Chapter

Smart Monitoring of Flat Wheel in Railway Using Optical Sensors

Preeta Sharan, Manpreet Singh Manna and Inderpreet Kaur

Abstract

The need for improved safety, reliability and efficiency is one of the most important aspects of the railway industry worldwide. Optical sensors can be used in smart condition monitoring system that can allow real time and continuous monitoring of the structural and operational conditions of trains. Railway monitoring is carried by the use of Fiber Bragg Grating sensors which measures strain, vibration, temperature, acceleration in continuous manner. This chapter covers introduction and working of optical sensors, Finite Element Analysis of rail-wheel geometry and health monitoring of rail wheel. FBG as optical sensor is well known for its advantages such as easy multiplexing, wavelength encoding and multiparameter sensing, immune to electromagnetic interference, reliability, flexibility. Sensitivity of optical sensor in compare to traditional sensors goes as 1.2 pm/με and 10 pm/με for strain and temperature sensor at 1550 nm of wavelength.

Keywords: Rail Wheel Geometry, Wheel Flat, Strain Analysis, Fiber Bragg Grating Sensors

1. Introduction

An optical sensor converts light rays into electronic signals. It can be used as a smart condition monitoring system in different fields such as civil, mechanical, electronics, biomedical for real time and continuous monitoring. Many parameters of railways uch as weighing of wagons, constant speed and direction of the train can be tracked and monitored in continuous manner with the help of optical sensor. Health monitoring of rail and wheel is another important aspect which is covered in this chapter. Railway monitoring is carried by the use of Fiber Bragg Grating sensors which measures strain, vibration, temperature, acceleration in continuous manner [1–5]. Different sections of chapter covers introduction and working of optical sensors, application of FBG in railways, study of rail-wheel geometry by various methods and last is defects in wheel and how optical sensor detects it.

2. Fiber Bragg Grating

A Fiber Bragg Grating sensor is a distributed Bragg reflector, i.e. a periodical variation of refractive index, inside the core of optical fiber, able to reflect a particular wavelength of light and transmit all the others. WhenFBG is subjected to external factorssuch as pressure, vibration, temperature, stress and strain, refractive index and grating period varies, there will be corresponding changes in the reflected wavelength. Since the parameter of measurement is the wavelength of light which is not affected by electromagnetic fields, the process is immune to electromagnetic interference and hence is intrinsically more stable than any electrical monitoring system as explained in [6]. The reflected wavelength can be calculated as

$$\lambda_B = 2n_{eff} \wedge \quad (1)$$

Here λ_B is Bragg's Wavelength, is effective refractive index and Λ is periodic variation of FBG. **Figure 1** shows the general schematic diagram of Grating sensor and spectral response of the Fiber.

Bragg Gratings can be written into single mode fiber with inner core diameter 5 to 9 μm and cladding diameter of 125 μm. Core is made up of silicon doped with germanium whereas cladding is pure glass material. Due to this there is high difference in refractive indexes between inner core and cladding thereby making light to propagate inside the inner core only. In [7] fabrication method is given using Holographic method and Phase Mask Method. Phase mask method is commercially used to fabricate optical fiber as in holographic method more stable setup is required with good coherence light source. In Phase mask technique fiber is exposed to a pair of interfering UV beam then there are regions of constructive interference and destructive interference, the first region corresponds to high UV intensity and refractive index will increase whereas in destructive interference intensity of UV light is negligible, there is no index change. This exposure to an interference pattern will result in a periodic modulation of refractive index along the core of the fiber and gratings are formed which reflects a particular wavelength of light and transmits all others. The reflected wavelength is known as Bragg's Wavelength.

2.1 FBG as optical sensor

Fiber Bragg Grating can be used as various sensors based on the fact that Bragg Wavelength changes with the change in refractive index or period of the grating as given in [8]. Here it is explained how Bragg grating is applicable as strain and temperature sensor, pressure sensor and stress sensor. When FBG is subjected to various external parameters such as pressure, strain, temperature, displacement, load and vibration there is a change in the period of grating, either elongates or compressed and effective refractive index also varies, due to this there is a shift in Bragg wavelength. **Figure 2** describes the reflectivity response, explained in [8].

FBG can measure strain and temperature by means of detecting changes in the reflected wavelength of light which can be calculated as given in Eq. (2).

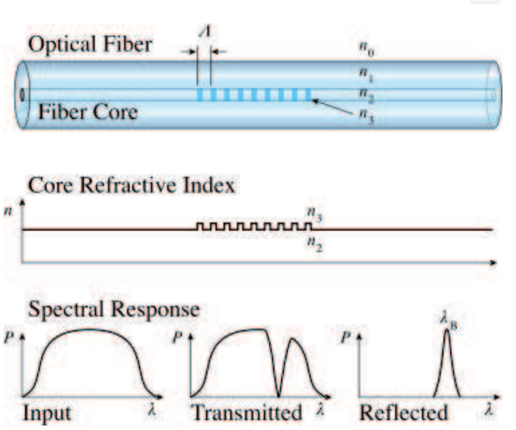

Figure 1.
Fiber Bragg Grating structure within the core of Optical Fiber.

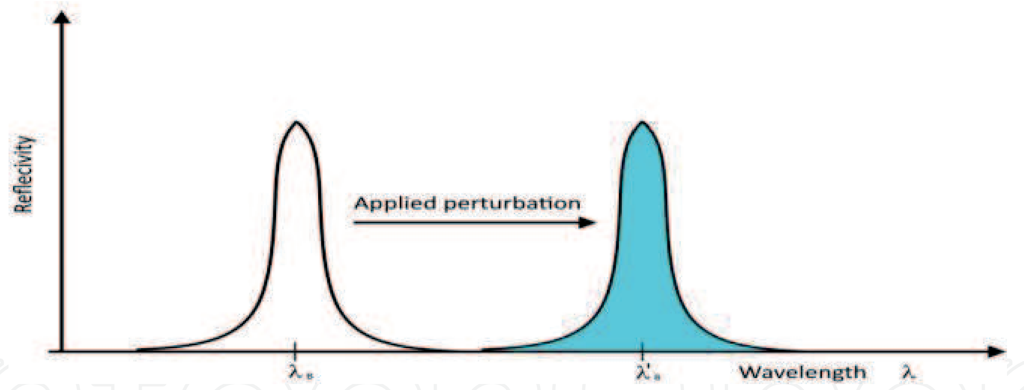

Figure 2.
New Reflectivity Response of FBG with the change in wavelength.

$$\Delta\lambda B = \lambda B\left(1 - \mathrm{Pe}\right)\Delta\varepsilon + \left(\alpha + \zeta\right)\Delta\mathrm{T} \tag{2}$$

Where Pe is photo elastic coefficient of the fiber, α and ζ are thermal expansion and thermo optic coefficient of the fiber material, $\Delta\lambda B$ is new wavelength. At 1550 nm centre wavelength, the wavelength strain and wavelength temperature sensitivities are 1.2 pm/με and 13 pm/°C. For measuring axial strain along the fiber due to applied pressure P is given in Eq. (3)

$$\varepsilon = \frac{\mathrm{P}\left(1 - 2\upsilon\right)}{\mathrm{E}} \tag{3}$$

here, ε is strain, P is pressure, v is Poison Ratio and E is Young's Modulus. The intrinsic pressure sensitivity of a bare FBG is only 3.04 pm/MPa, which is too low for the practical pressure measurement, methods proposed to enhance the pressure measurement sensitivity indirectly, such as embedding FBG in polymer, soldering metal-coated FBGs on a free elastic cylinder, and attaching the FBG fiber to a diaphragm given in [9].

2.2 Fiber Bragg Grating in railways

FBG can be used for health monitoring in railways as it can monitor different train parameters such as speed of the train, wagon weight, axle count and determine the rail-wheel condition and bogie health monitoring as given in [1, 2, 10]. Monitoring these parameters in railway continuously at minimum expenditure can help us to build a SMART RAILWAY SYSTEM for the betterment of mankind. This is possible by the use of Fiber Bragg Grating sensor which when compared with other electrical sensors such as strain gauges or accelerometers, optical fiber sensor has many advantages such as easy to install, more durability and reliability, cost effective, has multiplexing and de multiplexing characteristic and above all it is immune to electromagnetic interference.

In [3] how FBG act as novel optical sensor to detect flat wheel and weigh in motion is explained. Field trials have been carried out along the rail. FBG sensor clamped to rail, detects the vertical forces generated by the wheel rail contact in terms of wavelength shift in FBG. This shift gives a lot of information about the train in transit, such as wheels weight and their defective status in real time scenario. FBG as strain sensors gives the wavelength shift, characterized by a sequence of pulse. It is observed that pulse related to the wheels of engine gives large wavelength shift than the pulses of empty wagon. FBG for train axle count is described in [4]. Two parameters are considered here train detection and train control. Track circuits are used for train detection, by means of simple open and close circuit principles. FBG as optical fiber sensor detects number of axles when train passes over the rail. Sensor is installed on rail to measure the strain change in the rail upon the passage of trains. It is also given that a conspicuous and distinctive peak can be identified in the output strain signals measured by the grating sensor. In [5] optical Bragg Grating Sensor measures the ultrasonic guided waves in subway rail sample. Here FBG sensor detects the ultrasonic waves generated by the ultrasonic actuator placed along the rail, to detect cracks in rail. Two different approaches are used FBG sensor and piezo electric transducer (PZT) transducer to capture ultrasonic waves. The actuator was excited by 40 KHz Gaussian sine type with 13 cycles, 200Vpp amplitude. In compare to common PZT transducer, advantage of the use of FBG sensor is that it can be located far away from ultrasonic sensor as it can capture the waves transmitted at light speed without electromagnetic interference. It is concluded in this work that FBG sensors are capable to measure ultrasonic guided waves in rail transport monitoring.

3. Rail-wheel analysis

The railway train comprises of engine and number of wagons. The engine has 12 wheels, 6 axles. The wagon has eight wheels, 4 axles. This is the description of Indian Railways. Below **Figure 3** explains the rail cross section. Main parts of rail are

1. Upper region known as head of the rail, wheels of the wagon rotates on it.

2. Middle part between the head and foot is web region, mostly sensor is attached to this part.

3. Lower part is foot part

Rail track is an important part of the railways which gives persistent and level surface for movement of the train made up of steel. Rail act as guide for the wheels in a lateral manner. When wheels of the wagon rotates on the rail there are certain forces exerted on the surface of the rail and different static and dynamic stress and strain are developed on the rail. The stress distribution is an important factor at the rolling interfaces between rail-wheel which depends on the geometry of the contacting surfaces, loading and boundary conditions and material properties of wheel and rail as given in [11].

Defects on the rail surface occur due to the cracks generated by repeated passage of trains and may increase with time. When wheel rotates on the rail track the contact between the wheel and the rail, many problems may arise which are

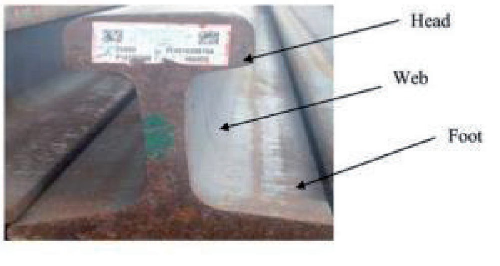

Figure 3.
Rail-wheel model.

DOI: http://dx.doi.org/10.5772/intechopen.97847

1. Flat spot on the wheel

2. Cracks on the rail

3. Thermo-elastic plastic behaviour in contact

The wheel and rail interaction can be carried out by different methods

a. Hertz contact theory

a. FEA Analysis using software

3.1 Hertz theory

Railway wagon is a complex mechanical structure with body, wheel and axle as three main parts. It has several degree of freedom which includes linear and non-linear springs and various types of damping system. When wheel rotates on the rail, different forces acting on the rail surface are vertical forces, horizontal longitudinal and transverse forces as given in [12].

Figure 4 gives the various forces acting on the railway track. The static force acting on the mass is the weight of bogie and car ($m_b + m_c$)gand Hertzian spring acting in the wheel/rail contact area is kHz. The 1/4 bogie model is a two-mass model, in which the other mass (mass of wagon m_b) is added over the mass in the 1/2 axle model that simulates the structure of the bogie, between the two masses is located the vehicle's primary suspension (k1, c1), and the static force acting on the superior mass is the weight of the car mcg.

Figure 5 describes the vehicle model as given in [13]. The 1/8 vehicle model is a three-mass model, in which the other mass (mass of wagon m_c) is added over the masses of the 1/4 bogie model that simulates the box of the vehicle, the vehicle's secondary suspension (k2, c2) is located between the upper masses.

3.2 FEA analysis using ANSYS software

Ansys 15.0 is a mechanical tool to perform finite element analysis (FEA) for structural analysis. Different types of model can be designed and analysed using this software [14]. The ANSYS software can be used for Finite Element Analysis of rail-wheel part. It has three working sub parts. They are

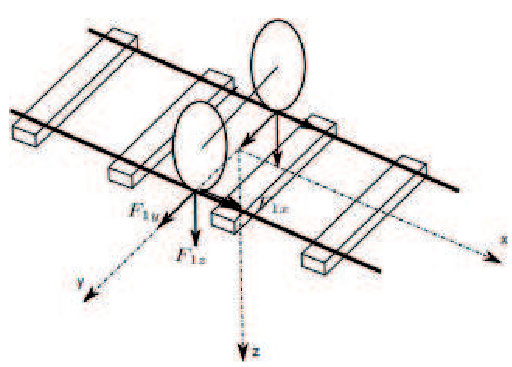

Figure 4.
Different forces applied on the rail.

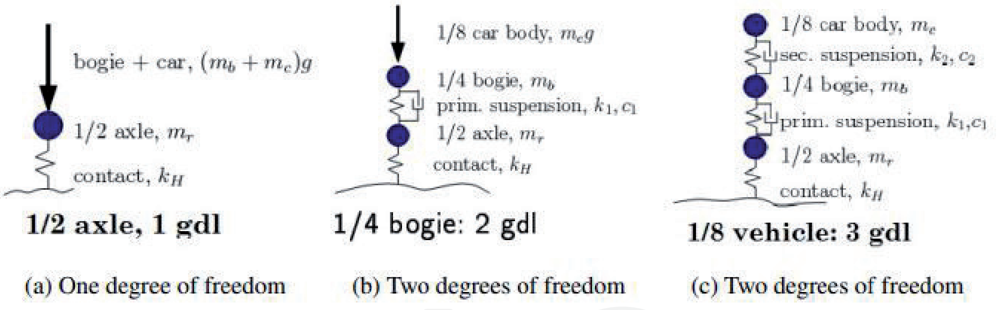

Figure 5.
Vehicle model.

A. In Preprocessor

i. Material properties are defined like structural steel, ballast, concrete.

ii. Element model is assigned.

iii. Build analysis model

B. In Processor

i. Boundary conditions are defined with the application of loads.

ii. Define the load characteristics.

iii. Control the convergence mode.

iv. Input parameters are taken here like pressure, bearing load, rotational velocity etc.

v. Start evaluation

C. Postprocessor

i. Evaluate the results.

ii. Draw diagram with results.

iii. List the results, note the values.

Mesh analysis of rail wheel model is given in **Figure 6**. Friction coefficient between the wheel and rail is 0.3. After defining material properties, the model

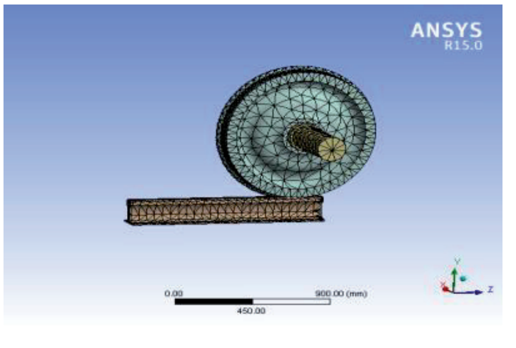

Figure 6.
Mesh analysis of rail and wheel.

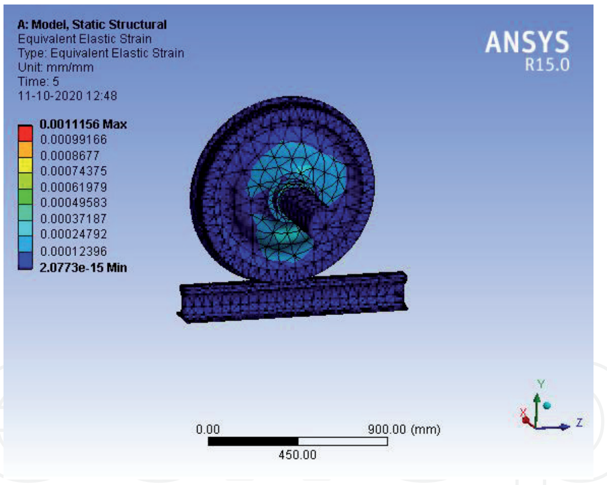

Figure 7.
Equivalent elastic strain.

is meshed. To obtain accurate results near the rolling contact surface, rail-wheel contact areaa fine mesh is done with element size 50 mm. **Figure 7** shows the output result of equivalent elastic strain.

To simulate 3D analysis of single rail wheel contact, following steps should be considered

1. Accurate modelling of railway parts wheel rail and sleepers

2. Material modelling, elastic or elastic–plastic, uniform and elastic

3. It is nonlinear and temperature independent

4. Boundary and loading conditions

5. Combinational, rotational and linear motion of wheel

6. Defining region of contacts to impacted elements

7. Considering straight track and standard rail profile

8. Defining nodal force and output parameters as equivalent elastic strain and stress with total deformation

4. Problems in rail-wheel: flat wheel

A wheel flat is a fault in the rail wheel shape, a geometric chord developed on the wheel surface caused when wheel slides on the rail or when wheel or axle has stopped rotating. There are many reasons for flat spot on the wheel which may include use of emergency brake or slip and slide conditions. Due to this wheel gets locked while train is in motion. Faulty brakes or wheel set bearings is another reason for flat spot. Wheel flat is also known as spalling or shelling or out of roundness. Flat spots on the wheel of the wagon is a primary cause of track and wheel quality deterioration as given in [15]. This is a very common problem which railway industry faces and leads to accidents. When a defect wheel rotates on the rail, large dynamic forces are produced, this increases acceleration levels on the track and vibrations are produced which is transmitted to the rolling stock. Force produce by flat wheel can damage the rail, suspension system, frame and also the body of rolling stock as given in [16]. If we look deeper into the mechanism of wheel flat loading, when the wheel with flat defect rotates on the rail, there is no contact between the wheel and the rail and it rises above the rail for a very short duration but recovery of this contact results in a high impact force which can damage the rail surface. **Figure 8** gives the mechanism of how flat wheel affects the rail. The vertical force of these wheels are ten times higher than the normal wheel as explained in [17]. Velocity of the train and weight of the wagon increases the dynamic forces produced by the flat wheel increases.

To detect wheel with out of roundness is an important task which have been carried out from past many years by researchers using various methods and different sensors. In [18] experimental analysis has been carried out in Lithuanian railways lines to measure the vertical force impact between the rail and the wheel. There are two types of sensors used, strain gauges to measure force and accelerometers to measure rail motion. Signal processors analyse the data to separate the wheel with flat irregularities. Here strain gauges act as wheel sensors that weigh each wheel of the train as it passes by. It has been observed that duration of the highest momentary force action in the wheel and rail contact depending on the velocity of the train is for few milliseconds and even less. This has been fixed by Wheel Impact Load Detector (WILD). Another method to detect wheel with flats is by using Fiber Bragg Grating optical sensor. As discussed earlier FBG sensors are widely used for their several advantages when compare to electrical sensors such as flexibility, durability, long life time and most important immune to electromagnetic interference and multiplexing property, many FBG with different grating on a single optical fiber. **Figure 9** shows the flats on the wheels restricted to 60 mm and depth 0.9–1.4 mm. In railways optical sensor can be easily installed along the track for various kilometres to detect several parameters of train. FBG readings is taken by the interrogator further connected to the computer.

In [19] Fiber Bragg Grating strain sensor has been used to study the vibrations from the passing train. **Figure 10** shows the reading of the sensor in terms of micro strain and time which is installed on the track with a passage of train with 12 wagons. Each wagon consist of 8 wheels, 4 axles, hence first four peaks on the left side correspond to first wagon. Here it is observed that wagon 6 and 8 have noisy or abnormal vibrations, hence the wheels of these wagon may have defects (**Figure 10**).

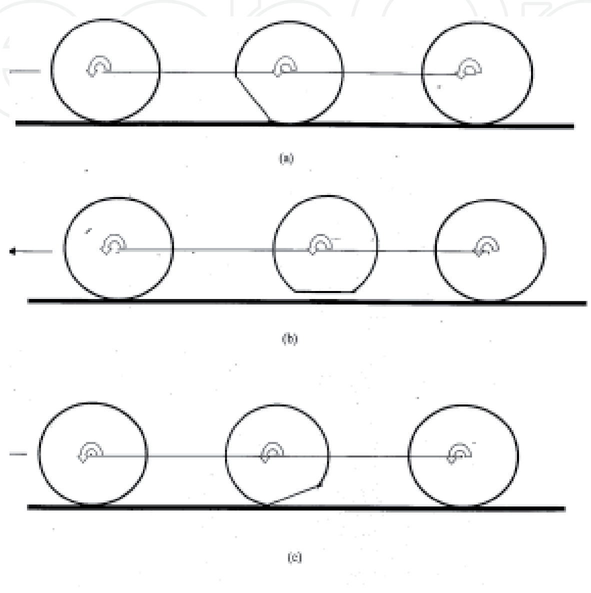

Figure 8.
Lift and hit motion of the wheel. (a) Rotation of flat wheel (b) centre wheel lift up (c) hit motion of wheel.

Figure 9.
Flat portion on the wheel.

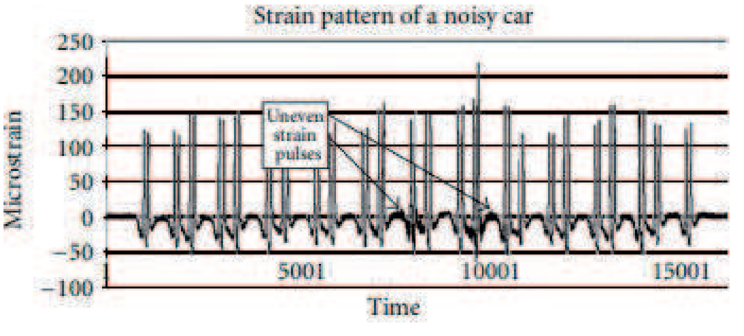

Figure 10.
Strain measured by Fiber Bragg Grating [19].

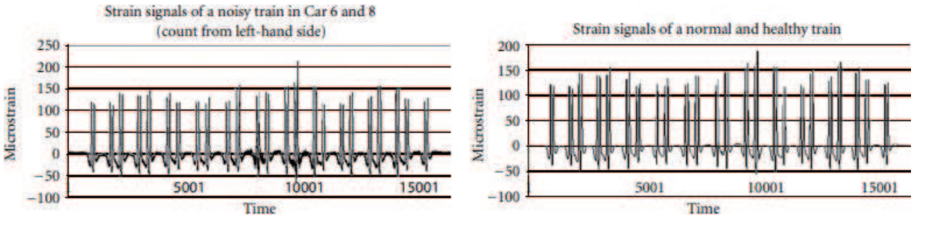

Figure 11.
Strain signal from noisy train and normal train [19].

Strain measurement at the track shows that the noisy trains may have imperfect wheels. It can be noted that defect wheel will produce an uneven strain impulse on the track as shown in **Figure 11**. Good wheel strain signal will be even and periodic in nature.

Fiber Bragg Grating as strain sensor is an effective means to distinguish between healthy and unhealthy wheels. It measures the strain in terms of shift in Bragg's wavelength and detects the vibrations from noisy trains which can be analysed further to find wheels with flat spot.

5. Conclusion

In this chapter, the basic rail wheel model is given and how we can analyse using various mechanical tool is explained, output includes elastic stress and strain and total deformation produced between the rail and contact. Various parameters in railway is considered and problems related to it are discussed in this chapter. The readings of Fiber Bragg Grating sensor in flat wheel can be further used for signal processing by using filters such as Low Pass Filter, High Pass filter to remove noise in the output and data acquisition by which we can study various parameters of wheel and rail and can also monitor the rail wheel condition. It can be concluded that in real time various dynamic parameters of train like speed, gross train weight, axle weights, axle spacing can be determined by strain monitoring data which optical sensor Fiber Bragg Grating can read.

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