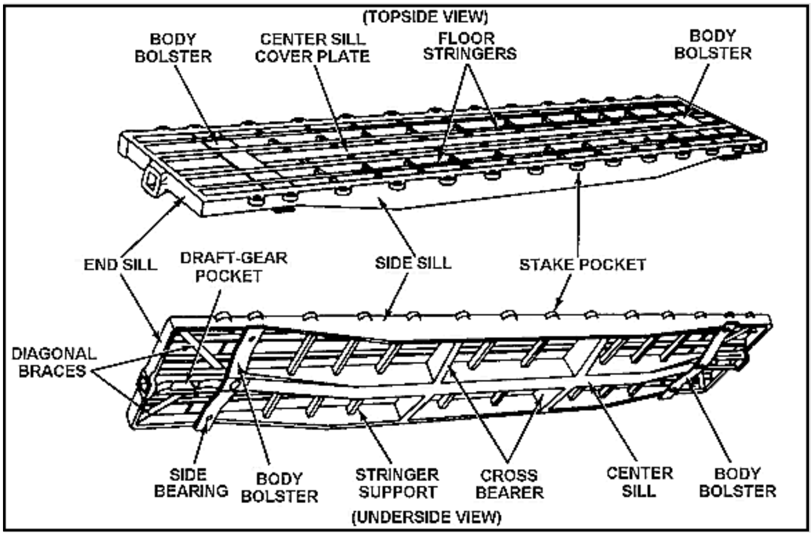


Figure 3 The diagram of underframe structure [9].

2.2 Bogie Structure

The main functions of bogies are to ensure the trains move safely along the railway and comfort ride for passengers by absorbing the vibration that generated by track irregularities [10]. The bogie are usually comprised:

(a) Bogie frames(sides frames)

(b) Wheelsets (wheels, axle, journal)

(c) Elastic suspension

(d) Carbody to bogie connection (bolster)

(e) Brakes

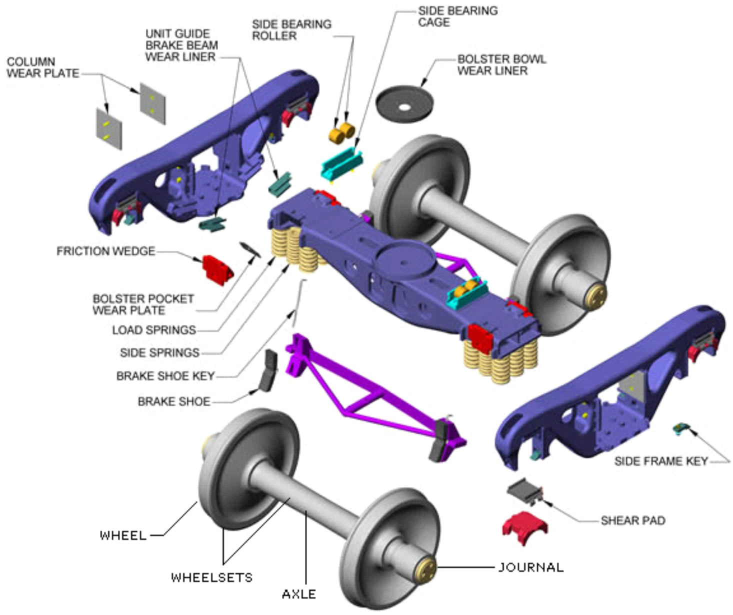


Figure 4 The components of bogie [11].

Basically, the wheelsets, elastic suspension, bolster and brakes are connected together to the two side frames as a bogie system and showed in Figure 4. Although, the wheelsets have many types design, but all these wheelsets have two common features: the rigid connection between the wheels through the axle and the cross-sectional profile of the wheel rolling surface, named wheel profile [10]. The main elements of a wheel profile are flange, tread and chamfer (Figure 5).

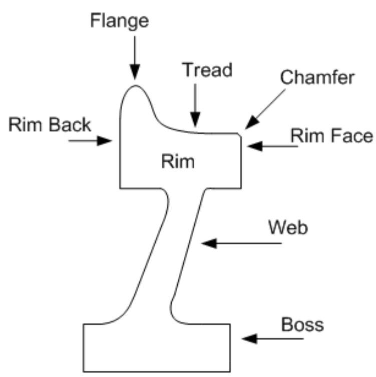


Figure 5 The elements of a wheel profile.

Figure 4 also shows a type of braking system that employed brake shoes to control speeds of trains and stop trains at the desired position. They generate large amounts of frictional heat at high running speeds and may present a risk of wear. Hence, another type of braking system, disk brakes is replaced the brake shoes and the brake discs configuration is showed in Figure 6. The brake discs are fitted on the wheelset and each disc has two faces joined by vanes to assist cooling. The forged steel disc brake is replaced by cast iron to prevent disc cracking caused by frictional heating especially for the high-speed railcars.

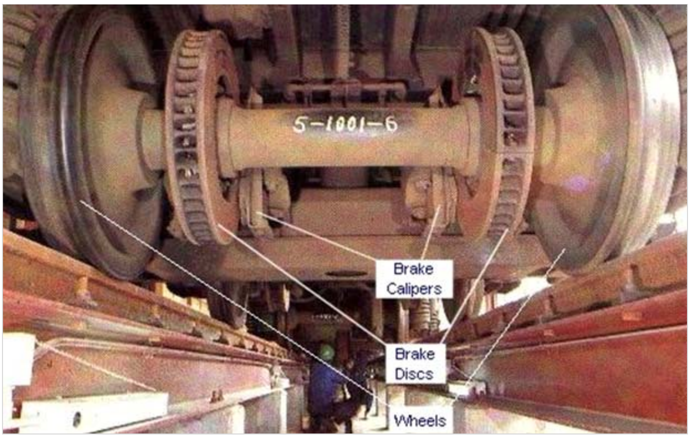


Figure 6 Braking system for discs plates [12].

3. Structure Damages

All train vehicles are designed by manufactures like Hitachi (Japan) are complied with the technical standard as established by the respective country [13] to provide the promising quality of trains structures that safe to ride. Indeed, when trains start serves their services, they will gradually deteriorate due to the structure life cycle and environment factors.

In addition, railway train is a complex dynamic system and running as a synergy system [10]. The train can run stable along on rail is due to the combination efforts of all train components especially carbody, bogie, brake system, suspension and wheelset. If one of the components is defect, this may lead to chain reaction damages among them and cause to derailment.

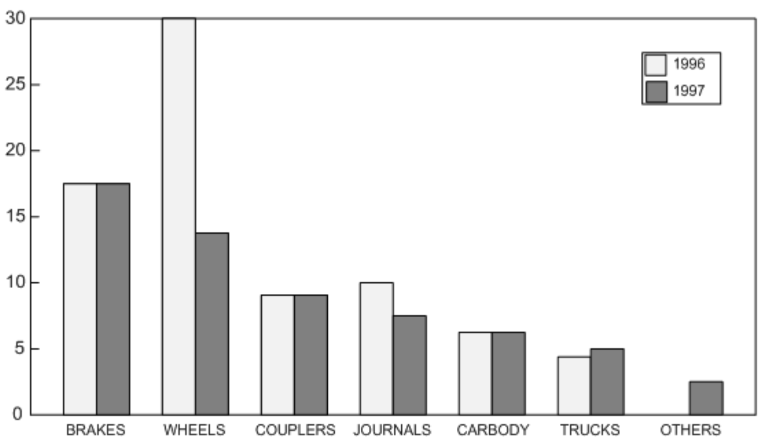


Figure 7 Train derailment on caused by mechanical components for year 1996 & 1997 [14].

Damage is defined as changes to the material and/or geometric properties of these systems, including changes to the boundary conditions and system connectivity, which adversely affect the system’s performance [15]. Conrail Corporate (Philadelphia, US) [14] had analyzed the types of mechanical caused derailments and the root causes in year 1996 and 1997 as shown in Figure 7.

The analysis was also reviewed inevitably that these components are the easiest to experience structural damages. There are many structural damages on trains and the summary of damages are tabulated in Table 1.

Table 1 Summary of damages of trains [14, 16-26]

Components	Damages
Wheel	Wear, slit fat, build-up tread, surface crack, spalling, shelling, breaks, cracks, plastic deformation
Bearing	Wear, spun core, corrosion, breaks, cracks
Axle	Cracks, corrosion
Axle box	Crack
Brake shoes	Uneven wear on the top and bottom brake shoe thickness
Center bowls (bogie)	Wear
Side bearers (bogie)	Wear

In trains system, the wheel-rail contact is a complex and imperfect link. The wheels are usually the component that always faces the highest concentrated stresses at the contact surface from axle loads [16, 26]. With this nature, the defects are frequently happened on the wheel surface, flange and tread. The wheel defects are caused by the malfunctions brake system and rolling contact [14, 18, 27, 28].

The malfunctions brake system are the release handbrake failure, brake control valve failure, or brake pad wear. These will cause the wheels rolled instable on the rail. This instability incident are called as wheel impact and wheel sliding that cause the wheel defects, plastic deformation, wear, rolling contact fatigue (RCF) crack, and others (Table 1). The damage mechanisms, wear and plastic deformation are the main contributor to wheel profile change.

In wheel-rail contact zone, the plastic deformation on the wheel profile is because repeated high friction load acted on the same zone. When beyond the elastic shakedown limit [17-20], the wear and RCF cracks will in wheel. The wear is the loss and the displacement of material from a contacting surface [17] and wear in wheel is usually occurs on wheel profile, flange and tread.

The rolling contact fatigue cracks are classified into two (a) subsurface-initiated and (b) surface-initiated. The high traffic intensity and axle load on the wheels are the main cause for surface-initiated cracks and usually occurred on the tread surface [17-19] (Figure 8). The subsurface-initiated cracks are caused by metallurgical defects and also named as shelling (Figure 9).

These RCF cracks will cause wheel impact and wheel sliding, and the damages will further magnify if no immediate remedy taken and will lead to other parts of components that associated with like rail, bearings, axles and etc., will defects too. In Canada, 2004, Canadian National train derailed while rolling over the crossover between the passing track and the main track. Figure 10 showed the broken rim of the wheel that cause the incident [31].

Figure 8 Tread spalling [29].

Figure 9 Tread shelling [30].

Figure 10 Fracture of rim of wheel [31].

Bearing works relatively close to the wheelset as the wheels are rolling and the wheel impacts that caused by flat spot on the tread, will shorten the bearing life-cycle due to the vibration on the surface contact between bearing roller and axle journal [14]. Consequently, the bearing will defects and it has classified into three types (a) spun cones, (b) water etched surface, and (c) broken roller. Spun cones occurs when a bearing with a loose inner raceway due to the wear on the bearing. Wheel impact may one of main factor that cause thedefect due to flat out-of round wheel, build-up tread or flat spot on thread. The rate of the bearing defect is associated with the speed of train [14, 21].

Lubricant handling is a factor and poor handling will cause the bearing defects [22, 23]. The irregular amount of the lubricant pumps into the bearing may cause additional wear. The wear in race or roller cage and solid surface are caused by the excessive lubricant and lack of lubricant respectively. Water etched surface is caused by the contaminated lubricant especially with water is being used in the bearing. With the water adding into the bearing, rust was formulated inside the bearing roller or raceway. Thus, it increases the corrosive potential and lead the etched and pitted surfaces from corrosion. Due to the chain reactive failure, the wear on surface increase due to the high friction forces between the contact between roller and raceway. Consequently, the roller will fatigue and broke. Figure 11 shows the axle and the damaged inner ring of inner bearing on a freight wagon.

Figure 11 The damaged cage of inner bearing [24].

Axle is the place that always acted by high stress especially at wheel seat and gear seat [32] and expose to weather change. This has shorten its life cycle and eventually cracks and corrosion on the surface. With the frequent wheel accelerating and deccelerating, the brake shoe easily uneven wear on the top and bottom brake shoe. The surface wear also defects bogies side bearers and center bowls frame.

4. Hot Spot

The trustworthy of data acquisition is imperative to optimize the accuracy level of structural damages analysis. Hence, the placement of sensors must install at the appropriate place and subsequently it reduces the number of installed sensors where have been placed at the inappropriate place. Inherently, it helps to save cost and reduces the data processing time.

(a) Axle

The initial cracks are always happen at wheel seat and gear seat which mounted with axle and showed in Figure 12.

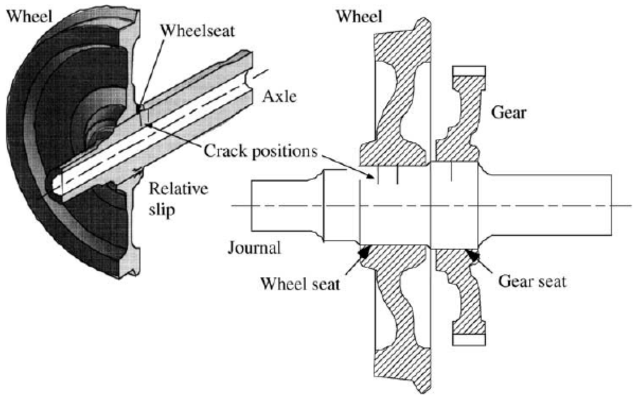
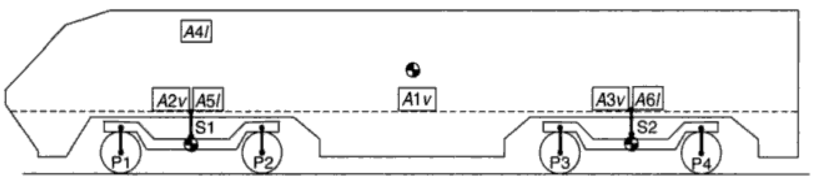


Figure 12 Typical positions of crack initiation at a railway axle [32]

(b) Carbody

Conventionally in the dynamic performance test [33], the accelerometers and displacements transducers are placed to the body, bogies and suspension, for ride test, passenger comfort, or dynamic response track tests as shown in Figure 13. This is important for the monitoring system to determine the vibration frequency of the carbody, so that, it will alert the operators before reach threshold point of natural frequency of carbody to prevent any structural damages.



A*x*v - vertical accelerometers, A*x*l lateral accelerometers, P*x* primary suspension LVDTs, S*x* secondary suspension LVDTs (Linear variable differential transformer).

Figure 13 Simple transducers placement layout to body [33].

The layout of sensors placements is able for us to acquire correct data for bounce mode at the center gravity (A1v) that responses to the track input. For A2v and A3v which placed on floor are used to determine bounce and pitch modes responses. A5l and A6l on the floor above the bogie center pivots are used to detect the lateral and yaw responses. Last, A4l is used to detect the combination of body yaw, lateral, and roll modes.

(c) Underframe

In crashworthiness, the accelerometers are placed on the underframe like center sill, body bolster, draft sill, end beam, and side sill [34] as shown in Figure 14. In the same principle, the sensors placement layout are able to use for the structural health monitoring purpose. The loads which acted on the underframe can be detected and then damages can be avoided.

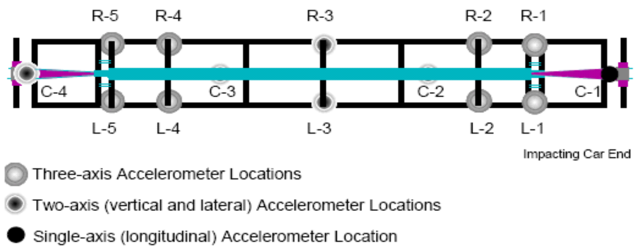


Figure 14 Schematic layout of accelerometer locations [34].

5. Structural Health Monitoring (SHM)

Structural health monitoring is defined as the process of implementing a damage detection strategy for engineering infrastructure related to aerospace, civil and mechanical. The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of structure health [35].

One of the SHM for railway vehicles is wayside detection. Wayside detection is a techniques of detecting specific faults on rolling stock by interrogating sensors placed along the sides of tracks. It monitors critical parameters relating to the condition of in-service railway vehicles. The vehicle performance will send to a railway's computer network and vehicle conditions are then reported through one of the many communication means available [20]. The types of detector are classified as:

(a) Wheel impact monitors
(b) Wheel profile detectors
(c) Weigh in motion
(d) Hot box detectors
(e) Sliding wheel detectors
(f) Acoustic bearing defect detection
(g) Skew bogies and hunting vehicle detectors
(h) Crack wheel detectors

Conrail Corporate [14] has employed the wayside detection to monitor the health of trains structure and it has improved the defect detection accuracy caused derailment from year 1996 to 1997 as shown in Figure 6.

(a) Wheel Impact Monitors

Wheel impact monitors are used to detect the defective wheels like flat spots, chipped-off tread surface, or spalling. Thus, the out of round shape wheels will induce high impact loads on wheel-rail contacts. With these characteristic, two sensors strain gauges and accelerometers are used to detect the transferred loads at the rail head. The strain gauges and accelerometers are normally mounted on the web and the foot of the rail respectively.

(b) Wheel Profile Detectors

There are two ways to inspect the change of wheel profile, they detect the change (a) based on mechanical indication and (b) base-on laser scanning images. However, both are used to detect wear on wheels. In mechanical profile monitors, the flange height is measured by a mechanism which presses a plate against the flange. The height of the wheel flange, relative to the rail head can provide an indication of both the radial profile of the wheel and the amount of wear and showed in Figure 15.

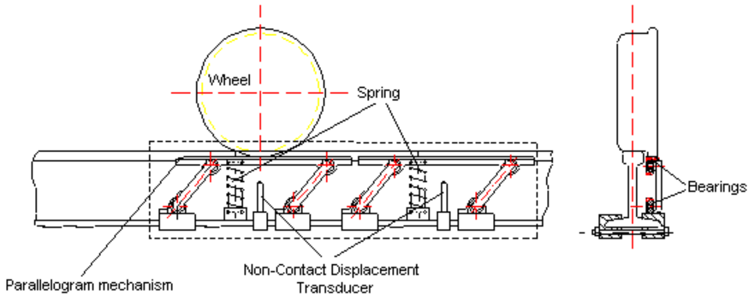


Figure 15 Schematic illustration of measuring the wheel flat and abrasion [36]

Figure 16 shows another types of wheel profile change detector. On the left side, the system is installed with mounted cameras and lasers at rail level. This is to make the image capturing can be done when train passing through. In this detector, the system is used two lasers and cameras to make scanning and images capturing respectively. The images will send to the computer system and process the images. After the analysis, statistical reports will be generated and will show the distribution of parameter values and wear rates by axle, vehicle unit and train fleet. Reference 37 has run the test and proved accurate to within 0.5 mm for checking moving vehicles.

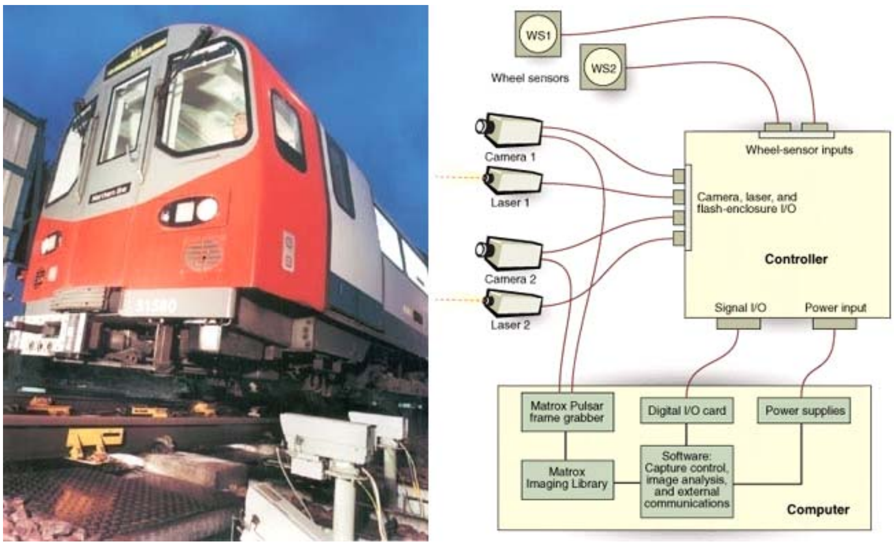


Figure 16 The VieW vehicle inspection system mounted at rail level (left side) and system schematic (right side) [37].

(c) Weigh in Motion

Basically, the system is to detect the axle load where the strain gauges sensors mounted on the rail. This is because by measuring the bending of the rail web or foot with the sensors will give the measurement of axle load. However, this detector can be replaced by the wheel impact monitoring systems because the later are capable of determining both the static axle load and the dynamic wheel load [20].

(d) Hot Box Detector

The detector is used to detect the heat emitted by the bearing and report the imminent failure. Normally, high temperature generated when bearing is defect. In early, thermoresistor was used to detect the heat emitted from the journal bearings. But later, it has been replaced by pyroeletronic sensors due to its accuracy detection is low [20]. The inboard scanners are mounted on the two sides rails (Figure 17) and are positioned to aim at the inboard side of the journal bearings when the train passing through. The middle inboard which mounted on the sleepers is to detect hot axle. The detectors also use for high speed photon scanner and the response time is two thousand times faster than a heat sensitive resistor. Thus, they are used to detect bearing and axle temperature of high-speed and qausi high-speed trains [21, 38].

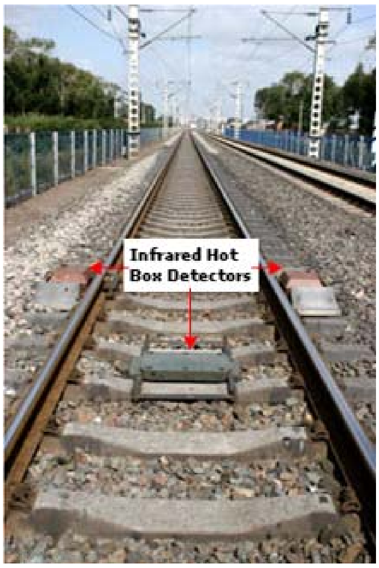


Figure 17 HTK-499 Infrared hot box detecting system [38]

(e) Sliding Wheel Detectors

The sliding wheel is normally caused by the malfunction brake control valve where the wheel will be locked up and caused the heat concentrates at the interface between the wheel and the rail. With this characteristic, infrared line scan camera is used to capture heat image to detect the heat distribution on the wheel [14, 20]. The heat distribution on the heat image is showed even on a wheel when the brake retardation is normal. Thus, the system is not only able to detect wheel sliding, but also the malfunction brake control valve.

The detector is also use another way to detect the sliding wheel based on mechanical roller. The detector is mounted on the rail as showed in Figure 18. The roller is placed near to the rail as will pressed in contact with flange for each time the wheel passing. The directions of rotation of the roller are the indication for wheel sliding occurrence. When the direction of rotation is same as the direction of train travelling, then it does indicating the occurrence of wheel sliding [14, 20].

Figure 18 The rail mounted sliding wheel detector [39].

(f) Acoustic Bearing Defect Detection

Reference 14 and 21 stated that vibration sound is emitted when the bearing is defects especially spun cones. In has the early, accelerometers were used to record the vibration sound. However, it was replaced by another method by install microphone which next to the track. The microphone is triggered and records the acoustic signature from the bearing by the train when train passing at track speeds [14]. In Reference 40, neural network algorithm for bearing defect detection was used to enhance the accuracy with which defects are detected and to determine the type of damage.

(g) Skew Bogies and Hunting Vehicle Detectors

Truck hunting is characterized by rapid sustained side-to-side motion of the trucks in a car and it imposes excessive lateral forces on the track structure thereby accelerating track degradation. Lateral strain gauges are applied to the rail and monitored by a data collection system. Truck hunting also can be detected by using lasers [14] to measure angle of attack to track position of a wheelset at different location along the rail. It is possible to infer the behavior of the bogie is hunting.

Progression Rail Technology [41] has design Truck Hunting that utilizes a series of non-contacting proximity sensor placed on the rails (Figure 19) to measure the trajectory of a wheel set through a test zone. The system analyzes an axle’s lateral displacement data to determine if it exhibits an oscillating pattern consistent with truck hunting. If such a pattern is detected then an alarm report is automatically generated and transmitted as required.

Figure 19 Non-contacting proximity sensor mounted in bracket on rail [41].

(h) Cracked Wheel Detectors

In generally, the wheel has to disassemble from the vehicle for the wheel crack inspection. Thus, nondestructive testing methods using ultrasonic wave is used to inspect the possibility of wheel cracking. Barke and Chiu [14] describes a nondestructive inspection method – ultrasonic nondestructive testing methods the Hackenberger and Lonsdale [42] suggested using one of ultrasonic nondestructive testing method – an array of water jets to test the wheel for defects. It was found that the pitch-catch method had the greatest sensitivity then using pulse attenuation. In addition, it was discovered that the shear wave produced better detection sensitivity than the longitudinal wave by detect a 1.2 mm wide cut of major and minor dimensions 34 and 7.1 mm, respectively.

6. Conclusion

The reviewed train structure and their damages have showed that the high frequency of damages was at the wheelsets due to the high loads from the carbody and make high concentrated streess on the wheelsets especially wheel-rail contacts. The train is a multibody dynamic systems, thus, a component defects may lead to another and eventually cause the whole system failure. In addtion, the accessibility of the parts for inspections is very difficult and make no choice have to dissamble the parts.

The current SHM, wayside detections have discussed. All the detections were mostly used non-contact inspection to test the condition of the wheelsets. The nondestructive testing, ultrasonic testing methods were also used in the wheels cracks testing. The carbody structural health inspection is not include in the wayside detections. Although the analysis showed the cause of derailment mainly is caused by the wheelsets, but structural health of the carbody cannot be ignore. This is because carbody is the body which direct protect the passengers and freight.

With the strong case, the SHM for carbody should further developments by using others nondestructive testing that can provide promising results to keep the train safe to ride.

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