Track geometry estimation of a conventional railway from car-body acceleration measurement

Mai ODASHIMA*, Shohei AZAMI*, Yasukumi NAGANUMA**, Hirotaka MORI*** and Hitoshi TSUNASHIMA****

* Graduate School of Nihon University
1-2-1 Izumi-cho, Narashino-shi, Chiba 191-8506, Japan
** Technology Research and Development Department, Central Japan Railway Company
1545-33 Ohyama, Komaki-shi, Aichi 485-0801, Japan
*** Traffic Safety and Environment Laboratory
7-42-27, Jindaijihigashi-cho, Chofu 182-0012, Japan
**** Department of Mechanical Engineering, Nihon University
1-2-1 Izumi-cho, Narashino-shi, Chiba 191-8506, Japan
E-mail: tsunashima.hitoshi@nihon-u.ac.jp

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Abstract

This study proposes a track condition monitoring technique using car-body acceleration that can be easily measured by an in-service vehicle for the sake of an increase in safety of railway transportation. This paper demonstrates the possibility of estimating track irregularities of conventional railway tracks using car-body acceleration only. The methodology proposed uses inverse dynamics to estimate track irregularity from car-body acceleration, applying a Kalman filter to solve this problem. This technique estimates the track irregularity in the longitudinal plane (track geometry and 10m-chord versine). The Kalman filter is able to apply to inverse analysis by expressing track geometry as a random walk model, and incorporating the model in an equation of state. The estimation technique can support a change of the vehicle velocity by selecting an appropriate impulse response in the measurement equation for the vehicle velocity. Estimation results in simulation and full scale tests revealed that the proposed estimation technique is effective for track condition monitoring with acceptable accuracy for conventional railways.

Key words: Railway, Condition monitoring, Track geometry, Kalman filter, Inverse analysis

1. Introduction

Track maintenance works based on irregularity recordings are essential in ensuring the safety and comfort of railway transportation systems. As track irregularity deteriorates the ride comfort and running safety of the rolling stock, hence track condition monitoring used to determine the level of maintenance required is one of the most important tasks for railway companies. Generally, track irregularity is measured several times a month by a specially designed track geometry recording rolling stock and track inspection teams. However, the measurement frequency of these methods is limited by problems of cost, track access rights and other maintenance issues.

Monitoring of railway track geometry from an ‘in-service’ vehicle has become an increasingly attractive proposition over the past decade (Weston et al., 2015). Track geometry measurement systems using in-service vehicles has been developed around the world but they are still in an early developmental phase. High frequency track inspections give an additional opportunity to characterize track geometry degradation throughout the seasons and over the full life of an asset. The obtained information can be fed back to the track maintainers to take any necessary action in an more efficient and targeted manner. Several kinds of track faults can be detected by measuring the acceleration of bogies. Weston et al. (2007a,2007b) demonstrated track irregularity monitoring using bogie-mounted sensors. Alfi et al. (2008) proposed a technique for estimating long wavelength track irregularities from on-board rolling stock measurements.
If track faults can be detected by sensors mounted in the vehicle body (‘in-cabin’), condition monitoring of track irregularities will be much easier due to removing the need to put costly and delicate sensors in the harsh environment of the bogie or wheelsets. However the distinctive signals of track faults are hidden in car-body vibrations due to the effects of the primary and secondary suspension. Advanced signal processing is therefore necessary of the accelerations measured in-cabin to detect track faults. Tsunashima et al. (2014) demonstrated the possibility to estimate the track geometry of high speed Shinkansen tracks using car-body motions only. A Kalman filter was applied to estimate track irregularity from car-body motions. A system that attempts to identify vertical and lateral track geometry irregularities using accelerometers placed on the car-body of in-service vehicles was proposed in (Tsunashima et al., 2011). This system also provides a function to listen for corrugation appearances using acoustic sensor (a microphone).

Further studies proposed a track condition monitoring technique using car-body accelerations measured by an in-service vehicle (Tsunashima et al., 2008, 2011, 2012). Additionally, this system is premising measurements by sensors mounted on service vehicle, with high frequency measurement and estimation possible, enabling preventive track maintenance planning. However, the car-body acceleration waveform is considerably different from track irregularity, and the amplitude greatly depends on the vehicle speed. Therefore, the track irregularity is required to be estimated from the car-body acceleration for the sake of the track condition monitoring.

In this study, an inverse problem method is applied to estimate the track irregularity as shown in Figure 1. This method is to estimate an unknown input signal (track irregularity) from a known output signal (car-body acceleration). Naganuma et al. demonstrated that a Kalman filter can be used to estimate vertical track irregularity from vertical car-body acceleration of a Shinkansen vehicle( Naganuma, et al., 2011 and Kobayashi, et al., 2012, 2014). The estimation technique using a Kalman filter is also applicable for conventional low and medium speed railways. In this paper, the Kalman filter based estimation technique is proposed for conventional railways and evaluated by simulation study and data collected in full scale trials.

**Fig. 1** Track irregularity estimation from car-body acceleration. In the forward analysis, track geometry is considered as a known input. However, in the inverse analysis, the track geometry should be estimated from vehicle vibration. In this study, the track geometry and its 10m-chord versine are estimated from the car-body acceleration using Kalman filter.

### 2. Outline of this study

In this study, this estimation technique is utilized to estimate the track irregularity in the longitudinal plane (track geometry and 10m-chord versine). The following simulation study steps (a) - (g) are taken to evaluate the proposed estimation technique which is shown in Figure 2.

(a) A vehicle simulation model expressed as second order differential equation is converted to the first order difference equation and an equation of state is obtained by discretization

(b) Create track geometry data that is similar to the actual track or use track recording car data

(c) Create a vehicle velocity profile expected for conventional railway operation

(d) Calculate car-body acceleration using the track geometry data (b) and the vehicle velocity data (c) from the vehicle model described in (a)

(e) Gaussian noise is added to the car-body acceleration to generate measurement data typical of that collected from sensors in full scale trials

(f) The track geometry and its 10m-chord versine are estimated from the ‘measurement’ data using the Kalman filter methodology

(g) Estimation performance is evaluated by comparing estimated track geometry (f) with the ‘true’ track geometry (b). 10m-chord versine are also compared and evaluated

Additionally, the following (a) - (e) shows steps that estimate track geometry from the measured car-body acceleration using Kalman filter.
3. Vehicle model and calculation of the car-body acceleration

3.1. Vehicle model

Figure 3 shows a railway vehicle model considered only in the vertical direction. This vehicle model represents a conventional railway vehicle with a vehicle body, two bogies and two wheelsets per bogie, parameters for which are shown in Table 1. Where $z_c$ is a car-body displacement, $z_{t1}$ and $z_{t2}$ are front and rear bogie displacement, $\theta_c$ is a car-body pitch angle, $\theta_{t1}$ and $\theta_{t2}$ are front and rear bogie pitch angle. Inputs, $r_{1a}$, $r_{1b}$, $r_{2a}$, $r_{2b}$, denote the vertical track irregularities. The equation of motion for 6 DOF railway vehicle running on a straight track can be written as

$$M \ddot{z}(t) + C \dot{z}(t) + K z(t) = D \ddot{r}(t) + E r(t),$$  \hspace{1cm} (1)
where

\[
M = \text{diag}\left[m_c I_c, I_{cl} I_{cl}^T, I_{ct} I_{ct}^T, I_{tr} I_{tr}^T, I_{t} I_{t}^T, I_{t} I_{t}^T, I_{l} I_{l}^T\right],
\]

\[
C = \begin{bmatrix}
2c_s & 0 & -c_s & 0 & -c_s & 0 \\
0 & 2c_s & -c_s & 0 & c_s & 0 \\
-c_s & -c_s & 2(c_p + c_s) & 0 & 0 & 0 \\
0 & 0 & 0 & 2c_p & 0 & 0 \\
-c_s & c_s & 0 & 0 & 0 & 2(c_p + c_s) \\
0 & 0 & 0 & 0 & 0 & 2c_p \\
\end{bmatrix},
\]

\[
K = \begin{bmatrix}
2k_s & 0 & -k_s & 0 & -k_s & 0 \\
0 & 2k_s & -k_s & 0 & k_s & 0 \\
-k_s & -k_s & 2(k_p + k_s) & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
-k_s & k_s & 0 & 0 & 2(k_p + k_s) & 0 \\
0 & 0 & 0 & 0 & 0 & 2k_p \\
\end{bmatrix},
\]

\[
D = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
c_p & c_p & 0 & 0 & 0 & 0 \\
c_p & -c_p & 0 & 0 & 0 & 0 \\
0 & c_p & c_p & 0 & 0 & 0 \\
0 & 0 & c_p & c_p & 0 & 0 \\
\end{bmatrix},
\]

\[
E = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
k_p & k_p & 0 & 0 & 0 & 0 \\
k_p & -k_p & 0 & 0 & 0 & 0 \\
0 & k_p & k_p & 0 & 0 & 0 \\
0 & 0 & k_p & -k_p & 0 & 0 \\
\end{bmatrix}.
\]

and \(z^T(t) = [z_c, l_c \theta_c, l_{cl} \theta_{cl}, l_{cl} \theta_{cl}, l_{ct} \theta_{ct}], r^T(t) = [r_{1a}, r_{1b}, r_{2a}, r_{2b}].\)

where \(M\) is the inertia matrix, \(C\) is the damping matrix, \(K\) is the stiffness matrix.

Discretizing the Equation (1) using numerical integration yields the following state equation and measurement equation

\[
x_n = F x_{n-1} + G u_n + w_n, \quad \text{(2)}
\]

\[
y_n = H x_n + v_n, \quad \text{(3)}
\]

where \(x_n\) is the state vector, \(u_n\) is the input vector, \(y_n\) is the output vector, \(w_n\) and \(v_n\) are process noise and measurement noise. \(F\) is the state transition matrix, \(G\) is the input matrix, \(H\) is the observation matrix.

For the discretization (data interval \(h\)), the Newmark \(\beta\) method was used \((\gamma = 1/2, \beta = 1/6)\) which is a linear acceleration method. The state transition matrix and the input matrix can be expressed by \(F = A^{-1} B\) and \(G = A^{-1} C\) using following \(A, B\) and \(C\).

\[
A = \begin{bmatrix}
I & 0 & -\beta h^2 \\
0 & I & -0.5h \\
K & C & M
\end{bmatrix}, \quad B = \begin{bmatrix}
I & h & (0.5 - \beta)h^2 \\
0 & I & 0.5h \\
0 & 0 & 0
\end{bmatrix}, \quad C = \begin{bmatrix}
0 & 0 \\
E & D
\end{bmatrix}.
\]
3.2. Calculation of the car-body acceleration

The car-body acceleration has been calculated using the vehicle model with a varying velocity profile. Figure 4 shows the track geometry and Figure 5 shows the corresponding vehicle velocity. The calculated car-body acceleration is shown on Figure 6. In this study, a Gaussian noise was added to the calculated car-body acceleration, and it was used as measurement data more representative of that found from full scale trials. The added Gaussian noise can be expressed by \( N(0, \sigma^2) \) with the standard deviation of \( \sigma = 1.0 \times 10^{-3}\text{m/s}^2 \).

![Track geometry](image1)

*Fig. 4 Track geometry used in the simulation. The track geometry is generated using shaping filter of first-order lag.*

![Vehicle speed profile](image2)

*Fig. 5 Vehicle speed profile. Speed profile for acceleration, coasting and braking operation are modeled.*

![Calculated vertical car-body acceleration](image3)

*Fig. 6 Calculated vertical car-body acceleration. It is generated by the 6DOF vehicle model (Figure 3) with the track geometry (Figure 4) and the speed profile (Figure 6)*

4. Track geometry estimation technique

4.1. State space model for the inverse analysis

This section shows estimation technique of track geometry from a measured signal on the car-body. A Kalman filter approach is a well-known estimation technique used in various fields. The track geometry is estimated from the measured car-body acceleration with measurement noise.
The equations for the Kalman filter fall into two part: time update equations and measurement update equations.

Time update equations:

\[ x_{n|n-1} = Fx_{n-1|n-1} + Gu_{n-1}, \]  

(4)

\[ P_{n|n-1} = FP_{n-1|n-1}F^T + GG^T, \]  

(5)

Measurement update equations:

\[ K_n = x_{n|n-1}H^T(HP_{n|n-1}H^T + R)^{-1}, \]  

(6)

\[ x_{n|n} = x_{n|n-1} + K_n(y_n - Hx_{n|n-1}), \]  

(7)

\[ P_{n|n} = P_{n|n-1} - K_nHP_{n|n-1}. \]  

(8)

\( Q \) is the covariance matrix of process noise. \( R \) is the covariance matrix of measurement noise.

In this approach, \( x_{n|n} = [x_n \ x_{n-1} \ \cdots \ x_{n-L+1}] \) is the track geometry, and \( y_n = [y_n \ y_{n-1} \ \cdots \ y_{n-L+1}] \) is the car-body acceleration. The inverse problem is to estimate the track geometry from the car-body acceleration. In a conventional state equation, the external input \( u_n \) is treated as a known deterministic input. However, in the inverse analysis, it is an unknown state to be estimated. Therefore, track geometries are defined as a random walk model with the external input \( u_n \) and the process noise \( w_n \). The state equation can be shown as

\[
\begin{bmatrix}
  x_n \\
  x_{n-1} \\
  \vdots \\
  x_{n-L+1}
\end{bmatrix} = 
\begin{bmatrix}
  0 & \cdots & \cdots & \cdots & 0 \\
  1 & \ddots & \ddots & \ddots & \vdots \\
  \vdots & \ddots & \ddots & \ddots & \vdots \\
  0 & \cdots & \cdots & \cdots & 1 \\
\end{bmatrix}
\begin{bmatrix}
  x_{n-1} \\
  x_{n-2} \\
  \vdots \\
  x_{n-L}
\end{bmatrix} + 
\begin{bmatrix}
  1 \\
  0 \\
  \vdots \\
  0
\end{bmatrix}(u_{n-1} + w_{n-1}).
\]  

(9)

The estimation technique has incorporated an impulse response calculated using the vehicle model in a measurement equation. The impulse response can be obtained by giving an impulse input to the Equation (2) with \( w_n = 0 \). As an example, Figure 7 shows the impulse response of 60km/h. When applying an impulse response to inverse analysis, the measurement equation can be given as

\[
y_n = \begin{bmatrix} h(0) & h(1) & \cdots & h(L) \end{bmatrix}
\begin{bmatrix}
  x_{n-1} \\
  x_{n-1} \\
  \vdots \\
  x_{n-L}
\end{bmatrix} + v_n.
\]  

(10)

The symbol \( h \) denotes the impulse response and the symbol \( L(=l_i/x) \) denotes the total number of impulse response. In this study, section length \( l_i = 80m \) is discretized with \( x = 0.1m \).

4.2. Generation of impulse response

In this study, an impulse response is calculated using the vehicle model for the sake of the inverse analysis. It should be noted that the vehicle characteristic is affected by the vehicle velocity. The impulse response is changed depending on the vehicle velocity so the inverse analysis can support a change of the vehicle velocity. In this study, impulse responses are tabulated at 1km/h increments and selected with reference to the vehicle velocity as shown in Figure 8 (Azami et al., 2014).

5. Estimation result of track irregularity

5.1. 10m-chord versine of track geometry

The wavelength band which affects the running safety and ride comfort is important for track maintenance. Therefore, the focus is on the 10m-wavelength track geometry that affect the running safety, it can be treated using as a 10m-chord
versine (mid-chord offset) method. This method emphasizes the 10m-wavelength track irregularity, and it is used in real maintenance. The 10m-chord versine method can be calculated by actual track geometry by following as

$$a(x) = b(x) - \frac{b(x + 5) + b(x - 5)}{2},$$

(11)

where, \(a(x)\) is the 10m-chord versine, and \(b(x)\) is the actual track geometry.

### 5.2. Estimation result

Figure 9 shows the estimation results of track geometry itself and its 10m-chord versine, also showing the true track geometry. This estimation result is obtained from the simulated car-body acceleration shown in Figure 6. The system noise variance is \(\sigma^2_u = 7.0 \times 10^{-2} m^2\), and the measurement noise variance is \(\sigma^2_v = 1.0 \times 10^{-3}(m/s^2)^2\) in this simulation. Those values are chosen so that the calculation gives a satisfactory result. The estimation is very smooth and consistent with the true 10m-chord versine, demonstrating that the estimation approach with Kalman filter is effective for the inverse analysis with acceptable accuracy. The estimated error of the 10m-chord versine was less than approximately 1mm. Track geometry is not estimated well. However, it is good enough to monitor the track condition using 10m-chord versine as it is used track maintenance.
Fig. 9 Estimation result of track geometry and its 10m-chord versine. True value (red) and estimated value (blue) are shown. It can be seen that the estimated track geometry is different from the track geometry itself in large wave length of track, but they have good agreement in the 10m-chord versine of track geometry. The bottom figure of Fig. 9 shows the estimated error in the 10m-chord versine of the track geometry.

5.3. Evaluation of estimation result using MPC metrics
We calculate the MPC metrics of the estimated track irregularity in 10m-chord versine using the Sprague and Geers correlation (Ray, et al., 2008). The MPC metrics can be expressed by following equations.

\[
\begin{align*}
M & = \sqrt{\frac{\sum e_i^2}{\sum m_i^2}} - 1, \quad (12) \\
P & = \frac{1}{\pi} \cos^{-1} \frac{\sum e_i m_i}{\sqrt{\sum e_i^2 \sum m_i^2}}, \quad (13) \\
C & = \sqrt{M^2 + P^2}. \quad (14)
\end{align*}
\]

The symbol \( e_i \) and \( m_i \) in equation represents the estimated value and measured value. The magnitude component \( M \) should be sensitive to difference in magnitude. The phase component \( P \) should be sensitive to difference in phasing. The component \( C \) is the combination with the magnitude and phase. These characteristics of MPC metrics allow the analyst to identify the aspects of the curves that do not agree. For each component of MPC metrics, zero indicates that the two waves are identical.

| Table 2 MPC metrics |
|---------------------|
|                     |
|                     |
|                     |
|                     |
|                     |

| Equations | Magnitude | Phase | Combination |
|-----------|-----------|-------|-------------|
| Result    | 0.0022    | 0.0278| 0.0279      |
Table 2 shows calculation results for the equations. It can be seen from Table 2 that the estimation performance in the phase is inferior to that in the magnitude. However, it is thought that the magnitude and the phase are small and the estimation performance is good enough (Tsunashima et al., 2014).

6. Track geometry estimation in field test

6.1. Track condition monitoring system

Figure 10 shows the compact on-board sensing device used in the track condition monitoring system (Mori, 2013 and Tsunashima, 2015 and Ogino, 2015) and the set-up of the on-board sensing device for field test. This device comprises three-axis acceleration sensors, a rate gyroscope, a Global Positioning System (GPS) receiver that is used to determine the train position and travel speed, and sensor interfaces that input sensor signals to a computer.

![Compact on-board sensing device and the field test set-up. Car-body acceleration was measured using the device. This device comprises three-axis acceleration sensors, a rate gyroscope, a GPS receiver that is used to determine the train position and travel speed.](image)

This device is battery-powered and capable of up to 6 hours of sustained operation. Thus, the device need only be placed inside a cabin to enable vehicle vibration measurements and does not require human supervision. If the vehicle is equipped with an on-board power supply, the device is capable of continuous measurement. Furthermore, the device is equipped with function for automatically transmitting measured data to a server via mobile phone network and writing data to a microSD card or other recording media. By further equipping the device with a microphone, it is also possible to "listen" to corrugation and diagnose the condition.

The measured data obtained from the measurement unit are transmitted to the analysis unit either by a mobile phone network or by writing to external media. The diagnostic results produced by the track monitoring software are used to provide feedback to railway operators through online channels via smartphones or tablet computers. Railway operators can use this information to establish the track maintenance priorities, thus facilitating the maintenance planning and work.

6.2. Field test

The actual measured data were obtained from rural railway lines using the developed track condition monitoring system. Figure 11 shows RMS values calculated from the measured car-body vertical acceleration. It should be noted that the largest RMS can be seen between 13.7km and 13.8km. Measured car-body vertical acceleration and vehicle traveling speed measured by GPS system between 13.7km and 13.8km are shown in Figure 12 and Figure 13 respectively.

6.3. Track irregularity estimation from measured car-body acceleration

The proposed track geometry estimation method was applied to estimate track irregularity in 10m-chord versine. Table 3 shows the vehicle parameters used in the estimation. Those parameters was determined so that the frequency response of 6DOF vehicle model agrees to that of measured car-body vertical acceleration.

Figure 14 shows estimated results of track irregularity in 10m-chord versine obtained by the proposed method. The estimated result is compared to the data obtained by track geometry recording car (TGC). In general, good agreement between those can be seen from the figure. However, some difference can also be seen especially at 13.751km. The proposed method estimate the track irregularity from car-body vibration which is affected by the external disturbances.
beside the track geometry. To avoid the effect of the external disturbances, statistical analysis with multiple measurement should be considered.

![Graph of RMS of vertical acc. vs Distance](image1)

Fig. 11 Measured vertical acceleration RMS of car-body. The measurement data was obtained using the on-board sensing device shown in Figure 10.

![Graph of Car-body acceleration vs Distance](image2)

Fig. 12 Measured vertical acceleration of car-body

![Graph of Vehicle traveling speed vs Distance](image3)

Fig. 13 Vehicle traveling speed measured by GPS system. The data also obtained from the on-board sensing device.

7. Conclusions

This study proposes the track condition monitoring technique using car-body acceleration easily measured by an in-service vehicle for the sake of increase in safety of railway transportation. This paper demonstrates the possibility to estimate the track irregularities of conventional railway tracks using car-body acceleration only. The Kalman filter based estimation technique is proposed for conventional railways and evaluated by simulation study. The research study has yielded the following conclusions:

- In this study, an inverse problem method is applied to estimate the track irregularity. This method is to estimate an unknown input signal (track geometry) from a known output signal (car-body acceleration).
- The Kalman filter became able to apply to inverse analysis by expressing track geometry in a random walk model, and having incorporated the model in an equation of state.
- The estimation technique has incorporated the impulse response calculated using the vehicle model in a measurement equation. The Kalman filter based estimation technique can support a change of the vehicle velocity by selecting impulse response in the measurement equation to cope with the vehicle velocity change.
- As a result of calculation, it was confirmed that the proposed estimation technique could estimate 10m-chord versine irregularity with an error within 1mm from the measured car-body acceleration. The result revealed that the estimation technique is effective for track condition monitoring with acceptable accuracy for conventional railways.
• Field test results show that the estimated results and the data obtained by track geometry recording car (TGC), in 10m-chord versine, has good agreement at the place that the large vibration was measured. But, some difference can also be seen by the external disturbances beside the track geometry. To avoid the effect of the external disturbances, statistical analysis with multiple measurement should be considered.

The proposed estimation technique can be integrated in the track condition monitoring software using compact size onboard device. To confirm the efficacy of the track condition monitoring technique, we need to test it using actual measured data.

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