Review study of irregularity track monitoring based on inertial measure unit and power spectral density analysis

Istiar and H Widyastuti

Civil Engineering Department, Institut Teknologi Sepuluh Nopember, Jl. Arif Rahman Hakim Surabaya 60111

E-mail: istiar@yahoo.com; h.w.dyas@gmail.com

Abstract. The maintenance of railway in Indonesia is determined by the track quality index (TQI). Analysed of TQI is based on track geometric inspection data. Currently, track geometric inspection uses a Track Geometric Vehicle (TGV) or Track Recorded Vehicle (TRV). The TRV’s provide accurate geometry measurements. But, it was expensive to run, may disrupt regular train services during their operation, need for occupation of track limit the number of measurement operations undertaken annually and optical sensors are sensitive to the dirt, found in the railway environment. TRV’s data was analysed by statistical function of the standard deviation to determine of TQI. TQI has some disadvantages, for example, it cannot represented the wavelength contents of the geometry defect, which is related to the particular issue in train-track interaction. Therefore, it is necessary to propose effective, efficient and reliable track quality assessment method. This paper will review some irregularity track monitoring methods that were probably used to track monitoring in Indonesia.

1. Introduction
The existence of railroad infrastructure must be able to guarantee the safety of train service. In 2018, most of train accident in Indonesia was derailment. Derailment was caused by irregularity track geometry [1]. Train accident would affect in disruption of train service. In order to keep the trains running without disruptions, an efficient maintenance policy based on risk assessment of the different components of the infrastructure is essential to anticipate problems before they occur [2].

The maintenance of railway in Indonesia is determined by the track quality index (TQI). Analysed of TQI is based on track geometric inspection data. Currently, track geometric inspection uses a Track Geometric Vehicle (TGV) or Track Recorded Vehicle (TRV). Track geometry was accurately measurements by TRV but are expensive to do, both in terms of operators side and the measurement system still worked correctly [3]. However, these vehicles may disrupt regular train services during their operation (O’Brien et al., 2016), high running costs and the need for occupation of track limit the number of measurement operations undertaken annually [4], and optical sensors are sensitive to the dirt, found in the railway environment [3]. Therefore, it is necessary to propose effective, efficient and reliable track quality assessment method.
Real-time automated monitoring systems are beneficial in terms of the effectiveness of condition monitoring in identifying maintenance issues in any structural health monitoring system (Malekjafarian et al. 2015 in [6]). Over last few decades railway vehicle dynamics has changed from being fundamental mechanical engineering discipline to one that utilizes sensors, electronics devices and computer processing [7]. The sensor reviewed on this paper is inertial measurement unit (IMU). Inertial measurement unit (IMU) usually used for track geometry monitoring system was accelerometer and gyro-meter. Accelerometer recorded moving acceleration an object in three axis. While gyro-meter measured orientation and angular velocity an object in three axis.

All recorded data by TRV was used for track quality index (TQI) analysing in Indonesia, track maintenance system commonly use the Track Quality Index (TQI) method, which is a statistical analysis of the standard deviation of each irregularity track. TQI has some disadvantages, for example, it cannot represented the wavelength contents of the geometry defect, which is related to the particular issue in train-track interaction [8]. So, PSD can be consider as a method to analyse track quality index in Indonesia. The application of Power Spectral Density in railway inspection is relatively new [8]. Various countries such as USA, China, France and Germany have modelled their own spectra of railway track irregularity. Various studies the use of IMU in-service railway vehicles and the use of PSD in the analysis of track irregularity have been proposed. Those studies are described in the next sections.

2. Monitoring track irregularity from in-service railway vehicles
An inertial measurement unit (IMU) is an electronic device that measures and reports a body's specific force, angular rate, and sometimes the magnetic field surroundings the body, using a combination of accelerometers and gyroscopes, sometimes also magnetometers.

Some researchers have been propose IMU as sensor to monitor track irregularity. [3] used accelerometer and gyro-meter to record dynamic response of vehicle. Two vehicles were measured the dynamic response, Tyne and Wear Metro and Class 175 in UK. Inertial measurement unit (IMU) were installed on axle-box and boogie. The detail location of IMU installation were showed on Table 1 and Table 2.

| Designation | Description | Range     |
|-------------|-------------|-----------|
| $z_{L, \text{axlebox}}$ | Vertically sensing accelerometer on rear-left axle-box | ± 100 g |
| $z_{R, \text{axlebox}}$ | Vertically sensing accelerometer on front-right axle-box | ± 100 g |
| $z_{L, \text{bogie}}$ | Vertically sensing accelerometer above rear-left axle-box | ± 10 g |
| $z_{R, \text{bogie}}$ | Vertically sensing accelerometer above front-right axle-box | ± 10 g |
| $\Delta z_L$ | Displacement (6a) to 8 | ± 38 mm |
| $\Delta z_R$ | Displacement (7a) to 8 | ± 38 mm |
| $\phi_{\text{bogie}}$ | Pitch-rate gyro installed on bogie | ± 50° s-1 |
| $\theta_{\text{bogie}}$ | Roll rate gyro installed on bogie | ± 50° s-1 |
| $\psi_{\text{bogie}}$ | Yaw rate gyro installed on bogie | ± 50° s-1 |
| $y_{\text{bogie}}$ | Laterally sensing accelerometer installed on bogie | ± 10 g |
| $z_{\text{body}}$ | Vertically sensing accelerometer over instrumented bogie installed on body | ± 4 g |
| $v$ | Voltage proportional to vehicle speed | 0 – 23 m/s |
Table 2. Installed sensors equipment on Class 175 [3]

| Designation | Description | Range |
|-------------|-------------|-------|
| \( z' \) bogie | Vertically sensing accelerometer (somewhat offset laterally) installed on bogie | ± 10 g |
| \( y' \) bogie | Laterally sensing accelerometer installed on bogie | ± 10 g |
| \( \varnothing \) bogie | Pitch-rate gyro installed on bogie | ± 50° s⁻¹ |
| \( \vartheta \) bogie | Roll rate gyro installed on bogie | ± 50° s⁻¹ |
| \( \Psi \) bogie | Yaw rate gyro installed on bogie | ± 50° s⁻¹ |
| \( z' \) body | Vertically sensing accelerometer over instrumented bogie installed on body | ± 4 g |
| \( v \) | Voltage proportional to vehicle speed | 0 – 10 V |
|  |  | 0 – 45 m/s |

An accelerometer installed on a bogie or axle-box senses acceleration roughly perpendicular to the trajectory of the sensor through space, see Fig 1.

![Figure 1. Side View Trajectory coordinate system [3]](image)

The sensed acceleration arising from following the instantaneous curvature of the trajectory is showed by:

\[
a = \frac{v_x^2}{R} = v_x^2 K, \quad K = \frac{a}{v_x^2}
\]  

(1)

where \( a \) is the (instantaneous) acceleration, \( R \) the radius of curvature, and \( K \) the curvature. In a similar way, assuming that the pitch of the bogie is basically the same as the angle from horizontal of the track under the middle of the bogie, it can obtain an approximate relationship between trajectory curvature and pitch-rate.

\[
\varphi = \frac{v_x}{R} = v_x K, \quad K= \frac{\varphi}{v_x}
\]  

(2)

where \( \varphi \) is pitch-rate. The prediction of vertical displacement related with the curvature, is obtained by double integrating the curvature with respect to displacement along the track:

\[
z = \int \int K \, ds \, ds
\]  

(3)

A plan-view trajectory can be described by the instantaneous (horizontal) curvature \( K(s) \) as a function of displacement \( s \) along the trajectory, as illustrated in Fig. 2. Lateral accelerometer installed on a bogie, inspects curvature through the centripetal force experienced by the accelerometer. Yaw rate gyro installed on a bogie inspects curvature from the turning rate of the bogie yaw. An accelerometer sensing acceleration perpendicular to a trajectory, inspects the instantaneous curvature according to:
\[ \alpha = \frac{v_x^2}{R} = K^a v_x^2, \quad K^a = \frac{a}{v_x^2} \]  \hspace{1cm} (4)

where \( a \) is the lateral acceleration, \( R \) the radius of curvature, \( K^a \) the accelerometer-derived curvature, and \( v_x \) the vehicle speed along the track. A yaw rate gyro offend the curvature of the trajectory through the bogie, ignoring the yaw and lateral resonances, according to:

\[ \Psi = \frac{v_x}{R} = K^\Psi v_x, \quad K^\Psi = \frac{\Psi}{v_x} \]  \hspace{1cm} (5)

![Figure 2. Horizontal coordinate system [9]](image)

Results from [3] showed effective vertical irregularity monitoring, specially the ability to monitor vertical irregularity over a wide range of vehicle speeds down to about 1 m s\(^{-1}\), where vertically accelerometers combined with displacement transducers are unable to function correctly. In principle, either bogie lateral acceleration or yaw rate can be processed to give a prediction of mean lateral track irregularity, but a yaw rate gyro provides consistent prediction down to lower vehicle speeds than does an accelerometer and does not require compensation for the impact of bogie roll. An improved prediction can be obtained by inverting the dynamic relationship between the mean track alignment and bogie yaw movement.

Another track geometry parameter predicted by IMU data was cross-level. Cross-level is the height difference between the left and right rails on a track. In the research of [10], cross-level data was collected by a number of spring nest displacement (SND) sensors. The sensors equipment installed between the bogie and the axle box as shown in Figure 3 (b). The readings of these sensors were a combination of relative extension/compression between the bogie and the wheel set, roll of the bogie and roll of the wheelset. This is illustrated in Figure 4.
Figure 3. (a) Instrumentation of the passenger wagon to measure track condition and dynamic response. (b) Detailed view of the Spring Nest Displacement Sensor measuring primary suspension behaviour. (c) Roll rate sensor to measure the bogie roll. (d) Tri-axial accelerometers and roll rate sensors to measure the dynamic response of the wagon body [10].

The mean measurement on the left and right wheels of a wheelset of the SND sensor gives the measurement of the relative extension/compression between the bogie and the set (mean (SNDleft, SNDright)). The absolute roll ($\phi$) of the bogie was the result of integration of the roll rate sensor measurement. The displacement contribution at SND from the bogie roll was determined by used the roll ($\text{SND}_{\text{Broll}} = w \times \sin(\phi)$). $w$ is the distance from the centre of the bogie to the attachment point of the SND sensor. Knowing the roll of the bogie and the raw measurement of the SND sensor, the relative extension/compression between the bogie, the roll of the cross level between the left and right rail can be calculated as shown in Equation 6.

Figure 4. Primary suspension motion represented as a sum of (a) vertical compression/extension (b) Wheelset Roll (c) Bolster Roll [10]

$$\text{CL} = (\text{SND Raw}_{\text{left}} - \text{mean(SND}_{\text{left}}\text{SND}_{\text{right}}) - \text{SND}_{\text{Broll}}) + (\text{SND Raw}_{\text{right}} - \text{mean(SND}_{\text{left}}\text{SND}_{\text{right}}) + \text{SND}_{\text{Broll}}) \quad (6)$$
3. Power Spectral Density (PSD) Analysis

Several countries such as Britain, Germany, USA and China have made comprehensive evaluations of the track irregularity spectrum (Zhipping and Shouhua, 2009 in [8]). Each country had specific characteristics of the track measured, which affect to analytical expressions of the PSD function. Those studies are described in the following sections.

3.1. The FRA PSD Standards (United States)

In USA, railway track was classified into 9 categories of track classes by the US Federal Railroad Administration (FRA). Classes 1 to 6 are designed for general tracks and Classes 7 to 9 are designed for high speed railways. One-sided power spectral density (PSD) function was used to described the random track irregularity for each track classes. The function is only applied to the wavelength range of 1.524 m to 304.8 m. Because the measurement equipment had limitation in the field measurement (Liu et al., 2011 in [8]). The empirical formula of PSD is as follows:

For vertical alignment:

\[ S_{av}(\Omega) = \frac{k \cdot A_{v} \cdot \Omega_{c}^2}{\Omega^2 (\Omega^2 + \Omega_{c}^2)} \] (7)

For lateral alignment:

\[ S_{al}(\Omega) = \frac{k \cdot A_{a} \cdot \Omega_{c}^2}{\Omega^2 (\Omega^2 + \Omega_{c}^2)} \] (8)

For gauge and super elevation irregularity (cross level):

\[ S_{gauge/cl}(\Omega) = \frac{A \cdot k \cdot A_{v} \cdot \Omega_{c}^2}{(\Omega^2 + \Omega_{c}^2) \cdot (\Omega^2 + \Omega_{c}^2)} \] (9)

where:

- \( S_{av} (\Omega) \) = PSD of track vertical alignment irregularity [cm²/(rad/m)]
- \( S_{al} (\Omega) \) = PSD of track lateral alignment irregularity [cm²/(rad/m)]
- \( S_{gauge/cl} (\Omega) \) = PSD of track gauge or super elevation irregularity (cross level) [cm²/(rad/m)]
- \( \Omega \) = spatial wave number (rad/m)
- \( \Omega_{c}, \Omega_{s} \) = critical wavenumber (rad/m)
- \( A_{v}, A_{a} \) = roughness coefficient related to the line grade (cm²*rad/m)
- \( k \) = a determined variable (≈ 0.25)

The spatial wavenumber (\( \Omega \)) is related to the frequency per time unit \( f_{h} \) (Hertz) by the following relation \( \Omega = 2 \cdot \pi \cdot f_{h}/v \). The parameters used in Equations (7) to (9) was presented in Table 3.

| Line Class | Max Line Speed | \( A_{v} \) (cm².rad/m) | \( A_{a} \) (cm².rad/m) | \( \Omega_{C} \) (rad/m) | \( \Omega_{S} \) (rad/m) |
|------------|---------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 1          | 16            | 24                       | 1.2107                    | 3.3634                   | 0.8245                   | 0.6046                   |
| 2          | 40            | 48                       | 1.0181                    | 1.2107                   | 0.8245                   | 0.9308                   |
| 3          | 64            | 97                       | 0.6816                    | 0.4128                   | 0.8245                   | 0.852                    |
| 4          | 97            | 129                      | 0.5376                    | 0.3027                   | 0.8245                   | 1.1312                   |
| 5          | 129           | 145                      | 0.2095                    | 0.0762                   | 0.8245                   | 0.8209                   |
| 6          | 177           | 177                      | 0.0339                    | 0.0339                   | 0.8245                   | 0.438                    |

Note: the coefficients of track classes 7 to 9 are not defined yet by the FRA.
3.2. German PSD Standard

Most of the European countries was used the German track PSD spectrum for dynamic simulations of railway vehicles (Zhiqiang et al., 2009 in [8]). The German track PSD spectrum is characterized by a single-sided spectrum. Irregularity track in the range of 0.01*2π to 0.4*2π (rad/m) was best representation of the German track PSD spectrum model (Zhang et al., 2010 in [8]). The PSD function is expressed by:

For longitudinal profile:

\[ S_v(\Omega) = \frac{A_p \cdot \Omega_c^2}{(\Omega^2 + \Omega_c^2)^2} \]  

(10)

For lateral alignment:

\[ S_a(\Omega) = \frac{A_a \cdot \Omega_c^2}{(\Omega^2 + \Omega_c^2)^2} \]  

(11)

For cross level or super elevation irregularity:

\[ S_{gauge/cl}(\Omega) = \frac{(A_p \cdot \Omega_c^2) \cdot \Omega^2}{(\Omega^2 + \Omega_c^2)^2 (\Omega^2 + \Omega_s^2)} \]  

(12)

\( S_v (\Omega) \) = PSD of track longitudinal profile irregularity [m²/(rad/m)]
\( S_a (\Omega) \) = PSD of track lateral alignment irregularity [m²/(rad/m)]
\( S_{gauge/cl} (\Omega) \) = PSD of cross level or super elevation irregularity [cm²/(rad/m)]
\( \Omega \) = \( 2\pi / \lambda \) denotes spatial wavenumber (rad/m)
\( \Omega_c, \Omega_s \) = critical wavenumber (rad/m)
\( A = 0.75 \) m (one half of track gauge)
\( A_p \) = scale factor for longitudinal profile (m²·rad/m)
\( A_a \) = scale factor for alignment (m²·rad/)

In Table 4 was showed the parameters for the above equations, which represent the track irregularity with low and high levels of disturbance.

| Parameters                  | \( A_a \) (10⁻⁷ m²·rad/m) | \( A_p \) (10⁻⁷ m²·rad/m) | \( \Omega_c \) (rad/m) | \( \Omega_s \) (rad/m) | \( \Omega_S \) (rad/m) |
|-----------------------------|-----------------------------|-----------------------------|------------------------|------------------------|------------------------|
| Low Disturbance             | 2.119                       | 4.032                       | 0.82                   | 0.0206                 | 0.438                  |
| High Disturbance            | 6.125                       | 10.8                        | 0.82                   | 0.0206                 | 0.438                  |

3.3. The Standard of Chinese PSD

The Chinese Academy of Railway Science (CARS) had published various spectra of track irregularities (also referred as PSD Standards). The standards of evaluation and diagnosis of track quality was suitable for three different operational speed classes: 200 km/h, 160 km/h, and 120 km/h (Xianmai et al., 2008 in [8]). The spectrum range of different operational speed classes is given to accommodate the disparity of spectral amplitude that may vary from one track section to another. The track condition with a certain spectrum is usually fitted with one of these ranges. The higher the track quality, the closer the spectral curve of the track section to the lower limit of the standard value. Conversely, the lower the track quality, the closer the spectral curve to the upper limit of the standard value.
The Chinese PSD function is described using single-sided spectrum, which depends on 6 coefficients as shown below:

\[ S(f) = \frac{af^2 + b}{cf^2 + df^2 + ef^2 + k} \]  

(13)

where \( S(f) \) denotes track irregularity PSD in unit [mm²/(1/m)] and \( f \) is wavenumber, often called spatial frequency of a wave, measured in 1/m.

The coefficients of spectral for Equation (13) are given in Table 5 to 7.

**Table 5.** The Parameters of Spectral for line speed design of 200 km/h (Xianmai et al., 2008 in [8])

| Track Irregularity          | a       | b       | c       | d       | e       | k       |
|-----------------------------|---------|---------|---------|---------|---------|---------|
| Gauge                       | Upper   | 362.2681| 0.2393  | 15370.86| 681.2174| 10.267  |
|                             | General | 54.0439 | 0.0357  | 8254.682| 365.8602| 5.5139  |
|                             | Lower   | 119.2536| 0.0783  | 36295.99| 1619.269| 24.2936 |
| Cross level (Super elevation deflect) | Upper | 951.449 | 2.1747  | 47442.79| 2121.78 | 25.473  |
|                             | General | 35.4842 | 0.0811  | 6369.446| 284.8838| 3.4199  |
|                             | Lower   | 238.6205| 0.5418  | 85347.97| 3842.441| 45.8306 |

**Table 6.** The Parameters of Spectral for line speed design of 160 km/h (Xianmai et al., 2008 in [8])

| Track Irregularity          | a       | b       | c       | d       | e       | k       |
|-----------------------------|---------|---------|---------|---------|---------|---------|
| Gauge                       | Upper   | 612.3768| 0.4046  | 8660.944| 383.8376| 5.7852  |
|                             | General | 213.1331| 0.1408  | 10851.22| 480.9504| 7.2484  |
|                             | Lower   | 187.2267| 0.1238  | 31792.31| 1407.659| 21.23   |
| Cross level (Super elevation deflect) | Upper | 1890.022| 4.2158  | 19981.09| 984.2226| 18.5928 |
|                             | General | 94.9519 | 0.2118  | 3613.811| 178.0026| 3.3627  |
|                             | Lower   | 511.6737| 1.1433  | 65036.82| 3191.977| 60.4676 |

**Table 7.** The Parameters of Spectral for line speed design of 120 km/h (Xianmai et al., 2008 in [8])

| Track Irregularity          | a       | b       | c       | d       | e       | k       |
|-----------------------------|---------|---------|---------|---------|---------|---------|
| Gauge                       | Upper   | 612.3768| 0.4046  | 8660.944| 383.8376| 5.7852  |
|                             | General | 213.1331| 0.1408  | 10851.22| 480.9504| 7.2484  |
|                             | Lower   | 187.2267| 0.1238  | 31792.31| 1407.659| 21.23   |
| Cross level (Super elevation deflect) | Upper | 1890.022| 4.2158  | 19981.09| 984.2226| 18.5928 |
|                             | General | 94.9519 | 0.2118  | 3613.811| 178.0026| 3.3627  |
|                             | Lower   | 511.6737| 1.1433  | 65036.82| 3191.977| 60.4676 |

**Table 8.** The Parameters of Spectral for line speed design of 80 km/h (Xianmai et al., 2008 in [8])

| Track Irregularity          | a       | b       | c       | d       | e       | k       |
|-----------------------------|---------|---------|---------|---------|---------|---------|
| Gauge                       | Upper   | 612.3768| 0.4046  | 8660.944| 383.8376| 5.7852  |
|                             | General | 213.1331| 0.1408  | 10851.22| 480.9504| 7.2484  |
|                             | Lower   | 187.2267| 0.1238  | 31792.31| 1407.659| 21.23   |
| Cross level (Super elevation deflect) | Upper | 1890.022| 4.2158  | 19981.09| 984.2226| 18.5928 |
|                             | General | 94.9519 | 0.2118  | 3613.811| 178.0026| 3.3627  |
|                             | Lower   | 511.6737| 1.1433  | 65036.82| 3191.977| 60.4676 |

The coefficients of spectral for Equation (13) are given in Table 5 to 7.
Table 7. The Parameters of Spectral for line speed design of 120 km/h (Xianmai et al., 2008 in [8])

| Track Irregularity          | a     | b     | c     | d     | e     | k     |
|-----------------------------|-------|-------|-------|-------|-------|-------|
| **Gauge**                   |       |       |       |       |       |       |
| Upper                       | 640.74| 0.4233| 6524.507| 289.1726| 4.3582| -0.0003|
| General                     | 255.976| 0.1691| 7819.645| 346.5745| 5.2233| -0.0004|
| Lower                       | 325.929| 0.2151| 28425.14| 1261.602| 18.9956| -0.0015|
| **Cross level**             |       |       |       |       |       |       |
| (Super elevation deflect)   |       |       |       |       |       |       |
| Upper                       | 1830.68| 7.3882| 20908.35| 1028.226| 30.9382| 0.008  |
| General                     | 110.624| 0.44649| 2527.1| 124.2566| 3.73927| 0.00097|
| Lower                       | 1077.07| 4.3434| 70234.04| 3460.22| 103.9562| 0.027  |
| **Alignment**               |       |       |       |       |       |       |
| Upper                       | 0.0   | 0.02622| 0.0   | 1.0   | 0.01893| 0.00003|
| General                     | 0.0   | 0.00874| 0.0   | 1.0   | 0.01893| 0.00003|
| Lower                       | 0.0   | 0.00306| 0.0   | 1.0   | 0.01893| 0.00003|
| **Longitudinal Profile**    |       |       |       |       |       |       |
| Upper                       | 0.0   | 0.01351| 0.0   | 1.0   | 0.00687| 0.0    |
| General                     | 0.0   | 0.00478| 0.0   | 1.0   | 0.00739| 0.0    |
| Lower                       | 0.0   | 0.00166| 0.0   | 1.0   | 0.00721| 0.0    |

*Note: Although PSD provides a limit range of the spectral amplitude, this does not mean that the track spectrum cannot be lower or higher than the threshold limit value. This range is proposed based on the expected amplitude span of the Chinese track irregularity spectra.*

3.4. SNCF PSD Standards (France)
SNCF proposed a PSD based on single-sided spectrum through an investigation on the railway track in France, which is suitable for vertical alignment. The equation used a function of cyclic wavenumber [cycles/m], described the track irregularities within the range of $2 \leq L \leq 40$ m [11]). The SNCF model is as follows:

For vertical irregularity:

$$G_{TT}(n) = \frac{A}{(1 + \frac{n}{n_0})^3}$$

(14)

where:

- $A$ = Indication of the state of rail surface [m$^3$] or [m$^2$/cycle/m])
  - $308 \times 0.509 \times 10^{-6}$ for good state
  - $308 \times 1.79 \times 10^{-6}$ for good state
- $n_0$ = Coefficient, equal to 0.0489 (cycle/m)
- $n$ = Cyclic wavenumber (cycle/m)

3.5. The Standard of Braun PSD
The International Organization for Standardization (ISO) formulate a uniform method to measure vertical surface of roads, highways, and off-road terrain. Braun, as cited by [11], has then adapted the road condition model from ISO to the context of the railway. The Braun PSD model has two value limits; upper and lower limit values, and it is based on single-sided spectra. The Braun model is described by the following equation:

For vertical irregularity:

$$G_{TT}(n) = G_{TT}(n_0) \times \left(\frac{n}{n_0}\right)^{-w}$$

(15)
where:
\[ G_{\Gamma}(n_0) = \begin{cases} 5 \times 10^{-7} & \text{for the upper limit} \\ 1 \times 10^{-7} & \text{for the lower limit} \end{cases} \]

\[ n_0 = \frac{1}{2\pi} \text{(cycle/m)} \]

\[ w = \text{waviness, with values usually ranging from 1.5 to 3.5} \]

\[ n = \text{cyclic wavenumber (cycle/m)} \]

4. Conclusion

Nowadays, irregularity track is determined by statistical analyses, based on track geometry vehicle measurement results. Statistical analysis of track geometry vehicle data cannot reflect the wavelength contents of the geometry defect, which is inherently related to the particular issue in train-track interaction. Irregularity track could be determined by inertial measurement unit (IMU), installed in service vehicle. Inertial measurement unit (IMU) usually used for sensor dynamic response, were accelerometer, gyro-meter and spring nest displacement sensor. The collected data of IMU was analysed by Power Spectral Density (PSD). So, the probability of research topic that could be proposed, based on review study was analyze track geometric index based on inertial measurement unit by power spectral density.

5. References

[1] Liu X, Saat R, and Barkan C P R 2012 Analysis of Causes of Major Train Derailment and Their Effect on Accident Rates TRB: J. Trans. Resc. Board 2289 154–163
[2] Jamshidi A, Roohi S F, Núñez A, Babuska R, De Schutter B, Dollevoet R, and Li Z 2016 Probabilistic defect-based risk assessment approach for rail failures in railway infrastructure IFAC-PapersOnLine 49(3) 73-77
[3] Westeon P F, Ling C S, Roberts C, Goodman C J, Li P, and Goodall R M 2007 Monitoring Vertical Track Irregularity from In-service Railway Vehicles Proc. IMechE 221 75-88
[4] OBrien E J, Bowe C, Quirke P, and Cantero D 2016 Determination of longitudinal profile of railway track using vehicle-based inertial readings Proc. Inst. of Mech. Eng. 231/5 518-534
[5] OBrien E J, Quirke P, Bowe C, and Cantero D 2017 Determination of Railway Track Longitudinal Profile Using Measured Inertial Response of An In-service Railway Vehicle Struct. Health Mon. 17(6) 1425-1440
[6] Quirke P, OBrien E J, Bowe C, Malekjafari A, and Cantero D 2018 Estimation of Railway Track Longitudinal Profile Using Vehicle-Based Inertial Measurements Int. Cong. And Exh. "Sust.Civ. Infr.: Innov. Infra. Geo. 145-148
[7] Chudzikiewicz A, Bogacz R, Kostrzewski M, and Konowrocki R 2018 Condition Monitoring of Railway Track Systems by Using Acceleration Signals on Wheelset Axle- Boxes J. Tran. 33(2) 555–566
[8] Berawi 2013 Improving Railway Track Maintenance Using Power Spectral Density (PSD) PhD Dissertation (Porto: Universidade Do Porto)
[9] Weston P F, Ling C S, Goodman C J, Roberts C, Li P, and Goodall R M 2007b Monitoring Lateral Track Irregularity from In-service Railway Vehicles Proc. IMechE 221 89-100.
[10] Nadarajah N, Shamdani A, Hardie G, Chiu W K, and Widyastuti H 2018 Prediction of Railway Vehicles’ Dynamic Behaviour with Machine Learning Algorithms Elect. J. of Struct. Eng. 18(1) 38 – 46
[11] Broeck 2001 A prediction model for ground-borne vibrations due to railway traffic PhD Thesis (Leuven: Katholike Universiteit Leuven)